LICENTIATE THESIS

Qualification of Metal Additive Manufacturing in Space Industry

Challenges for Product Development

Christo Dordlofva

Product Innovation

LULEÅ
UNIVERSITY
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Abstract

Additive manufacturing (AM), or 3D printing, is a collection of production processes that has received a good deal of attention in recent years from different industries. Features such as mass production of customised products, design freedom, part consolidation and cost efficient low volume production drive the development of, and the interest in, these technologies. One industry that could potentially benefit from AM with metal materials is the space industry, an industry that has become a more competitive environment with established actors being challenged by new commercial initiatives. To be competitive in these new market conditions, the need for innovation and cost awareness has increased. Efficiency in product development and manufacturing is required, and AM is promising from these perspectives. However, the maturity of the AM processes is still at a level that requires cautious implementation in direct applications. Variation in manufacturing outcome and sensitivity to part geometry impact material properties and part behaviour. Since the space industry is characterised by the use of products in harsh environments with no room for failure, strict requirements govern product development, manufacturing and use of space applications. Parts have to be shown to meet specific quality control requirements, which is done through a qualification process. The purpose of this thesis is to investigate challenges with development and qualification of AM parts for space applications, and their impact on the product development process. Specifically, the challenges with powder bed fusion (PBF) processes have been in focus in this thesis.

Four studies have been carried out within this research project. The first was a literature review coupled with visits to AM actors in Sweden that set the direction for the research. The second study consisted of a series of interviews at one company in the space industry to understand the expectations for AM and its implications on product development. This was coupled with a third study consisting of a workshop series with three companies in the space industry. The fourth study was an in-depth look at one company to map the qualification of manufacturing processes in the space industry, and the challenges that are seen for AM. The results from these studies show that engineers in the space industry work under conditions that are not always under their control, and which impact how they are able to be innovative and to introduce new manufacturing technologies, such as AM. The importance of product quality also tends to lead engineers into relying on previous designs meaning incremental, rather than radical, development of products is therefore typical. Furthermore, the qualification of manufacturing processes relies on previous experience which means that introducing new processes, such as AM, is difficult due to the lack of knowledge of their behaviour. Two major challenges with the qualification of critical AM parts for space applications have been identified: (i) the requirement to show that critical parts are damage tolerant which is challenging due to the lack of understanding of AM inherent defects, and (ii) the difficulty of testing parts in representative environments. This implies that the whole product development process is impacted in the development and qualification of AM parts; early, as well as later stages. To be able to utilise the design freedom that comes with AM, the capabilities of the chosen AM process has to be considered. Therefore, Design for Manufacturing (DfM) has evolved into Design for Additive Manufacturing (DfAM). While DfAM is important for the part design, this thesis also discusses its importance in the qualification of AM parts. In addition, the role of systems engineering in the development and qualification of AM parts for space applications is highlighted.

Acknowledgements

Starting a PhD project in the middle of my career was an easy decision at the time. I had found an interesting project that would let me dig into a subject in a way not possible in the industry. Little did I grasp the difficulty and complexity in academic research, and the difference to what I was used to do. It has been an interesting journey which has developed me on so many levels.

First of all, I want to say thank you to my team of supervisors consisting of Professor Anna Öhrwall Rönnbäck, Senior Lecturer Peter Törlind and Professor Ola Isaksson. All of you have contributed with so many valuable insights into doing research and how to relate to being an industrial PhD student. Above all, you have patiently answered my questions that sometimes might be a bit too basic. To my colleagues at Product Innovation, thank you for providing me with such an inspiring environment. A special thank you also to Professor Mario Štorga and his research team at the University of Zagreb who challenged me in our discussions on design research.

I would also like to thank the support I have received from the industry, and all the interest that is shown into my research. Most of all the respondents and other research participants that have contributed with such valuable knowledge.

A special thank you goes to the support in funding. The RIT project (Space for Innovation and Growth) with its project leader Johanna Bergström Roos who has arranged many interesting meetings that has allowed us to find industry cases. The Graduate School of Space Technology and its coordinator Professor Marta-Lena Antti that has provided a research setting with so many talented people. The Swedish National Space Board that provides funding through the Swedish National Space Research Programme (NRFP).

Lastly, thank you to my family which, despite being distant, always support me and remind me not to work too much. But above all, Anna, I did not realise how much this journey would impact you as well. Thank you for being so supportive and understanding. Only two more years.

Christo Dordlofva

December, 2017

List of Publications

Appended papers

Paper A

Dordlofva, C., Lindwall, A. & Törlind, P. (2016). Opportunities and Challenges for Additive Manufacturing in Space Applications, Proceedings of NordDesign 2016, Trondheim, Norway.

Author's contribution

The initiative for the paper came from Törlind who set the initial framework. The study visits and literature review were performed by Dordlofva and Lindwall. Dordlofva had the lead responsibility in writing the paper, with specific contribution on the qualification and space industry aspects. Lindwall contributed with the perspective of Design for Additive Manufacturing, while Törlind provided general comments on the text and guidance for the academic perspective.

Paper B

Lindwall, A., **Dordlofva, C.** & Öhrwall Rönnbäck, A. (2017). Additive Manufacturing and the Product Development Process: Insights from the space industry, Proceedings of the 21st International Conference on Engineering Design (ICED 17), Vancouver, Canada.

Author's contribution

The idea of a paper was a collaboration between Dordlofva and Lindwall, based on the data collection done together. Lindwall designed the framework of the paper and did most of the writing after the first analysis of the data. Dordlofva cross-checked the analysis and the results and discussion was thereafter updated by Dordlofva and Lindwall. Dordlofva specifically contributed with the literature review on the space industry. Öhrwall Rönnbäck assisted with the methodology, and all three contributed to the final version.

Paper C

Dordlofva, C. & Törlind, P. (2017). Qualification Challenges with Additive Manufacturing in Space Applications, Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium, Austin (TX), USA.

Author's contribution

The idea for the paper came from a discussion with Törlind. Dordlofva did all the data collection and analysis, as well as the writing. Törlind assisted with cross-check analysis, methodology and an academic perspective.

Table of Contents

1 Introduction

This chapter describes the background and motivation for the research presented in this thesis, together with clarification of important terminology. The purpose of the thesis is stated and the research questions are defined, including a section on delimitations.

1.1 Background

Additive manufacturing (AM) is a production technology that has received a good deal of attention in recent years within different industries due to its many benefits. One major advantage that is often highlighted is the potential for the rapid manufacture of customised designs. The increased availability of 3D printers using polymers has received much attention in the popular press, often with the notion that only the imagination limits what is possible. 3D printing is therefore often used as a collective term for AM technologies, regardless of the process or material (Gibson et al., 2015). For many industrial applications it is, however, 3D printing with metals that has seen a rapid increase in use (Wohlers et al., 2016), where the term AM is more often used. AM has also become the official industry term according to the ISO AM terminology standard (ISO/ASTM, 2015, p. 1), that defines AM as the:

> *"process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"*

AM has changed from being used for prototyping at early stages in the product development process (Rapid Prototyping) to the production of end-use parts (Rapid Manufacturing) due to the fast development of AM processes and different materials (Frazier, 2014; Gibson et al., 2015). Rapid manufacturing shows particular promise for the space industry due to the potential benefits of lower costs for product realisation, reduction in development time, simplification of the supply chain and improved product performance stemming from design freedom (Begoc et al., 2017). The research behind this thesis should, in the long term, contribute to the use of AM in space applications.

1.1.1 The Space Industry

The space industry is characterised by organisations, such as space agencies and large corporations, being capable of running projects requiring huge investments in time, money and resources (Fortescue et al., 2011). To cope with the investments needed to develop space products, it has historically been dominated by government-funded programmes (Anderson, 2013; Peeters, 2003). However, the industry has changed and has become commercialised and globalised, and with that has come a need to be innovative to stay competitive (Cornell, 2011; Peeters, 2003). The governing factors for this change have been: (i) a reduction in public funding, (ii) a high degree of maturity in space-related technologies, (iii) a change in the geopolitical scene with increasing market opportunities, and (iv) market globalisation (Peeters, 2003). Several new companies started in the 2000s, forming what is now called *New Space* (a term mainly linked to the USA). SpaceX is a main player in this New Space industry, with a successful history since its foundation in 2002 (Cornell, 2011). These new actors have an entrepreneurial approach to business, focusing on cutting costs and striving for innovation, making them compete for market share (Anderson, 2013; Cornell, 2011). This competition has put pressure on the established actors in the industry, making cost awareness and cost reduction both major drivers in new development projects (Brodin et al., 2016). One example of this is the long-term proposal from the French space agency (CNES) to the European Space Agency (ESA) to develop a next-generation rocket engine with a cost target of a 90% reduction compared to the current Ariane 5 main stage engine (SpaceNews, 2016). To meet such aggressive objectives, there is a need for cost-efficient product development and manufacturing. AM is a technology that is promising from both of these perspectives (Campbell et al., 2012).

Despite the need to stay competitive, two characteristics of the space industry cannot be forgotten – risk management and risk mitigation. The failure of parts is a question of huge financial impact, but also, in some cases, human lives (Kreisel & Lee, 2008). Space applications are simply not allowed to fail since there is no return once a rocket is launched, or no possibility of repairing a broken part in orbit. At the same time, space applications are exposed to harsh environmental conditions. Some parts, such as a rocket engine, have short life cycles (a rocket launch usually takes in the order of 10 minutes) but in extreme environments (e.g. temperature, pressure and vibrational loads) that they need to endure, while others may not be exposed to extreme loads but need to survive the launch and then function for several years in space, e.g. a satellite antenna. This puts very strict requirements on the development, manufacturing and use of parts for space applications, and minimising risk is therefore an inherent part of the space industry. As a consequence, there are strict regulations for space products (ECSS, 2008b). Qualification of a part before it is considered flightworthy is, therefore, standard procedure, and the more critical a part is, the tougher the requirements for qualification. Since AM processes are relatively immature, qualification of aerospace parts manufactured using AM is one of the most important challenges to overcome (Frazier, 2014).

Adding to the complexity of these products is the fact that they are usually produced in low volumes, where, for example, a specific satellite sub-system or an interplanetary rover can be a one-of-a-kind product, while rocket sub-systems are built in numbers of tens per year. These low volumes are challenging when it comes to finding material suppliers that are willing to produce parts at a reasonable cost. Weight is another factor that plays an important role in space applications since the cost of launching 1 kg of payload material into space is usually estimated to be between \$10,000 - \$30,000 depending on the mission (Fortescue et al., 2011). This has an effect on launcher systems as well, since weight saved on the launcher can be used for payload. These challenges could beneficially be addressed with AM due to the ability to realise complex, functional products through part consolidation, internal design features, lightweight design and part customisation (Campbell et al., 2012; Gibson et al., 2015).

1.1.2 Additive Manufacturing in the Space Industry

A review of the future of AM technologies in the aerospace sector concluded that *Powder Bed Fusion* (PBF) and *Directed Energy Deposition* (DED) are the processes that are currently most applicable for the aerospace industry (Uriondo et al., 2015). Figure 1 shows the classification of metal AM processes suitable for aerospace applications, divided according to the material supply and energy source.

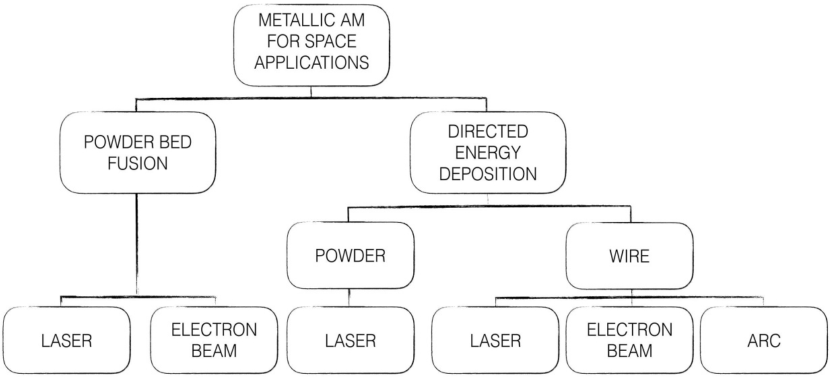

Figure 1 - Overview of metal AM processes in the aerospace industry (inspired by Uriondo et al., 2015)

In respect of direct part manufacturing using AM, the choice of process has to be taken considering the product to be made. PBF offers a finer surface quality and part accuracy, and is also more advantageous for producing more complex 3D geometries with features such as overhang, due to the additional support from the powder bed and support structure (Ding et al., 2015; Thompson et al., 2015). Wire-feed technologies are more promising for larger features with moderate complexity, such as flanges or to stiffen panels, and when high deposition rates are needed (Ding et al., 2015; Frazier, 2014). In this thesis, the term AM will be used throughout to mean metal AM processes. Furthermore, PBF has been seen to be used in many cases in the space industry (examples can be found in Begoc et al., 2017; Orme et al., 2017; Rawal et al., 2013) and this technology is therefore the one focused on (although the discussion can be applicable for other processes as well).

In PBF processes, a layer of powder is deposited onto a build plate from a powder delivery system using some form of mechanism, usually a roller or a rake. For each subsequent layer, the plate is then lowered a pre-set distance which is the layer thickness of the process. An energy source (laser or electron beam) melts the pattern of each 2D layer to build the part. Parameters such as layer thickness, scanning strategy, energy input, build orientation, and support structure (for overhang features) can be selected as determined by the part (Gibson et al., 2015). Figure 2 shows a schematic diagram of how the PBF process works in principle.

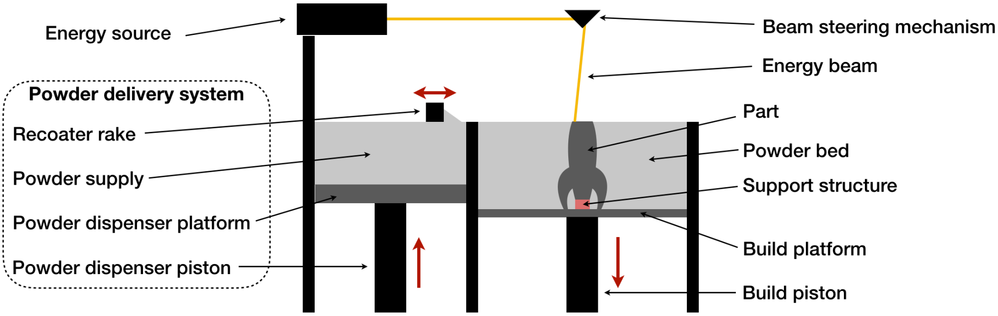

Figure 2 - Schematic diagram of the powder bed fusion process

1.2 Clarification of Terminology

This section gives an explanation of specific terminology that is used throughout this thesis.

1.2.1 Aerospace Industry

The terminology used for aerospace related industries is somewhat ambiguous. In the US, aeronautics seems to be the word used for aircrafts (civil and military) while aerospace is considered to mean the space industry. In the media and literature, the term aerospace is often used as a collective term for the industry, both civil or military aircraft, as well as space-related products. For clarity, this thesis will use the word *aeronautics* for the aircraft industry and *space* for the space industry if there is a need to distinguish between the two. The term *aerospace* will be used as a collective term for both.

1.2.2 Qualification

The word *qualification* is ambiguous, and whose meaning depends on the context. The words *verification* and *certification* are also used in similar contexts. In aeronautics, qualification seems to be used for manufacturing processes, while certification is the final proof of a product meeting all its requirements (performance and governmental regulations, i.e. FAA or EASA). In the space industry, the word qualification is used for both processes and products. Verification is mostly used in both contexts as a way to show repeatability or agreement with expectations or simulations. The term *qualification* will be used in this thesis referring to both products and processes, and a suitable description of its purpose is: *"While qualification procedures vary between applications or industries, the goal of qualification can be summarized as the collection of sufficient data to demonstrate that a material or process will function as expected."* (NIST, 2017).

1.2.3 Systems Hierarchy

There are several actors involved in the development of space products that are referenced in this thesis. Figure 3 shows a simplified view of a typical hierarchy in the European space industry, where governmental and national space agencies are at the top providing regulations and guidance for the development, manufacturing and use of space applications.

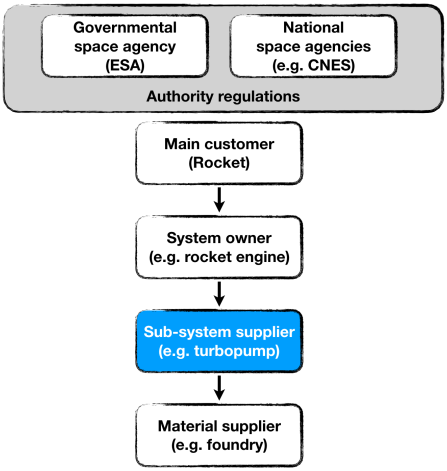

Figure 3 - Simplified overview of a typical hierarchy in the space industry with the sub-system supplier as the focus (inspired by ECSS, 2008 and Fortescue et al., 2011)

The perspective of this thesis is from that of a sub-system supplier for e.g. a rocket engine, where the rocket engine is considered to be the system (being part of another system, the rocket). The system owner in this case has responsibility for the engine, setting requirements for the sub-system. The sub-system supplier, on the other hand, has its suppliers e.g. a foundry for castings materials, to which they specify the requirements. When the terms *system owner*, *sub-system supplier* and *supplier* are used in this thesis, Figure 3 should be referenced.

1.3 Research Motivation and Purpose

The motivation behind this research is the need for established methods to qualify AM parts for space applications. A great deal of effort in industry and academia is put on AM process and material development, while the need for including the product development process in qualification is also important. The purpose of this thesis is to investigate challenges with development and qualification of AM parts for space applications, and their impact on the product development process.

1.4 Research Questions

The following research questions have been set up to guide the research presented in this thesis.

RQ1: What characterises development and qualification of parts in the space industry?

RQ2: Why is qualification of AM parts challenging for critical space applications?

RQ3: How does development and qualification of AM parts impact the product development process for space applications?

1.5 Delimitations

While much research on AM qualification has focused on the development of processes and materials for AM, this is not the focus of this thesis. It should also be mentioned that AM in this context refers to manufacturing parts on Earth for use in space, not manufacturing in space.

1.6 Thesis Outline

The next chapter will address the research method that has been followed to provide an understanding for the research setting and the methods used. Chapter 3 describes the theoretical framework on which the appended papers and the thesis discussion is based. Chapter 4 is a summary of the appended papers, while their results are presented and discussed in chapter 5. Conclusions and future research are described in chapter 6.

2 Method

This chapter describes the scientific approach that has been used and how the research was designed to answer the research questions. Four studies constitute the data collection and each is described in detail.

2.1 Scientific Approach

The scientific approach chosen for this research project was determined by the research context and the experience of the researcher (the author). This section describes the logic and motivation behind the chosen approach.

2.1.1 Research Context and the Role of the Researcher

Before starting this PhD project, the author worked for several years on product development in the space industry, including different roles from design engineer to lead engineer. The research was carried out in an industrial setting where the author had the role of an industrial PhD student at one of the companies included in the studies. The studied phenomenon, i.e. development and qualification of AM parts for space applications, is a topic of great interest within the industry (as stated in chapter 1), and the research has therefore received much attention in this company, with expectations for the practical use of the results. It has therefore been important to stress the scientific perspective of the research, and the author has taken the role as an independent researcher without direct participation in specific company-related projects. At the same time, the internal knowledge and industry experience of the author has helped the analysis of internal documents and interview transcripts due to a deeper understanding of their meaning in the context. As discussed by Kvale (1988), the knowledge or expertise of the studied field by the researcher can also be seen as a prerequisite for arriving at valid interpretations.

2.1.2 Research Approach

To understand the implications of AM for product development and the qualification process, a deeper insight in how these are carried out was a relevant starting point. Case study research was considered as a relevant approach for this exploratory step of the research project, focusing on ‘how’ the company currently works (Yin, 2014). The research context and the position as an industrial PhD student also presented the opportunity to carry out such case studies.

While reviewing steering documents gives an overview of how a company has defined their product development process, the experience and knowledge of the engineers working in the process are best captured through interviews (Brannen, 2007). The primary method chosen for the case studies has, therefore, been interviews, coupled with the study of internal steering documents. The research approach for this thesis is hence of *qualitative* nature, which has the potential to gain a holistic and real-world perspective based on testimonies from respondents (Yin, 2014).

The objectiveness in a researcher can always be debated, and what is considered right or wrong is a matter of philosophical worldview (Creswell, 2014). As an internal researcher, i.e. a researcher having experience of, and insight into, the studied phenomenon from within a company, studying a phenomenon with practical consequences means that the pre-knowledge of the researcher cannot (and should not) be ignored.

2.2 Research Design

The methodological approach for the PhD research project is inspired by the framework given in *DRM – Design Research Methodology* (Blessing & Chakrabarti, 2009), shown in Figure 4. There are four steps in this framework: *Research clarification*, *Descriptive study 1*, *Prescriptive study* and *Descriptive study 2*. The aim of the research clarification stage is to gather enough evidence to support and formulate the envisioned research goal, and is typically achieved by reviewing the literature. The output is an initial description of the current situation (state of the art). In the descriptive study 1 stage, this description is developed by further literature studies, but empirical studies are included to strengthen the findings with deeper insight of the studied phenomenon. The output is a more comprehensive description of the current situation (ibid.). To address the purpose of this thesis, these two stages have been used to explore the research problem. Qualitative studies are relevant for such exploration (Creswell, 2014), and interviews and workshops have been used as sources of data collection. As is further illustrated in Figure 4, three papers (appended) constitute the research presented in this thesis, based on four studies involving three different companies. A study tour was used in addition to a literature review for the research clarification stage.

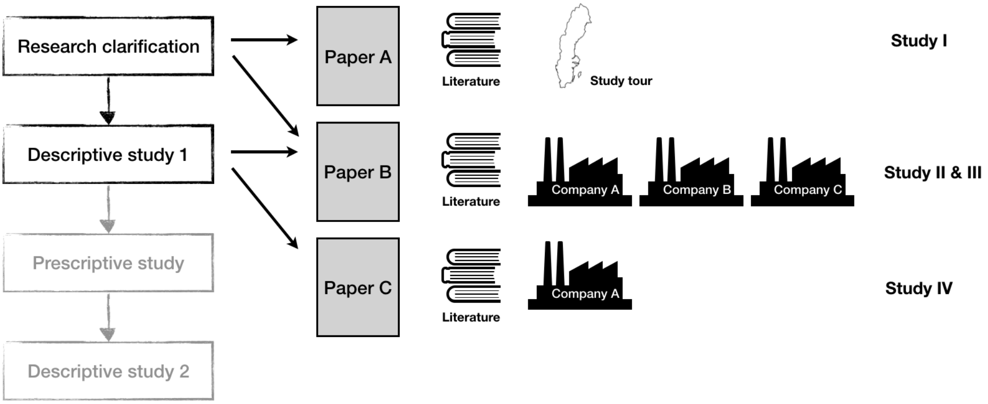

Figure 4 - The steps in the DRM process (adapted from Blessing and Chakrabarti, 2009) and their link to the appended papers and the studies

2.3 Description of the Studies

The data collection for the appended papers was realised in four studies labelled I, II, III and IV, that were carried out chronologically in the given order. Table 1 shows the objective of each study, the unit of analysis, the research methods used and the main data collection sources. A description of each of the companies participating in the studies is presented in Table 2.

Table 1 - Summary of the studies

Study	Objective	Unit of analysis	Research method	Main data collection sources
I	Describe state of the art and state of practice of AM and identify research gaps	*AM processes as manufacturing technologies*	- Literature review - Study visits	- Scopus - 11 study visits
II	Describe the product development process in the space industry and what expectations there are for AM	*Product development process in the space industry*	Case study	- 8 interviews - Documents
III	Describe the expectations for AM from the perspective of multiple cases	*Use of AM in the space industry*	Multiple case study	- 3 workshops
IV	Describe the qualification process(es) and what implications there are for AM	*Qualification process in the aerospace industry*	Case study	- 15 interviews - Documents

Table 2 - Description of the participating companies

Company	Description
A	The company develops complex and high-performance components for aerospace. The studied part focuses on product development and manufacturing of sub-system components for launcher applications.
B	The studied company operates in the space industry, an industry that currently sees a number of new competitive initiatives in Low Earth Orbit (LEO) constellation programmes. The responsibility includes the whole chain from R&D to sales for several product areas.
C	The studied company provides advanced space services and product development subsidiaries. The visited site focuses on product development for experimental platforms and satellite propulsion.

2.3.1 Study I

The first study was of explorative nature with the purpose of gaining an understanding of AM, to define the current state of the art and state of practice in different industries, and to identify challenges as well as research gaps. Of special interest to the author was to map what had been done relating to AM qualification. Since AM was a relatively new domain for the author, there was a need to understand the different AM processes that are available. At this stage, it was considered important to have an open mind in the selection of relevant AM processes to study, and therefore care was taken not to exclude any from the start.

In case study research, the first step should always be a thorough literature review to enable the asking of relevant research questions (Yin, 2014). This first study therefore consists of a structured literature review, coupled with a tour of study visits to companies and universities active in AM around Sweden.

Literature review

The structured literature review used the term *additive manufacturing* in combination with specific words of interest, where the most relevant are shown in Table 3. After a comparison between *Scopus* and *Web of Science*, Scopus was chosen as the main source due to its inclusion of many conferences, and since a large discrepancy between the two could not be seen for journals. It became clear that much of the available literature had been written by industrial representatives attending conferences, and it was considered that these articles were important to capture the state of the art of AM.

