Additive Manufacturing in Product Design for Space Applications
Opportunities and Challenges for Design Engineers

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Abstract
Additive manufacturing (AM), or 3D printing, refers to the collection of manufacturing technologies that make it possible to produce complex geometries layer-by-layer. This is especially interesting for industries such as the space industry, characterised by design of highly complex products produced in low volumes. AM has recently attained increased attention in the space industry since it is considered to reduce both design cost and production lead times compared to traditional manufacturing technologies, such as cutting or casting methods.

Even if it is perceived that AM technologies hold great potential for space application product design, current research points at a lack of understanding about how design engineers adopt AM in their design practices. The objective of this research is therefore to advance understanding of the effect that AM technologies have on product design practices, seeking answers to the following two research questions: (1) “What opportunities and challenges can engineers encounter in design practices due to additive manufacturing?” and (2) “How can additive manufacturing be introduced in product design practices?”.

These matters have been explored through a pre-study and two main studies. The pre-study focused on the opportunities and challenges with AM in space applications. AM technologies were explored through a literature study and study visits to AM actors in Sweden. The first main study considered AM and the product development process within the space industry, which were explored through a literature study, interviews and workshops with design engineers in product development performing companies in the space industry. The second main study focused on identifying design heuristics (“rules of thumb in design”) for AM and testing these in a workshop that included actors from the space industry performing product development.

With regard to opportunities, research findings have revealed new possibilities in product design, such as material compositions and decreased part count. Furthermore, research findings have also shown that to explore the potentials of AM in design, strong support is required from management. Findings also point to challenges in design, such as design engineers having high expectations of the potential of AM, that are difficult to meet. These high expectations can have an effect on how well engineers adopt AM in their design practices. Results also highlight areas such as the need for increased availability of design for additive manufacturing (DfAM) methods and the use of desktop AM machines, which can assist engineers in early encounters with AM in design.
Acknowledgements

I am very grateful for the past couple of years, where I have had the privilege to develop myself, not only as a researcher, but also as an individual. First of all, I would like to thank the RIT project with project leader Johanna Bergström Roos and the Graduate school of Space Technology with its coordinator Professor Marta-Lena Antti for both funding and support during my studies. Both have brought amazing platforms for discussions and new insights. Secondly, I would like to thank my research group, Product Innovation, for the great support I have received during my studies. Without each and every one of your challenging questions and discussions, this thesis would never have been what it is today. Of course, I would also like to thank Dr Johan Wenngren for the time and effort he put into reviewing this thesis in an earlier stage, and contributing to developing this work.

A special thank you to my supervisor team, Professor Anna Öhrwall Rönnbäck, Professor Vinit Parida, and Associate Professor Åsa Wikberg Nilsson. You have all contributed to my development, and I look forward to see what the coming years working with you will bring.

Finally, I would like to thank my family and friends, especially my husband Johan, for the great support you have given me in this process.

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List of publications

This thesis has been based on three conference papers listed below. Each paper has been reviewed before publication and are appended to this thesis.


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1 Introduction

This chapter introduces this thesis through four sections. It begins with a presentation of a background description and is followed by the objective and research questions. Then the delimitations are addressed before the chapter is ended with presentation of the disposition of the thesis.

1.1 Additive manufacturing and a new design space

In the late 1980s, technology development caught up with the idea of manufacturing products with an additive approach, rather than through traditional subtractive or forming approaches (Gibson et al., 2015). Among other things, the idea was to open up a new design space, where e.g. new geometries or material compositions could be explored. These new manufacturing processes initially focused on something called rapid prototyping (RP), where 3D software models could be rapidly produced for design evaluations, usually in polymer materials. However, the technologies have matured since then and are now also considered useful in producing end-use products in various materials such as metals (Wohlers & Caffrey, 2015). These manufacturing processes are collectively known as additive manufacturing (AM), and are considered to present new possibilities in design. Some of these possibilities are considered to give engineers a higher degree of design freedom, which has not been possible with traditional manufacturing constraints, set by, e.g., limitations with casting or cutting tools technologies. However, when choosing AM manufacturing technologies, many of these constraints can be avoided in design (Gibson, 2017). These newfound freedoms in design bring a change in boundaries of the design space, which present possibilities for exploring new designs.

Even though AM is considered to open up a new design space and bring a higher degree of design freedom, some research has suggested that it can be hard for engineers to understand how to include AM in their design work (e.g. Campbell et al., 2012; Kumke et al., 2016). For example, it is suggested by Klahn et al. (2015) that while engineers can be inspired by benefits in design for AM, they might at the same time feel swamped. Therefore, this thesis focuses on exploring what opportunities and challenges engineers encounter when additive manufacturing is considered in product design practices. From previous studies of AM in such practices, the following three areas have been identified as key issues for engineers:

- Difficulty for engineers in fully utilising the design freedom (Campbell et al., 2012; Leutnecker et al., 2016; Klahn et al., 2015)
- Insufficient understanding on how to design for AM (Thompson et al., 2016; Mellor et al., 2014; Campbell et al., 2012, Yang & Zhao, 2015; Gibson, 2017; Maidin et al., 2012)
- No common framework for helping engineers to adopt an understanding of “design for additive manufacturing” (DfAM) (Kumke et al., 2016; Krantz et al., 2015)
Research presented in this thesis has an emphasis on space industry applications, where this industry is considered to be a ‘perfect fit’ for AM with low production volumes and complex products (Wohlers & Caffrey, 2015). Actors in the space industry have an increased interest in AM (Wohlers & Caffrey, 2015; Steenhuis & Pretorius, 2017; Gibson, 2017), and many companies in the industry are now in the process of introducing and adopting AM technologies to their design practices. In connection with high requirements for extreme conditions, the space industry is considered to offer a high potential in reaching an understanding of how AM can be used in design.

1.2 Objective and Research Questions
The objective of this research is to advance the understanding of the effect that additive manufacturing technologies have on product design practices. The following two research questions have been formulated to direct the research through literature studies, empirical data collections and analysis to reach the research objective.

**RQ1:** What opportunities and challenges can engineers encounter in design practices due to additive manufacturing?

**RQ2:** How can additive manufacturing be introduced in product design practices?

1.3 Delimitations
The research presented in this thesis is limited to companies operating in the space industry that have sites located in Sweden and that have a focus on product design. Product design is in this thesis defined to be the concept phases in product development and the focus of the research is on the design engineer and the interface with other engineering disciplines. Research presented in this thesis has been limited to metal AM methods, since it is mainly these methods that have been of primary interest to the companies included in the studies. Since AM for space applications is also being developed for manufacturing in space, it should be noted that AM in this thesis refers to manufacturing on earth with the intention of use in space.

1.4 Thesis outline
This thesis consists of eight chapters and three appended papers. Chapter 2 presents industrial contextual aspects of the space industry. The third chapter consists of a presentation of the methods of this thesis, with a presentation of the research setting, research design and quality of research. Chapter 4 presents the theoretical framework. Chapter 5 provides a summary of the appended papers and is followed by chapter 6, a presentation of the findings made in the research studies. In chapter 7 the results and theoretical framework is discussed. Finally, chapter 8 presents the conclusions of the research and a presentation of areas for future research.
2 Industrial context

This chapter aims to present the contextual aspects of this thesis. Descriptions show a general introduction to historical and present industry conditions as well as specific activities in the Swedish space industry, where this research has been conducted. The contextual descriptions are completed with a presentation of additive manufacturing activities in design for space industry applications.

2.1 The space industry

The first successful satellite, Sputnik 1, was launched into orbit in 1957 by Russia and marked a new era of space exploration (Fortescue et al., 2011). Actors in the space industry have since launched thousands of objects into space with various focuses such as increased performance, decreased lead times and reduced cost. After the cold war, the American space industry faced less competition which also reduced the intense focus on creating innovations (Cornell, 2011). This made it possible for other countries throughout the world to get into space development and catch up with both American and Russian space explorations. Global initiatives eventually together founded the international space station in the 1990s, where such international collaboration can be considered to be one of the greatest achievements of humankind (Cornell, 2011). However, the space industry today is moving towards a commercial marketplace that once again reinforce a greater competition again (Fortescue et al., 2011). The industry consists of both public and private initiatives in large and small companies that focus on producing hardware and services for space applications such as launchers and satellites (Bromberg, 1999). These products enable commercial applications, e.g. communications, broadcasting, navigation and earth observation (Macdonald & Badescu, 2014). Due to these various possible applications, the space industry is generally characterised by multidisciplinary character, where e.g. aeronautical, chemical and electrical engineering are involved in research and development (Bromberg, 1999).

Even though some argue that the space industry has seemed quiet during the past 20 years, there has been a great shift in the industry (Cornell, 2011). New actors such as SpaceX and Blue Origin have pressured the industry towards commercialisation and are considered to constitute the so-called “New Space” with a greater focus on, e.g., entrepreneurship. There have been major trends in the space industry towards larger, more expensive and longer-lasting spacecraft during the past two decades (Hastings et al., 2016). However, due to the shift towards entrepreneurial perspectives in the industry, various initiatives have arisen to, e.g., decrease cost. One example of such initiatives in established organisations is the focus to reduce cost by half for the new-generation launcher Ariane 6 (ESA, 2017a). On the other hand, another attempt to increase product value in the industry is the greater focus on re-using spacecrafts (SpaceX, 2015) and of conducting maintenance of satellites in orbit (Hastings et al., 2016), which results in increased long-time sustainability. Such initiatives have already been realised in the space industry through initial technical developments at, e.g.,
NASA and SpaceX. However, it is argued that it is important that customers are willing to make architectural design changes to implement new infrastructures for re-usage and maintenance (Hastings et al., 2016). Technologies behind launch vehicles have exponentially matured, but the development time required to build, test and deliver vehicles typically extends several years from concept to launch (Hastings et al., 2016; Fortescue et al., 2011). It is suggested that large, traditional companies that remain in older mind-sets have a more difficult time changing culturally, compared to the New Space actors. New Space actors are described as generally having a younger workforce that strives for new ways of thinking, designing and producing products for space applications (Cornell, 2011).

2.1.1 Swedish space industry
The Swedish space industry strongly contributes to the growth of Swedish innovation through new companies and technologies (Swedish Aerospace Industries, 2015). Sweden has a long history in space industry activities, with e.g. the IRF (Institute of Space Technology) having 60 years of experience in developing products for space research projects (IRF, n.d.). National research and innovation programs result in opportunities for developing new technologies and collaborations. However, even its national programs are mostly carried out in collaboration with other countries and international cooperation is highly necessary for a small country like Sweden (snsb, 2017a). Many programs are carried out on ESA projects where the majority of companies in Sweden often have a low-cost and short-term profile compared to many of the long-term projects within ESA. The Swedish National Space Board aims to create opportunities for companies to contribute to a competitive Swedish industry, where Sweden has an established competence in the space sector (snsb, 2017b). Another important factor in Swedish space industry activities is the connection to the space centre, Esrange, which is located in northern Sweden.

2.2 Additive manufacturing in the space industry
With the aim of creating high-value products, aerospace industries such as space have had an increased interest in AM (Steenhuis & Pretorius, 2017; Gibson, 2017). Products in the space industry, such as satellites and rockets, are considered ideal for AM applications, since parts are produced at low volumes and are often difficult to manufacture using traditional processes (Wohlers & Caffrey, 2015). It is expected that AM will increase the chances of engineers to create, e.g., complex rocket engines and to reach higher efficiency in the production of future spacecrafts (NASA, 2017). There are already proofs of concept for AM in space applicationsm and some of the most renowned are for example the rocket part that was printed as a whole by Lawrence Livermore National Laboratory for a proposed nanosatellite launch vehicle (Wraith, n.d). The first prototype was printed in eight days with a total cost of $10 000, which makes it more cost-effective than the traditional manufacturing processes. One of the main incentives to implement AM within the space industry is the possibility of reducing weight and for creating new, complex geometries (Lockheed Martin, 2014). Lockheed Martin have focused on having engineers from different areas working side-
by-side to increase the understanding of what engineers are capable to design with AM. This focus has resulted in geometrically complex designs and Lockheed Martin’s focus is for the next generation of engineers to think additively while designing space components.

Other examples include SpaceX, which launched their first AM printed part into space in 2014. The part is argued to have superior strength, ductility and fracture resistance compared to parts produced using traditional manufacturing methods (SpaceX, 2014). The continuous work with AM within SpaceX is aimed at developing more reliable, robust and efficient vehicles. Lockheed Martin also aims to continue to widen the usage of AM, with the expectation of creating more complex parts and eventually maybe full satellites (Lockheed Martin, 2015). AM is currently used for developing satellite parts, and is implemented to reduce cost, cycle time and material waste. Some components on-board the Juno spacecraft were produced with AM, and have been orbiting Jupiter since 2016 (Lockheed Martin, 2014). Large, established organisations such as NASA and ESA have also pushed the boundaries, where AM is considered a key technology for enabling improved space vehicle designs (NASA, 2017; ESA, 2013). For example, NASA has produced a rocket fuel pump with AM, that has 45% fewer parts compared to pumps produced by traditional manufacturing methods (NASA, 2017). ESA has established a collaboration with the “manufacturing technology centre” (MTC) in the UK to investigate possibilities of AM in their space-related work (ESA, 2017b). The aim of MTC is not to compete with, but rather to assist, companies interested in AM to investigate whether the technology should be adopted or not. Examples show that the specific interest of AM in the space industry offers a possibility of adopting the benefits provided by AM. The complex and special setting with high safety requirements and various stakeholders in design makes it an important arena do exploring AM.
3 Method

This chapter discusses the methods used in the research presented in this thesis. The chapter begins with a presentation of the research setting before the research design is described. The pre-study is then presented, followed by the main empirical data collections and data analysis. The chapter is concludes with a discussion of the quality of this research.

3.1 Research setting

Research presented in this thesis has been conducted within a collaborative research project called RIT (Rymd för Innovation och Tillväxt, i.e. Space for Innovation and Growth) with the aim of promoting the region of Norrbotten as the leading space region in Sweden. The collaborative research within RIT has brought access to various space-related companies that have sites in Sweden and hence operate in the Swedish space industry. The author has a background in industrial design engineering, but has no previous experience in design for space applications. Therefore, the close collaboration with a PhD student with several years of experience in design in space systems has been supportive (c.f. Dordlofva 2018). Since it is important to include different perspectives and insights in research (Creswell, 2013), the close collaboration between the two PhD students is considered to be a valuable asset in the presented research.

3.2 Research design

Due to its novelty, there is a lack of existing theories or explanations on how AM as a new manufacturing technology affects early phases in design. This is the main reason why studies presented in this thesis have been designed as qualitative empirical studies (Merriam, 2009). Qualitative research often seeks to capture individual ways in depth, to describe a phenomenon that is occurring (Flick, 2014). This thesis has been based on a pre-study and two empirical studies, designed to explore the two research questions (Table 1). Each study has been designed to describe findings in the shape of stories given by individuals, and therefore, results of this thesis are presented in a descriptive manner. The qualitative studies have been designed as an abductive process. An abductive process is based on a combination of inductive and deductive processes from an empirically studied phenomenon, while a deductive process aims to test hypotheses derived from previously conducted research (Merriam, 2009). Therefore, research studies that are designed abductively are based on an interplay between existing theory and empirical findings.
Table 1, Overview of studies presented in this thesis and their coverage of the Research Questions (RQs).

<table>
<thead>
<tr>
<th>Study</th>
<th>RQ</th>
<th>Type</th>
<th>Objective</th>
<th>Unit of Analysis</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-study: State-of-the-art and state-of-practice</td>
<td>1</td>
<td>Literature study + study visits</td>
<td>Understand what opportunities and challenges that comes with AM in design</td>
<td>Additive manufacturing in engineering design</td>
<td>A</td>
</tr>
<tr>
<td>Main study I: The perspective of individuals</td>
<td>1 + 2</td>
<td>Literature study + interviews + workshops</td>
<td>Understand current product development for space applications and the expected influence of AM in this work</td>
<td>Individuals working with product development</td>
<td>B</td>
</tr>
<tr>
<td>Main study II: Identifying and observing the usage of AM design heuristics</td>
<td>2</td>
<td>Literature study + workshop</td>
<td>Understand possibilities in design for AM</td>
<td>Support in AM design for individual engineers</td>
<td>C</td>
</tr>
</tbody>
</table>

Qualitative methods were recognised as being the most favourable for the research presented in this thesis, due to the need for in-depth understanding of a relatively recent phenomenon (AM in design) that has a lack of existing theory or explanations. Empirical data collections in qualitative research are characterised by various theoretical approaches and focus on gaining a subjective standpoint from participants in the study (Flick, 2014). Research presented in this thesis has been designed through a multiple-case study strategy (Yin, 2014), since case studies are aimed to describe specific cases such as organisations, persons or social communities (Flick, 2014). Two multiple-case studies have been performed with different focuses, where the first study focused on exploring AM in design practices and the second on exploring the usage of design heuristics for AM in design work. A multiple-case design has the aim of analysing contextual conditions in relation to the cases in order to understand specific situations (Yin, 2014).