Table 3 - Words and expressions used in combination with "additive manufacturing" in the structured literature review

Words used with ‘additive manufacturing’	
Review	‘Design for additive manufacturing’
Qualification	‘Design process’
Verification	‘Rocket engine’
Certification	Aerospace

Study visits

The study visits were chosen from what was learnt during the literature reviews when research groups or companies were identified. The visited companies and universities are shown in Figure 5. These visits were important as they gave a broad overview of different activities within AM and gave a valuable understanding of the context of AM.

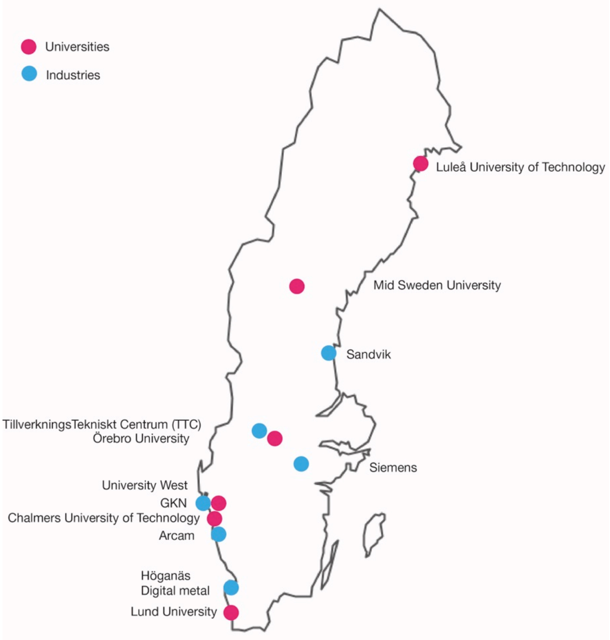

Figure 5 - Visited companies and universities during the AM tour of Sweden (map by Angelica Lindwall, published with permission)

Each of the study visits was documented soon afterwards, following a procedure where one of the participants summarised the visit based on notes and memory. The remaining participants (usually two) then read through the summary, making adjustments or additions in agreement with the others.

The experience gathered from this study was used to write Paper A, which resulted in the background used to design the studies II, III and IV.

2.3.2 Study II

The purpose of the second study was to understand both the product development process in the space industry as it is currently practiced, and how AM is expected to impact this process. This investigation consisted of an in-depth study of one company (Company A). The study was designed and carried out together with the co-authoring PhD student of Papers A and B, with feedback from a senior researcher during the development of the study.

Data collection

For the purpose of understanding the product development process, internal documents from the company management system were first studied. The industry experience of the author helped the reading of the documents through interpretation of industry jargon. With the gathered insight into the company's product development process, and with gathered knowledge from the literature, an interview guide was designed for a series of interviews with engineers working with space products (see Appendix A for interview guide). The interviews had both the purpose of recording the respondents' understanding of the product development process, as well as their expectations for introducing AM into this process. Eight engineers were chosen from a pool of roughly 60 employees working with space products. The engineers were chosen based on seniority, to capture the opinions of those who had experience of working with product development in different phases. All interviews were recorded (sound).

2.3.3 Study III

The purpose of the third study was to map the expectations of the space industry for what AM would bring in terms of new opportunities, but also what the major challenges are considered to be. To be able to draw broader conclusions, three different companies (Company A, B and C) were included in this study that consisted of a workshop series. The study was designed and carried out by the author, the co-authoring PhD student of Papers A and B, and two senior researchers.

Data collection

The companies were chosen based on their established presence in the space industry, and their expressed interest in AM when approached during industrial meetings. The workshops followed the same structure for each company (see Appendix B for the agenda). All workshops were documented using the same format by one researcher who did not actively participate in the workshop activities. All notes were written text, complemented with pictures of the outputs from the workshops (post-it notes and canvases). Each set of documentation was sent to the company in question a few days after the workshops for comments.

The results from studies II and III were described in Paper B.

2.3.4 Study IV

This study focused on describing the development and qualification of different manufacturing processes in the aerospace industry, and was an in-depth study of Company A. The study was designed and carried out by the author himself, with feedback from a senior researcher during the development of the study.

Data collection

Since the studied company is active in both aeronautics and space-related development programmes, several of the respondents had experience of working in both areas, which gave an insight into the differences and similarities between the two. The interviews were designed and planned based on experience from Study II, with three research questions set up for this study:

1. How are conventional manufacturing processes qualified?
2. How are new manufacturing processes introduced and qualified?
3. What are the challenges regarding qualification of AM processes?

The study was divided into two parts, where the first mainly focused on the first two questions. Eight senior engineers and process specialists were chosen based on their role in the company and were then interviewed using a semi-structured approach (see interview guide in Appendix C). The second part of the study mainly focused on the last research question. Seven new respondents were chosen based on recommendations from the first set of interviewees (snowball effect), and the interview questions were modified according to what was learned in the first part, as well as the area of expertise of the respondent (see Appendix D for an example of the interview guide). The collective manufacturing process experience of the respondents covered casting, welding, forging, fibre composites and different AM technologies (powder bed fusion and directed energy deposition). All interviews were recorded (sound).

The results from study IV were described in Paper C.

2.4 Interview Data Analysis

There is no standard way of carrying out interview analysis which is a consequence of the complexity and richness of qualitative data (Kvale, 1988). For the interviews carried out in this research, an approach was used as described by Miles & Huberman (1994). The basic principles are shown in Figure 6. The process of collecting interview data was presented in the description of studies II and IV. The analysis of the interview data is described in this section, and was the same for studies II and IV.

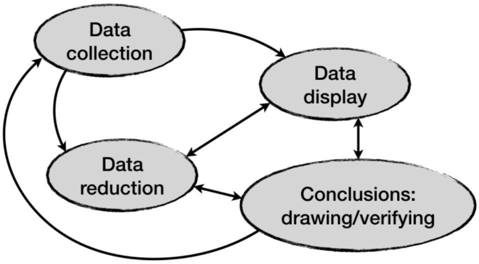

Figure 6 - The components of qualitative data analysis (adapted from Miles and Huberman, 1994)

Data display

The recordings from all interviews were transcribed into text to be used for the analysis. The transcriptions of the interviews were shared among the two PhD students for Study II, and the author carried out all transcriptions for Study IV. While the transcription of an interview is an important step in data analysis, it should be remembered that it is not able to capture all of the interactions that occurred during the physical interview (Kvale, 1988). In the transcription of Study II, the transcriptions were therefore made at a 'micro-level', including 'ers', 'ums' etc. in an attempt not to exclude reactions by the respondents. This approach was rather time-consuming and produced texts that were extensive and difficult to read.

The choice of using exact verbatim transcripts versus edited, more readable, transcripts should be dependent on the nature of the material and the purpose of the study (Kvale, 1988). For Study IV, an approach was therefore chosen in favour of a more readable text. The motivation for this was that the purpose of the interview was explorative (which was also the case for Study II), and the relevance in the analysis was to follow up the interesting aspects of what was said during the interview in order to investigate the discussed topics (Tesch, 1987, in Kvale, 1988). Significant hesitations or pauses were, however, noted.

Data reduction

Data reduction through pattern matching (selective coding) was then used to identify recurring and dominant themes (Miles & Huberman, 1994). The pattern matching was achieved through two steps:

1. Identifying common sub-categories when reading the transcripts
2. Moving extracts (quotes) from the transcripts into the suitable sub-categories

It should be noted that, as shown in Figure 6, the process of data display, data reduction and drawing conclusions was iterative. The reduced data was displayed in a separate format to ease the analysis and was further reduced within the new display format when necessary.

2.5 Research Quality

The quality of qualitative research can be expressed through its validity and reliability (Creswell, 2014), and this chapter describes the strategies that have been used to assess the quality of the research that was carried out for the presented studies.

2.5.1 Validity

Validity in qualitative research addresses the accuracy of the findings by adopting certain strategies to assess its trustworthiness, authenticity and credibility. *Triangulation*, *bias clarification*, *external auditors* and *member checking* are four such strategies (Creswell, 2014).

Triangulation has been used in the analysis of interviews as presented in this chapter. Where applicable, the intention has been to state clearly if a finding is based on the testimonies of one or a few respondents. The interviews in studies II and IV constitute the main source of data collection presented in this thesis, and care has therefore been taken to be as transparent as possible given the request for confidentiality from the studied companies. Study III contributed to the external validity of the results presented in Paper B with complementary perspectives from different companies through multiple case studies (Yin, 2014). The research setting has also been explained, along with how the author is bound to have a certain bias in the design of the research and the analysis of the results due to a background within the field. This has been compensated for by using co-authors with less experience of the specific industrial context as external auditors of the data analysis.

It could be argued that there is a lack of validity in that interview transcripts or major findings were not sent back to respondents to check their accuracy. However, the close collaboration with the industry in the research project has required finished papers to be screened before publication, as well as maintaining a continuous discussion of the results. This has compensated for the lack of member checking, although it is acknowledged that the individual opinions of the respondents are not accounted for in this procedure.

Spending *prolonged time* within the research setting is another strategy that contributes to the validity of research through in-depth understanding of the studied phenomenon (Creswell, 2014). In the role of an industrial PhD student, information is gathered from meetings and talks with engineers that is not formally documented as research data. However, given the author's previous experience from different product development projects, this information contributes to the overall understanding, and is valuable secondary data. The study visits in study I also provided secondary data that have added to the overall understanding of the research, as has conversations with industry experts at conferences and other industrial meetings.

2.5.2 Reliability

Reliability of qualitative research is a question of showing that the research has been carried out in such a manner that the derived findings are consistent. This is often described as the way in which another researcher could follow the same procedure, and carrying out the same study over again, to arrive at the same findings and conclusions (Yin, 2014). This should be ascertained through documentation of the procedures, and as many steps of these procedures as possible, as well as documentation of the results (ibid.). It should however be noted that there is a practical limitation in the possibility to repeat exactly the same study, but the strive should be to make an as detailed account as possible.

To ascertain the reliability of the presented research in studies II, III and IV, the design of the studies included structured documentation of: the purpose of the studies, the planned interview respondents (studies II and IV), and planned workshop activities (study III). These procedural documents were updated during the studies if changes were made so as to keep track of what was planned from the beginning, and what was finally carried out.

The documentation of the data collection in studies I to IV followed structured procedures that have been described in this chapter. Since more than one researcher was involved in each of the studies, cross-checks of texts, transcripts and coding were carried out to avoid obvious mistakes and to make sure that the meaning of the codes was interpreted in the same way (Creswell, 2014). Since workshops can be dynamic, making it difficult to document all the activities, photographs and diagrams of the activities and the outcomes were included to enrich the documentation.

3 Theoretical Framework

This chapter presents the theory that forms the foundation for the design of the studies and has helped to build the argument in this thesis. Product development and additive manufacturing are central areas of this research, while unique characteristics of the space industry add an important part to the context and are therefore introduced here as well.

The theoretical framework presented in this chapter is based on four main subjects: *product development*, *additive manufacturing*, *the space industry* and *product qualification*. Each of these areas are, in themselves, multifaceted and only specific relevant areas have been considered here. Figure 7 shows a context map of this chapter covering what is described, but also depicting where the thesis discussion is expected to contribute.

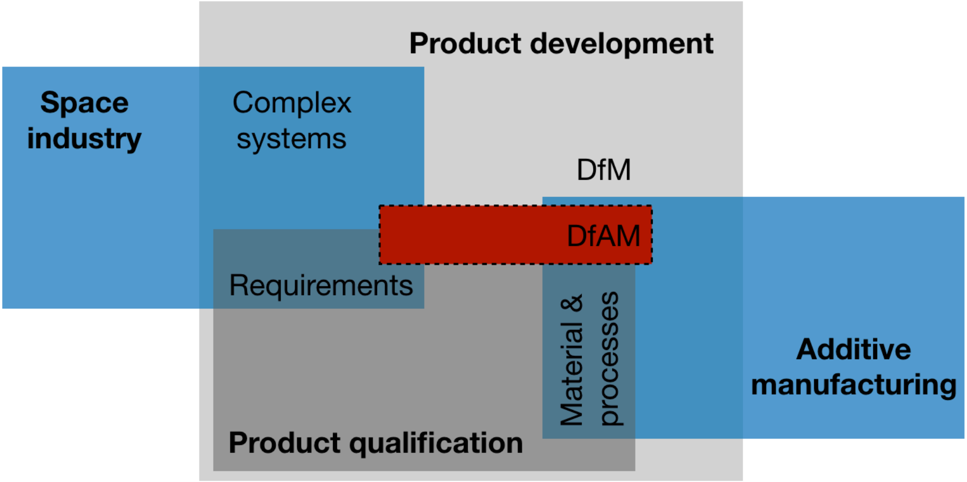

Figure 7 - Context map of the theoretical framework with the contribution area of the thesis in the centre (dotted line, area in red), where Design for Additive Manufacturing (DfAM) is a central part

3.1 Product Development of Complex Systems

The design and development of products is a process, a sequence of activities that is carried out with the aim of defining a product and releasing it to the market (Ulrich & Eppinger, 2012). The form of the product development process can be different depending on the product, company and/or industry. In some cases, the use of a structured process is not beneficial, while in others it is essential (ibid.). The studies in this thesis have focused on larger organisations where there is usually a need for a structured way of working (Ahmed-Kristensen & Daalhuizen, 2015). A well-established representation of a structured product development process is described by Ulrich & Eppinger (2012), where the process is divided into six phases: *planning*, *concept development*, *system-level design*, *detail design*, *testing and refinement*, and *production ramp-up*. The task of the design team is to interpret the given requirements into tangible physical constraints and functions, i.e. to develop technical solutions and make the abstract concrete by following the steps in the process. However, in practice, the distinction between the steps is not always clear, and iterations are often, rightly so, needed (Pahl et al., 2007; Ulrich & Eppinger, 2012). A common alternative term for system-level design is *embodiment design* (see e.g. Pahl et al., 2007) which will be used in this thesis to avoid confusion with the term systems design. Larger systems, such as aircraft, cars or rocket engines, are generally considered to be complex engineering systems (Simpson & Martins, 2011). In this thesis, the term *complex system* refers to these types of large systems and *systems engineering* is the field of development of complex systems (Blanchard & Fabrycky, 2006).

3.1.1 Systems Engineering and Interface Management

Systems engineering is the typical approach to product development in the space industry (Fortescue et al., 2011). Most products in the space industry are complex systems of systems working together, where each sub-system contributes to the overall function (e.g. thrust for a rocket engine or earth monitoring for a surveillance satellite). The typical approach in system development is to decompose the requirements of the upper levels in the hierarchy to manageable pieces, that flow down to lower levels (sub-systems) (Crawley et al., 2004). Due to the complexity of these systems, the system owner must maintain a holistic view of the complete system, making sure that all parts function and fit together. Interface management is, therefore, a crucial part in the development of complex systems, assisting this holistic view when development is divided between different actors. The purpose is to achieve functional and physical compatibility between sub-systems and parts in the product architecture (ECSS, 2015). External interfaces (between sub-systems) are controlled by the system owner, while internal interfaces (within the sub-system) are controlled by the sub-system supplier (ECSS, 2015). Figure 8 shows a simplified diagram of the product development process in sub-system development that will be used in this thesis.

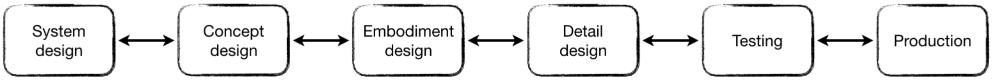

Figure 8 - Simplified product development process in systems engineering from the perspective of sub-system design (inspired by Fortescue et al., 2011; Pahl et al., 2007; Ulrich & Eppinger, 2012)

3.1.2 Requirements for Space Applications

For the purpose of this thesis, the standards from the European Cooperation for Space Standardization (ECSS) have been used to define requirements for space parts. The standards have been made available for projects within the European space industry and are applicable for the development of all space products (ECSS, 2008b).

Part criticality

In the development of a space part, an assessment has to be made as to the severity of the result of the part failing (ECSS, 2009a). This assessment includes quantitative structural screening as well as qualitative hazard analysis. If a failure is considered to lead to a hazardous event (accident resulting from a condition of the part), four categories exist in which the part function is classified according to dependability[1] and safety[2], where the customer (system owner) agrees to the criteria (ECSS, 2017a, 2017b). The categories are given in Table 4.

Table 4 - Classification of severity categories for space parts (adapted from ECSS, 2017a, 2017b)

Category	**Level**	**Type of consequences**	
		Dependability	**Safety (examples)**
Catastrophic	1	Failure propagation	- Loss of human life - Loss of system
Critical	2	Loss of mission	- Severe but not life-threatening injury - Major damage to an interfacing flight system
Major	3	Major mission degradation	---
Minor or Negligible	4	Minor mission degradation or any other effect	---

If the structural failure of a part is considered to result in either a catastrophic or critical hazard, fracture control has to be applied during the development. This is based on the assumptions that: (i) all structural elements contain crack-like defects located in the most critical area, in the most unfavourable orientation, and (ii) materials exhibit a tendency to propagate cracks after a sufficient number of cycles at sufficiently high amplitudes (even in non-aggressive environments). This holds for both cyclical and sustained tensile stress loads. The fracture control includes a *damage tolerance* design approach for the part, i.e. it has to be shown to withstand local defects without degradation below the specified performance. Analysis and/or testing can be used for the verification of the part, and a Non-Destructive Test (NDT) method has to be verified to detect the assumed defect size with sufficient confidence (ECSS, 2009a).

Safety factors

Safety factors are used in the development of space parts for dimensioning and design verification, where the purpose is to *"guarantee an adequate level of mechanical reliability for spaceflight hardware"* (ECSS, 2009b, p. 11). The factor is a number that is applied to loads in the design analysis and is typically in the range of 1.1 to 1.5 (but can be higher), depending on load case according to established tables. For fatigue analysis, a factor of 4 is usually applied to the number of cycles. The exact safety factor is determined by considering the uncertainty of loads, design, material, manufacturing and verification parameters, and is always agreed with the customer (system owner) (ECSS, 2008a, 2009b).

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[1] The extent to which the fulfilment of a required function can be justifiably trusted. Its main components are reliability, availability and maintainability (ECSS, 2012b).

[2] State where an acceptable level of risk is not exceeded (ECSS, 2012b).

Technology Readiness Levels

To ascertain that new technologies or product concepts are mature enough when they are introduced, the technology readiness level (TRL) scale was developed by NASA in the 1970s, and later formalized by Mankins (1995). The scale is a tool to measure the TRL of a new technology, and to compare different technologies to each other. The need for the TRL scale stems from that the emergence of a new technology usually builds on the success of its predecessors (Mankins, 2009). The scale goes from TRL 1 for early research and development activities, to TRL 9 for flight proven technologies. The use of new technologies in product development usually requires that they have been developed and demonstrated to TRL 6 (Fortescue et al., 2011).

3.2 The Qualification Challenge of Additive Manufacturing

The popularity of AM has increased the number of applications within different industries, with examples of AM parts in the aeronautics industry found in for example GE (2015) and Safran (2017). However, information about the criticality level of such parts is rather scarce (Gorelik, 2017) and, within the space industry, secondary structures and other non-critical parts have been in focus (Brandão et al., 2017). Examples of space applications using AM can be found in work such as that by Orme et al. (2017) and Rawal et al. (2013). The general approach for introducing AM has been to *"walk before you run"* as stated by Gorelik (2017, p. 171), leading to a careful selection of suitable parts to build up knowledge gradually about the processes. This challenge of using AM for direct manufacturing of critical applications has been discussed in several earlier research studies (see e.g. Frazier, 2014; Seifi et al., 2016; Taylor et al., 2016).

The qualification of AM parts and processes is dependent on the development of the AM processes themselves, but also on the methods and technologies used throughout the product development process assisting the production of AM parts. Brandão et al. (2017) described this as a need to establish an 'end-to-end manufacturing process', where early design, material supply, manufacturing, post-processing and qualification are all linked to the production of critical AM parts. With this holistic perspective of product development for AM parts, a summary of a literature review was given in Paper C, where critical areas involved in AM qualification were identified. These areas are further explained in the following section.

3.2.1 Characteristics Impacting the Qualification of Additive Manufacturing

The areas identified as impacting the qualification of AM are shown in Figure 9. The areas are applicable to AM technologies in general, but with specific concerns dependent on the process characteristics. For this reason, the consequences of using PBF technologies will be discussed explicitly, when appropriate, due to the specific interest in their characteristics in this thesis. Different PBF technologies utilise different mechanisms for the fusion of powder particles during the build: solid-state sintering, chemically induced sintering, liquid-phase sintering or full melting (Gibson et al., 2015). Full melting is the most common mechanism for metal alloys, where the energy input is normally high enough to partially re-melt already solidified material, thus creating well-bonded, high-density structures (ibid.). Only full melting is considered in this thesis, restricting the processes to laser PBF and electron beam PBF, often called Selective Laser Melting (SLM) and Electron Beam Melting (EBM) respectively.

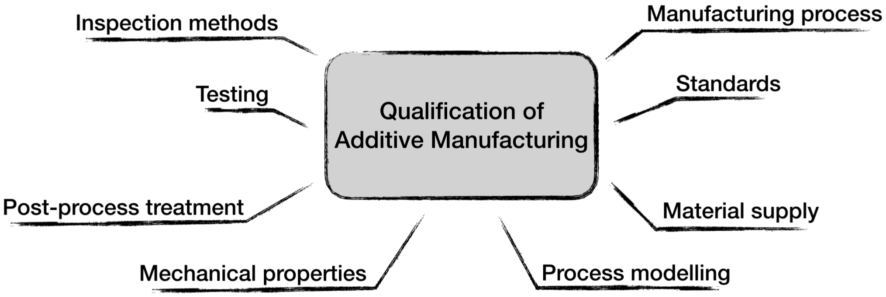

Figure 9 - Areas linked to the qualification of AM parts

Manufacturing process
Current AM processes produce variations in the material of the final printed parts, both on a part-to-part basis as well as a machine-to-machine basis (Frazier, 2014; Slotwinski & Garboczi, 2015). This process variability is not completely understood at present (Slotwinski & Garboczi, 2015), but needs to be since it could otherwise be a limiting factor in the use of AM for critical components (Seifi et al., 2016). While similar process variability is seen in conventional processes such as casting or welding, these can be handled because of decades of development and characterisation. There are established standards for their use, established test methods for material characterisation and established inspection methods for the verification of materials and parts (Taylor et al., 2016). AM processes, on the other hand, are new and continuously evolving with a wide variety of AM technologies being available (Wohlers et al., 2016). The possibility to vary and develop process parameters (e.g. scan strategy and energy input) within one machine, and different machine types having different process characteristics, makes it difficult to compare built parts and machines (Lewandowski & Seifi, 2016).

Standards
The lack of standards is regarded as one important barrier for the use of AM on a broader scale in regulated industries (Monzón et al., 2014; Uriondo et al., 2015). Both the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) have formed working groups specifically for this task and, in 2013, they agreed to develop common AM standards jointly within an ISO-ASTM working group. Currently, there are seven published AM ISO standards, with 12 under development (ISO/TC-261, 2017). However, the particular characteristics of AM processes and materials, and the range of available processes, makes standardisation of AM complex, and standards used for conventional manufacturing processes or materials are not always suitable (Monzón et al., 2014). Standardisation of new technologies takes time and, therefore, early adopters usually have to rely on their own internal proprietary specifications for implementation (Seifi et al., 2017). An example is NASA that said *"NASA cannot wait for national Standard Development Organizations to issue AM standards"*, and has consequently developed their own standards with a target release date in 2018 (Clinton, 2017, p. 16). However, the contribution of future general standards is still significant since they could potentially give a reference of minimum requirements that might help the implementation of AM (Seifi et al., 2017). Standardisation (or the establishment of specifications) is relevant for the manufacturing process itself, and for all of the following areas.

Material supply

Powder quality can have a significant impact on the part being built and there are several properties of powder that have been shown to be important: morphology (particle size and size distribution, shape, and surface roughness), chemistry and microstructure (Sutton et al., 2016). While these properties are known to impact a part's properties, more research is needed to fully understand their implications (ibid.). A powder's properties depend on the process by which the powder was manufactured, e.g. plasma-atomised or gas-atomised (Li et al., 2016), making it necessary to control the material supply source as well. Since there can be a substantial amount of unmelted powder after each build, it is possible (and often practiced) to re-use powder for successive builds. There is, however, still a lack of understanding of the difference between using virgin and re-used powder, and the impact it has on part quality (Slotwinski & Garboczi, 2015). Characterisation of powder is therefore an important part of securing powder quality, and while several techniques exist and are being used, they still need further development, especially for industrial use (Sutton, et al., 2016). Another issue with PBF that has to be considered is contamination (foreign particles). Brandão et al. (2017) discussed how contamination during the powder manufacturing process or cross-contamination when different powder alloys are used in the same machine, can result in the introduction of foreign particles that can have detrimental effect on material properties. Therefore, they recommend that only one powder alloy should be used for each AM machine.

Process modelling

Simulation of AM processes is still quite rudimentary but is an important step in the understanding and qualification of the process (Gockel et al., 2014; Martukanitz et al., 2014). Accurate models are essential for prediction of the resulting material characteristics and need to be developed. Physics-based modelling to correlate micro (phases), meso (grain size) and macro (residual stresses) structures with processing variables are needed, as well as their coupling to fluid dynamics (e.g. transient melt pools) (Uriondo et al., 2015).