3.2.1 Case selection
While selecting cases for studies presented in this thesis, an initial criterion has been that the company performs product design practices where products for space applications are being designed. The focus on companies working with space applications is due to the emphasis this thesis has on the space industry. This criterion (companies working with space applications) was considered the main backbone in choosing cases, since the research aimed to explore the phenomenon of product development activities within the special context of the space industry. Since AM is the studied phenomenon, another important criterion was that the company had a strategic interest in AM for their product development work. Hence, each company included in these studies has been considered as a case, and the four case companies all operate in the space industry that both develop and manufacture complex and high-performance products (Table 2). Finally, engineers within the companies that are included in the studies were required to be able to relate to AM in their design work.
Table 2. Overview of the case companies included in the studies

<table>
<thead>
<tr>
<th>Case company</th>
<th>Description</th>
<th>Size of company</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The company is developing complex and high-performance components for the aerospace sector. The studied part of the company focuses on product development and manufacturing of sub-system components for launcher applications.</td>
<td>Approximately 17,000 employees</td>
</tr>
<tr>
<td>B</td>
<td>The company operates in a wide range of satellite programs. Responsibility includes the entire chain, from R&amp;D to sales for several product areas.</td>
<td>Approximately 8,700 employees</td>
</tr>
<tr>
<td>C</td>
<td>The company provide advanced space services and product-developing subsidiaries. The visited site focuses on product development for experimental platforms and satellite propulsion.</td>
<td>Approximately 500 employees</td>
</tr>
<tr>
<td>D</td>
<td>The company focuses on product development for space systems and satellites, and is involved in several highly critical projects. The company is also considered to be a leading company within Europe for electrical propulsion.</td>
<td>Approximately 2,200 employees</td>
</tr>
</tbody>
</table>

3.3 Literature studies

To find current state-of-the-art in the area, three rounds of literature studies were performed with three different focuses (Table 3). Since new content is continuously published in research articles, it is important to have continuous coverage of the research that has been and is being conducted. Therefore, the three rounds do not only cover slightly different focuses, but also include extra searches on the same content as the previous literature searches. These searches were mainly conducted in Scopus with no time limit, and in some searches, limited to certain areas such as Engineering or Business to reduce the non-relevant documents in the findings. Since AM has historically been called various names, such as Layered Manufacturing, Rapid Prototyping and Free Form Fabrication, such synonyms have been included in each literature study.

**Literature study 1** investigated both technical characteristics of AM and the usage of AM in product development at the time. The space industry context was to some extent also included in the study, to gain a better understanding of the phenomenon in the specific industrial context. **Literature study 2** 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, the literature study to some extent also included the civil aerospace industry due to its close connection to the space sector. **Literature study 3** aimed to identify design heuristics for AM that could be presented to engineers with extensive experience in product design, but limited experience with AM. Findings in the literature were related to traditional design for manufacturing guidelines and space industry design prerequisites. This resulted in a tentative model of design heuristics for AM that was tested with space-related cases in Study II.
Table 3, the state-of-the-art literature studies

<table>
<thead>
<tr>
<th>Time period</th>
<th>Literature study 1</th>
<th>Literature study 2</th>
<th>Literature study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus</td>
<td>Additive manufacturing in design. Specifically in the space industry</td>
<td>Product development in space industry applications and design practices in general</td>
<td>Identifying design heuristics and understanding the importance of them</td>
</tr>
<tr>
<td>Keywords</td>
<td>Additive Manufacturing (and synonyms such as Layered Manufacturing and Rapid Prototyping); Additive Manufacturing Technologies; Design for Additive Manufacturing; Additive Manufacturing together with Space Industry (and synonyms such as Space Applications)</td>
<td>Design for Additive Manufacturing; Additive Manufacturing together with Product Development; Additive Manufacturing together with Space Industry (and synonyms such as Space Applications); and Product Development and Space Industry (and synonyms such as Space Applications)</td>
<td>Additive Manufacturing and Design for Additive Manufacturing that was searched together with keywords such as product design; design strategies; design heuristics; design; design freedom; and design optimisation.</td>
</tr>
</tbody>
</table>

3.4 Pre-study: state-of-practice and state-of-the-art
Before designing the research studies, initial state-of-practice investigations were conducted to gain an understanding of the condition that the phenomenon AM was used in within Swedish companies and universities.

3.4.1 Study visits: “Swedish AM-tour”
To investigate the state-of-practice of AM in Sweden, an “AM tour” was performed to gain an initial understanding. The tour was covered by 13 field studies in both industry and academia with informal interviews and a short tour in their facilities. Six Swedish universities and seven organisations working with additive manufacturing were visited (see tour design in Appendix A) by the author and two PhD student colleagues. The purpose of the field tour was to gain a basic understanding of how additive manufacturing is incorporated in the Swedish research and industry communities. The intention was to map opportunities and challenges with AM in design for space applications and to highlight gaps both in both literature and practice.

Data was collected through observations, informal interviews and booklets given by the visited sites, which had a variation of interests from material design and machine manufacturers to product development. The informal interviews were conducted at the sites as a type of ethnographic interviews with a local and temporal framework that depended on the specific site (Flick, 2014). The questions emerged during the visits, depending on what the host wanted to show. Therefore, the answers of the questions were collected as field notes together with the observations that occurred on the sites (Yin, 2014).
3.5 Main empirical data collections
For this thesis, the main empirical data collections were made in two studies. The first study aimed to explore AM from the perspectives of individuals in the space industry and was explored through studying secondary data, conducting interviews and performing workshops. The second study aimed to investigate the usage of AM design heuristics and was explored through observations of a joint workshop with different projects related to various products.

3.5.1 Main study I: AM in the perspectives of individuals in the space industry
The first study was performed during the period from April 2016 to October 2016, with a study of internal steering documents, semi-structured interviews and workshops. Internal steering documents of product development activities that are available for employees at case company A, were studied both for complementary purposes and to bring an understanding (Flick, 2014) of what is expected during product development in space applications. Due to confidentiality, the internal documents were accessed through the case company at their Swedish site. Notes were taken by the two PhD students involved in the research during study of the documents. Short discussions with one of the individuals responsible for the documents were also performed to fully understand the intention of each component.

Eight semi-structured interviews were conducted with engineers working within two product areas at the space department of company A. The usage of semi-structured interviews allowed the respondents to present their subjective view and knowledge of the topic, and to express their individual story with encountering the phenomenon (Flick, 2014). The respondents were chosen from a pool of approximately 60 engineers working with product development and were selected based on their experience and seniority (leading engineering roles). A senior engineer could more easily provide an understanding of product development during all phases, since there was a higher probability that they had time to be involved in them. They had various roles in the product development organisation, such as chief engineers, design leaders, design engineers and a manufacturing engineer. The interviews were performed at one of the sites of the company, and were initiated with a short briefing of the study and a short discussion of the roles of each interviewer (Kvale & Brinkmann, 2009). Since one of the interviewers had been employed by the company, and therefore had some kind of relationship to the interviewees, he took notes and was responsible for the audio recording. The author of this thesis had no relationship to either the interviewees or the company, and therefore was the one who managed the session. This was made to maximise the possibility of the respondent to both feel safe (Kvale & Brinkmann, 2009) and to include all information that could have been lost if the respondent perceived it to be ‘common knowledge’ for individuals who were part of the organisation (Flick, 2014). Each interview had a duration of approximately 45-70 minutes (See interview guide in Appendix B).
Three workshops were conducted at case companies A, B and C (Table 4), which to some extent, were designed as active focus groups. The workshops were performed at a Swedish site of each case company and had a total duration of four hours per workshop (see agenda in Appendix C). Each workshop was initiated with 15 minutes of introduction followed by 75 minutes of activities to explore the expectations on additive manufacturing in design from both the case company and their customers. The activities in the workshops were filled with need-finding, customer quotes, and clarification of the possibilities and challenges of AM. After a short coffee break, a 15-minutes highlights lecture was given. Then the focus was shifted towards ideation for AM with the needs found earlier in the workshop as a basis, and ended with rough concepts of the ideas. A majority of the workshops were based on discussions among the participants.

Table 4, Participants in the workshops in Study I

<table>
<thead>
<tr>
<th>Case company A</th>
<th>10 participants</th>
<th>Participants had roles such as department manager, quality manager, design leaders, manufacturing engineers and design engineers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case company B</td>
<td>6 participants</td>
<td>Participants had roles such as department manager, chief engineer and design engineers.</td>
</tr>
<tr>
<td>Case company C</td>
<td>4 participants</td>
<td>Participants had roles such as company management, subsidiary CEO and design engineers.</td>
</tr>
</tbody>
</table>

3.5.2 Main study II: Identifying and observing the usage of AM design heuristics

The second study was based on the third round of literature studies. Findings from the literature study resulted in a tentative model of design heuristics for AM that was aimed to be tested with space-related cases. A creative workshop was therefore held on September 25-26, 2017 one and a half day (See agenda in Appendix D). The workshop was conducted at case company D, together with participants from both academia (LTU and CTH) and case companies A, B and D (Table 5).

Table 5, Participants in the workshop included in Study II

<table>
<thead>
<tr>
<th>Case company A</th>
<th>4 participants</th>
<th>Participants had roles such as design leaders and design engineers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case company B</td>
<td>2 participants</td>
<td>Participants had the roles design engineer and computation engineer.</td>
</tr>
<tr>
<td>Case company D</td>
<td>3 participants</td>
<td>Participants had roles such as system engineer, project manager and chief technology officer.</td>
</tr>
</tbody>
</table>

The workshop began with an introduction of the hosting company, followed by a 30-minutes tour in their facilities, where some of their products were presented. Then, the facilitator presented information regarding both the research and the project that all the companies were involved in. It was followed by a 40-minutes presentation of the simplified design heuristics, derived from literature. After lunch, the case companies each had approximately 45 minutes to present the products that they wanted to work with in the workshop, where each company had one or two suggestions. Each case had
their own discussions (both general and on AM), where participants tried to gain an understanding of both the purpose of the component and the boundaries where the customers have prerequisites. Each company chose one case to work with, and the first day was ended with an hour of filling in a use case canvas, provided by the researchers from LTU. The second day was focused on ideation which was initiated by creative exercises to find new solutions to the cases together. Each case had its own time, where all participants focused on how to redesign the component to fit the AM methods. A majority of the workshops were based upon discussions among the participants and sketches of the ideas.

3.6 Data analysis

Data analysis of study visits in the pre-study was, to some extent, already initiated at the sites when overlaps of information occurred. This was noted by the observers and used later in the analysis. Since each individual has different perspectives and realities (Creswell, 2013), all three PhD students documented the visits and discussions at the sites, and afterwards combined these into one document. Of course, the context of the sites and each discussion with a respondent was taken into consideration during reflections of the documents (Graneheim & Lundman, 2004). The document was reflected upon to discover both differences and similarities in the discussed subject (Graneheim & Lundman, 2004). This brought new insights for the final discussions (in Paper A) in relation to the relevant literature found in the study.

All interviews were audio recorded and transcribed, where transcriptions also included notes on laughter and interruptions when the respondent needed time to consider his or her answer. This approach was an attempt to include some of the key non-oral reactions to the discussions that would otherwise be easily missed (Kvale & Brinkmann, 2009). All workshops were documented in real-time by the author while colleagues were facilitating both activities and discussions, and two colleagues, to some extent took notes and shot photographs. Participants also made sketches and drawings on their ideas during the discussions, which have been included in the analysis. A final document was designed from notes, pictures, sketches and drawings which set the basis for the data analysis. The documentation of each study has served as support in contextualising the information given by both interviews and workshops, as suggested by Flick (2014).

The data collected from both interviews and workshops were analysed through cross-sectional analysis, across the entire data set (Mason, 2002). The data were coded into pre-decided categories of a coding frame that was designed from both the empirical data and literature (Flick, 2014). Categories included in the analysis of study I were design freedom; limitations in creativity; being innovative; creativity between engineers; and future expectations. In the second study, the categories were instead each design heuristic. Boundaries for each category were set and described to ease the categorisation. The data set was then analysed and clustered into the categories to include only the significant details from the original data (Krippendorff, 2004).
3.7 Quality of research
To increase the quality of research, both reliability and validity need to be considered from the early stages of planning to the presentation of results. Such perspectives are addressed in this section, where methods included in the research presented in this thesis have strived to be of high quality.

3.7.1 Reliability
Reliability assessment is the perspective by which the study is evaluated to be comparable and consistent throughout the entire research process. To assess reliability in qualitative research, the researcher needs to pay particular attention to the quality of recording and documenting data (Flick, 2014). The studies presented in this thesis were documented through audio recordings, field notes, pictures and sketches, which together have represented the research documentation. Since the reliability is greater if the research process is documented as a complete representation of the process (Flick, 2014), each study has a finalised documentation that includes all the data collection methods. All data collections were gathered by two or more observers looking at the same phenomena, to reach a higher degree of reliability of the data (Krippendorff, 2004). Analysis of the data has mainly been carried out through categorisation and coding, which also can be significant for assessing reliability of the final conclusions (Flick, 2014).

3.7.2 Validity
Validity is often considered to be the discussion of whether researchers actually see what they think they see (Flick, 2014). The main problem in assessing validity is to specify the relation between what is studied and the version that the researcher provides. Therefore, it is important for researchers to question themselves whether the constructed findings are really based upon the empirical raw data or if the findings reflect on prior assumptions (Flick, 2014). This thesis is based on three studies that have all been carried out together with other researchers to decrease such occurrence. There are various strategies for a researcher to address to increase validity, such as triangulation, engagement in data collections and peer examination (Merriam, 2009). However, Kirk & Miller (1986) presents three errors that can occur during qualitative data collections where the researcher can (1) see relationships that are not there, (2) reject relationships that are there and (3) ask the wrong questions. To address these potential errors, it is important for researchers to be prepared early in the designing of the research (Yin, 2009). In an attempt to decrease these potential errors in the research, interview questions, workshop designs and focus of field studies have all been reviewed by at least two other researchers before entering the data collection situation. Therefore, this thesis has an investigator triangulation (Flick, 2014) included in its research design, where multiple observers and interviewers are involved. Another attempt to increase validity of the research, key individuals both within academia and industry have reviewed the drafts of the papers (as recommended by, e.g., Yin, 2009).
4 Theoretical framework

This chapter aims to describe the theoretical background that research presented in this thesis is based on. It covers an overview of previous research in three main areas that begins with describing ‘product design in space applications’, followed by a presentation of general ‘design practices’. Additive manufacturing is then addressed through ‘additive manufacturing in design’.

4.1 Product design in space applications

Products designed for space applications are often categorised as a complex product system (Fortescue et al., 2011), where systems of systems are working together. Each sub-system has its own product design process, and all parts in the system work towards the same goal: to deliver a product system that can either be launched into space or operate on earth. To work with product systems in design is often called systems engineering where a system architecture is pre-defined before each design team starts the design work (Crawley et al., 2004). Such system architecture can determine a design for several generations of systems, since systems are re-used and long-lived. This can be seen in the space industry, where, for example, rocket engines generally have had the same system architecture since the 1940s (Fortescue et al., 2011). A highly complex product system can be hard to manage due to the need for synchronising people, processes and models within the system (Simpson & Martins, 2011). It can therefore often be difficult for individual engineers to fully see the “big picture” and understand how their decisions impact other parts in the complex system.