Mechanical properties

The mechanical properties of built AM parts are at the centre of the qualification challenge since they dictate the performance of the part but are difficult to characterise due to the variation in the process. This has meant that material properties has been scrutinised by both academia and industry, and a comprehensive review of this research can be found in Lewandowski and Seifi (2016). While the material properties of AM parts have been shown to be comparable with, and sometimes even exceed, those of conventional materials (e.g. casting and forging), the research on standardised test coupons is still limited and very little research has been presented on fatigue properties (e.g. low cycle fatigue, fatigue crack growth and fracture toughness) or environmental effects (e.g. hydrogen embrittlement) (ibid.). Fatigue properties are especially important to aerospace applications since such applications are often characterised by loaded, fatigue exposed components that, in turn, become fracture critical (Seifi et al., 2016).

Microstructure and anisotropy

Parts that are built layer-upon-layer exhibit a change in heat distribution in the part as it cools down from the bottom and up towards the heat source. This has an impact on the thermal history of the part and the achieved microstructure and residual stress which in turn govern the material properties (Gu et al., 2012). Furthermore, the geometry of the part impacts the thermal history, making it unique for each PBF part (Murr, 2015). This has the effect that

PBF materials exhibit anisotropy, i.e. a dependence on direction, and location dependent properties (Gorelik, 2017; Gu et al., 2012; Lewandowski & Seifi, 2016). Scanning strategy and selection of process parameters play an important role in the achieved microstructure (Murr, 2015).

Defects

Material defects is a factor with a significant impact on mechanical properties, and therefore the characterisation of material defects (anomalies) is one of the most important tasks to carry out (Gorelik, 2017). Common defects that are encountered in PBF processed materials are pores, unmelted powder (lack of fusion), cracks (often due to residual stress or pores) and inclusions (contamination) (Brandão et al., 2017; Everton et al., 2016; Gu et al., 2012). Both internal and sub-surface defects impact the fatigue properties of AM parts, but if sub-surface defects are present, the fatigue limit is lower than if they are deeper in the part (Beretta & Romano, 2017; Romano et al., 2017). It is interesting to note that an increase in packing density of the build chamber and the volume of the build (impacting build time) has been seen to have an increasing effect on the number of defects, and hence on the mechanical properties (Haeckel et al., 2017).

Surface roughness

To be able to utilise the design freedom of AM and enable complex shapes, one driver in the aerospace industry is to use ‘as built’ surfaces as often as possible (Seifi et al., 2016). However, this sets restrictions on the surface roughness that is acceptable from a fatigue resistance perspective, and also for functional surfaces (e.g. flow surface) (Begoc et al., 2017). The surface roughness of as-built PBF parts is generally rougher than machined counterparts for the following reasons: (i) the staircase effect associated with the deposition of finite layers, which is dependent on surface curvature and layer thickness, (ii) partially melted powder particles adhering to the surface, which is dependent on the powder size, (iii) the presence of material defects such as porosity and unmelted regions, which depend on processing parameters, and (iv) support structures, which produce a rough surface when removed (Begoc et al., 2017; Li et al., 2016). This rough surface acts as multiple areas of stress concentration, which means that as-built parts can show a significant decrease in fatigue properties (Li et al., 2016; Seifi et al., 2017), as much as 40–50% compared to machined parts (Beretta & Romano, 2017).

To summarise mechanical properties, varying thermal history, defects and surface roughness are inherent characteristics of PBF (and other AM processes), all of which affect the mechanical properties of a part. For fatigue exposed parts, the significance of process-induced defects, surface roughness and residual stress should be highlighted since they can overshadow microstructural effects (Lewandowski & Seifi, 2016; Romano et al., 2017). It should be mentioned that the material properties vary between SLM and EBM due to inherent characteristics of each technology. It is not within the scope of this thesis to compare the two, instead, a general description of PBF processes has been presented.

Post-process treatment

While heat treatment is used to relieve stress and HIP (hot isostatic pressing) has been shown to be able to close pores and other PBF process-induced defects, the impact on mechanical properties differs depending on what is measured (e.g. tensile stress or fatigue) (Lewandowski & Seifi, 2016), and which PBF process that has been used. Stress-relieving heat treatment seems to be necessary for SLM, but less so for EBM, while HIP is often considered to be needed for both processes to increase fatigue properties (by closing defects) (Beretta & Romano, 2017; Gong et al., 2014; Li et al., 2016). More research is still needed to fully understand the impact of these heat treatments on the mechanical performance of parts, and it is evident that any remaining defects or rough surfaces have a detrimental effect on fatigue life (Lewandowski & Seifi, 2016). The importance of surface treatment (or machining) for fatigue exposed parts is, therefore, re-emphasised.

Testing

Conventional qualification approaches usually require thousands of individual tests (coupons and parts) that may take 10–15 years and cost millions of dollars (NIST, 2017). Such an approach is not suitable for variable and evolving processes such as AM (Frazier, 2014; Seifi et al., 2016). This is especially true for low volume applications (where AM is desirable) since the cost and time cannot be justified (Seifi et al., 2016). Furthermore, the variability in the AM material properties of parts require that test coupons or test artefacts are representative of the part that needs qualification (Gorelik, 2017; Seifi et al., 2017; Taylor et al., 2016). The use of witness coupons is common in PBF (even mandatory in the NASA standard for qualification of AM components according to Romano et al. (2017)), where the idea is that coupons that are built in the same build as the actual part should be representative of it. However, the largest defects that can be found in witness coupons can differ from those in the actual part, and it could therefore be seen as unlikely that the testing of a few test coupons could be used to validate a complex part (Romano et al., 2017). A combination of testing and NDT inspection is currently used to validate parts, and until a defect catalogue and NDT detection limits have been established, this testing and inspection will have to be part-specific (Seifi et al., 2017).

Inspection methods

The layer-by-layer process makes it possible to inspect each layer during the build. Defects could therefore be identified while a part is being built, and product quality assurance carried out by *in situ* monitoring. Although this is one of the paths towards process and part qualification, it is still being developed and is in its infancy (Seifi et al., 2016). However, there is a strong industry pull for *in situ* inspection and closed-loop control, not only to detect deficiencies in the material, but also to understand the processes better (Everton et al., 2016).

Several NDT methods are currently used on conventional materials e.g. X-ray, ultrasonic, eddy current (all sub-surface) and florescent dye penetration inspection (surface). However, the use of these conventional methods is not straightforward with AM due to part property variation, part geometric complexity, surface roughness and access to surface or volume inspection (Seifi et al., 2017). Furthermore, the defects that can be encountered in AM materials are usually not similar to those characterised for conventional processes, and the use of established standards has, therefore not yet been recommended for AM (ibid.). One NDT method that is frequently discussed for AM is X-ray Computerised Tomography (XCT) that can be used for both detecting defects and dimensional control of geometry and surfaces (A. Thompson et al., 2016). The achievable resolution of XCT is still a limitation for larger parts, making it difficult to use for industrial applications since it is dependent on size, thickness and geometrical complexity of the part (Seifi et al., 2017). This difficulty with inspection will probably require many parts to have multiple NDT methods to give full coverage (ibid.).

3.2.2 Qualification Work in Previous Literature

The general impression of the author after visiting conferences (industry and academic), AM machine manufacturers, universities and companies utilising AM, is that the industry tends to carry out extensive research that does not always reach open literature. The following is a summary of qualification work found in the literature.

Holistic views

From the description in this chapter, it is clear that the qualification of AM parts requires an understanding for how their quality can be guaranteed throughout the product development process (see Figure 8). The following are examples of approaches that take a holistic view of qualification, presenting frameworks that could be used.

Yeong & Chua (2013) highlighted the need for a quality management framework for the implementation of AM in regulated industries (e.g. aerospace), and proposed a conceptual approach for such a framework. The framework includes (i) control of input data files, (ii) product understanding, (iii) equipment qualification, (iv) AM process understanding, and (v) continuous process verification. The framework is conceptual without being demonstrated on an actual part. They further highlighted industry regulations and standards as an important contributor to the establishment of qualification approaches.

Taylor et al. (2016) acknowledged the multidisciplinary complexity of AM qualification and proposed a building block approach inspired by composite structures (see CMH-17 (2012), chapter 4). Such an approach could build confidence by connecting design, testing, analysis and inspection at different size scales (test coupons, structural elements, components and full-scale products). They continued by describing the importance of adapting such an approach to the specific requirements (e.g. criticality level) and prerequisites of a part (e.g. production volume), and stating that experience from qualification approaches for established manufacturing processes (e.g. wrought, composites, casting, powder metal, and welding) has to be used. Important aspects for AM qualification that are needed for the approach is the characterisation of process variability to develop appropriate safety factors, the availability of appropriate standards, the development of test correlated analysis methods, and the attention to geometry dependence of material properties.

Part-based qualification

In the part-based qualification approach, the focus is on showing that the part in question fulfils its requirements, rather than showing that the process is repeatable. This requires that the same qualification steps are taken for each part that is built, and is hence suitable for one-off production or a few identical parts. However, given the uncertainties of AM processes, this approach is currently used for AM parts (Taylor et al., 2016). An example of its use for space parts in literature can be found in Orme et al. (2017), where an assembly to hold a small spacecraft engine is described. In the design, highly conservative design data were used with an additional safety factor for AM to compensate for the lack of an established materials database (added to those already applicable for space parts, see discussion on safety factors in section 3.1.2). The build included several test coupons that were tested for their mechanical properties to show that they met the design data, and the actual parts were XCT scanned for defects with no deviations found that impaired both fit and function. Dynamic structural testing of the parts was then carried out (results not yet available in the article). The logic will be then either to accept the parts, or to tweak the AM process parameters iteratively (including new testing of coupons and parts) until structurally sound parts can be guaranteed. This approach shows how the AM process is adapted to part requirements, and how a combination of destructive and non-destructive testing is needed, as discussed by Seifi et al. (2017). It should be mentioned that little information is given about the criticality level of the parts and, in this specific case, the geometry of the parts seems to be suitable for XCT.

Statistical approaches for defects

As discussed above, defects in AM materials are one of the most important characteristics to understand, and for critical space applications, a damage tolerance design approach is mandatory (ECSS, 2009a). An analytical damage tolerant design method relies on having a relevant defect size to analyse, i.e. an initial crack size. The defect size that is used for damage tolerance methods is in practice the largest defect that can be missed using a NDT method, verified to a specified degree of confidence. Due to the limitation in accuracy for small defect sizes (0.1 mm) that can be detected with NDT methods (not only for AM materials), this defect size usually becomes conservative, and in the range of millimetres (ibid.). Statistical approaches are one way to reduce this initial defect size, and the use of such approaches for AM has been suggested by, for example, Gorelik (2017) and Romano et al. (2017).

Gorelik (2017) compared AM materials to casting and powder metallurgy (PM) processes and concluded that there are many similarities to AM material properties, in that they are location-specific and stochastic in nature, i.e. the size of the defect and the frequency with which it appears varies. One approach to treat these material characteristics has been historically to divide a part into zones with specific attributes for e.g. material properties, anomalies distribution and NDT requirements, and then use probabilistic damage tolerance to assess the probability of failure (ibid.). The probabilistic model however requires that the defect distribution function is known, and since the defect distribution may not be equal in different parts of a structure, i.e. different locations may be more or less prone to have defects from the manufacturing, this becomes challenging. Especially since suitable NDT methods for AM materials are still to be developed (Seifi et al., 2017). Romano et al. (2017) proposed the use of XCT on several witness specimens to estimate the largest defects at the origin of specimen failure, and then use extreme value distributions to calculate the largest defects in the part. As discussed above, it cannot be taken as certain that specimens are representative of the actual part, and therefore such a statistical approach could be applied. The purpose of using statistical approaches is to mitigate risks, without the need for safety factors that are too conservative, and it could be an intermediate approach until the industry has gained sufficient knowledge of AM and higher production scales (Gorelik, 2017).

3.3 Product Development with Additive Manufacturing

Building layer-upon-layer brings the theoretical possibility to build parts with rather intricate geometries, outside the scope of what is feasible with traditional manufacturing technologies. Free-form design, part consolidation (reduction in the number of parts in an assembly), functional integration, and topology optimised lightweight structures are some of the possibilities that increase the design space (Gibson et al., 2015). ‘Geometrical complexity for free’ is an expression often linked to AM (Kumke et al., 2016), as is the possibility to individualise products to customer needs (Gibson et al., 2015). Figure 10 shows this in a conceptual manner, comparing AM to traditional manufacturing processes.

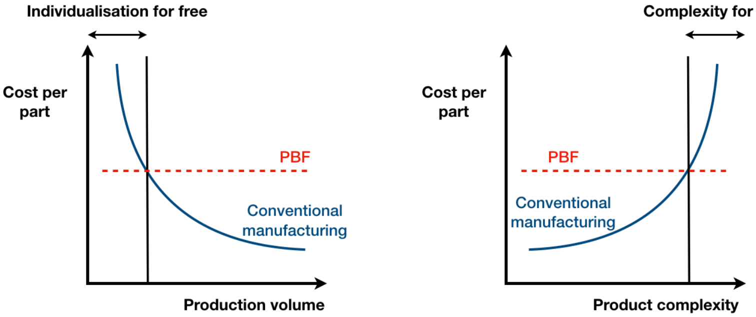

Figure 10 - Schematic comparison of product cost versus production volume and product complexity between powder bed fusion (PBF) and conventional manufacturing (adapted from EPMA, 2017, p. 5)

Several researchers have pointed out that designers may have difficulty in grasping AM and all the possibilities these manufacturing technologies bring (Rosen, 2007; Campbell et al., 2012; Klahn et al., 2015). There are two major reasons for this: (1) CAD software tools need to be adapted to facilitate the freedom given by AM, and (2) the creativeness of the designers needs to be expanded to make the previously unthinkable thinkable (Campbell et al., 2012). The first of these is outside the scope of this thesis, while the latter will be discussed in the following section from the perspective of understanding the prerequisites of AM processes.

3.3.1 Design for Additive Manufacturing

Despite the common use of the phrase 'geometrical complexity for free', geometric freedom is not unlimited with AM (Kumke et al., 2016). The term should, therefore, be used with reason. To utilise the potential of AM, the designer has to take the prerequisites of the specific process into account and design the part according to any restrictions it might impose (M. K. Thompson et al., 2016). The term *Design for Manufacturing* (DfM) has been transferred to AM with its own designation – *Design for Additive Manufacturing* (DfAM) (Gibson et al., 2015). Rosen (2007) makes an important distinction between DfM and DfAM when he concluded that while DfM methods typically focus on the constraints of a manufacturing process, DfAM should be concerned with the exploration of expanded design spaces. He proposed a definition of DfAM as (ibid., p. 403):

> *"Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives."*

At a high level, (Klahn et al., 2015) proposed that there are two strategies for the design of parts to be produced with AM:

- The *manufacturing driven design* strategy uses AM as a production technology, where the design is made with conventional manufacturing processes in mind as a substitute. As such, it is a less risky design with the option to fall back on other manufacturing processes if needed for reasons of cost or limitations with the AM process.
- The *function driven design* strategy aims at utilising the full potential of AM to maximise the function of the part, with possible novel or radical designs as a result. This involves a greater risk since falling back on conventional manufacturing might be impossible, and the decision to use AM has to be made in the early phases of the design process.

DfAM has to be considered in both cases, but when opting for the latter it is essential. Kumke et al. (2016) acknowledged that the term DfAM is not used consistently among researchers, making it a broad field. To clarify DfAM, they proposed a classification of previous research into two categories: *DfAM in the strict sense* and *DfAM in the broad sense*. These two categories are summarised in Table 5. It should be noted that *DfAM in the strict sense* is incorporated into *DfAM in the broad sense*.

Table 5 - Classification of current research in DfAM (adapted from Kumke et al., 2016, p. 4)

Category	**Approach**	**Explanation**
DfAM in the broad sense	Process selection and production strategy	Various decision support systems have been proposed for choosing the right process or the right production strategy depending on product and process.
	Selection of parts/applications	The selection of suitable parts for AM is still a challenge given the novelty of the technologies. These approaches aim at aiding the designer with this task, both from a strategic level and at part level.
	Manufacturability analysis	These approaches focus on analysing the designed part to evaluate its manufacturability making it possible to re-design if needed.
DfAM in the strict sense	AM design rules	These rules build on the fact that geometric freedom is not unlimited and certain rules have to be followed to design manufacturable parts e.g. minimum wall thickness or build orientations. Such rules are process specific.
	Utilisation of AM potentials	The purpose of these guidelines is to expand the designer's notion of what is possible with AM, e.g. improve product performance and part consolidation.
	Combined approaches	The need for using both design rules and design potentials is evident. Several researchers have combined different approaches to both foster manufacturability and novel designs.

While *DfAM in the strict sense* includes design rules imposed by the specific AM process, and guidelines aiding the utilisation of the AM design freedom, *DfAM in the broad sense* expands DfAM to include several phases of the product development process, including activities before and after the design of the part. These include the selection of appropriate parts to be manufactured with AM, the selection of suitable AM processes, as well as manufacturability analysis of the part based on process characteristics (Kumke et al., 2016). The framework further acknowledges the need to consider activities that are linked to the manufacturing, e.g. build orientation, the manufacturing itself and post-processing, although they are not explicitly included in *DfAM in the broad sense*. It should be mentioned that, despite the progress on DfAM methods and guidelines, they are still mainly presented within academia and with that target audience in mind. There is still a challenge to transfer this knowledge into industry (Leutenecker-Twelsiek et al., 2016).

3.3.2 Product Development Process with Additive Manufacturing

For the purpose of this thesis, it is needed to consider the product development process shown in Figure 8 in the context of using AM. Gibson et al. (2015, p. 45) described this process using eight steps: (1) Conceptualisation and CAD, (2) Conversion to STL/AMF[3], (3) Transfer to AM machine and STL file manipulation, (4) Machine setup, (5) Build, (6) Removal and clean-up, (7) Post-processing, and finally (8) Application. However, they emphasised that the activities in the steps may differ depending on the AM process used and the requirements of the product. This process shows the 'direct manufacturing' nature of AM, where a design is taken from CAD to part in an effective process, and also that the manufacturing itself is a step in the product development process for AM. For this reason, a specific manufacturing phase should be added to the product development process shown in Figure 8, including steps (2) – (7). It should be noted that the need for post-processing of AM parts, as discussed in section 3.2.1, is shown here in step (7). Furthermore, the importance of post-process verification through non-destructive and destructive testing for metal parts was also discussed in section 3.2.1, and is therefore explicitly added to the testing phase in Figure 8. Another characteristic of product development with AM is that, the phases *embodiment design* and *detail design* are merged, since the distinction between the two cannot be made with DfAM (Kumke et al., 2016), which should also be taken into consideration in the representation of a product development process for AM.

Based on this description, a refined model of the product development process for AM is shown in Figure 11, which will be used in this thesis.

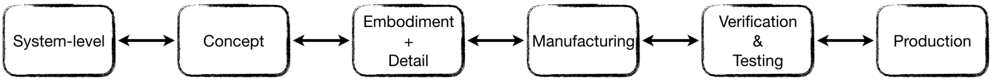

Figure 11 - The product development process for AM in space applications (inspired by Fortescue et al., 2011; Gibson et al., 2015; Kumke et al., 2016; Pahl et al., 2007; Ulrich & Eppinger, 2012)

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[3] STL/AMF are standard file formats used for data transfer from CAD to AM machines (ISO, 2014)

4 Summary of Appended Papers

This chapter gives a summary of the appended papers and ends with a description of how the papers relate to the thesis and to each other.

4.1 Paper A

Dordlofva, C., Lindwall, A. & Törlind, P. (2016). Opportunities and Challenges for Additive Manufacturing in Space Applications, Proceedings of NordDesign 2016, Trondheim, Norway.

Summary

The paper is a state-of-the-art review of AM in the space industry based on study visits and a literature review. The purpose of the work was to map the opportunities and challenges of AM in space applications, and to identify the research gaps. As the first paper written by the authors on this subject, it also provided an understanding of AM and a direction for future research.

It was found that the space industry sees potential in using AM due to its industry characteristics, and several examples are given in the paper. There are two AM processes of interest to the industry for the production of metal components: Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). However, several challenges could be seen, and the paper describes these from two perspectives: (i) designing products for AM and (ii) the qualification of products manufactured using AM technologies.

4.2 Paper B

Lindwall, A., **Dordlofva, C.** & Öhrwall Rönnbäck, A. (2017). Additive Manufacturing and the Product Development Process: Insights from the space industry, Proceedings of the 21st International Conference on Engineering Design (ICED 17), Vancouver, Canada.

Summary

The need to approach product development with AM in mind became clear after Paper A was written. The purpose of the work for Paper B was to gain a deeper insight into how AM is believed to impact the product development process from an engineering design perspective. The paper was based on a workshop series at three companies in the space industry, and a case study at one company. The case study consisted of a review of steering documents for product development, and interviews of a sample of engineers working with space products. Two perspectives were studied: (i) product development in the space industry and (ii) the use of AM in space applications.

There was a belief among the respondents that AM would be able to introduce new innovative designs, facilitate faster product development and reduce the cost of manufacturing. However, it was also mentioned that the structure of the conservative space industry imposes challenges due to restrictions in financing and a heavily gated development process. Furthermore, product quality was highlighted as important in space applications, and the maturity of AM processes and lack of knowledge about their capabilities was therefore raised as a great challenge for its introduction. The need for an understanding of how to design for AM was also seen as necessary among the respondents since they acknowledged that the capabilities of AM differ from conventional manufacturing processes.

4.3 Paper C

Dordlofva, C. & Törlind, P. (2017). Qualification Challenges with Additive Manufacturing in Space Applications, Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium, Austin (TX), USA.

Summary

To describe further the challenges of qualification of AM parts that were raised in Paper A and Paper B, a deeper insight into product and process qualification in the space industry was needed. The purpose of the work for Paper C was to understand how qualification of conventional manufacturing processes has been/is carried out in the aerospace industry, and what challenges there are to introducing new manufacturing processes. For this work, four conventional manufacturing processes were chosen: welding, casting, forging and fibre composites. The presented results are based on interviews with engineers at one company in the aerospace industry, all chosen due to their expertise from different fields in materials and product development.

From the analysis of the data, the process of qualifying products (and their manufacturing processes) could be described. Three approaches for process qualification are described, and a discussion of the implication for AM processes is presented. Furthermore, the implications of the space industry on AM qualification are discussed. The literature review shows how each step of the product development process is involved in the pursuit of qualified AM products.

4.4 Relation to the Thesis

The papers followed a sequence where the knowledge needed to address the research questions was built on, step-by-step, as shown in Figure 12. First, the areas of product development and qualification with AM were reviewed to map the state of the art and to understand the opportunities and challenges with regard to developing products for space applications (Paper A). Thereafter, product development in the space industry was researched, using knowledge from the previous study, but delving deeper into the expectations of the industry for AM (Paper B). Finally, the qualification process in the space industry was addressed to understand the prerequisites for AM qualification (Paper C). Gathered knowledge was, in this sense, used and taken one step further in the following studies. The link between the research questions and the papers is also shown in Figure 12, where an underlined <u>RQ</u> indicates a strong contribution to the research question, and a regular RQ indicates a weaker contribution.

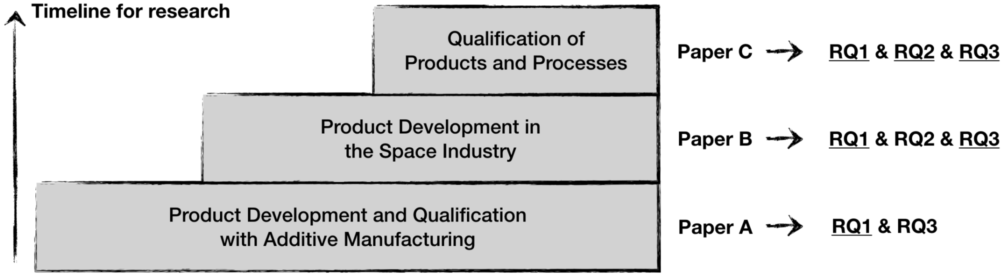

Figure 12 - The logic for building knowledge in this thesis. Each paper's idea was developed based on the findings from the previous paper(s)

5 Results and Discussion

This chapter describes the results from the studies detailed in the appended papers, together with a deeper discussion of the theory. The purpose is to address the three research questions.

To identify the implications of introducing AM into the process of developing, manufacturing and qualifying parts for space applications, an insight was needed into the product development process in the space industry, as well as the qualification of parts and manufacturing processes. The research questions were designed to address these issues in order, and so this chapter is arranged such that each of the research questions is addressed as shown in Figure 13.

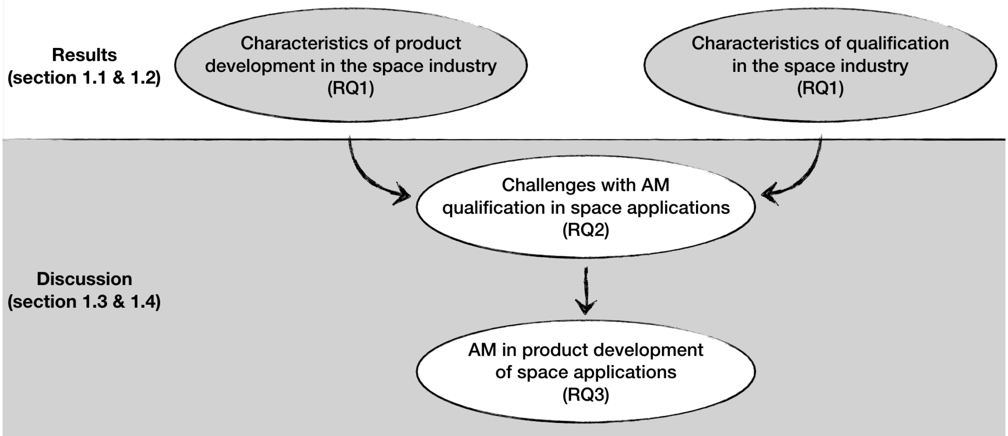

Figure 13 - Arrangement for the presentation of results and their discussion

5.1 Characteristics of Product Development in the Space Industry

This section is based on the testimonies of engineers working in the space industry on what characterises product development in the space industry (Paper A and Paper B).