While designing complex engineering systems in a big design projects there is a risk of overrunning both cost and schedule (Sinha & De Weick, 2016), which makes it important to verify each step that is made in the projects (Fortescue et al., 2011). By using a stage-gate approach (Cooper, 1990), such verifications can be made where each phase (the so-called stage) is followed by a gate to verify that the phases have been successfully conducted. Many product design projects in the space industry are designed in a stage-gate approach, since there is a great emphasis on producing high-quality products with high performance. Stage-gate processes are considered to verify the work throughout the process. Therefore, this thesis will use a product development process (Figure 1) designed in a version of a stage-gate approach for projects carried out in the space industry, where product design is considered to comprise the concept design phases.

Figure 1, General product development process in space applications adapted from Pahl et al., 2007; Fortescue et al., 2011; and Ulrich & Eppinger, 2012
4.1.1 Technology Readiness Level (TRL)

Technology Readiness Level (TRL) can be considered during engineering design for space applications to verify new technology in relation to certain requirements (Fortescue et al., 2011; Macdonald & Badescu, 2014). Verified technologies can more quickly and successfully be integrated in products (Ulrich & Eppinger, 2012), hence simplifying the design process. During the design process, the technology that is involved is often considered to be on a TRL 7-8, where level 8 is reached when the completed system has been verified for flight through tests (Fortescue et al., 2011; Macdonald & Badescu, 2014).

4.2 Engineering design practices

Engineering design work is often considered to be involved in concept development, detail design and testing phases in the product development process. Design activities (Figure 2) in these phases (such as need-finding, idea generation, concept generation, detail development and design evaluations, e.g., prototyping) are strongly linked to design practices (e.g. Ulrich & Eppinger, 2012; Pahl & Beitz, 1996).

![Figure 2, Illustration of activities in engineering design work (adapted from Johanneson et al, 2004; and Wikberg Nilsson et al., 2015)](image)

It is suggested that successful management of design practices is dependent on the motivation of engineers to seek novel ideas and solutions in design (Lukumon, 2010). To influence the motivation of design engineers, it is important for management to have an understanding of factors that affect motivation (e.g. good working conditions, organisational supports and effort recognition). Thus, the encouragement of creativity in a physical environment should not be underestimated since an atmosphere of encouragement, trust and risk-free exploration is important in creative cultures (Mamykina et al., 2002). It is also important to know that there is a difference in how novice and experienced engineers approach design problems. It has been shown that novice engineers tend to use a trial-and-error approach, while experienced engineers used particular design strategies (Ahmed et al., 2003).

It was also observed that the most experienced novice engineers were moving towards the behaviours of experienced engineers. When introducing new design tools, there can be a risk of higher amounts of design rework in aerospace design projects (Dostaler, 2010). For example, three-dimensional drawing tools are capable of storing more information compared to traditional drawing tools, but are argued to bring higher risk of mistakes in design. With this in mind, it can be important to have a smooth transition
between old and new design tools, to increase the possibility of learning about unfamiliar aspects of the new design tools. Another key issue that was brought up by Dostaler (2010) is that time pressure in design is a key issue in many industries, including the aerospace industry. One way to address such an issue is to support design teams through efficient and smooth partner integration. There are various aspects in design practices that affect the chances of conducting the work successfully. Successful design practice is in this thesis seen as when design activities result in product ideas being implemented in product or production systems. Table 6 shows an overview of literature that discusses the various factors that can affect design practices. The first factor is project organisation, where the structure of an organisation affects product design practices through cross-functional teams, good communications, strong leaderships and effort recognitions. The second factor addresses project scope, where product definition, opportunities for evaluating products and having field tests affect the possibilities of conducting successful design practices. The last factor addresses the project members, where individuals can improve their performance in product design practices through quality-of-execution, dedication and experience.

Table 6, Overview of factors that affect successful design practices

<table>
<thead>
<tr>
<th>Factors</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project organisation (Cross-functional teams,</td>
<td>Cooper &amp; Kleinschmidt (1995); Dostaler (2010); Mamykina</td>
</tr>
<tr>
<td>good communications, strong leadership,</td>
<td>et al. (2002); Lukumon, 2010; Chen et al. (2010)</td>
</tr>
<tr>
<td>effort recognitions)</td>
<td></td>
</tr>
<tr>
<td>Project scope (Product definition, evaluation</td>
<td>Cooper &amp; Kleinschmidt (1995); Chen et al. (2010)</td>
</tr>
<tr>
<td>of products, field tests)</td>
<td></td>
</tr>
<tr>
<td>Project members (Quality-of-execution,</td>
<td>Cooper &amp; Kleinschmidt (1995); Lukumon, 2010; Chen et al.</td>
</tr>
<tr>
<td>dedication, experience in both individual and</td>
<td>(2010)</td>
</tr>
<tr>
<td>team)</td>
<td></td>
</tr>
</tbody>
</table>

Cooper & Kleinschmidt (1995) suggest that in organising design work, cross-functional teams are one key success factor in design, where there is a need to include engineers from various functions within organisations. However, the most important gain to be made is when these engineers are included in design teams throughout the project and not merely in occasional meetings. An additional importance of collaborations in a multidisciplinary team is that different and often complementary perspectives of problems assist the possibility of breaking away from obvious solutions (Mamykina et al., 2002). When various stakeholders are involved in the design process, effective partner integration is also suggested to be a key success factor in design (Dostaler, 2010). The main design practices that affect partner integration and the amount of necessary design rework are good communications, collocation and cross-functional integration. Having good communications between different sites both within the organisation and with partners is another key factor in having successful design practices (Chen et al., 2010; Dostaler, 2010). Strong leadership in all levels is one perspective that also can affect product practices. Among other things, it is suggested that managers need to understand how to handle, e.g., motivation amongst
engineers (Lukomon, 2010) to reach the desired properties of a product. It is not only high-level management that need to be strong, but also leadership (Chen et al., 2010) in order that individuals can sense the support needed for their design work. It is important that engineers have the feeling that small mistakes can be made (Dostaler, 2010), so that they can be relaxed and that they might dare to bring up new perspectives in design. Since it has been shown that novice engineers use a “trial and error” approach (Ahmed et al., 2003), it is very important to have support from management if engineers are to have the opportunity to learn and develop. Another factor to consider is having a sharp product definition early on in the project (Cooper & Kleinschmidt, 1995). This is in line with the suggestion that creativity is enhanced when individuals have a clearly defined problem to solve (Csikszentmihalyi, 1996). Hence, having a clear problem definition improves the chances of both experiencing creativity within teams and having a successful final product. It is often perceived that high creativity and innovativeness leads to higher success in product design (Cooper & Kleinschmidt, 1995), with the potential of reaching product innovation. Even though this can be true in some cases, it is important to know that it is not always applicable.

4.2.1 Creating new knowledge in design

Engineering design practices are not all about technology perspectives, but also include understanding the assignment, and listening to experiences and reflections among engineers (Backlund, 2006). It is suggested that a person goes through five steps in creating skills and knowledge (Figure 3), which begin with being a novice and ends with being an expert (Cheetham & Chivers, 2005).

Novice learners tend to stay close to rules and guidelines, while experts no longer rely on such supports (Cheetham & Chivers, 2005). However, it is also suggested that experienced engineers tend to use design strategies in their design practices, which novice engineers do not have knowledge and/or understanding of yet (Ahmed et al., 2003). An advanced beginner still uses guidelines for actions, but these are often based on individual properties in which the learner is learning (Cheetham & Chivers, 2005). An individual on the competent step now conducts work in a routinised process, where multiple activities are being carried out and actions start to get integrated with each other. The last step before reaching expert level is the proficient step, where situations are seen in a holistic perspective, instead of individual actions and steps. There is also
Theoretical framework

a learning and knowledge that not only involves the individual, but the team as a whole (Backlund, 2006). Individuals in design teams can help each other develop new skills and increase the total team understanding of various perspectives in design. Both sides of a working relationship need to exchange knowledge with each other to achieve a higher degree of progress in design (Mamykina et al., 2002). The factors presented in Table 6 are also important in creating new knowledge and understanding in design. As discussed earlier, cross-functional teams over geometrical sites both inside and outside an organisation can enhance product performance. This perspective can be related to learning in design, as well, since it is suggested that geographically dispersed engineering design courses can increase learning (Dym et al., 2005).

It is also suggested that when learning engineering design there is a need to have engaged design coaches to help manage design practices (Dym et al., 2005). This is in line with the presented factor of strong leadership that affects design practices. Since it is suggested that novice engineers approach design problems through a “trial and error” approach (Ahmed et al., 2003), supporting such emotional environment should also be of interest to a design team. It can therefore be of importance to have a risk-free environment where engineers feel that they can make small mistakes while learning (Dostaler, 2010; Mamykina et al., 2002).