5.1.1 Involvement of External Actors

As was presented in the theory section, product development in the space industry is a rather complex task involving many different stakeholders such as governments, system owners and suppliers of sub-systems, parts and materials. The studies for Paper B showed that this involvement of several actors gives rise to rather special conditions for the engineer working on product development for sub-systems.

Government involvement

When working in government-funded programmes, the engineers have to deal with funding that is released over short-term periods (e.g. for ESA every third year). These periods are usually shorter than the time needed to mature technologies to higher TRL levels. Typical development times in the space industry are 10–15 years, making heavy investments in new technologies an economic risk. This means that there has to be an awareness of how unexpected changes due to shifting political interests will affect future strategies.

Customer involvement

The system owner (the customer of the sub-system supplier) is heavily involved in the product development of sub-systems since they have responsibility for the whole system and set the requirements. This involvement is considered positive from the perspective of securing safe and robust products, but it also involves additional work related to reviews and the risk of late design changes due to altered requirements. Furthermore, being a sub-system supplier means complying with interface specifications, limiting the possible design solutions. The close collaboration with the system owner does, however, also give the potential to impact design changes, with the stage-gate process of product development ensuring product quality. It should be noted that the companies involved in the studies have different customers, and it became clear that the level of customer involvement differs.

Supplier involvement

The sub-system suppliers work with suppliers delivering manufactured materials, e.g. castings or forgings that are then machined to the final shape. Here, the sub-system supplier is the customer, and sets the requirements for the suppliers. A close collaboration is needed to set requirements that result in a part that can be produced.

5.1.2 Long Development Lead Time

Development projects in the space industry are characterised by long lead times, typically 10–15 years as mentioned above. The respondents interviewed for Paper B acknowledged this and referred to political involvement, the need to secure robust and safe products, and long *production* lead times. A traditional development process in the space industry from the detail design phase onwards, where casting was used as an example of the production method, was described in Paper A (see Figure 14). As is shown at the bottom of the figure, the lead time to produce castings can range from 4 to 12 months. This includes a DfM phase with the casting supplier to adapt the design to the casting process. The process usually includes several casting trials before the final design is reached and a first production configuration casting is manufactured for evaluation through destructive testing (cut-up). In reality, the first batch of production parts is usually cast at the same time as such an evaluation part, due to the long lead time and in order to reduce the cost of manufacturing. This is obviously a risk since, if the evaluated part is considered not to meet the specifications, the already manufactured parts become useless (scrap). To mitigate this risk, design margins are usually needed from a production point of view, possibly leading to unnecessary weight being added to the final part.

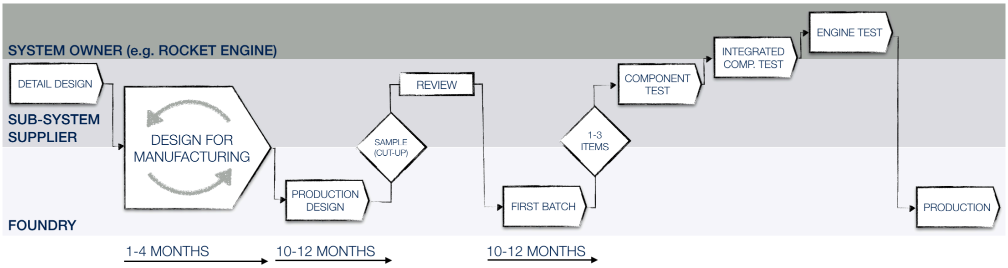

Figure 14 - Traditional development process in the space industry for cast products

Another consequence of the long manufacturing lead time is that castings (and other materials) are usually ordered before the final design of the part has been set, which also has to be taken into consideration. A design margin applied to the casting dimensions is usually added for this purpose as well, possibly resulting in a conservative design. The final phases of the development process in Figure 14 are that of part (component), sub-system (integrated component) and system (e.g. complete engine) testing. These phases are both financially expensive and time-consuming, with a test campaign possibly lasting for several years at a system level. These long lead times and costly phases mean that the engineers have to be careful in their design decisions, and development is usually rather incremental from one product to another, and innovation is, in that sense, restricted. The risk of too bold designs not fulfilling their requirements at a late stage is simply too high.

5.1.3 Cost Awareness

The emergence of new commercial actors into the space industry was often mentioned by the respondents. As one senior project leader expressed it (Paper A):

> *“Traditionally space applications had an extreme focus on weight and performance, but today the emergence of new actors in the market (e.g. SpaceX) has driven the focus towards competitiveness in cost.”*

While manufacturing is one area associated with high cost as argued above, product development work is equally important in respect of cost reduction and should not be forgotten. Cost awareness has an impact on project budgets and hence the room for developing new ideas that challenge conventional designs. However, the respondents also experienced how a focus on cost can be an enabler for new ideas and the introduction of new manufacturing technologies due to an emerging need for innovation. The close collaboration with the customer was seen as positive from a cost-awareness perspective since it gives the opportunity to discuss cost and production issues.

5.1.4 Critical Parts

The criticality level of parts in space applications was often mentioned by the respondents interviewed for Paper B. Risk assessment and risk mitigation was an integral part of their daily work, and part quality was considered to have high priority. To manage the development and qualification of critical parts, the respondents mentioned the following approaches:

- The reuse of proven ‘old’ designs brings confidence to the development of new parts from a qualification perspective. However, this could also lead to a more incremental product development approach that might hinder exploration of radical designs.

- Suitable safety factors are used in design analysis if there is an uncertainty in e.g. the maturity of material data (Paper C). These factors can be additional to the standard safety factors imposed by specifications (e.g. ECSS) in the verification of part designs. The appropriate level of safety factors is usually set in dialogue with the system owner.
- Demonstrator programmes were considered to be beneficial to test new technologies, and there was a wish for more of these to be able to explore new ideas. By maturing technologies to TRL6 through demonstrators, they can then be used in product development. Low TRL technologies imply little experience and knowledge about the processes, impacting the design potential and hence innovation.

5.2 Characteristics of Qualification in the Space Industry

To understand the challenge of qualifying AM parts for space applications, the qualification process in the space industry was studied for Paper C. The sampling of respondents represented experience from both conventional manufacturing processes and different AM technologies. The conventional manufacturing processes that the respondents had experience of were casting, forging, welding and fibre composites. The main findings from Paper C are presented in this section.

5.2.1 Conventional Product and Manufacturing Process Qualification

The aim of *product qualification* is to show that the *design intent* of the product is fulfilled i.e. to show that all the requirements are met from a structural and functional perspective (e.g. providing the right amount of torque for a turbopump in a rocket engine). The final part of this qualification is done at system level, where all the sub-systems have been integrated. Supporting this qualification is the part, or sub-system, qualification, of which the sub-system supplier is responsible. The links between these are shown in Figure 15 (from Paper C), where system-level qualification is referenced as (A).

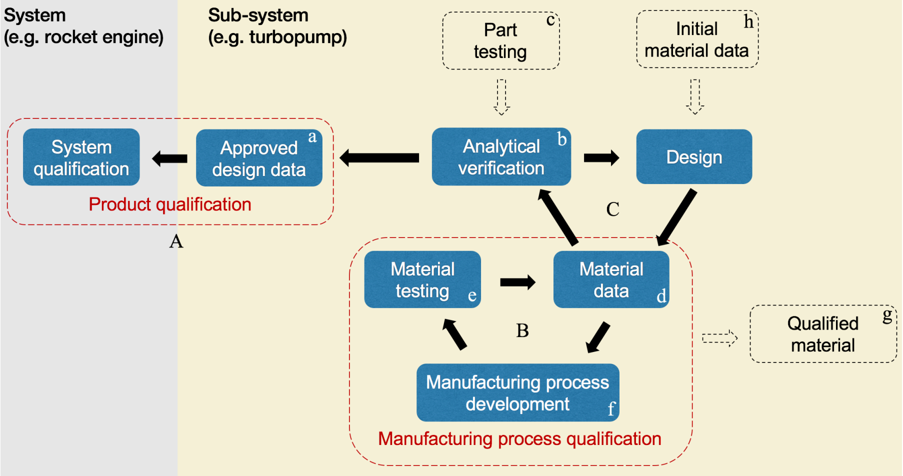

Figure 15 - The role of manufacturing process qualification in the design and qualification of products for aerospace applications (letters are referred to in the text)

The responsibility of a sub-system supplier is often to provide the system owner with a design data package (a) showing the evidence of verification that the sub-system requirements are met. Among other descriptions of requirement fulfilment, this design data package includes proof that the manufacturing process used for the part(s) has been qualified, and that the part is shown to fulfil its structural requirements using analytical methods (b). Since analytical calculations might need verification, part testing (c) can complement the design verification (e.g. burst test of a pressure vessel), and these results are also included.

The link between the part design and the manufacturing process is the material data (d) as one respondent said, and a manufacturing process needs to be verified by material testing (e) to show compliance with the required material data (d). Establishing this material data is a challenging task in manufacturing process development (f) since it requires time and money. If sufficient data have been gathered for a process to build a generic material database, this material is referred to as a 'qualified material' (g). For such established manufacturing processes where a company has previous experience, where there are established material standards, and where there are developed simulation tools for the processes, the link between the part and material data is made easier since there is previous knowledge to fall back on. However, since many of the parts within aerospace can be rather complex and unique, there is usually always a need to establish product specific material data (d). This process is shown by the design and manufacturing process loops in Figure 15 (B and C). So, even if there are previous material data that can initially be used for part design (h), the manufacturing process has to be verified for the part in development, and vice versa if the part has to be redesigned to fit the manufacturing process capabilities. This was shown in Figure 14 as the DfM process. Some of the respondents interviewed for Paper C stressed that there is no requirement to have a *qualified material* to qualify a part. The requirement is to show that the part with its manufacturing process fulfils the design intent (the design requirements). For this reason, specific material requirements can be defined for one part (d).

Critical manufacturing processes

Authority regulations (e.g. ECSS) require that the manufacturing of critical parts has to be controlled. Ordinary manufacturing processes, such as milling or lathing, are called *standard processes* and are well established with no requirement for qualification when used on a new part. Manufacturing processes that might produce what the respondents call 'hidden properties', e.g. inclusions or pores, are called *critical processes* and require qualification for each new design (Paper C). All of the processes that were discussed in the interviews i.e. welding, casting, forging and fibre composites, are critical processes.

5.2.2 Introduction and Qualification of New Manufacturing Processes

The level of qualification that is needed will vary depending on the part. If the part is similar to a previous one, and the same manufacturing processes are used, past experience might lead to a qualification process that 'only' has to verify that the material data are within the expected range. However, for parts (or geometries) that are new, or if a new manufacturing process is used, a more thorough qualification is usually needed. The general logic for qualifying a critical process is (Paper C):

Step 1: Give approval for the manufacturing method based on standards or specifications
Step 2: Develop a specific process that fulfils the material requirements of the part
Step 3: Freeze the process

While these steps are general, the activities that have to be carried out might differ between processes and/or part designs. As is clear from the discussion so far, knowledge about material behaviour is the foundation for qualification. From the results gathered and analysed for Paper C, three approaches for qualifying a manufacturing process have been formulated:

1. Rely on a generic material database which can be used as a reference for any product to be built using that process. This is the case for many of the traditional processes with known materials.
2. Use a known material database (i.e. similarity) as the reference and show that the known material database can be used to give the minimum properties for the new material, i.e. that the new material is at least as good as the reference. This approach does require sufficient material testing to show that the new material is better than the minimum properties.
3. Start from the application and look at its specific requirements, as with composites. This approach gives the opportunity to tailor the manufacturing process according to the product requirements at the same time as knowledge about the process is being built, step-by-step.

These three approaches were derived using the gathered data from the respondents on how qualification is approached for different manufacturing processes. Apart from the conventional manufacturing processes, challenges with qualification of AM were also discussed in the interviews and contributed to the formulation of these approaches.

5.3 Challenges with Additive Manufacturing Qualification in Space Applications

The following discussion is from the perspective of using AM in space applications, but since many challenges with qualification of AM are similar to other industries, especially aeronautics, the discussion can be considered general to a certain extent as well. In first hand, PBF processes are considered; however, the term AM is also used in the text as it is a general term used in literature, despite focusing on a specific process. Furthermore, several challenges are applicable to other AM processes as well.

The use of PBF for a non-critical, non-fracture sensitive part has been flight demonstrated in space by, for example, Rawal et al. (2013) for a wave guide bracket on a spacecraft. Despite the part being considered as a secondary structure, the decision to approve the part for flight was based on mechanical testing of both test coupons and the part itself, motivated by the 'low' maturity of the EBM process used. Furthermore, the part was fully machined to avoid fracture sensitive as-built surfaces. Applying AM to fracture critical applications is still a challenge due the lack of understanding of process capabilities (Seifi et al., 2016). For fatigue exposed parts, there are four main considerations that are specific for AM materials: (i) presence of defects, (ii) anisotropy, (iii) surface roughness, and (iv) similarity between test coupons and actual parts (Seifi et al., 2017). All of these are of concern for space applications; (i), (ii) and (iv) are always present in AM, while (iii) is an issue if the design freedom of PBF is to be utilised, since complex geometries might result in surfaces that are not possible to machine. According to Romano et al. (2017), the impact of large defects could be more significant than anisotropy and location-dependent properties in PBF parts. The possible presence of multiple defect types (porosity, lack of fusion, cracks, inclusions) in PBF materials (Brandão et al., 2017; Everton et al., 2016; Gu et al., 2012) makes it difficult to qualify critical space parts since it has to be shown through testing and/or analysis that such a part can withstand a defect without failure (ECSS, 2009a). Material defects are, therefore, of greatest concern for fracture critical parts since they have been shown to have a detrimental effect on part life (Lewandowski & Seifi, 2016). The implications of using AM for critical parts on the three qualification approaches presented in section 5.2.2 should be discussed in light of these concerns.

Qualification approach 1

The sensitivity of AM processes to part geometry, the variability of process outcomes, the possibility of tweaking process parameters, and the multitude of different AM processes, makes it questionable if a generic database is even feasible for AM materials (Paper C). This approach is also debated in the literature (NIST, 2017; Seifi et al., 2016). Alternative approaches are hence needed, and therefore qualification approaches 2 and 3 should be considered.

Qualification approach 2

If similarity is to be pursued, a suitable reference material has to be chosen. While the properties of AM can be shown to compare with the strength of forging (Lewandowski & Seifi, 2016), one interview respondent (Paper C) expressed a belief that if AM cannot be shown to be defect free, it will be difficult to compare it with forging. Instead, the option would be to compare with castings that show similar process sensitivity to the part being manufactured, as well as having defects as an inherent part of the process (Paper C). Since defects have been shown to be inherent to PBF processes as well (Brandão et al., 2017; Everton et al., 2016), it would seem that casting materials are a viable option for a similarity approach. At the same time, both welding and fibre composites have other characteristics resembling AM, such as machine-by-machine qualification in welding and geometry dependent material properties of fibre composites (Paper C). Looking at already existing experience from conventional manufacturing technologies could therefore bring valuable insight into developing a qualification approach for AM. This need to refer to established manufacturing technologies to find a suitable approach for qualification of AM parts has been highlighted in literature before (e.g. Gorelik, 2017; Taylor et al., 2016).

Qualification approach 3

The complex coupling between part and process has so far made it necessary to have a part-based qualification approach for space applications (see e.g. Orme et al., 2017; Rawal et al., 2013). The part-based qualification includes the combined use of analytical verification, coupon and part testing, as well as NDT to verify the material integrity of the part. Orme et al. (2017) described how they designed the part using conservative safety factors to account for the uncertainty of the AM process, and further how the AM process parameters were iteratively changed until the part was shown to meet its requirements. This approach shows the potential for using AM for low volume applications. The process can be developed iteratively with short lead times to fit the part, and the part can be designed with the uncertainty of the process in mind. This is particularly true for one-off parts, where sufficient data can possibly be gathered with a reasonable amount of testing, complemented with part testing. It should, however, be noted that the part criticality level is one parameter determining the amount, and what type, of testing that is needed; for critical parts, this has been shown to be challenging (Seifi et al., 2017).

In summary, the link between the part properties and the AM process has to be considered, regardless of the approach, as is testing to show the requirements fulfilment of the part. The following sections discuss challenges with part development and testing from the perspective of space applications.

5.3.1 Challenges with Part Development

The important consideration with part development is to understand what material properties are feasible with AM, and develop parts and processes according to what is actually required by the part. A close collaboration with the system responsible could aid in defining these requirements for the sub-system, both for the development of a part and establishing the qualification requirements. Safety factors used in analytical verification should always be agreed with the customer and can vary depending on the amount of testing that will be carried out (ECSS, 2008a, 2009b). This can give the opportunity to develop a suitable qualification approach relying on analytical verification and testing, explicitly defined for the part.

For fracture critical applications, a damage tolerance design approach has to be used (ECSS, 2009a) which makes it necessary to establish the appropriate defect sizes to be used. An understanding for what type of defects could be present is therefore needed, and what their impact is on the given part. Seifi et al. (2017) summarised this with three questions to ask: (1) what is the largest defect that can go undetected, (2) what is the effect of a given defect type, size and distribution on part performance and safety, and (3) what is the consequence of catastrophic part failure stemming from such inspection misses. Statistically-based approaches to handle defect distribution in AM materials are suggested by, for example, Gorelik (2017) and Romano et al. (2017). Whilst being reasonable approaches, they require a certain amount of material data to draw statistical conclusions on defect distribution. To build such a database, manufacturing and testing of parts and test coupons are needed. From a space industry perspective, this can be challenging due to the low production volumes, which imply that less material is produced, and hence less data can be gathered. Furthermore, such statistical approaches relies on NDT methods, which for AM are still in need of development, and where the use of test coupons to represent a part is a concern (Seifi et al., 2017). This stresses the need for developing the process for the part and applying/developing suitable NDT methods to establish what defects are likely to be encountered.

Since surface and sub-surface defects are more critical to the life of a part than defects deeper in the material (Beretta & Romano, 2017; Romano et al., 2017), understanding the limitation of surface roughness on PBF parts is critical. Given the maturity level of PBF processes, Begoc et al., (2017, p. 117) stated that their *"parts cannot be used with the surface roughness inherent to both processes*" (the parts were fuel injector elements and a turbopump housing for fluid rocket engine manufactured with SLM and EBM respectively), and concluded that surface treatment is necessary.

5.3.2 Challenges with Testing

Establishing representative testing environments for space parts is a challenge. As one respondent said, real loads for a space part are not encountered until it is actually launched (Paper C). For an aircraft engine, flying testbeds can be used to introduce new solutions gradually, and part behaviour can be monitored over hundreds of hours with parts being replaced if needed. As an example, a PBF manufactured engine fuel nozzle has been reported to have been tested on several airplanes and logged over 285 flights and 800 hours before first commercial delivery (3ders.org, 2016). In comparison, once a rocket or satellite is launched it will be inaccessible, and the failure of a critical part could have severe consequences (see Table 4 in chapter 3). Due to the high cost of launching a rocket (Fortescue et al., 2011), ‘flying test beds’ are not practically feasible, and each launch usually has a dedicated mission. Even inaugural launches usually have payload customers who are given a discounted price due to the increased risk of using an unproven system. This means that compared to e.g. aeronautics, there are limited opportunities to introduce AM parts in the actual system to monitor its behaviour. This creates a dilemma, and is another reason for the incremental development of products in space applications, as mentioned in Paper B. The space industry does, however, have a culture of working with technology demonstrators to introduce new technologies (product concepts or manufacturing processes) (Fortescue et al., 2011), as well as dedicated development and qualification test programmes (ECSS, 2012a). Demonstrators are considered valuable to mature technologies before introduction into product development (Paper B), and dedicated test programmes show proof of sub-system or system design once in product development (ECSS, 2012a). However, such testing programmes are often expensive and time-consuming, and to mitigate risk, parts in such testing already require a certain level of verification.

This limited opportunity to test parts in ‘real’ applications places higher demands on testing at a sub-scale level i.e. coupons, part, and possibly integrated sub-system level. The combination of part testing, coupon testing, and NDT is considered necessary at present for AM materials, especially for parts that are fracture critical and hence sensitive to defects (Seifi et al., 2017). To develop a suitable testing approach for a critical space part is therefore challenging for the following reasons:

a) The representativeness of test coupons for the actual part behaviour and defect distribution cannot be guaranteed for AM materials, and therefore test coupons or artefacts have to be designed to represent the part (Gorelik, 2017; Seifi et al., 2017; Taylor et al., 2016).

b) Part testing under representative conditions can be difficult for space applications (Paper C), and additional margin has to be applied when testing is used for verification (ECSS, 2012a). The most suitable approach has to be defined according to specification requirements (e.g. ECSS) and in collaboration with the system owner.

c) Established NDT methods and NDT standards for AM materials do not exist yet, but will be an important part of any qualification approach (Seifi et al., 2017). It is likely that a combination of several NDT methods will have to be used to cover the inspection need fully, including both sub-surface and surface inspection techniques. The inherent rough surface of as-built PBF parts increases the complexity of developing NDT standards and methods (ibid.).

5.3.3 Challenges with the Critical Manufacturing Process

Qualifying the manufacturing process is part of the product qualification as shown in Figure 15. Given that AM can result in ‘hidden properties’, it is considered a critical process and hence there is a need to freeze a process as part of the qualification (Paper C). Looking at the steps in the general approach for qualifying a new critical manufacturing process (Paper C) presented in section 5.2.2, the following can be deduced when applied to AM:

Step 1: General standards are being developed for AM (ISO/ASTM, 2015), but they are still not mature enough, nor extensive enough, to meet the requirements of the industry. As mentioned by Clinton (2017), the industry has to develop their own. This requires a huge effort from any company that wants to introduce AM as a manufacturing method, to characterise the processes themselves. It might therefore be challenging to initially approve a process, depending on the amount of knowledge that has been built up in an organisation. Step 2 will, therefore, be of importance to build knowledge to eventually develop the needed specifications for certain AM processes.

Step 2: Since AM processes are still developing and the characteristics of the processes are not fully understood (Slotwinski & Garboczi, 2015), the approach to adapt the process to the part is not straightforward. One approach is exemplified by Orme et al. (2017). However, given the uncertainty of defect distributions and other material properties, adapting the part for the AM process should also be considered, e.g. to design for defects as discussed in section 5.3.1. This means that responsibility is put on engineers to design for AM. This does not only include *DfAM in the strict sense,* utilising the design potential of AM and the process capabilities, but also includes choosing the right part and process and carrying out manufacturability analysis i.e. *DfAM in the broad sense* (Kumke et al., 2016). This link of DfAM to qualification means that qualification could be, and has to be (Paper C), taken into consideration early in the design process.

Step 3: The possibility of changing and adapting process parameters in AM underlines the need to freeze the process. The challenge lies in knowing what process parameters need to be frozen.

In summary, the interdependence between part and process, and the lack of understanding of AM processes, makes it necessary to take the development of the manufacturing process into consideration during the development of a part, and in establishing a qualification approach. DfAM has been introduced as a branch of DfM, where the purpose is to take the characteristics of AM processes into account in product development.

5.4 Additive Manufacturing in Product Development of Space Applications

In all of the appended papers, it was concluded that the whole product development process is impacted by the introduction of AM. The results from Paper B show that engineers in the space industry work under rather special conditions where there are several factors influencing their decisions, and where some external factors are not under their control. Political decisions or the need for late design changes can unexpectedly change the course of a product development project. Requirements at system level dictate the design space for a specific sub-system (Crawley et al., 2004) and, therefore, possibly the opportunity to utilise the design possibilities of AM. If the given interfaces are too strict, the freedom to explore new design solutions can be hindered (Paper B). In addition, given the complex coupling between part and process, DfAM will be important to enable both new designs and their qualification.

Combining the presented theory with the presented results in this chapter, three factors can be identified that impact the assessment of a part's feasibility for AM in the early phases of product development:

1. AM process experience
2. Design freedom
3. Part criticality

While *process experience* can be considered to be independent of the system design, *design freedom* and *part criticality* are impacted by the system. These three factors are discussed below.

AM process experience

While AM process capabilities can be realised from the literature or by contacting a machine manufacturer or machine owner (could be in-house or external), the level of process experience among the engineers will impact the understanding of these capabilities and how to utilise them for the design (M. K. Thompson et al., 2016). Talking to several senior engineers from different disciplines within product development, it became obvious that knowledge and experience are the foundations for 'good' product development (Paper C). Therefore, the strategy for choosing and designing a part for AM should depend on the experience of AM. The two design strategies proposed by Klahn et al. (2015) are *manufacturing driven* and *function driven* and, from the perspective of building knowledge, these strategies can be seen as a learning process. This process starts with the redesign of products for AM giving the opportunity to build knowledge about the process, continues with more function-oriented designs that are not possible to manufacture with conventional processes, and eventually explores new radical designs as shown in Figure 16.

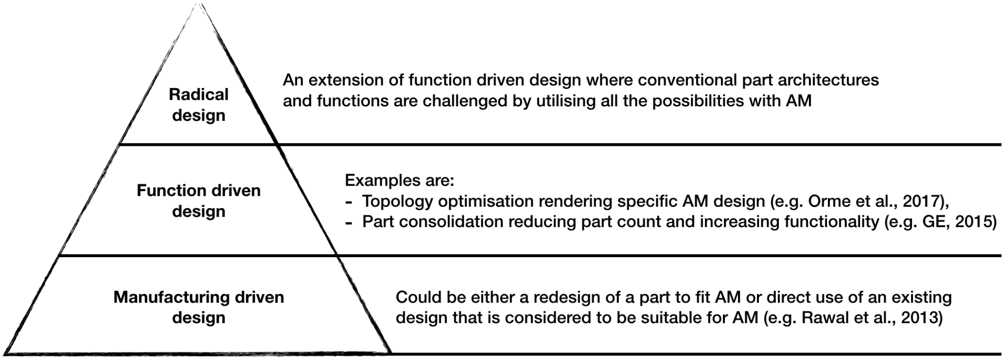

Figure 16 - Utilising the design strategies of Klahn et al. (2015) to build knowledge towards the exploration of radical designs

The short-term financing that can characterise product development in the space industry has historically had the effect of incremental product development due to tight budgets and short time frames (Paper B). While the feeling that cost awareness has made it easier to propose new ideas, critical applications still foster a step-by-step approach. The building of sufficient knowledge (or experience) of a manufacturing process is a long-term commitment (Paper C), and requires resources (funding and time). This highlights another challenge in government programmes since they may impact the decision to make long-term commitments to technology development. Such commitments are necessary for early adopters since AM is still a relatively new technology and the development of process knowledge is imposed on companies that want to use such technologies (Seifi et al., 2016). The study visits (Paper A) were an opportunity to talk to different actors in the AM industry and one point became clear: without dedicated investment and 'learning by doing', it is difficult to build the needed knowledge to advance, both from the perspective of designing parts for AM, and to understand other process characteristics that have an impact on the qualification.

Design freedom

The impact of the system design restrictions depends on the strategy chosen. For redesign, the need to change interfaces or design space could be minimal, while for more explorative designs, interfaces have to be included in the conceptual design phase to allow more design freedom ('thinking outside the box'). Many systems have a set architecture based on legacy, which means that to increase value and/or performance of the system, innovation is pushed to sub-systems (Crawley et al., 2004). Traditional interfaces might need to be challenged to allow for the AM-enabled free-form design, which might interfere with traditional sub-system responsibilities (Paper C). One example could be part consolidation of parts that have traditionally been designed and manufactured by separate sub-system suppliers. From an AM perspective, it might be favourable to merge these into one, while from a political perspective, such decisions might become sensitive and the best solution for the system might not be feasible due to decisions that are out of the control of the design team. Flexibility, adaptability and changeability are important in efficient system development (Golkar & Crawley, 2014), which implies a close collaboration with the system owner since a reluctance to adapt interfaces might impede the DfAM process. This does not only require system knowledge about both parts (or sub-systems) to facilitate a redesign, but would also be a question of company interests. In a competitive industry such as the space industry, where companies usually specialise in specific systems or sub-systems (ECSS, 2008b), this might be a hurdle where the impacted companies want to protect their business. From an engineering design and product perspective, the system owner has the best idea of what is the best solution.

One observation made during the studies is that the hunt for cost reduction and the hype of AM risk removing the objectivity in choice of products suitable for AM. Everyone wants to 'jump on the AM train', and this can be seen in a broad spectrum of industries. Kumke et al. (2016) recognised that the task of choosing the right product is included in *DfAM in the broad sense*, and that a product might as well be considered not suitable for AM. The system owner has valuable knowledge in assessing the suitability of introducing AM, especially when more functional or radical designs are pursued because more explorative AM designs might require changes in the system design. Since cost is considered to be the main driver for product development in the space industry at present (Paper B), added value from AM has to be put in perspective. A question that needs involvement of the system owner is whether added value in the form of e.g. increased function can allow relaxation of the requirements on e.g. cost or weight.

Part criticality

The level of criticality of a part in space applications sets the requirement for qualification, and for a part considered to be critical, the requirements are higher (ECSS, 2017a, 2017b). Given the relatively low maturity of AM technologies, it has therefore been natural that parts of low criticality have been introduced first (walk before you run) (Gorelik, 2017). Gorelik (2017) argued that a system-level approach is needed for the design, manufacture and life management of parts, when new manufacturing processes are considered. He based his argument on previous field experience (from aeronautics) showing that even if a non-critical part is considered for the new manufacturing process, the consequence of it failing could, in the worse-case scenario, start a chain of failures that was not anticipated. Hence, the need for a systems view of part criticality, and a collaboration with the system owner to find the right qualification requirements can be seen as well.

5.4.1 Refined Model of the Product Development Process with Additive Manufacturing

A product development process including AM for a sub-system supplier in the space industry was shown in Figure 11 in chapter 3. The need for a holistic approach to AM qualification has been discussed by e.g. Taylor et al. (2016) and Yeong & Chua (2013), and further developed from the perspective of the space industry in this thesis. The parallel work of product development and manufacturing process development was described in section 5.2.1 and shown in Figure 15. The necessity to link product and manufacturing process development to develop and qualify AM parts was discussed in section 5.3. Based on this, Figure 17 (below) is a refined model of the product development process with AM, combined with the AM process development, including highlighting and explanation of the need to enable DfAM through a system-level perspective.

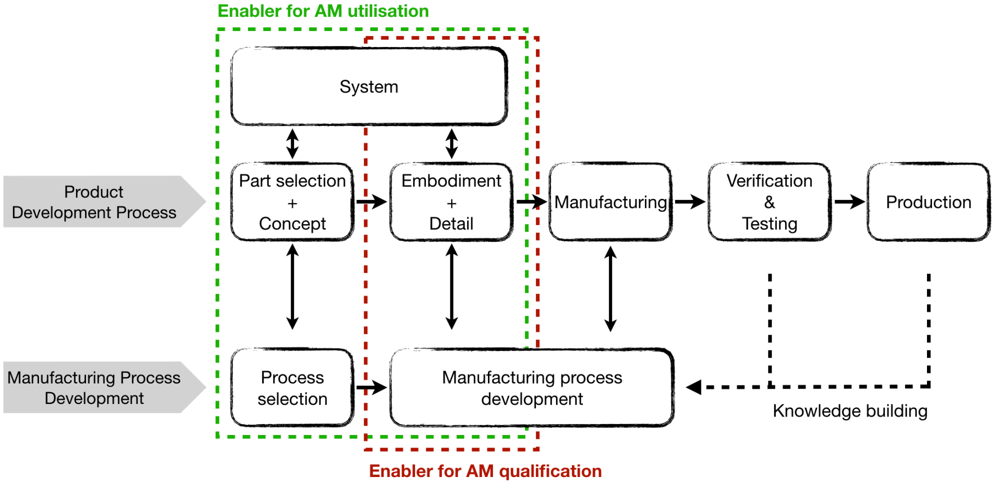

Figure 17 – A refined model of the product development process to enable AM design and part qualification through the practice of systems engineering and concurrent manufacturing process development

Three aspects have been described that should be considered in the feasibility assessment of a part for AM, and to enable its qualification: *AM process experience*, *design freedom* and *part criticality*. The influence of these aspects on the product development process is illustrated in Figure 17 with the green and red boxes respectively. The green box highlights the need for a system-level approach in the selection and design of sub-system parts, as well as the need for having (and building) process experience. The red box overlaps the green, but highlights the need for a system-level perspective on part criticality, as well as the close relationship between part design and manufacturing process development to enable qualification. The importance of testing and NDT inspections as means to qualify AM parts was discussed in section 5.3.2, and is included in Figure 17 as the feedback loop included in product and manufacturing process development. The role of *in situ* inspection of AM processes to both inspect parts and build process knowledge (Everton et al., 2016) has not been discussed in detail in this thesis, but it is acknowledged that it will probably be a vital tool to speed up process understanding and to complement other NDT methods.

To enable full utilisation of DfAM for sub-systems in space applications, systems engineering could be essential for the ability to explore new design spaces and find suitable parts. To enable qualification, the design engineers have to work closely with the AM process developers to find process parameter settings that fulfil the material characteristics of the part. Equally important is this collaboration to understand AM material limitations to be able to design parts accordingly. The approach is similar to that explained in the example of castings in Figure 14. This is an iterative process, where the rapid manufacturing of AM should give an opportunity to test design solutions and their impact on the material properties. This iterative process has been described by Orme et al. (2017), which requires the used product development process (currently usually a stage-gate) to be flexible to allow for a more explorative design process. The traditional long lead times in the space industry have led to an incremental approach for introducing new solutions (Paper B), but with AM, this lead time could be substantially reduced through such an iterative process. This could also enable a more cost-efficient product development which was mentioned as equally important for cost reduction (Paper B). At the same time, the suitable part, its requirements, and level of risk that can be accepted, all have to be agreed with the system owner.

6 Conclusions

This final chapter presents the conclusions that have been drawn based on the research presented in this thesis. Contributions to academia and industry are discussed and suggestions for future research are given.

The research questions are restated below for ease of reading this chapter. Included in parenthesis after each question are the papers that mainly contribute to the answer of each question, as shown in Figure 12 in chapter 4.

> *RQ1: What characterises development and qualification of parts in the space industry? (Papers A, B and C)*
>
> *RQ2: Why is qualification of AM parts challenging for critical space applications? (Paper C)*
>
> *RQ3: How does development and qualification of AM parts impact the product development process for space applications? (Papers B and C)*

The following sections present the conclusions drawn for each research question.

6.1 Research Question 1

The development and qualification of parts from a sub-system supplier perspective in the space industry are characterised by two main themes: (i) they are influenced by external factors, where some are not always under the control of the engineers, and (ii) parts that are not allowed to fail due to the severe consequences (critical parts). Both of these define the circumstances under which parts are developed and, from the results presented in this thesis, the following can be stated:

- Product development in the space industry is usually carried out in a hierarchical structure, with a customer-supplier relationship at each level. At the top, authority regulations govern the requirements for product development (e.g. ECSS).
- In government programmes, which govern the major part of space industry development, political decisions exert a strong influence and impact financing and strategic commitments, especially due to the short time frames of project funding (typically three years within ESA) compared to the long time frames for technology development.
- In recent years, the focus has shifted towards competitiveness through cost rather than performance and low weight, putting pressure on companies to be innovative and efficient in their product development and manufacturing.

- Long lead time in both development and manufacturing impact innovation since it tends to promote incremental development. This is due to the risk of negative technical and financial consequences if new solutions are shown not to meet the requirements at a late stage.
- Requirements for part design (interfaces and function) are usually set by the system owner, while requirements for part qualification are set by the sub-system responsible in accordance with governing specifications, and in agreement with the system owner.
- Qualification of parts includes the qualification of manufacturing processes, where it has to be shown that critical manufacturing processes are controlled, and that the effect of possible anomalies have been mitigated, both through manufacturing process development, and suitable safety factors in part design. Unique designs often make it necessary to develop manufacturing processes according to the requirements of the part.

6.2 Research Question 2

The first major challenge that can be seen for the qualification of critical parts in space applications is the requirement of a damage tolerance approach for design verification. The challenge lies in the inherent material characteristics of AM processes, which are: (i) anisotropic microstructure (resulting in both part and location specific properties), (ii) the possible presence of multiple defects (porosity, lack of fusion, inclusions, cracks) and (iii) rough surfaces. With these in mind, the following should be considered for fracture critical parts manufactured with PBF:

- Defects are more detrimental than microstructural effects (Lewandowski & Seifi, 2016).
- Surface and sub-surface defects are more detrimental than defects deeper in the part (Beretta & Romano, 2017).
- The surface roughness of as-built parts can decrease the fatigue life by as much as 40–50% compared to machined parts (Beretta & Romano, 2017).
- Increasing packing density and volume of the build chamber has been seen to increase the occurrence of porosity (Haeckel et al., 2017).
- Powder quality has been shown to impact part quality (Sutton et al., 2016).
- HIP and surface treatment are often considered to be necessary to improve fatigue properties for both SLM and EBM (Begoc et al., 2017; Gong et al., 2014; Li et al., 2016).
- Little research has been done on the impact of environmental effects (e.g. hydrogen embrittlement) on AM material properties (Lewandowski & Seifi, 2016).

As these material and process characteristics are not yet fully understood, qualification of a part is expected to rely on part and material testing to show damage tolerance, combined with NDT inspections and analytical verification. This highlights the second major challenge for space applications, which is the limited opportunity to test parts in relevant environments, since many applications are not subjected to their actual loads until they are actually launched. This requires testing that can be carried out on coupons and parts (dedicated rigs for e.g. vibrational loads or pressure loads) and systems (e.g. engine tests), which poses a challenge for critical space applications because of the following reasons:

- System-level testing is expensive and time-consuming for many space applications, which requires an already verified confidence in performance for parts that are submitted for such tests.
- The characteristic low production volumes in the space industry result in less material that can be used for material characterisation.
- The representativeness of test coupons for the actual part behaviour and defect distribution cannot be guaranteed for AM materials. Test coupons or artefacts, therefore, should be designed to represent the part.
- An approach for analytically verifying defects is needed, which requires NDT methods capable of detecting sufficiently small defects.
- Established NDT methods and NDT standards for AM materials do not exist yet, but will be an important part in any qualification approach. The inherent rough surface of as-built PBF parts increases the complexity of developing such standards and methods.
- A suitable qualification approach has to be defined according to specification requirements (e.g. ECSS) and in collaboration with the system owner.

6.3 Research Question 3

The current level of AM process maturity makes ‘learning by doing’ an inevitable approach, where both manufacturing engineers and design engineers have to work closely together to map the processes. Manufacturing process development is therefore closely linked to DfAM, and both should be considered a necessity for the qualification of AM parts. The process and geometry dependent material properties make it necessary to understand the implications of a chosen process and a developed part. To utilise the potential of AM to enhance product performance through part consolidation and free-form design, design engineers need personal experience of AM process capabilities. Furthermore, designing AM parts with the assumption of a completely defect-free material is probably not realistic given the inherent characteristics of AM technologies, and considerations for the ‘effect of defect’ for the specific part are needed. For the above reasons, DfAM has been suggested to be an important part of AM qualification, where the challenge lies in: (i) finding the right part design for the chosen AM process, and (ii) defining the right level of requirements for that part.

In the development of sub-systems, a close collaboration with the system owner has been suggested as beneficial for both of these challenges. This has been discussed both from the perspective of exploring the design freedom enabled by AM, and finding suitable requirements for AM qualification. The exploration of design freedom might need to challenge traditional system interfaces, where the system owner has the best knowledge of what the best solution for the system is. To set the requirements for qualification, an understanding of the requirements of the system and the specific part has to be balanced with the capabilities of the AM process, making sure not to overspecify the qualification, while not increasing the risk of system failure. Apart from using system knowledge in defining the right requirements for the part, AM process characterisation is needed to understand the capabilities of the chosen process. The rapid manufacturing and flexibility in tweaking processes parameters with AM processes could result in a more efficient and quicker product development process, where manufacturing process development can occur simultaneously. While this has the potential to decrease lead time and the cost of product development, as well as increasing the possibilities for testing new designs, it also sets requirements for the flexibility and adaptation of the product development process. Compared to conventional manufacturing processes, where low volumes mean less business for the material supplier (e.g. castings) leading to possibly less attention in the DfM loop, the potential of AM to offer iterative development of new concepts could have considerable impact on innovation of space parts.

6.4 Concluding Remarks

Although AM materials are often compared to conventional materials, the results from this thesis indicate that the challenge does not lie in showing that the material properties of AM parts exceed or meet conventional manufacturing processes. Rather, the challenge is to show what the properties are so that these can be used in the development of new parts. If the properties are known, the requirements for the parts can be set thereafter. Figure 18 is an updated version of the areas linked to qualification presented in chapter 3, where DfAM has been added based on the discussion in this thesis.

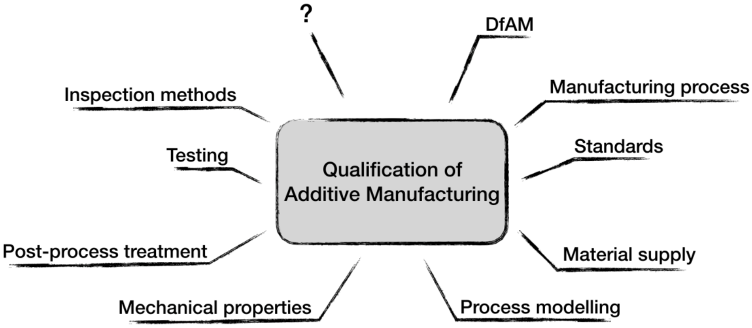

Figure 18 - Areas involved in the qualification of AM parts, including the addition of DfAM and the uncertainty in the current understanding of the processes that impact the potential to develop and qualify critical parts

Also added in Figure 18 is a question mark, representing the current lack of full understanding of AM processes (Frazier, 2014; Slotwinski & Garboczi, 2015), and that AM is still a collection of several manufacturing technologies with relatively low maturity that are continuously evolving. This should, therefore, be mentioned as one part of the challenge of developing and qualifying parts and processes. Since the processes are not fully understood, it is not possible to draw exact conclusions on what factors will influence AM qualification i.e. there might be unknowns that are yet to be discovered (e.g. new failure modes not encountered in conventional materials, or other unexpected process characteristics). Here, the rather common use of the term AM as the collective term, not specifying which process is meant could be questioned. Instead, it can be argued that due to the sensitivity of AM materials to process characteristics (type of energy source, raw material, build process etc.) makes it important to distinguish between processes, and the same qualification logic might not be applicable over several processes.

6.5 Research Contributions

The contribution to academia in this thesis is an insight into the challenge of qualifying parts in the space industry and the special conditions under which engineers develop products in this industry. Furthermore, the holistic perspective of this thesis has merged material science research with research in product development, indicating the equal importance of both disciplines in the pursuit of a qualification approach for AM.

The contribution to the space industry is an overview of current research and the state of the art in AM. Furthermore, the holistic approach taken on AM qualification suggests that utilising available knowledge from conventional manufacturing processes is important, but also that gaining knowledge about AM process capabilities is needed to enable DfAM. The importance of 'learning by doing' and working continuously with process development has been highlighted, as has specific challenges for qualification of AM in space applications. The challenge of building experience with low volume production, often a prerequisite in the space industry, gives an indication towards that strategic partnerships could be used to enhance knowledge building.

6.6 Future Research

From the discussion in this thesis, it is obvious that more research is needed on AM processes and material characterisation, post-build treatment and non-destructive inspection methods. These are huge fields of research already, and their importance has been emphasised in this thesis. Of special interest when treating AM as a critical process is to determine which parameters that have to be frozen to ensure a repeatable process.

In light of the different approaches to qualification that have been presented, a guideline for choosing the suitable qualification approach, taking current experience and part requirements into account, would be a help for companies choosing to include AM in their portfolio of manufacturing processes.

From a DfAM perspective, its involvement in qualification has to be further researched. An approach for assessing the qualification needs of a specific part should be developed, allowing AM qualification to be taken into consideration in the early phases of product development.

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Appendix A

Interview guide for Study II. Interviews were conducted in Swedish, and the questions have been translated for this thesis.

Background

1. Tell us about yourself in your role here at the company?
2. How long have you been working in the company?

Product development process (design process)

3. A) How could the product development process for space products be described according to you?
   B) Are there documents to follow?
   C) Do you do it in your daily work?
4. What parts of the product development process have you been involved in?
5. A) To you perceive that there is a difference in how the product development process is used between different projects and/or products?
   B) In what way?
6. Are there any external parties involved in the product development process?
7. A) Do you work together with manufacturing/production in the product development process?
   B) If so, in what way are you working with them?
8. How much do you feel that restrictions in production govern design choices?
9. A) How long does the development take from concept until hand over to production?
   B) What parts of the product development do you perceive are most time consuming?
10. To what extent are previous designs reused in the development of new products?
11. A) What is a prototype according to you?
    B) How do you perceive that the company use prototypes in the product development process?

Additive Manufacturing

12. How much and in what way have you come in contact with additive manufacturing?
13. A) How would you describe additive manufacturing?
    B) What processes do you believe are relevant for use in space products?
14. A) Do you perceive that there is great interest in additive manufacturing as a manufacturing method for space products?
    B) What do you perceive is the reason for this interest?
15. What parts of the product development process do you believe additive manufacturing can impact the most?
16. What do you perceive that additive manufacturing can contribute with in the development of your space products?
17. A) Do you believe that design optimisation for additive manufacturing will be different compared to conventional design optimisation?
    B) In what way?
18. What restrictions do you perceive exist if additive manufacturing would be introduced into the product development process?

Appendix B

Agenda for the workshop series in Study III. Each workshop followed the same agenda and were conducted in Swedish.

Introduction (13:00-13:15)
- What is everyone working with?
- What is additive manufacturing?

Session 1 (13:15-14:30)
- Needs identification
- Costumer quotes
- What possibilities and challenges do you see with additive manufacturing?

Fika

Highlights (14:45-15:00)
- Presentation of state of the art and state of practice in additive manufacturing

Session 2 (15:00-16:40)
- Work with ideas for products using additive manufacturing
- Presentation of concepts

Feedback (16:40-17:00)
- I like – I wish

Appendix C

Example of interview guide for first part in Study IV. Exact version may differ depending on the expertise of the respondent. Interviews were conducted in Swedish, and the questions have been translated for this thesis.

Background

1. Tell me about yourself in your role here at the company?
2. How long have you been working in the company?

Qualification

3. What is qualification for you?
4. Is there a difference in qualification, verification and validation?
5. Is there a difference in process qualification, material qualification and product/component qualification?
6. Do you know if the requirements for qualification differ between commercial aircraft products and space products?

Space products

7. A) What sets the requirements on process qualification?
   B) What sets the requirements on material qualification?
   C) What sets the requirements on product qualification?
   D) What are typical requirements?
8. Is it possible to describe the main steps in qualification in a general manner?
9. Does the criticality of the product impact how the product and the material is qualified, respectively?
10. A) What are the challenges in process qualification?
    B) What are the challenges in product qualification?
11. Do you perceive that consideration for qualification (process/product) is taken during the product development work? How?
12. Is there any described working method for how new processes shall be handled when they are to be qualified?
13. A) What type of test methods are used in the qualification of processes?
    B) What type of test methods are used in the qualification of products?

Extra questions

14. A) Do variations normally occur in the process outcome?
    B) Does this differ between processes and materials?
    C) How are variations handled?
15. Is there someone that you think I should talk to based on the discussion we have had?

Appendix D

Example of interview guide for second part in Study IV. Exact version may differ depending on the expertise of the respondent. Interviews were conducted in Swedish, and the questions have been translated for this thesis.

Background

1. Tell me about yourself in your role here at the company and how long you have been working in the aerospace industry?
2. What is qualification for you?

Qualification of Additive Manufacturing (AM)

3. What is your experience in additive manufacturing? What processes have you worked with?
4. A) Have you worked with qualification of AM?
   B) Has the qualification focused on process or product?
   C) Do you know how critical the AM part is (from a functional perspective)?
   D) Do you know what TRL level the AM process is considered to have?
5. A) Did you have to ”rethink” how to qualify compared to conventional processes?
   B) Was there something unique with the AM process that made it necessary?
6. Is it possible to describe the logic that was used in the qualification of AM?
7. A) Do you know how the requirements were set for the qualification of AM?
   B) Do you know if the requirements are specific for the product or general?
   C) What do the requirements focus on (pores, geometry, post-processing, …)?
8. A) Are any test methods used in the qualification of AM, non-destructive or destructive?
   B) Is periodical testing used?
9. What do you perceive are the challenges with qualification of AM?
10. Within what area do you see the most need for development to be able to qualify AM products at a larger scale?

Extra questions

11. Do you perceive that there is a common picture within the industry of how qualification of AM should be done? Both aerospace and other industries.
12. A) Do you perceive that consideration for qualification is taken in the development of products for AM?
    B) Is this something that you think is necessary?
13. Is there someone that you think I should talk to based on the discussion we have had?

Paper A

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Opportunities and Challenges for Additive Manufacturing in Space Applications

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Abstract

Additive Manufacturing (AM) is a fast developing manufacturing technology that brings many opportunities for the design teams at companies working with product development. One industry that has embraced this is aerospace, and more specifically within space applications (satellites and launchers). Although there are huge possibilities with this technology, there are also several challenges that need to be overcome. This paper is based on interviews, study visits and a state of the art review from the current literature. The focus of this work has been to map the opportunities and challenges with AM in space applications and to highlight the research gaps that have been found. There are few documents available that address AM and/or innovation within space applications. The results show that design for AM, as well as product and process qualification, are areas that need to be further investigated.

Keywords: *Additive manufacturing, design processes, qualification of components, DfAM, innovation*

1 Introduction

Additive manufacturing (AM) has been heavily promoted over the last few years because of the success of cheap 3D printers and the emerging Maker Movement. In industry, AM has mainly been used for prototyping in the early phases of product development. Now companies are starting to use metal-based AM for more regular production of components. Three main manufacturing methods exist for metals – powder bed, wire feed and powder feed. Powder bed has the advantage of better tolerances, better surface finish, and it can also create more complex geometries, while the deposition rate of wire feed is unparalleled. The unit cost for metal-based AM is often very high and the business case has to be carefully chosen to beat the cost of traditional manufacturing methods. A sector that seems to be most suitable for AM applications is the space industry, which involves high performance parts with complex designs, specialised materials and very small series (the European expendable launch vehicle Ariane 5 has had roughly 80 launches in 20 years). With AM it is possible to introduce new optimised designs for increased functional performance (using geometries impossible to achieve with traditional manufacturing methods), short lead-times from concept to final product and independence from expensive castings. This paper highlights the opportunities for using AM in space applications and also points out challenges for engineering design research. The results given by this paper will give a direction for future research for design, innovation and qualification for AM within space applications. The paper is based on interviews with both manufacturers of AM machines, designers developing rocket engines and a state of the art review. These investigations result in a summary of the opportunities and challenges for AM that could emerge within space applications. Firstly, the method of the conducted research is presented in order to structure the information gathering. Later the state of the art and state of practice for AM are explained before the opportunities and challenges that come with AM are explored. Finally, the conclusions are presented, which target future research that needs to be conducted.