4.2.2 Design for manufacturing and assembly

Many product design processes focus on a design for manufacturing and assembly (DFM/A) approach, with one of the major outlooks to decrease cost (Ulrich & Eppinger, 2012; Pahl & Beitz, 1996). There are various aims in focus in DFM/A guidelines. A list of the 15 most commonly addressed aims have been summarised in Figure 4, which involves, e.g., reducing part count and assembly time. The aim of these guidelines is considered to be to simplify, standardise and automate manufacturing and ensuring quality products (Pahl & Beitz, 1996). It is suggested that DFM/A is mainly considered to be of value for large quantities, but it is argued to be of even greater importance in low quantity production (Boothroyd et al., 1994).

![DFM/A Guidelines](image)

Design rules, or rules of thumb, are set up to limit cost and assist engineers in their daily design work (Ulrich & Eppinger, 2012), and can, together with DFM/A guidelines, support the goal of designing for a low production cost. It is during the
conceptual design phase that an assembly of the product is considered and planned (Poli, 2001). There is in this phase a need to consider the risk of having specific engineering design guidelines affecting both manufacturing and assembly operations (Pahl & Beitz, 1996). Detailed design activities consider any of the remaining dimensions, tolerances and material information that are needed for production personnel to manufacture the product (Poli, 2001).

When the overall function of a product is designed, requirements on and from production can be managed and the DFM/A guidelines can be applied in the next design steps (Boothroyd et al., 1994). However, designs can result in expensive products when engineers simply do not understand the capabilities and constraints given by the production processes (Ulrich & Eppinger, 2012). It is, therefore argued that engineers need extensive knowledge of the production processes and their capabilities (Boothroyd et al., 1994).

4.3 Additive manufacturing in design

Additive Manufacturing (AM) comprises the production technologies whereby a software 3D model is physically built in a layer-upon-layer approach. The manufacturing method is known by many names such as 3D printing, rapid prototyping, layered manufacturing and rapid tooling, and it has the following definition:

“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.”

[ISO/ASTM52900, 2015]

AM has been under development since the early 1980s and has been successfully used for Rapid Prototyping (Gibson et al., 2015), where models are used as both evaluation and communication tools in design. During the past decades, both polymer- and metallic-based AM have been developed to such a degree that the process can be considered to produce end-use products. Since metal-based additive manufacturing techniques have been greatly improved, several industries such as medical and aerospace have produced products for end-usage (Vayre et al., 2012). There are various AM technologies available, but the general AM process (Figure 5) is the same where it is initiated with a software 3D model (Gibson et al., 2015). The model is then converted into an STL file that describes the geometry and calculates 2D layers. The file is then transferred to an AM machine that builds the layers upon each other and creates a physical 3D model in different ways, depending on the chosen AM process.
4.3.1 Additive manufacturing technologies

This thesis has mainly focused on two AM technologies for metal AM: the directed energy deposition (DED) and the powder bed fusion (PBF) (Figure 6), due to the great interest of these in the space industry (Paper A). DED technologies melt (with a thermal source such as a laser or electron beam) material, while being deposited onto a surface where the part will be built, and can have either a wire or powder feed (Gibson et al., 2015). In many cases, the process can be compared to welding, where materials are joined together with the help of a fusion method (Bouge, 2015). PBF technologies have a thermal source (laser or electron beam) melting or sintering powder for each layer, where a new layer of powder is distributed over the previous layer (Gibson et al., 2015). These two AM approaches bring different values in design, where, for example, DED has a bigger building area compared to PBF.

Even though the two AM approaches bring great benefits in design, it can be beneficial to use hybrid systems (Gardan, 2015; Gibson et al., 2015). A hybrid system is a machine that joins AM technologies and numerical control (NC) technologies into one solution (Vartanian & McDonald, 2016). The different values in these processes make it beneficial to combine the additive and subtractive manufacturing methods within one system (Gibson et al., 2015; Vartanian & McDonald, 2016).
4.3.2 Design for additive manufacturing

The expression design for additive manufacturing (DfAM) has been taken out of design for manufacturing and assembly (DfM/A) to guide engineers to utilise AM in design. However, available design guidelines for AM are often seen as a way to help engineers to understand the restrictions of conventional design instead of providing knowledge in how to take full use of AM (Yang & Zhao, 2015). Kumke et al. (2016) propose that DfAM can be classified in either a broad or a strict sense. The strict sense includes AM design rules, the utilisation of design potentials of AM, and the possibility of combining approaches and methodologies in design for AM (Table 7).

Table 7, descriptions for DfAM (adapted from Kumke et al., 2016)

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design rules for AM</td>
<td>New restrictions in AM design are often dependent on process and machine selection. However, some of the rules that need to be considered are wall thickness, gap features, surface roughness as a function and geometrical element transitions. Involvement of such design rules in design guidelines for AM is increasing.</td>
</tr>
<tr>
<td>Utilisation of design potentials for AM</td>
<td>New geometrical design freedom that comes with AM is often considered to assist design work. This freedom is considered to increase product performance, reduce assembly cost and realise innovations. However, the purpose of AM design is often based on improving existing products rather than assisting new product development.</td>
</tr>
<tr>
<td>Combined approaches and methodologies for AM</td>
<td>Optimal AM products can be prevented if guidelines only focus on design rules or design potentials for AM in design. Systematically including both perspectives in design for AM can assist engineers in seeing unrealised possibilities and ideas.</td>
</tr>
</tbody>
</table>

DfAM in the broad sense also includes such perspectives as selection of parts, process selection, production strategies and manufacturability analysis. However, this thesis follows the definition of DfAM that is described by Kumke et al. (2016), where activities regarding the manufacturing process such as build orientation, are not included. Such perspectives can nevertheless still be taken into account in, e.g., AM design rules. Two main design strategies can be considered when including AM in design work (Klahn et al. 2015). One is called a “manufacturing-driven approach”, where the product is designed for various possibilities in production. This approach can be seen as cautious, since engineers can lean back on traditional manufacturing methods and use AM more as a method for confirmation. The second strategy is called “function-driven”, where the designer uses any design possible and in the end, alternates the design to fit the limitations of the manufacturing method that seems suitable (Klahn et al., 2015). The function-driven design approach is considered to help the designer open up their 3D design understanding for AM. However, to fully utilise the geometrical freedom that AM brings it is important to continue the development of design guidelines (Krantz et al., 2015).
But why is there an expression entirely for AM, and not for processes such as casting or forging? Some researchers have argued that since AM needs such a different design approach (additively instead of subtractively), there is a need for specific guidelines. This thesis considers DfAM as a part of DFM/A, where the function and manufacturing-driven design approaches (Klahn et al. 2015) are not only considered for AM, but also for other manufacturing processes. As seen in Figure 7, DfM/A is the overall expression that involves all manufacturing methods.

**Figure 7, the expressions DfM/A and DfAM in relation to each other**

4.3.3 Additive manufacturing and the design freedom

AM is argued to bring geometrical values to design through approaches such as part consolidation (Yang & Zhao, 2015) and topological optimisation (Leary et al., 2014). Therefore, many industries see the potential of new and innovative geometries for their products when implementing AM in production systems. AM creates possibilities for making late changes in design, without changing an already set manufacturing process (Gibson et al., 2015) due to the relatively short lead times compared to traditional manufacturing processes. At the same time as lead time and cost reductions can be performed with AM, design approaches have been developed to assist engineers (Campbell et al., 2012). However, it can be important for engineers to explore when the manufacturing method brings increased value in design in relation to a cost perspective (Mellor et al., 2014). While many possibilities emerge by including AM in product design, it is also the case both that old limitations linger and new ones arise (Gibson et al., 2015; Vayre et al., 2012). It is important for engineers, design teams and management to be aware of these. Some AM processes have a relatively low geometrical accuracy (Krantz et al., 2015), which leads to the fact that a virtual 3D model needs to be scaled properly before printing in order to produce the part in the desired dimensions (Vayre et al., 2012; Gao et al., 2015). At the same time, it is important to acknowledge that most printed parts, to some extent, need post-processing (Gibson et al., 2015; Vayre et al., 2012), where hybrid systems can manage such aspects.