2 Method

The research has been performed in collaboration with GKN Aerospace and one of the authors is situated at GKN as an industrial PhD student and has several years of experience in design of space systems. The focus of the literature study has been on finding state of the art and state of practice of AM, specifically for space application.

The empirical data gathered in this project is based on interviews and visits to manufacturers of AM equipment and companies that use AM in their product development process. The interviews have been focused on identifying current design processes (focusing on rocket engine sub-components) and how AM can change this process. From the empirical data, opportunities and challenges have been identified, these findings have been presented to experts at the company in order to receive feedback and to ensure that the analysis is consistent with perceived problems, opportunities and existing processes.

Systematic literature studies have been conducted to investigate the current situation for AM within space applications with a focus on product design and innovation. The studies are limited to articles and conference papers. The literature study process is made through four steps: Identifying keywords, Screening, Filtering and Analysis of the document. Firstly the keywords are identified within the area of the study. In this case the keywords *Additive Manufacturing*, *Layered Manufacturing* and *Rapid Manufacturing* are at the centre of each search. Then a second keyword is added in order to direct the results towards documents that are of interest in this study. Examples of those keywords are *Product Development Process*, *Design Process*, *Challenges*, *Opportunities*, *Space*, *Space Applications*, *Qualification*, *Innovation* and *Design*. The search has been mainly made in Scopus.

The results are then screened through looking at the title of each document, if the title is within another area than preferred then the document is discarded from the study. In order to filter the results and to capture the relevant references, each document is investigated. Firstly the abstract is read, and if the document seems fit for the study then the results and discussion are read. If the document is still interesting for the study, the entire document is read and analysed.

3 State of the Art for Additive Manufacturing in Space Applications

AM is a layer-upon-layer manufacturing method where a 3D CAD model is sliced into 2D layers that together produce a physical 3D model. The technology of AM has successfully been developed over the past 30 years, where the first machines were mainly used to rapidly produce prototypes (Gibson et al, 2015). Rapid prototyping still remains the main application for AM processes within polymer materials (Mellor S. et al, 2013) but within metallic AM the models are nowadays often used as an end-use part (Vayre et al., 2012).

Within space applications there seems to be a main focus on two AM processes: *Powder Bed Technologies* and *Deposition Technologies*. An overview of different AM methods suitable for space applications is shown in Figure 1.

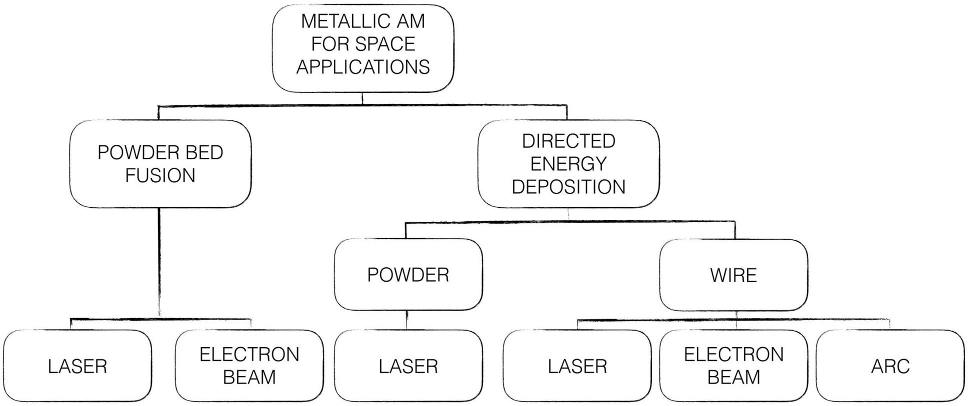

Figure 1. Overview of additive manufacturing methods for space applications

Uriondo et al. (2015) have made a review of the future of AM technologies in the aerospace sector. Their conclusion was that Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) are the processes that are currently most suitable for the aerospace industry. Within PBF technologies they identified Electron Beam Melting (EBM) and Selective Laser Melting or Sintering (SLM/SLS). Within DED the technologies are Laser Metal Deposition (LMD) for powder and wire, and Wire and Arc Additive Manufacturing (WAAM). For space applications, and especially rocket engine applications, the most commonly used processes belong to the PBF category.

PBF is a method where powdered materials are applied on a platform, layer by layer. Then a thermal energy source induces fusion between the powder particles, where a controlling mechanism steers the fusion to a prescribed area of each layer. A rake or roller controls the adding and smoothing of the powder layers. As indicated, there are different fusion technologies, but the most common is laser (Gibson et al., 2015). Within the DED technologies there are the wire and powder processes where both have a fusion technology for building the part. The powder deposition uses a laser technology while wire deposition can use laser, electron beam or arc (plasma or gas) technology (Ding et al., 2015).

3.1 State of Practice for Additive Manufacturing

AM for metallic materials is highly protected by patents and trademarks and different technologies are often unique to each manufacturer (e.g. powder bed using electron beam is only used by Arcam AB). For aerospace the number of applications are rapidly increasing and some examples of current implementations are the 3D printed bionic partition for Airbus A320, manufactured using direct metal laser sintering in Scalmalloy (3Ders.org, 2015). The partition is not only stronger than the existing model, but also about 25 kg lighter. Perhaps the most well-known aerospace application is the fuel nozzle designed by GE Aviation for the LEAP engine, planned to be produced in quantities of 30,000 parts per year. The specifically AM-designed fuel nozzle will have intricate solutions such as internal cooling channels and will combine 18 parts into 1 while reducing the weight of the part by 25% (Wohlers Report, 2015). For space applications there are fewer reports of implementations, however several secondary structures and demonstrators have recently been evaluated. Examples include the Main Oxidizer Valve (MOV) body in one of the nine Merlin 1D engines in the Falcon 9 rocket launched by SpaceX. The mission marked the first time SpaceX had ever flown a 3D-printed part (SpaceX, 2014). NASA (2015) demonstrated a SLM printed breadboard engine (where all parts are connected so that they work the same as they do in a real engine but not packaged together in a flight configuration) in December 2015. GKN Aerospace in Sweden (formerly Volvo Aero) has manufactured and proven a nozzle extension demonstrator for a possible upgrade of the Vulcain 2 engine (used on the Ariane 5 launch vehicle). LMD using wire as material feed was used to produce 3D features on the outside of the nozzle wall with the intention of structural strengthening and producing weld preparation areas. The complete nozzle was eventually tested and proven in a full-scale demonstrator engine test (Honoré et al., 2012).

3.2 Current Design and Manufacturing Processes

Many rocket engine parts today are manufactured using traditional processes such as casting, with subsequent machining and finishing. Once the detailed product design is set by the design team responsible, a 3D CAD-model is communicated to the material supplier (the foundry in the case of casting) and an iteration loop is started between the design team and the supplier to make minor changes to improve the producibility (often including casting trials and/or process simulation). When a final design is agreed, a first article is produced for verification, usually through a cut-up including material testing and microstructure evaluation. Gating and feeding systems are often problematic to design and there are usually several iterations until an acceptable process is found. Once the article is approved, the first batch for part testing is made, and even at this point there is usually additional rework (grinding and welding) needed for defects found using non-destructive testing (NDT). Due to the long lead-time involved, it is not uncommon that the first batch is produced simultaneously with the first article used for verification (cut-up). This means that if process difficulties are not captured in process simulation or casting trials, finished parts might become useless if a problem comes up at a late stage, bringing about additional costs. Furthermore, late updates in load specifications from the end customer might also lead to already-produced castings becoming useless. In the case of casted products, the casting process is characterised by long lead-times, 10-12 months is not unusual for aerospace applications, just for the casting. A typical design and manufacturing process is pictured in Figure 2.

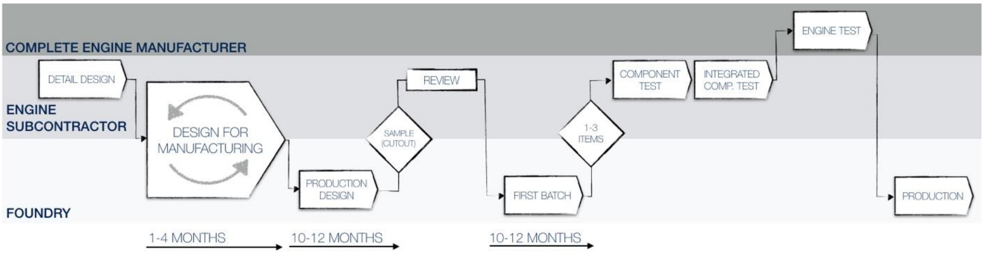

Figure 2. Overview of a general casting process.

Apart from the long lead-time when dealing with casting suppliers, the low series of production in the space industry (e.g. 6-10 parts per year) might be a disadvantage when looking for suppliers. The business case is normally small in comparison with e.g. the automotive industry, or even civil aerospace, leading to expensive castings.

The casting process is well established with standards and specifications setting the minimum requirements for acceptance of products and materials. The process parameters are known and some simulation models also take microstructure, residual stress and phase transformations into account. Once the part-specific casting process has been shown to fulfil the requirements set by the customer (who has responsibility for the design), the process is frozen. Ideally it then gives similar results for each subsequent batch (with small variations), but there is usually still a need for rework after NDT.

4 Opportunities and Challenges

AM in general has huge potential – it is possible to control the distribution of materials within objects with a high degree of precision (Hiller & Lipson, 2009) which leads to the possibility of improving performance and also adding new functionality (Hammetter et al., 2013). However, the potential benefits aside, AM for metallic materials is still evolving, and there are still challenges to overcome. In fact, the biggest hurdle to implementation of AM into "main stream manufacturing" is quality and consistency (Yeong, 2013). The following sections highlight the identified opportunities and challenges with AM in general but also specifically for space applications.

4.1 Opportunities

There are four main reasons to use AM: customise products for the requirements of individuals; improve product functionality with adoption of complex geometries; reduce part numbers through consolidation; increase the value to the customer with specific design features (Campbell et al., 2012). Many products that are available today are an assembly of several parts and are often divided into more parts than necessary due to manufacturing methods (Yang et al., 2015). When using AM instead of traditional manufacturing methods there is a greater possibility to merge these parts into more complex parts and assemblies which could reduce the time for the manufacturing process.

Aerospace, and more specifically space, is one industry that could benefit from introducing AM into the production process. The space industry is characterised by complex products in low volumes which is an ideal match for AM (Gibson et al., 2015). It gives the opportunity to optimise product design for increased functionality - internal cooling solutions that are not feasible with traditional manufacturing methods and part consolidation are some examples. Weight has always been a driver in space applications due to cost and practical reasons. Lower launcher weight will ultimately allow for increased payload weight and increased value for each launch. The estimated cost for each kg into orbit is in the order of $10,000. Light-weight materials, such as titanium, are available for AM and more net-shaped, weight-optimised products can be produced. Furthermore, traditional manufacturing processes such as casting are characterised by long lead-times (4-12 months, as mentioned above). AM has the potential to both substantially decrease the lead-time (3-6 weeks), and possibly (if desired) move manufacturing in-house. An example of this is from SpaceX development of the engine chamber for the Super Draco launch escape system. The chamber, printed in Inconel, resulted in an order of magnitude reduction in lead-time compared with traditional machining – the path from the initial concept to the first hotfire was just over three months (SpaceX, 2014). Another example is Lockheed Martin Space Systems in the U.S.A. which has used the Sciaky electron beam wire system (EBAM®) to manufacture a satellite propellant tank in titanium, consisting of two hemispherical halves of roughly 150 cm in diameter. Allegedly, product cost could be reduced by 55% and total manufacturing time by as much as 80% using the EBAM process. The tank has not been used in service yet, but Lockheed Martin sees the process to be a viable option in the future (Lockheed Martin, 2015; Sciaky, 2016). New actors in the space industry are also changing the industry in a disruptive way, *"Traditionally space applications had an extreme focus on weight and performance, but today the emergence of new actors in the market (e.g. SpaceX) has driven the focus towards competitiveness in cost"* (senior project leader at engine sub-component development). AM gives opportunities to decrease cost since the need for expensive tooling is removed and the possibility to make late changes in the design is added (without changing an already set manufacturing process) (Gibson et al., 2015). Both Cronskär M. et al. (2013) and Baumers M. et al. (2016) also state that AM technology will enable reduced unit cost, especially for low and medium production scale (Mellor et al., 2014).

4.2 Challenges

The AM processes, as they are today, show a variation in the printed products, which can be seen on a part-to-part basis as well as machine-to-machine (Frazier, 2014). It is vital to understand this process variation, since it could otherwise be a limiting factor in the use of AM in mission critical components (Seifi et al., 2016). Parameters such as internal defects, surface roughness and geometry tolerance are all important to master. For example, to be able to utilise the design freedom enabling complex shapes within aerospace, one driver is to use "as deposited" surfaces (Seifi et al., 2016). This however sets requirements on what surface roughness is acceptable from a fatigue resistance perspective (risk of crack initiation due to rough surface structure) and possibly a functional perspective for internal flow surfaces. Process control, material characterisation, part inspection through NDT and post-processing are areas that need development for qualification of AM (Uriondo et al., 2015). The design freedom increases with AM since the designer is able to to create geometries that have not been feasible with traditional manufacturing methods. However, this also means that the designer has to adapt to the AM process and take new factors into account in the design process, i.e. Design for Additive Manufacturing (DfAM) (Yang & Zhao, 2015). Part orientation, support structure, topology optimisation and multi-functional features for increased performance are some examples of design aspects that need to be included (Gibson et al., 2015; Vayre et al., 2012). However, it is hard for the designer to take full advantage of the AM capabilities due to the new design framework (Yang & Zhao, 2015).

4.2.1 Design for Additive Manufacturing

It might be hard for the designer to take in all the possibilities of the design freedom that AM comes with, and one challenge is to identify the parts and assemblies with which AM can bring value to the customer (Klahn et al., 2015). AM can often be more expensive per part compared to traditional manufacturing methods if printed in a higher volume, but parts in a low volume are often less expensive (Mellor et al., 2014). Therefore, many designers see several areas where customised products have potential. It is necessary to understand when the use of AM is beneficial from both a cost and geometrical perspective.

There are several different approaches available for DfAM but, as yet, none of them have been deeply investigated yet. Emmelmann et al. (2011), Gao et al. (2015) and Gibson et al. (2015) state that the designer is limited to the CAD tools and the holistic design guidelines available. The possibilities of today's CAD systems for AM usage are not ideal due to the limitations the solid-modelling-based systems have (Gibson et al., 2015). Yang & Zhao (2015) state that CAD systems have difficulties in precise geometric modelling and have problems with complex constraints and modelling information. This might also affect the possibilities of using CAD systems for AM. Klahn et al. (2015) propose that there are two types natures of design strategies. The first one is manufacturing driven which gives the designer the option to be cautious and design for any manufacturing method. This makes it easy to use AM as a confirmation method, where the product is tested on a customer base and altered into the perfect shape before the selection of all manufacturing methods in relation to cost per part. The second one is function driven where the designer uses any shape possible for AM in order to optimise the function of the product. This could be seen as a more insecure approach where there is only one manufacturing method available for the design. Yang & Zhao (2015) propose that to find an optimal design, a new method should be developed from an upstream point of view where the first step is to optimise the existing part. However, there is also a need to find a method for optimal design while designing a new product.

4.2.2 Qualification

Qualification and verification of AM materials and products is a topic subject to intensive research by universities and industry, and there is still a need for technology development in this field. Ways of qualifying the processes need to be found (Frazier, 2014) in the establishment of sufficient TRL-levels (Mankins, 1995). It is not possible to use conventional NDT methods due to the characteristics of the material (internal and at surface) (Uriondo et al., 2015). Furthermore, the conventional qualification processes for metallic materials require extensive testing that may take up to 15 years and considerable amounts of money, and are not suitable for variable processes like AM (Seifi et al., 2016). Therefore, alternative methods need to be developed to be able to qualify AM if it is to be applied as a “de facto” manufacturing process in the industry in the coming years. Standards are being developed (e.g. ISO/ASTM) but are not yet available for the qualification requirements on parts (Monzón et al., 2015).

To be able to qualify AM products and also to establish AM technology as a competitive manufacturing process, there is a need for in-process control systems (Frazier, 2014). The nature of the layer-by-layer process makes it possible to inspect each of the layers while they are created. In this way, defects could be identified while the part is being built, and product quality assured in-situ. The machine manufacturers have understood this need and several systems are under development. Some examples are Concept Laser (QM meltpool 3D), Arcam (LayerQam) and EOS (EOState) (Everton et al., 2016). Simulation of the AM process is also still quite rudimentary but is an important step towards understanding and qualifying the process (Gockel et al., 2014; Martukanitz et al., 2014).

AM is a process where the material is “created” in the process getting properties that are linked to the thermal environment in the building process. E.g. cooling rate and temperature history has a direct connection with the achieved microstructure (Gu et al., 2012; Murr, 2014). Although a challenge, since this means that the new material has to be characterised, it also brings about opportunities. Mastering the process and understanding the microstructure would mean that it is possible to adapt the material characteristics within the build towards the part’s geometry and function. Furthermore, new alloys can be created that are specifically developed for AM (Seifi et al., 2016).

Yeong et al. (2013) have suggested a quality management framework for implementing AM into the biomedical industry. The framework highlights the deficiencies of AM and suggests activities throughout the industrial chain for assuring product and process quality. Although being suggested for biomedical use, the principles are the same for other industries with high demands on product quality. The essence is that the complete industrial chain is involved in assuring product and process quality, from the generation of the STL file to understanding the product requirements and verifying process and material characteristics.

5 Conclusions and Discussion

Traditionally space component development has focused on performance and robustness, often developed in large international consortiums with governmental support. The product development process is very detailed and complex because of all the stakeholders involved. With the introduction of new commercial players there has been a radical shift to innovation, rapid iteration and cost. Traditionally, many details of rocket engines have been developed for casting or other conventional processes, with subsequent machining where the manufacturing time from finished geometry of the first component can be more than six months. Therefore, components are developed incrementally; designers do not dare to introduce radical new solutions.

This paper has identified several opportunities and challenges that are of importance for future research. AM in general has huge potential – it is technically possible to produce components with varying stiffness (by altering the internal structure of the component), build anisotropic components or mix materials in a solid component (for certain AM processes). Also, compared to traditional processes the manufacturing of a single component can be reduced from 6 months to less than a week. This could give the opportunity to create a more explorative iterative design cycle and explore more radical design solutions.

AM also introduces challenges, firstly the whole product development process is affected. Design for Additive Manufacturing is a complex approach due to the few design tools and CAD packages that exist for AM. There are few support tools and methods that help the engineers to adopt AM in the design process. Traditional CAD tools are designed for conventional manufacturing methods such as drilling and lathing (features like holes/pockets/ etc). This forces the engineer into design in a traditional way, instead of encouraging the wider geometrical possibilities that AM brings. A new tool should fit the new possibilities and encourage engineers (especially engineers who are inexperienced with AM) to think in an AM perspective. In a proposed CAE system the engineer could design in a top-down approach, describing functional requirements (e.g. interfaces, cooling, embedded electronics, structural requirements) and let the system perform topology optimisation (similar to existing FE programs for structural topology optimisation). There is also little experience of AM within companies, which results in a more cautious approach as regards embracing new solutions with low TRL. These uncertainties can both lead to a longer design process and a lower level of innovation within companies and processes.

Qualification is another important area for space applications – products should not fail. Traditionally design simulations are verified and complemented with empirical testing of both material and products. This would be time consuming and imply large costs for the qualification of each AM process and machine. Therefore, it is a great challenge to develop simulation models for the manufacturing process in order to understand how process parameters influence the final products. Also the verification and qualification processes need to be assessed and developed for AM.

Future work includes more detailed studies of the current design and qualification processes, and also how design and qualification processes have been implemented when introducing new manufacturing methods. A broad perspective needs to be taken to understand how the product development process as such will change to allow for new innovative designs and solutions. Several breakthroughs in AM for space applications have been reported in news channels (NASA, 2015; SpaceX, 2014; 3Ders.org, 2015) but cannot yet be found in research papers. Also the literature studies indicate a lack of research regarding both additive manufacturing and innovation within space applications, which gives a clear indication of where further investigations and research should be conducted.

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Paper B

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ADDITIVE MANUFACTURING AND THE PRODUCT DEVELOPMENT PROCESS: INSIGHTS FROM THE SPACE INDUSTRY

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Abstract

With Additive Manufacturing (AM), manufacturing companies have the potential to develop more geometrically and functionally complex products. Design for AM (DfAM) has become an expression implying the need to design differently for the AM process, compared to for conventional, usually "subtractive" manufacturing methods. There is a need to understand how AM will influence the product development process and the possibilities to create innovative designs, from the perspective of the product development engineer. This paper explores the expected influence of AM on the product development process in a space industry context. Space industry is characterized by small-scale production, and is increasingly cost-oriented. There is a general belief that AM could pave the way for more efficient product development. Three companies have been studied through interviews, observations and workshops. Results show that engineers' expected implications of introducing AM in the space industry are: the involvement and influence of customers and politics on innovativeness; the need for process understanding and usage of new tools for DfAM-thinking; the need for qualification of AM processes.

Keywords: Design for Additive Manufacturing (DfAM), Design engineering, Design process, Space industry, Product development process

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1 INTRODUCTION

The expression "Design for Manufacturing" (DfM) has been a familiar concept in design engineering, and is based on a collection of different manufacturing methods such as milling, drilling or forging (Ulrich and Eppinger, 2012). These conventional methods have either a subtractive or forming manufacturing approach. With the emergence of Additive Manufacturing (AM) approaches, the expression DfM has been further developed into "Design for Additive Manufacturing" (DfAM) (Gibson et al., 2015). Earlier DfM approaches were implemented primarily in the embodiment and detail design phase, while the DfAM approach relates to the whole product development process and is included in all of its phases (Kumke et al. 2016). Many companies within various industries have recognised the advantages of AM technologies, which have the potential to radically change design work in the product development process (Gibson et al., 2015). Studies have shown that, in the case of low production volume or geometrically complex products, use of AM results in a lower price for the final product. This means a considerable potential for increased value of individualised products (Campbell et al., 2013). Product designs can also be optimised in terms of e.g. weight and strength (Gibson et al., 2015). At the same time, this puts design engineers in a new situation in which they may be required to move from their conventional manufacturing thinking to an additive manufacturing thinking (Kumke et al., 2016). This need for a change of mind-set resembles what has already been experienced with the introduction of polymer matrix composite materials. The characteristics of these materials places considerable responsibility on the designer, since choices made early on in the product development process will impact the final material properties and product performance (CMH-17, 2012).

The space industry is characterised by large-scale national and international programmes, financed by state investments for science and technology development (Fortescue et al., 2011). These are affected largely by pan-national political intentions and agreements. Combined with strict requirements in terms of the technological solutions applied (due to the extreme environments), this implies special conditions for engineering work. Large multinational or national space programs are launched (e.g. by ESA or NASA) with huge budgets, but from a space company perspective, the space technology market means competition for the best technological solutions. Combining this with what is, from a technological point of view, irrational political intents and decisions concerning participants (or participating countries), represents a challenge for the development of new technologies in the long-term. At the same time, pressure on ecological footprint reduction, and a constant need for large cost reductions lead to research and development in lighter materials and new development methods (EU, 2016). In this respect, AM is an interesting technological development that is paving the way for radically new design concepts and manufacturing in new materials.

This paper gives an insight into the expectations of AM in terms of the product development process in the space industry from the perspective of engineers in a design team. The study was conducted at three companies that are active in the international space industry, and the results presented here are based on an analysis of data from interviews and workshops.

2 CHARACTERISTICS OF PRODUCT DEVELOPMENT IN THE SPACE INDUSTRY

The space industry is a typical capital-intensive industry with high-risk projects, and with development historically influenced by government-run programs. However, new actors (e.g. SpaceX or Blue Origin) are changing the scene, moving the industry towards a commercial marketplace and consequently also greater competition (Fortescue et al., 2011). In order to keep up, the established actors need to ensure that their offerings remain attractive, i.e. providing products at a competitive price. This has increased cost awareness, and reduction in cost is highlighted as the major key driver in new development projects (Brodin et al., 2016). An example of this is the proposal from the French space agency (CNES) to the European Space Agency (ESA) to develop a next-generation rocket engine with a challenging cost target of a 90% cost reduction compared to the current Ariane 5 main-stage engine (SpaceNews, 2016). Unfortunately, the trend is for large development projects (not only space-related) of complex engineering systems to overrun in terms of both cost and schedule (Simpson et al., 2011; Sinha et al., 2016).

Many products in the space industry consist of complex "systems of systems" working together, in which every sub-system contributes to the overall function (e.g. thrust for a rocket engine or earth monitoring for a surveillance satellite). The development of such a system is a large project spanning several years from concept to launch (Fortescue et al., 2011). Managing a task of this kind requires the system responsible (Original Equipment Manufacturer, OEM) to follow the development work, both internally, and externally done by the sub-system suppliers. At the same time, the OEM's customer expects continuous status updates in order to understand how the project is progressing. Systems engineering is the field of complex systems development (Blanchard and Fabrycky, 2006) and as such, it is highly relevant to the design of space systems. The typical approach in system design is to decompose the requirements of the upper levels in the hierarchy into manageable pieces to be flowed down to lower levels (subsystems) (Crawley et al., 2004). Interfaces are the boundaries that the sub-system designer sees and therefore they need to be well-defined in order to facilitate design work. However, fixed interfaces also limit the freedom of design for the sub-supplier, which is forced to adapt its design to the given interfaces. At the same time, the overall architectures of many systems have been set in the past, and the same system designs have been used since then. For example, rocket engines have had basically the same system design since the 1940s when Werner von Braun designed the V2 rocket. Propellant in the form of a fuel liquid and an oxidizer liquid are still used in rocket engines today (Fortescue et al., 2011). In such cases, new development, or innovation, is pushed out to the sub-systems (Crawley et al., 2004) in order to achieve increased product performance and/or value. This means that the sub-system responsible is forced to find innovative design or technology solutions in order to increase the competitiveness of the system as a whole, while at the same time being hampered by set interfaces and requirements from the OEM.

3 ADDITIVE MANUFACTURING IN PRODUCT DEVELOPMENT

Two major issues involved in implementing AM in the product development process are the designer's ability to absorb all the opportunities offered by AM (Campbell et al., 2012), and the designer having knowledge of the numerous limitations in design that these manufacturing processes entail (Thompson et al., 2016). When designing products for the purpose of manufacturing with AM, one of the first choices is whether to re-design an existing model or to design a new one. Klahn et al. (2015) discuss two alternative types of design strategies for AM, the first of which is called the *manufacturing-driven strategy*. The designer retains a conventional design, changes the model slightly and uses AM as a substitute for other manufacturing processes. The other approach, referred to as *the function-driven strategy,* aims to use the full potential of AM and take advantage of the characteristics of AM in order to improve a product's functions (Klahn et al., 2015). Regardless of the chosen approach, there are several opportunities for optimising the final product, such as parts consolidation and improved functionality (Campbell et al., 2012).

A study conducted by Kumke et al. (2016) shows that previous DfAM research lacks integration into a common framework. This means that design engineers are not provided with a methodical AM product development process to guide them from product concept to detailed design. However, even if they suggest a broader AM product development framework (Kumke et al., 2016), many other researchers have realised the limitations of creativity among design engineers, and therefore computational topology optimisations have emerged to assist in design (Leary et al., 2014). Maidin et al. (2012) found that use of an AM design feature database was considered inspirational, useful and helpful during the conceptual design of products, in particular for less-experienced designers. However, it is important for design engineers to understand the design rules (including process capability) in order to ensure manufacturability (Kumke et al., 2016; Thompson et al., 2016).

Within space applications, the rapid manufacturing time, design freedom and high material utilisation (buy-to-fly ratio) are characteristics that are promising with AM. Some typical factors in the space industry that could benefit from using AM are: (i) the industry is characterised by complex products in low volumes, (ii) low weight is essential to ultimately allow for increased payload weight, (iii) optimisation of product design for high (or increased) functionality and novel solutions, (iv) cost-driven products (Gibson et al., 2015). For the space industry, both metal powder bed (PB) and directed energy deposition (DED) with metal powder or wire are of interest (Dordlofva et al., 2016). Whereas PB methods use powdered materials for each layer, and a thermal energy source such as laser or electron beam fuse together the particles with a controlling mechanism, the DED method builds each layer with either powder or wire simultaneously with the thermal energy source located above the surface (Gibson et al., 2015). These two general approaches have different application areas. DED has a high deposition rate but a low capacity for producing complex geometries and is, therefore, more suitable for larger structures (meters in dimension) with less complexity. PB, on the other hand, is more suitable for the manufacturing of smaller products (decimetres in dimension) with intricate geometries.

Given the recent fast development of metallic AM, there are still challenges with process instability rendering a variation in microstructure and hence mechanical properties of AM parts (Uriondo et al., 2015). It is important to keep in mind what material characteristics that are needed for a specific design (Seifi et al., 2016). In any case, if the AM process can be controlled at a level sufficient for the extreme requirements of the space industry, the possibility of radically changing the product development approach has to be considered.

4 RESEARCH METHODOLOGY

To begin with, a literature study was conducted to explore the product development process and the use of AM in a space industry context in which complex product systems are developed. In order to include a broader perspective of how the product development process is used, literature study also included the civil aerospace industry due to its close connection to the space sector. The findings of these literature studies were then used to establish the basis of this paper and to build up the methodology for data-collection.

4.1 Gathering empirical data

Three companies from the space industry were included in the study. Company A was studied in order to obtain a deeper understanding of the development work within a company, while Companies B and C were included in order to acquire a broader perspective and to understand the general applicability of the results. In order to fully understand the work approach in product development at Company A, management and guiding documents for the product development process that are available internally were studied and documented. Based on these findings and the literature review, a set of interview questions was drawn up covering two main subjects: (i) *The Product Development Process* and (ii) *Additive Manufacturing*.

Eight semi-structured interviews were conducted at Company A, with respondents chosen from a pool of approximately 60 engineers working with product development in space applications. The respondents were selected based on their experience and seniority (leading engineering roles). In addition to the interviews, three workshops were conducted at Companies A, B and C. These focussed on exploration of expectations and requirements from the companies and their customers if AM were to become feasible in the space industry. All companies are global and the visited sites are all located in Sweden. Table 1 summarises the data-collection approach.

Table 1. Companies included in the study

General description of the companies included in the study	Company	Study of Internal documents	Interview respondents	Workshop participants
All three companies operate in the space industry. The companies develop and manufacture complex and high performance products, such as sub-system components for launcher applications and satellites, as well as experimental platforms.	A	Yes	Eight engineers within different roles in the product development organisation, including chief engineer, design leader, design engineer and manufacturing engineer.	Roles from different levels of the company, including department manager, quality manager, design leader, manufacturing engineer and design engineer.
	B	No	N/A	Roles from different levels of the company, including department manager, chief engineer and design engineer.
	C	No	N/A	Roles from different levels of the company, including company management, subsidiary CEO and design engineer.

The interviews were conducted by two of the authors. Duration was 45-70 minutes and all interviews were recorded and transcribed. One of the authors has several years of experience in the design of space systems and has a placement as an industrial PhD student at a company in the space industry. Interviews were conducted together with the PhD student among the authors who is new to the space industry. The third author participated in workshops, committee meetings, and company visits. In an attempt to avoid biases in the material, the first analysis of the collected data was conducted by the PhD student not employed at a company, who could take the role of external auditor (as suggested by e.g. Creswell, 2009) throughout the research process. Even unconscious bias could otherwise appear if a person had in-depth knowledge about case data. The advantage of the dynamic of having one "inside" observer, for interpreting e.g. internally used language and expressions, and two "outside" observers, has been used as a way in which to improve the overall validity of the research.

4.2 Model of analysis

In designing the interview and workshop guides, the studies were divided into two sections. The first focused on the Product Development process in a Space Industry Context and the second focused on Additive Manufacturing in Space Applications. During the initial analysis of the transcribed interviews, 5 categories were found to be the most commonly-addressed subjects within the first section, and 4 subjects within the second section (Table 2). The interviews were therefore coded according to these categories in order to deepen the analysis, and the workshops were documented and related to the same categories. The steering documents available for the design engineers at Company A were documented and analysed in relation to both previous product development process research and the interviews conducted. Finally, the empirical findings were related to the literature findings in the discussion part of this paper.

Table 2. The nine categories extracted from the interviews

Focus Area	Categories
The Product Development Process in a Space Industry Context	Influence of politics and customer involvement
	Similarity and difference between space and civil aerospace industry
	Shift towards cost
	Prototypes
	Innovation
Additive Manufacturing in Space Applications	The involvement of prototyping in the product development process
	Challenges with AM process understanding
	Product qualification of AM in the product development process
	Reduction in lead-time

5 RESULTS FROM ANALYSIS OF THE EMPIRICAL DATA

This section presents the results from analysis of the empirical data collected in this study. The analysis is divided into *the product development process in a space industry context* and *additive manufacturing in space applications,* with the subsections described in Table 2.

5.1 The product development process in a space industry context

The steering documents available for design engineers at Company A show the use of a stage-gate approach in the product development process. The documents are well formulated and every step is clearly described. If an engineer has a specific task, such as design leader, the system also makes clear what gates or tasks this specific person is responsible for. All the respondents in the interviews talked about this system when discussing the product development process at the company, but not all were familiar with each specific task in the stages since they had not worked in all phases.

5.1.1 Influence of politics and customer involvement

According to the ESA structure, most of the financing is obtained from political rather than internal sources, with funding released every third year. This results in short-term goals in order to ensure financing in the next three-year period, which makes it difficult to take major steps in the development process. Since each product is expensive, it is uncertain that the product development projects will get the financing needed for developing a new product. Many of the respondents' report experiencing that it is "space Europe" that determines what kind of technology that will continue to be developed, and this can quickly change due to the short financing time frame (every third year) and different political objectives. This leads to an environment in which the industry feels that they need to not only verify and qualify their products, but also prove their confidence in future technology with limited possibilities for experimentation.

Furthermore, the customer is considered by the respondents to be involved in almost every step of the product development process, with the project driven by an iterative cooperation. Requirements and guidelines from the customer are received early on in the project, with consideration given to the complete product system. The respondents' experiences are that apart from the internal requirements set by steering documents, the product development is also heavily influenced by the customer requirements. As system responsible, the customer has control over the product development, which leads to late changes to requirements, potentially leading to unexpected work. Since both costumer and internal reviews occur, it can lead to double gates. Some of the respondents found that they spent most of their time either preparing for, or attending, a review. This leads to the feeling of not having enough time to be creative and to utilise the full capability of the design engineers at the company. However, the respondents acknowledged that this customer involvement is also positive since it brings a certain structure and requirement in terms of documentation.

5.1.2 Similarity and difference between space and civil aerospace industry

Since Company A performs product development in both the space and civil aerospace industries, discussions of similarities and differences in the work approach occurred naturally. Product development projects within civil aerospace also have a strong customer involvement, just as with space, and in the same way, the high requirements from both the company and the customer sometimes collide. However, projects in the space sector generally have a longer lead-time than within civil aerospace, where the customer often gives a distinct deadline within 1-2 years. Today, development within space can last for up to 10-15 years. This was attributed partly to political involvement and the need for demonstration of technology by means of extensive testing. In civil aerospace, there are more opportunities for testing a part on a flying test bed, whereas space products do not have the same opportunities. Another major difference between the two development streams is the expected volume of the final product, with space products manufactured in tens of parts per year compared to several hundred within civil aerospace.

5.1.3 Shift towards cost

There is an experience of having both political and customer requirements steering the project towards a less costly final product. Some of the respondents talk about the goal of Ariane 6 being less expensive than Ariane 5, and they experience the iterative collaboration with the customer as positive since they have the opportunity to discuss production and cost. The final product needs to be manufactured efficiently, as that would result in a less costly final product. Since the space industry mainly manufactures parts at a low-volume production scale, it would be beneficial to avoid expensive investments such as castings. The respondents also discussed the fact that lighter products and less expensive materials could also lead to a lower final product cost. There is a general feeling of having newer, private initiatives pushing and challenging the industry towards faster developments and less costly products. The respondents expressed a feeling of having both the customer and other design engineers believing that AM can contribute to these aspects.

5.1.4 Prototypes

There was a large spread in the experience of prototypes, with some respondents reporting having worked with them on some projects, while other respondents claimed never to have encountered them. However, many of the respondents were somewhat unsure on how they should describe a prototype, with most providing several different descriptions. These included the prototype being built for testing an idea or to learn something, and descriptions of having prototypes mainly for testing the manufacturing processes. Some of the respondents reported feeling that more extensive use of prototypes would help the product development. One respondent talked about having difficulty thinking in 3D while designing in a CAD tool, and there were experiences of ideas that did not work in the end and ultimately proved costly. It was believed that greater use of prototypes would help design engineers to get a sense of the part and to understand whether the concept was feasible.

5.1.5 Innovation

Many of the respondents reported not feeling innovative when working with product development for space applications. They discussed the strategy of re-using previous designs, with most believing that this hindered opportunity for innovation, while others thought that they did not re-use old designs enough. Most of them talked about mainly having an incremental development approach, with some feeling secure in such an environment. A small number of respondents expressed a feeling that this restraint is slowly resolving due to the new focus on cost. Capability in the production system was something that most of the respondents felt to be part of the restriction on design. There was a generally expressed feeling of wanting to work without the limits of some of the manufacturing processes, such as casting. Some of the respondents expressed a need for more demonstrator projects, as they want most of the risks eliminated before product development with the customer for a shorter development time. Since space products have high requirements, the possibility to create radical solutions are affected and even though the design engineers expressed a desire to be more innovative, they felt that they did not have the margin within project budgets to challenge conventional designs.

5.2 Additive Manufacturing in space applications

According to the respondents, some aspects need to be considered in order to successfully implement AM into the product development process. Besides the obvious geometrical benefits, with respondents being positive to the new complex geometries now available, they also apparently realise the advantages of e.g. material transitions or new material compositions. One respondent discussed the possibility or ordering a powder material alloy according to the mechanical properties needed, which was a typical feeling of what AM could bring in the future. However, the discussions concerning the work approach involved prototyping, process understanding, machine availability and product qualification. The findings presented here are mainly from the interviews, but the outcome from the workshops is also included in order to relate the expectations of AM from different company perspectives.

5.2.1 The involvement of rapid prototyping in the product development process

Most of the respondents expressed a belief in the use of AM in the concept development phase, with the opportunity of making quick design alterations. They showed considerable interest in the ability to change the CAD-model slightly and easily print it out for evaluation. Because they have had some situations in which ideas and models have not been as successful as predicted, they feel some hope that part of this uncertainty will be eliminated with an iterative AM prototyping development process. They talked about their current work of evaluating AM in some of their products, with some of the respondents expressing the importance of understanding whether the process ultimately gives added value to the product.

Since many of the respondents expressed an opinion that AM brings with it a new mind-set in order to benefit from the degree of freedom, they feel that they need help with new design tools and design systems that are not currently available at the company. A lot of the early work today is done in 1D or 2D, and the thought of a shift towards 3D-thinking with prototypes was encouraging. One respondent, however, acknowledged that this would probably also imply more extensive use of 3D calculations (FEM and CFD) even in the early phases. Many of the respondents felt that AM would allow them to work with several concepts simultaneously, and the ability to use physical models to evaluate concepts relative to each other seemed to be a driving force. According to the respondents, these physical models could be made from metals cheaper than those used in the final product, or in some cases from polymer materials. These models are supposed to help designers to evaluate concepts and to take the next steps faster than would be the case for product development without rapid prototyping. One respondent talked about the possibility of more component-testing if parts could be printed in the intended material, instead of waiting for expensive castings. There was a general belief in all companies included in the workshops that use of AM in prototyping would help them not only to understand the AM process, but also increase their iterations during the design process.

5.2.2 Challenges with additive manufacturing process understanding

Most of the respondents discussed the feeling of AM being the latest new trend within the industry. One respondent talked about the phenomena of belief in AM being similar to the trend of composites that took off within the company about 10 years ago. Many of the respondents expressed considerable belief in the new manufacturing method, but most of them also understood that there are limitations in the process that are not fully understood yet. This is something that caused general uncertainty regarding how to include the manufacturing process in product development in order to fully utilise it. They requested a new design method in order for design engineers to understand the process, and design tools that could help them to know where the limits were. Some of them also discussed the need for training and having an expert explain the opportunities and limitations inherent in the process. One respondent expressed the feeling that most of the work done on AM within the company involves developing the manufacturing process, with little attention paid to learning how to design for AM. Some of the respondents expressed a need for machines in-house in order to learn how to use the process. While they are currently experimenting with AM, they are dependent on external manufacturers or colleagues at another site for help learning about the process. This leads to the feeling of not being able to learn the process fully. There was slight concern about the need for complementary processes in order e.g. to improve the surface finish, which also leads to some discussion as to whether AM brings greater value to the final product. These discussions also featured prominently in the workshops. The participants talked about the need for general training in process understanding for their design engineers in order to keep the manufacturing process in mind while designing.

5.2.3 Product qualification of additive manufacturing in the product development process

Every respondent raised the issue of having the product qualified for flight, with the space industry generally having strict demands for mission-critical parts. One respondent referred to the qualification of a product being complete after the first flight. These strict requirements for products to be developed and used in space applications are the reason why demonstration of technology is required. The aim is to include technologies matured to a certain level (TRL6) in product development, while demonstrators are used for lower levels of development. There was a general concern about the familiar problem (e.g. Seifi et al., 2016) of machine instability and variation in material properties, which made them realise that there is a great need to involve product qualification early on in the product development process. The need for a methodology for qualifying individual parts was expressed, in order to ensure success of the print. Two other concerns regarding product qualification were the quality of the powder and whether implementation of product qualification would entail new limitations in terms of the design possibilities. These issues were raised by all the companies during the workshops as the main reason for caution on the part of both the companies and their customers in having AM implemented into their manufacturing choices.

5.2.4 Reduction in lead-time

Most of the respondents discussed the significant potential for AM to shorten their lead times. However, one respondent added that the development work itself is time-consuming, and shortening the lead-time required not only part production to be shortened, but also efficiency-improvement in design work. One respondent had heard about a company that saved 60% in lead time while implementing AM and another talked about having 1.5 years of waiting for casting while AM only took a couple of months. Because the lead time for casting is so long, projects are often forced to order them long before the design is set, resulting in more material being used in the design as a margin. There was a general feeling that AM eliminates this problem. However, one respondent did express the concern of having design engineers postponing some of the details to later on in product development because they “have more time” with AM. This could ultimately lead to details of the design not being finished towards the end of the product development work.

6 CONCLUDING DISCUSSION

The product development process in the space industry is strongly influenced by both politics and customers, which makes the development more complex compared to e.g. civil aerospace. However, workshops indicated that the level of politics involved can also vary in the space industry, depending on the customer, whereas with commercial customers there is usually less politics and more aggressive product development. Our study indicates that the space industry adopts a stage-gate approach (Ulrich and Eppinger, 2012) due to the importance of verifying the quality of the product throughout its development. Despite a strong connection to the customer and use of an iterative work approach with the customer, many of the respondents felt that this put too much emphasis on reviews instead of development work. Together with the feeling of not having sufficient financing or time for product development, this made them feel that they were not making the most of their potential for innovation. However, the feeling of not being sufficiently innovative was not something that the respondents seemed to care about very much in their daily work due to the importance of safe and qualified products. Thus, one of the major expectations of AM was the ability to create new, complex and innovative products that could help the company to deliver quality products to their customers. This was also suggested by the results of the workshops: that there was a willingness to use AM as a bridge towards new, radical solutions. However, some of the respondents expressed the sense of security in having an already proven design to lean on, hence using an incremental product development process. These discussions related to the uncertainty of financing and not knowing whether the project would be allowed more time for completion.

Our study indicates that there is a great willingness to learn how the AM process works and how to design for AM, but there is a feeling of not having enough resources for this experimentation. An initial general suggestion for design engineer teams in a space industry context is to gain as great understanding of the process as possible and to ensure that there is access to machines. Availability of machines seems to promote process understanding and confidence in the process, thus creating substantial opportunities for creating innovative products that can not only reduce cost but also increase functionality and/or value. Another suggestion that was put forward in both the interviews and the workshops was the need for opportunities for training, with an expert teaching design engineers about both process understanding and general AM thinking. A third suggestion that was broadly discussed, again both in the interviews and the workshops, was the use of prototypes in the product development process. It is generally thought that rapid prototyping would help not only to acquire a limited process understanding, but also an understanding of how the model and idea are actually feasible. Some of the respondents displayed some doubt concerning their ability to understand 3D from either a 2D drawing or a virtual 3D model, and that increased use of prototypes could help. This, together with the feeling of having a fast and iterative product development with AM machines early on in the project, created some certainty amongst the respondents that their future space products would have an opportunity to evolve and radically change.

Among the interview respondents and workshop participants, there is a general belief in AM and all the opportunities it enables, but there was also an awareness of the maturity level of the processes. All the respondents brought up the issue of qualifying the product throughout the entire product development process. This included material properties, powder quality and part accuracy. In order for customers, management and the design engineers themselves to fully adopt AM into the product development process, there is a great need for a systematic and reliable qualification process.

Of the nine categories identified in the analysis of the data, it can be concluded that the most important expected implications of introducing AM into the product development process for space applications are as follows:

- AM is believed to entail a potential for innovation, however, this potential is affected by the way in which the general product development process is set up (e.g. gates from both company and customer) and the extent to which financing can be guaranteed in the long-term from a political perspective.
- New tools and methods are needed to aid the design engineer design in 3D. Prototypes, software and tuition are requested aids and recommended by the authors.
- Human aspects need to be considered (e.g. having an already proven design to lean on, fear of the process, machine availability, initial prototypes).
- The need for qualification is evident – not only in terms of the processes and products manufactured using AM, but also in terms of the engineers working with the processes and products, i.e. understanding AM.

This study was limited to eight interviews with design engineers at one company, and workshops with two additional companies, all of which develop products for space applications. The respondents and workshop participants had limited experience of using AM. The interview respondents and workshop participants had limited experience in using AM, and therefore, this study should be seen as a guidance for in what direction a future extended study should be focused. More extended interview rounds should be conducted at more than one company and in industries other than space, and preferably with respondents with varying experience of AM.

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Paper C

Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
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Reviewed Paper

QUALIFICATION CHALLENGES WITH ADDITIVE MANUFACTURING IN SPACE APPLICATIONS

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Key words: *Additive Manufacturing, Space application, Qualification, Product development process, Manufacturing process development*

Abstract

Additive Manufacturing (AM) has the potential to remove boundaries that traditional manufacturing processes impose on engineering design work. The space industry pushes product development and technology to its edge, and there can be a lot to gain by introducing AM. However, the lack of established qualification procedures for AM parts has been highlighted, especially for critical components. While the space industry sees an advantage in AM due to expensive products in low volumes and long lead-times for traditional manufacturing processes (e.g. casting), it also acknowledges the issue of qualifying mission critical parts within its strict regulations. This paper focuses on the challenges with the qualification of AM in space applications. A qualitative study is presented where conclusions have been drawn from interviews within the aerospace industry. The results highlight important gaps that need to be understood before AM can be introduced in critical components, and gives insight into conventional component qualification.

I – Introduction

The space industry is seeing an increase in demand for access to space to enable space-based services and human space flight, with new actors opting for market shares. This implies a need for a business-oriented evolution of technology development, decreasing cost and time to market. Additive Manufacturing (AM) is a manufacturing technology where a lot of potential is seen concerning free-form design, short lead-times and economical low-series or customized production (Gibson et al., 2015). This paper focus on applications manufactured by metal AM, and AM will hereafter refer to metal processes. For reviews of metal AM processes, see for example Frazier (2014) and Uriondo et al. (2015). The use and development of AM is growing rapidly within the aerospace industry, and this study focuses on the application of AM in space applications, ranging from satellite components (e.g. antennas) to launcher sub-systems (e.g. rocket engines). Some of the characteristics of the space industry are; expensive product development, high-performance products in harsh environments, low volumes (from one-off production to tens of parts per year) and strict regulations. However, AM also comes with challenges, and one of paramount importance for space applications are process qualification and part qualification (Dordlofva et al., 2016). The purpose of this paper is to identify the challenges with qualification of AM parts for space. It gives an insight into the qualification of traditional manufacturing processes and the results will give a direction for future research in understanding the implications AM has on the engineering design process. The paper is based on a literature review to establish the state of the art of AM qualification, and case study interviews conducted at a sub-system supplier in the European space industry. First, the theoretical framework for the study is presented, followed by a description of the method used for data collection and analysis. The results from the interviews are thereafter presented and then discussed in the end to conclude on implications for designing and qualifying AM parts for the space industry.

II – Challenges with Additive Manufacturing

The introduction of low TRL level technologies (Mankins, 1995) in critical space applications (e.g. launcher applications) is associated with high risks due to the cost of development and potential market impact (Underhill et al., 2016). AM is considered a technology with the potential to reduce development and production cost, as well as increasing product performance (Begoc et al., 2017). There are examples in literature and popular media on flight proven or qualified space components (see e.g. Rawal et al. (2013), SpaceX, (2014)), but they are still few. This is mainly due to the requirements on high reliability on space hardware, and it is still considered that there is development needed on the AM processes to facilitate their use (Martin-iglesias et al., 2017). While the efforts for developing AM for space flight are many (see e.g. Lasagni et al., (2016); Soller et al., (2016); Orme et al., 2017)), the need for established qualification methods is highlighted (Seifi et al., 2016; Uriondo et al., 2015). Areas in need of further development to enable qualification of AM and its implementation on a larger scale as production method include those listed in Table 1.