AM technologies can open up the opportunity to change material composition by changing powder feeder mixtures (Gibson et al., 2015) for both DED with powder feed and PBF. It is, therefore, possible to focus stronger and more expensive materials onto the areas where it is needed, and other materials on the less critical areas. DED also provides possibilities for producing functional grading of materials and multi-axis
deposition (Thomson et al., 2015). Such opportunities open up a higher degree of freedom for engineers while developing a product. In addition to this, DED is also useful for adding features onto already existing structures which makes the process ideal for repairs. When a part is damaged, the AM process with DED or PBF has the ability to easily repair parts in any direction (Gibson et al., 2015; Wong & Hernandez, 2012; Vayre et al., 2012). The process also offers the possibility of adding a structure onto an existing part, where the structure would be hard to build using another available manufacturing method.

PBF has the ability to produce complex structures in a way that DED cannot do. This limitation is due to the larger melt pool that DED has, which results in the reduced ability to print small-scaled features (Gibson et al., 2015). PBF has the capability of producing structures with over-hanging parts, which the Powder DED does not (Thomson et al., 2015). According to Vayre et al. (2012) the cost is higher, and the dimensional accuracy for DED is very poor compared to PBF variants. The limitation of the poor part accuracy and surface finish makes the post-processing possibilities even more important than for other AM processes (Gibson et al, 2015). This poor surface finish is partly due to the slow build speed that is also considered to be a limitation for the process (Gibson et al., 2015). Much of the usage of DED today is spent within research labs and for low volume production (Thomson et al., 2015).

When it comes to the actual printing, there are three main aspects that the designer needs to be aware of to utilise the design freedom. Firstly, there are variations between machines that leads to the difficulty of producing the exact same part in another machine (Frazier, 2014). Another aspect that should be considered is the need of support material for finalising the build (Vayre et al., 2012). Gaynor et al. (2016) express that support material in AM designs is a far more complicated issue than described in the literature. It is important to have a general understanding of when support material is required and when it is disadvantageous. In some cases, support material is needed to avoid distortions resulting from the solidification process (Gaynor et al., 2016), but when support material is removed, the surface is rougher in that area compared to the rest of the part (Gao et al., 2015). To avoid too many unnecessary design iterations and post-processing, it is important to take part orientation into consideration while designing for AM (Leutnecker et al., 2016). Part orientation can also assist the design through good properties and to determine where support material is needed (Gao et al., 2015). Therefore, this is something that should be taken into consideration early in the product development process in order to know how to generate ideal designs for AM (Leutnecker et al., 2016).
5 Summary of papers

This chapter presents a summary of each appended paper and includes a relation of the paper towards this thesis. Each sub-chapter for the papers ends with a description of author contribution of each appended paper.

5.1 Paper A

5.1.1 Summary paper A
Since this was the first paper produced for this thesis, it provides a general understanding of AM in space applications as well as directions for future research areas. The aim of the paper was to (1) highlight opportunities in using additive manufacturing in space applications, and (2) point out challenges for engineering design research in AM specific applications. Empirical data collections were gathered through informal interviews and study visits at seven Swedish companies involved with AM in areas such as developing machines, powders and product development for AM. The paper also includes a state-of-the-art review of AM in space applications. Results in the paper show that product development for space applications is detailed and complex due to involvement of various stakeholders. When AM is considered in design, limited experience brings a more cautious approach towards new solutions. Such limited experience can be assisted by guidelines, but there are few support tools and methods available to assist engineers adopting AM in design. In relation to this thesis, the paper provides an overview of AM in design for space applications. It addresses the first research question on opportunities and challenges given by AM.

5.1.2 Author contribution paper A
This paper was initiated by Törlind with the initial idea and framework based on study visits and literature reviews made by Dordlofva and myself. Data collections and analysis was a joint effort between Dordlofva and me. Besides participating in writing conclusions of the paper, I specifically contributed with the literature review on design for AM and the overall state-of-the-art of AM.

5.2 Paper B
5.2.1 Summary paper B
To gain further understanding of AM and its involvement in product design practices, this paper studies expectations of engineers in the space industry. The aim of the paper was to explore the perception of design engineers in the space industry on AM in product design. It was investigated through interviews, workshops and a study of internal steering documents. Findings reveal that product development in the space industry is strongly influenced by external factors such as customer involvement and political decisions, which make product development more complex. Even though AM technologies are considered to bring new possibilities in design, results also show that new tools and methods are needed to assist engineers in adopting an understanding of design for AM. When addressing tools and methods in design for AM, human aspects need to be considered since people can influence design work through e.g. proven designs and a caution with respect to AM processes. In relation to this thesis the paper shows, similar to Paper A, that product development for space applications is complex due to the involvement of external stakeholders. It addresses both research questions on opportunities and challenges for AM, and how AM can be introduced in product design practices.

5.2.2 Author contribution paper B
The idea of this paper arose in discussions between Dordlofva and myself after the first paper, and data collections was a joint effort between the two of us. Initial data analysis was performed by me and was then discussed with Dordlofva and Öhrwall Rönnbäck. I designed the framework of the paper, managed a majority of the writing and specifically contributed with a literature study of AM in product development. The paper was presented by me at the ICED conference (2017) in Vancouver, Canada.

5.3 Paper C

5.3.1 Summary paper C
This paper investigates the involvement of design heuristics for AM in design for space applications. The aim of the paper was to (1) identify design heuristics for AM that can be presented to design engineers in the space industry with limited experience of AM, and (2) explore the usage of the identified heuristics for AM in a creative workshop with space-related products. Design heuristics were identified through literature studies and presented in a creative workshop, designed especially for exploring new solutions in design for space applications. Findings from the literature study provide a presentation of 10 identified design heuristics for AM, which have been formed for usage in early design phases in the space industry. Findings from the workshop show that such design heuristics for AM seem useful for products designed for space applications. There are also indications that the heuristics for AM can assist engineers in understanding how to explore a new design space. In relation to this thesis, it shows
initial understanding of how supports in design, in this case design heuristics for AM, can assist design for space applications. It addresses both research questions: how AM is used in product design and how engineers relate to AM in product design.

5.3.2 Author contribution paper C

The paper idea was initiated in discussions between Törlind and me, based on initial literature studies made by me. Preparations and collections of empirical data was a joint effort between Törlind and myself, and I conducted a majority of the literature studies. The framework of the paper was designed by me, and I did a majority of the writing. The paper was presented by Lindwall at the Design Conference (2018) in Dubrovnik, Croatia.

5.4 Relation between the papers

Paper A gives an overview of opportunities and challenges with AM, as seen in the context of the space industry. Furthermore, Paper B complements Paper A with insights on opportunities and challenges seen by engineers and factors they perceive to be of importance when introducing AM in product design practices. Paper C goes deeper into one of the factors (supports and methods for understanding AM in design) and focuses on identifying heuristics that can assist engineers in adopting AM in their product design practices.
6 Findings

This chapter aims to present findings from the three studies covered by literature studies and empirical data collections to complement the appended papers. Due to the combination of literature and empirical studies, findings are presented in both perspectives.

6.1 Findings from pre-study

The aim of the pre-study was to highlight gaps both in the literature and in practice with respect to opportunities and challenges presented by AM in design for space applications. This study was covered in paper A, where a state-of-the-art and state-of-practice was presented for AM in design for space applications.

6.1.1 State-of-the-art and practice for AM in design for space applications

It was suggested by Uriondo et al. (2015) that powder bed fusion (PBF) and directed energy deposition (DED) are the most suitable AM processes in the aerospace industry. This is in line with data given by the field studies, where main discussions regarding AM processes showed that the space industry mainly involved these processes while considering AM. In Paper A, it is suggested that the PBF process through laser and electron beam, and the DED process through laser, electron beam and arc were the main focus for companies when considering AM in the space industry. These two suitable processes have different constraints and possibilities in geometrical design, which are presented in Table 8. DED was initially designed for remanufacturing or repairs (Vayre et al., 2012), and are often still considered to be best suited for this purpose.