Table 1 – Areas in need of development for AM qualification

ID	Development need	Reference
(a)	Methods to identify suitable parts for AM, both from an economical perspective and manufacturability	(Lindemann & Koch, 2016)
(b)	Standards for AM materials and processes	(Seifi et al., 2017)
(c)	Design methods for engineers to utilize the possibilities with AM	(Thompson et al., 2016)
(d)	Understanding of process and geometry impact on material properties	(Seifi et al., 2017)
(e)	Machine-to-machine as well as process variation	(Frazier, 2014)
(f)	In-situ measurements systems for mapping and controlling the AM process	(Everton et al., 2016)
(g)	Process modeling as a mean to understand and develop AM processes	(Martukanitz et al., 2014)
(h)	Post-processing methods, including surface treatment and heat treatment	(Frazier, 2014)
(i)	Non-Destructive Testing (NDT) methods suitable for AM	(Waller et al., 2015)

Many organizations and universities are dealing with the issue of qualification for aerospace applications, and some approaches have been suggested. Portolés et al. (2016) propose a generic qualification procedure that has to be adapted for each combination of AM technology, material and component. They point out the importance of raw material control, the development of an allowable process window and the importance of identifying the key variables impacting the manufacturing. Taylor et al. (2016) made a comparison of qualification methods for conventional manufacturing processes and concluded that an approach for qualification of AM parts would have to combine the knowledge and methods from the qualification of different manufacturing processes. Central in their reasoning is the use of a building block approach similar to what is used for fiber composites (CMH-17, 2012).

As a highly-regulated industry, the space industry is especially dependent on the maturity of AM technologies (as is the aerospace industry in general). Standards and specifications are central in product development of products in the space industry, where for example ESA (European Space Agency) based projects are regulated by the *European Cooperation for Space Standardization* standards (ECSS, 2017). The requirements for the qualification of a product depends on its criticality. External (or third-party) standards are widely used in the space industry. However, in the introduction of new technologies, internal standards are usually developed (Seifi et al., 2017) since companies cannot wait for external standards to be developed and formalized. An example of this for AM is NASA with their *Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware* (Clinton, 2017). However, Seifi et al., (2017) point out the importance of the establishment of external standards since that would help the implementation of AM in industry by setting a minimum level of requirements as a reference for organizations developing the technologies for their needs. Current applications of AM in space products have mainly focused on secondary structures or other non-critical applications (Brandão et al., 2017). The interest of this work is the possibility to introduce AM in mission critical components, enforcing the need for applicable specifications.

Many products for space are complex systems-of-systems involving several companies and organizations. In the development of such engineering systems, e.g. a rocket engine, there is usually one Original Equipment Manufacturer (OEM) responsible for the system, while there are several sub-system suppliers. The product development usually follows a stage-gate process, to assure product design and manufacturing processes (Lindwall et al., 2017). The introduction of AM is expected to have an impact on the design process (Kumke et al., 2016), and the need for an end-to-end AM process for initial design, material supply, manufacturing, post-processing and qualification is highlighted by the space community (Brandão et al., 2017). There are examples of adaptions to the product development process for space products for AM (Begoc et al., 2017; Orme et al., 2017; Soller et al., 2016). A review of different work methods identifies key steps when working with AM PBF processes, and these have been illustrated in Figure 1. Included in the figure is also a reference to the areas (a) to (i) in Table 1 that are in need of development, showing where they are needed. The purpose of the illustration is to show that the whole product development process is impacted by the introduction of AM, and that development is needed through all steps. Although the suggested work methods usually include the verification of an AM part, this step is still a challenge. Martin-iglesias et al. (2017) acknowledge that knowledge about the effect of defects is needed, as well as acceptable verification criteria since complex geometries make it difficult (if at all possible) to use conventional NDT. X-ray Computerized Tomography (XCT) is often mentioned in the context of AM as a mean to detect internal defects.

However, complex geometries become a challenge also for this technology (Seifi et al., 2017) and further development is needed. Soller et al. (2016) showed that XCT is useful for verification of cleanliness after production (internal remnants of material) which is important for many space applications. The impact of product geometry on the material microstructure is an inherent characteristic of the AM processes, especially PBF technologies. This is due to that the microstructure is dependent on the thermal environment of the built part, which in turn is influenced by the build set-up (Fitzgerald & Everhart, 2016). The use of reference (traveler) specimens is a common approach to monitor the quality of the build (Orme et al., 2017; Soller et al., 2016). However, due to the geometrical dependency on the microstructure, the representativeness of such reference specimens is not evident and needs to be further researched (Seifi et al., 2017). Test specimens have to represent the actual part and should therefore be taken from a geometry as similar to the product as possible (Taylor et al., 2016). The understanding of geometry impact is crucial for the verification of AM parts and should be addressed already in the design phase. This need for early consideration of the built part's influence on qualification is represented in Figure 1 by the area (d) from Table 1 as part of the verification step. In-situ monitoring (f) is also included for the same reason; to highlight that qualification of AM is dependent on up-stream activities in the product development process, and not only done in the end.

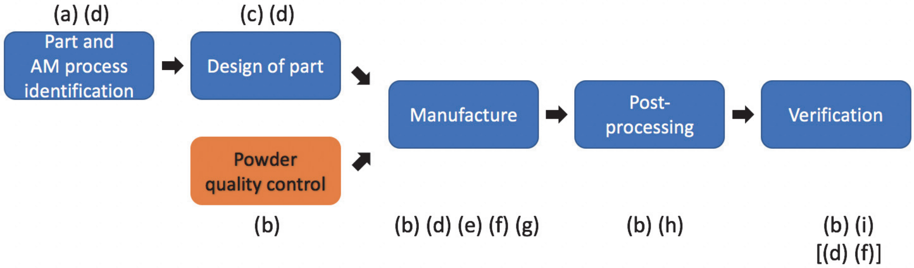

Figure 1 – Important steps in the development of products for AM, inspired by Begoc et al., 2017; Gibson et al., 2015; Orme et al., 2017; Soller et al., 2016*. The letters (a) to (i) refer to the development needs for AM in Table 1.*

III – Research Design

The present research is based on an interview study with engineers in a large manufacturing company focusing on aerospace and space design. In the design of the interview study, the aim was to understand how qualification is currently done, how new manufacturing processes are introduced as well as challenges regarding qualification of AM. The interview series was divided into two phases; the first focused on understanding qualification in the aerospace industry and the second on the introduction of new materials. The sampling of engineers was created to get a mixture of people with component responsibility, process specialists (i.e., forging, casting, welding) as well as materials experts and experts responsible for newly introduced materials such as composites and AM. For the first phase (understanding of qualification) eight people were interviewed, and for the second phase (introduction of new materials and processes) seven people were interviewed. Semi-structured interviews were selected as the main data collection method; all interviews were based on an interview guide with the following focus:

- How are conventional material processes qualified?
- How are new manufacturing processes introduced and qualified?
- What are the challenges regarding qualification of AM processes?

After analyzing two of the interviews, it became apparent that the first question needed to be divided into sub-categories, such as definition of qualification and requirements; how materials and products are tested; how the product influences the qualification; design methods being used and work methods for qualification. The interview also included more general questions relating the respondent's background, experience, current and previous roles. The respondents were free to elaborate when answering the questions and follow-up questions were used to encourage detailed descriptions and explanations. All interviews were performed in Swedish, recorded and transcribed; all quotes in this paper are consequently translated by the authors. The interviews were conducted by one of the authors that have several years of experience in design of space systems and is situated as an industrial Ph.D. student at a company within the space industry. The internal author brought understanding and knowledge of the particular context, official processes, internal lingo, etc. for the analysis. The external author contributed with the objectivity that was utilized when analyzing the material and drawing conclusions. To clarify the empirical data and identify recurring and dominant themes, selective coding was used. Data reduction in the form of pattern matching followed by displays of the data was utilized to draw conclusions and synthesize the findings (Miles & Huberman, 1994). Data coding and analysis consisted of the following steps:

1. The selective coding involved the selection of central categories based on the main research issues identified before performing the interview series.
2. Interview transcripts were read through and instances relating to research issues highlighted.

The result from the coding was compiled in a spreadsheet with columns for the central categories and one column labeled other. During this step, relevant quotes were copied into the table.

IV – Empirical Findings

The following sections present the results from the interviews analysis performed for this paper based on the respondents' answers.

Concept of Qualification

Throughout the interviews, it was clear that the word "qualification" had a different meaning depending on the viewpoint, and often also depending on the background of the respondent (civil aerospace, military or space products; material, design or process engineering). There is also a confusion with other words that are used in similar contexts, e.g. verification or certification, which tend to depend on what word a customer is using. The respondents were asked to distinguish between material, process and product qualification, however, most of them expressed that they are linked to each other, and in the end, it is the product qualification that matters. Regardless of the terminology, the purpose was the same; to gather evidence showing that a product meets a certain set of defined requirements on e.g. loads, life cycles and performance. In other words, to show that the design intent of a product is met. Being part of a sub-system supplier in the aerospace industry, the respondents reflected on the responsibilities in product qualification. Working with systems of products, e.g. a rocket engine, the end system is qualified by the system responsible, while the sub-system product is qualified by its design responsible. Due to practical reasons, sub-systems are usually qualified as part of the system qualification. Depending on the agreement between the system responsible and the sub-system supplier, the formal responsibility of the sub-system qualification in such cases can be on either. If it is on the system responsible, the sub-system design responsible delivers a design data package showing compliance to the requirements. The space industry is based on levels of regulations and requirements. On the highest level, there are authority (or customer) specifications instructing organizations how to work with product development and include such quantitative requirements as what margins are needed in the design, what type of material data is needed and how to qualify products. On the next level, there are the product technical specifications written by the system responsible that holds the requirements on the sub-systems. The design responsible for the sub-system plans the product qualification to meet this specification. Requirements for product qualification are therefore set by the design responsible, in accordance with the design specifications, and according to the needs of the product.

A – Product Qualification

The approach to qualification has changed over the years, where testing was the dominant way of showing compliance in the past. Simulation and analysis have received a larger role in the qualification work during the last 50 years, but still with complementary testing. “Not all things are possible to calculate that needs testing” as one respondent expressed it. Often, calculations are correlated towards testing for validation. One part in establishing analytical methods is the availability of material data used for design. An approved database is built on material testing, both through standardized material testing and product specific material testing. The respondents frequently came back to that a manufacturing process needs to be verified with material data. Hence, product qualification is closely linked to the manufacturing processes, and in the end, it is the produced (or manufactured) material that needs to be qualified in its application. The relation between the product qualification and the manufacturing process qualification can be depicted as in Figure 2.

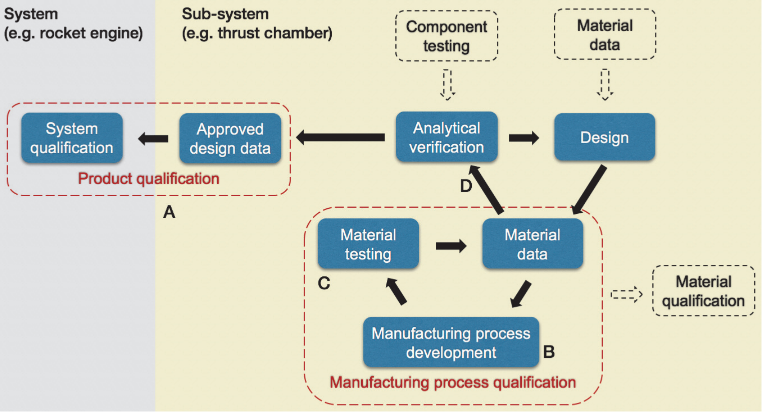

Figure 2 – The role of manufacturing process qualification in product qualification. The letters A-D refer to the corresponding sections in the text.

B – Manufacturing Process Development

Authority regulations require that a design organization must have control over the manufacturing of critical components (hence a company's management system). Within the scope of this study, four traditional manufacturing processes were discussed; forging, casting, welding and fiber composites. The following synthesis is based on the common approach that could be deduced for all of them. The term *qualification of processes* is used for manufacturing processes that are considered critical. A critical process is a process that can render what the respondents call `hidden properties´, e.g. pores, cracks or inclusions that cannot be measured using NDT techniques (standard operations such as milling or drilling are not such processes). Given the question if the qualification procedure is different depending on manufacturing process or product, the respondents answered that the logic is always the same, but the exact activities may differ. In general, it was also said that the exact qualification approach is dependent on the customer since they have different experience and different philosophies on how products and processes are qualified. The following general logic could be deduced from the interviews.

1. Give approval for the manufacturing method based on standards or specifications
2. Develop a specific process that fulfills the material requirements of the product
3. Freeze the final process

The approval of a manufacturing method (1) is usually done on a generic level (independent of the part) and is based on internal knowledge (internal specifications aided by third-party material standards) specifying the parameters, machines, etc. that have an impact on part quality and that need to be controlled. Raw material control is practiced for all manufacturing methods and material standards are normally used as a reference. In the development of the manufacturing method to comply with the product specific needs (2), concurrent engineering with the process owner (often a supplier for traditional materials) is practiced to utilize the process capabilities and limitations. Once a process is developed, evidence is gathered for how the product will perform with that process. Since hidden properties are evaluated, destructive testing is always included in the qualification of a critical process, i.e. one or more parts are sacrificed. The purpose is to identify what hidden properties there are that cannot be measured on the final product using NDT, and verify the ones that are dimensioning for the life of the part. Normally this is done using microstructure evaluation and material testing, comparing it with a known material database to show that it is within the population. In serial production, NDT has to be used to find indications for process drift which requires that the used NDT methods are shown to find the type of defects that are sought for in parallel with the process development. Having enough evidence that the product will meet the design intent, the process is finally frozen (3). The idea behind freezing a process is to make sure that a product is manufactured the same way, every time.

Compared to forging and casting, welding is based on a machine set-up and method approval is usually done through the qualification of a process parameter window for each machine individually and a process parameter window. Furthermore, due to the tough, and usually product specific, requirements in aerospace, it is difficult to use the same welding parameters for two different products. Fiber composites processes also differentiate since the mechanical properties of products made of fiber composites are dependent on the geometry of the product. One respondent expressed that "the principle for processes where your properties depend on your product and process is to break it down into sub-process and sub-materials, and finally to freeze your process”. Practically this is done by approving the suppliers of the materials used in the process, e.g. fibers or the epoxy. At manufacturing process level, there is normally no material specification that is used as a reference, rather the requirements on the fiber composite process are set based on the application.

C – Material Testing

The material data is the link between the product design and the manufacturing process as one respondent expressed it. Once a manufacturing process is developed, or in the process of being developed, material testing is therefore commenced to establish the material data which is then used to verify the product. The authority regulations include what accuracy/confidence you need in the data (how much testing you need, how many batches that have to be included, etc.), but given the cost and time of establishing a complete database, there is usually a dialogue with the customer to set a practical and appropriate level, and what safety factors that have to be used in the design to compensate. This is especially the case within space programs where there can be a lack of produced material due to the low number of products. There are usually no requirements from the customer on what the material should look like in a cut, it is up to the design responsible to verify its fulfillment. Engineering judgment and experience plays a vital role in the process acceptance, and the amount and size of defects that can be accepted are set by the design responsible. Periodical cut-ups (e.g. sacrificing every 10th part) was mentioned among the respondents indicating that it was used on occasions. Although sacrificing a part is the best approach to get representative material data, it is expensive for follow-up testing. The use of ‘hang-on bars’ is therefore practiced, where additional material is added to the part to be cut-off for inspection. For forgings, a prolongation of the forged material is used which usually makes it easier to show it to be representative. For castings, it is more difficult since the geometry of the product and placing of the gates (used to pour the metal into the tool) has an impact on the material flow and the solidification of the material. Castings are therefore more dependent on the geometry of the product. Hang-on bars can be used to evaluate the bulk material, but defects are dependent on location and sacrificing a part is therefore often needed for castings. For composites and welding, there are usually test pieces that are manufactured in parallel with the process development for cut-up and testing to show the product properties fulfillment. Periodical testing is also rather common for composites, but then statistical data is used to reduce (or increase) the interval.

D – Material Data and Design Verification

A challenge for the design responsible is to develop the manufacturing process quick enough to be able to establish the material data needed for the design. Usually, the product design is already set and when the manufacturing process has been developed, you need to show that the product meets the analytical calculations. Normally, a known material database is used for the product design, but then for the manufacturing process, this data is not necessarily the same since it will be product specific. Many of the respondents associated the term “material qualification” with the development of a new material and the building of generic database for its properties. However, building material data is time-consuming (and costly), and within a development project where you usually have less manufacturing in the beginning, this becomes a challenge. Furthermore, the situation is not always ideal and sometimes there is a need to develop a material or a process in parallel with the product development, knowing that the material data is a risk.

Some of the respondents stressed that to qualify a product, it is not a requirement to have a qualified material since in qualifying a product the aim is to show that the product, with its manufacturing process(es), meets the design intent. Often, specific material requirements for a product are therefore defined explicitly for that product. Following that logic, material standards or specifications are not necessary for the qualification of a product, although they make it easier.

The product requirements are less precise early in the design process but become more set as the development progress. This uncertainty in requirements puts a need to set a plan for the verification already in the early design phases, and to consider how design choices will impact the qualification. An example is casting where much thought is put into the product design. Castings are usually designed for less stress in the material since the robustness of the process (i.e. spread in material characteristics) is larger than compared to e.g. forgings. Given the question on how castings can be approved although they include material defects (e.g. pores), the respondents came back to that the amount of experience in using castings for many years gives confidence. The material specialists can draw conclusions based on earlier applications and use *similarity* to either approve or require re-design of a product or process. Again, appropriate safety factors can be used for the design. Compared to AM, there is also confidence within the industry that the processes are stable enough. As for castings, composites include defects (e.g. pores), and a certain level has to be accepted, e.g. a percentage of the material volume is allowed. Safety margins are used to reduce the material properties accordingly. However, this requires that there is a proven NDT method that is capable of finding defects to this level, and this will decide in practice if you can use the material or not in the given application.

Verification of space products through testing is more difficult since the real loads are not experienced until they are launched, either as part of a rocket or a payload. At the same time, a low production volume means less material data from produced components, adding to the challenge of building knowledge and material data for the verification. The criticality level of a product adds another factor to the qualification. While the qualification *procedure* of a critical process is the same, the critical level of a product might impact the *requirements* on the qualification since they are part specific. It can also have an impact on follow-up testing in serial production, how often and how tough the requirements are on the NDT.

Challenges with new Processes and Additive Manufacturing

The respondents were also asked about the challenges with process qualification and the discussions that followed went into both challenges for traditional processes and what challenges there are with AM. One respondent said that on a high level, “the challenge is to find the appropriate and relevant requirements on products”, and that the key to process qualification is process knowledge and understanding. Setting the right requirements is a question of both product function and economical production. Depending on the previous experience of a process, the level of development will differ. If it is a new material, then a new set of material data has to be deduced through testing. However, testing in itself is also a challenge since it might not be evident what you should measure, as compared to traditional processes where there are established methods. *Similarity* can be used for proven manufacturing processes, and if the same notion can be used for AM, showing that it is at least as good as some known material, then that might be one approach. However, then you need to gather enough evidence to show that it is feasible. In literature, AM is often compared to forging and casting, with examples of AM having similar properties as forging (Frazier, 2014). However, one of the respondents believed that if the AM processes cannot be shown to be more or less defect free, they will be difficult to compare with forgings, ending with the option to compare with castings. Small variations in the material can be handled through statistics, it is, however, the larger surprises that are more difficult (e.g. inclusions (Brandão et al., 2017)). New manufacturing methods should therefore be methodologically introduced to minimize the risk, i.e. start with less critical components to gather experience. This step-by-step introduction has been the approach with Metal Deposition (MD) technologies within the studied company. The process has been used in low stressed areas or in non-critical applications to gather experience and periodical testing has been used to follow the process. MD has also been treated much like a welding process with the requirements for acceptable defects specified explicitly. One respondent compared AM to welding and mentioned that the elimination of process defects in welds has been pursued for years, without succeeding, and questioned if it will be possible to get fully rid of them in AM. Another respondent said that; ”if we are working with powder, pores are something that we are not going to be able to avoid. I don’t think so […] we are going to have to live with pores, just like in castings.” In line with this, one concern for AM processes that was brought up by several of the respondents was the characterization and quality assurance of raw material, especially powder. The lack of standards for AM materials is believed to be another hurdle for AM in space applications according to one of the respondents. It is a conservative industry and before a new process is introduced you need all the facts on the table before you move on, hence the logic to follow the TRL scale. The customer is often involved in setting the requirements for each TRL level if a technology is developed for an application, and the experience is that increasing the TRL level is easier if there is an application.

V – Discussion

Throughout this study, it has been clear that knowledge about material behavior is the foundation for product qualification. In a conservative industry as the space industry, this becomes a challenge for mission critical components if sufficient knowledge and material data are not available. The structure of working with TRL levels stems from the need of maturing a technology before it can be used in real applications. Based on the interviews for this paper, basically three approaches for qualifying a manufacturing process in a product can be deduced:

1. Rely on a generic material database which can be used as a reference for any product to be built using that process, as is the case for many of the traditional processes with known materials.
2. Use a known material database as the reference and show that the known material database can be used as minimum properties for the new material, i.e. that the new material is at least as good as the reference. This approach does put a need for sufficient material testing to show that the new material is statistically within the minimum properties.
3. Start from the application and look at its specific requirements, much like with composites. This approach gives the possibility to tailor the manufacturing process according to the product requirements, at the same time as knowledge about the process is built, step by step.

Working from the bottom-up with these approaches gives the possibility to build knowledge and data about the process, and is the logical path to build a materials database that can be used to possibly qualify a material in the end. However, since the material properties are highly dependent on the AM process (e.g. machine type, process parameters), the question should be asked if a generic database is feasible and practical, considering the fast development of AM technologies, the cost of material testing, and the application driven mechanical properties. The complexity of coupling between part and process has made it necessary to have a part-based qualification approach for already implemented applications. It has been discussed in this paper that analytical verification is an important part of the product qualification. However, given that there are still many unknowns with the AM processes, component testing is likely to be important in product qualification of AM. Fiber composites use this type of working methodology where the approach towards defects has been that a certain amount has to be accepted. However, for AM this approach has to be assessed and the design responsible needs to develop an understanding of what type of defects that could be present, and what implications these have on the design, the "effect of defect". Seifi et al., (2017) summarize this in three questions to ask: (1) what is the largest defect that can go undetected, (2) what is the effect of a given defect type, size and distribution on part performance and safety, and (3) what is the consequence of catastrophic part failure stemming from such inspection misses? Regardless of the approach, there is a strong need for reliable inspection methods, both in-situ and NDT.

All stages of the product development process need adaption for AM (see Figure 1), which implies that a close cooperation is required among the parties involved. Designing for AM will require engineers to not only think in new ways to utilize the potential of the technology but also in how they work with the prerequisites of each AM process. In the field of systems engineering where there are multiple levels of requirements and suppliers, this becomes more challenging since the design of sub-systems might impact other sub-systems (Lindwall et al., 2017). The present paper highlights the importance of taking the product qualification into consideration early in the design process. This is especially important in processes like casting where the material is created in the process and is sensitive to the part geometry, similar to AM. There are different approaches for product qualification, and engineering experience and understanding of manufacturing processes are key ingredients to set sufficient requirements to fulfill regulations. Building knowledge is therefore important in the introduction of AM, and the identified areas in need of development (see Table 1) have to be addressed in parallel.

Implications for Space Applications

The space industry is built on regulations, standards and specifications, and the lack of standards for AM materials could, therefore, be a hurdle for AM in space applications. However, since the experience is that it is easier to mature a technology for an application, this should be utilized for a more efficient development of AM. This approach favors the qualification approach of developing your process from the needs of the product, again building knowledge towards a more comprehensive process understanding.

The tough environments on many space applications push the limit on what the materials are capable of. These extreme conditions could lead to unnecessary conservative designs and requirements when working with AM due to the current status of the technologies with many unknowns. Setting the right level of the requirements was mentioned as a challenge by the respondents, but by involving the customer (or OEM), this could be achieved.

Another challenge for the space industry compared to e.g. the civil aerospace industry is the lack of possibility to implement an AM part in its application and use regular inspection to monitor its behavior. Once a part is launched, it will be inaccessible and a failure could have severe consequences for the mission. This makes it difficult to have a gradual introduction of AM components. The use of technology demonstrators is an established approach for the introduction of new technologies within the space industry and is recommended for mission critical AM components.

While the characteristically low production volumes of the space industry are usually seen as one enabler of economical AM production, it is also a challenge. To build confidence in a new manufacturing method, statistically based production data is needed to be able to show its robustness. However, the low volumes imply less produced material, and given the rapid development of AM technologies, this could be a hurdle since the idea of a frozen process makes it difficult to adapt new and better technologies.

Finally, from an engineering design perspective, AM brings many possibilities to find new design solutions given the design freedom and possibility to consolidate parts. However, in the development of a system (e.g. a satellite or a rocket engine) there are often several sub-systems, and the use of "free form design" might lead to making the traditional interfaces between these sub-systems more diffuse. The possibility to challenge traditional interfaces or not might impact both the ability to utilize the capabilities of AM, but also how to maintain the responsibilities of each sub-system.

VI – Conclusions

The qualification requirements for a space product are set by the design responsible, but is influenced by customer and authority regulations. Product and manufacturing process qualification are linked together, where the purpose of the qualification is to show that the design intent of the product is fulfilled. This purpose should be seen as a guideline for the qualification of AM products. Resemblances can be seen between AM and the traditional metal processes welding and casting. Both AM and welding are dependent on specific machines and machine-by-machine qualification is the practice for welding. Castings are sensitive to the manufacturing process and part destruction is vital to understand the material structure in a specific product. At the same time, the geometry dependence on mechanical properties that is seen in AM can be seen in composites where component testing is common. Hence, elements from the qualification of traditional manufacturing should be considered and combined in the qualification of AM. Building industry confidence in AM technologies is probably the biggest challenge in the conservative space industry, and process knowledge is important. Balancing the requirements of qualification is a question of understanding the requirements of the product and the capabilities of the process, making sure not to over specify the qualification.

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