Another important perspective of geometrical design for AM is the limitations in creativity for design engineers. It was found that researchers have claimed that it can be hard for engineers to take in all the possibilities of AM (Klahn et al., 2015) and that the holistic design guidelines available do not bring an understanding in design for AM (Gao et al., 2015; Gibson et al., 2015; Campbell et al., 2012). This claim is something that was widely discussed during the field studies as well, where the main focus of the field studies was to show the amazing possibilities that AM can bring in design. The topic led to discussions on the need for new design guidelines, tools and methods adapted for AM. Literature also suggested that the designer is limited to CAD tools (Gao et al., 2015; Gibson et al., 2015), since the programs are often designed for the purposes of solid modelling. Another issue that was brought up at the field studies was the unease of the digitalisation that comes with AM, and the risk that CAD files and process parameters could get into the wrong hands and harm the company.
Table 8. Summary of opportunities and limitations with geometrical design for PBF and DED

<table>
<thead>
<tr>
<th>Constraint and/or possibility</th>
<th>Powder bed fusion</th>
<th>Directed energy deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constraints</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size of build chamber</td>
<td>E.g. one of the biggest currently available sizes is 500x280x365 mm for a laser machine (SLM-solutions, n.d.).</td>
<td>E.g. one of the biggest currently available size is 1000x800x650 mm (Insttek, n.d.).</td>
</tr>
<tr>
<td>Support structures</td>
<td>Preventing collapses in parts when having big overhangs, supports need to be designed in some cases (Vayre et al., 2012; Gibson et al., 2015).</td>
<td>Preventing collapses in parts when having big overhangs, supports need to be designed in some cases (Gibson et al., 2015).</td>
</tr>
<tr>
<td>Releasing powder</td>
<td>With internal geometries, removal of powder need to be considered.</td>
<td>No need to consider this in geometrical design.</td>
</tr>
<tr>
<td>Shrinkage of part</td>
<td>Melting processes can affect the parts through a shrinkage due to the high temperature that bring no or few porosities (Vayre et al., 2012).</td>
<td>Not as significant as for PBF, but still an issue.</td>
</tr>
<tr>
<td><strong>Possibilities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimised part</td>
<td>Reducing number of parts and including internal geometries (Gibson et al., 2015).</td>
<td>Not as pronounced as for PBF, but have similar possibilities.</td>
</tr>
<tr>
<td>Multi-functional features</td>
<td>Assemblies and functions such as joints can be can be produced in one build (Gibson et al., 2015).</td>
<td>Not as pronounced as for PBF, since DED has larger melt pools (Gibson et al., 2015).</td>
</tr>
<tr>
<td>Complex material composition</td>
<td>It is possible to vary materials at different layers at a time (Vaezi et al., 2013).</td>
<td>It is possible to gradually and continuously vary between materials during manufacturing (Vayre et al., 2012).</td>
</tr>
<tr>
<td>Complex geometries</td>
<td>PBF can reach any point in the part during manufacturing, part complexity can be considered as virtually unlimited (Gibson et al., 2015).</td>
<td>Combination with NC (numeral control) machines can make it reach the part in several directions due to a 5-axis (Vayre et al., 2012).</td>
</tr>
</tbody>
</table>

6.1.2 The involvement of additive manufacturing in Sweden

All six universities that were visited had at least one subject focusing on AM. There has been a distinct increase in applications for funding for AM and several universities have applied for funding together with other universities and industry actors. Sites such as TTC “tillverkningstekniskt centrum” (e.g. manufacturing centre) has emerged, where universities together with industry install AM machines to start exploring the possibilities and limitations that different AM processes bring to design. By doing this, both large and small companies have the opportunity to try using AM without having to buy their own machines before they know if AM is a suitable process for their designs.
6.2 Findings from study I

Study I aimed to explore the usage and the perception on the usage of AM in product design. This study was presented in Paper B, where implications on the expected influence that AM can have on design for space applications were explored. This study initially gave an understanding of how product design is performed in space industry applications. Documentations of product development showed a clear link to a typical stage-gate process, where both the case company and their customers had a high focus on gates. These gates aimed to verify both the design process and the product itself. Interviews showed that political decisions have great influence on product development for space applications, since political funding often steers the directions of, e.g., “space Europe”. Product development is characterised by high customer involvement, where customers are often system-responsible and can bring late changes in product requirements. These late changes can potentially lead to unexpected work, and respondents both in interviews and workshops hoped that AM could assist in such situations, due to digital models and the ease to print new versions of the design.

6.2.1 Using additive manufacturing in product design for space applications

Both interviews and workshops showed that there is a great desire to learn how the AM process works and how it can be included in product design practices. There were positive perspectives on AM, where discussions showed the interest of having an opportunity to design complex geometries and new material compositions. This was one of the main viewpoints: that the design freedom that is offered by AM is one of the most interesting aspects of design. However, something that also was clear is the experience that the new freedom is hard to grasp and understand. Several respondents mentioned this paradox, where engineers’ biggest challenges are also the one that can bring the highest value in design.

“(AM brings) a higher degree of freedom, but how can you create these geometries? That is what will be the stick and carrot, but also the big challenge”

Interview respondent #2

There seemed to be a general belief that AM could be used as a bridge to find new and radical solutions in design, but that there are insufficient support tools for engineers to involve AM in their design practices. Such tools and methods were among the main topics in the discussions, where, e.g., using prototypes could assist engineers in understanding the AM process and to increase their design iterations. Other ways of increasing the understanding of AM in design that were discussed included involving AM experts and attaining a higher degree of machine availability. Some respondents discussed the risk of feeling safe with an already proven design. This was according to some respondents an aspect that could hinder radical solutions, but was to other respondents something that was of importance for delivering quality products.
“I think that we can get better at that, to make use of what we previously have learnt.”
Interview respondent #7

“There is nothing wrong with it [leaning on old designs], but you don’t take the big steps”
Interview respondent #1

Two areas were found to be the main aspects that need to be considered for engineers when introducing AM in design practices (Figure 8), and the first was specifically the need for tools and methods of learning AM. The second area involved the influence of human aspects in design, where the need for AM design understanding was highlighted in many discussions. A lack of understanding design for AM was also discussed in relation to AM process understanding, where there generally was a cautious approach towards the AM process, since there still is much less understanding of material and mechanical properties of a printed part compared to traditionally produced parts.

![Figure 8, two areas of importance when introducing AM in design](image)

6.3 Findings from study II
Study II aimed to explore the involvement of design heuristics for AM in design practices. This was mainly covered by the literature and empirical implications from observations in a workshop. Results were presented in paper C, where the involvement of design heuristics was explored.

6.3.1 Design heuristics for additive manufacturing
While investigating what design aspects and strategies that can be important to address when designing parts for AM, three design areas were identified (Figure 9). These areas were identified through investigating literature and combining several of the aspects and strategies that were presented in similar perspectives in literature.

<table>
<thead>
<tr>
<th>Part consolidation</th>
<th>Connection elements</th>
<th>Structure design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated design</td>
<td>Form synthesis</td>
<td>Form synthesis</td>
</tr>
<tr>
<td>Internal design</td>
<td>Topology optimisation</td>
<td>Topology optimisation</td>
</tr>
<tr>
<td>Embedded design</td>
<td>Anisotropic structures</td>
<td>Anisotropic structures</td>
</tr>
<tr>
<td>Interlocking features</td>
<td>Multiscale structures</td>
<td>Multiscale structures</td>
</tr>
<tr>
<td>Embedded points</td>
<td>Multi-materials</td>
<td>Multi-materials</td>
</tr>
</tbody>
</table>

![Figure 9, The identified design areas and heuristics for AM](image)
The first area was identified when a majority of the literature discussed the possibility of consolidating parts from various perspectives (e.g. Gibson et al., 2015; Thomspson et al., 2016; Gao et al., 2015). These perspectives were combined into three design heuristics for AM, where the first is called integrated design. **Integrated design** (Figure 10a) can be seen as a backbone in part consolidation, where the aim is to enable production of a part that traditionally would have required an assembly of several parts (Thompson et al., 2016; Gao et al., 2015). Therefore, final product weight can get reduced when integrating features and eliminating assembly features (Gardan, 2016). The second identified design heuristic is called **internal design** (Figure 10b), which enables complex internal structures that can increase both functionality and performance of final products (Thompson et al., 2016). Therefore, while managing an inner part through an internal design perspective, it can bring a greater value to the final product (Gardan & Scheider, 2015). The third design heuristic for AM that was identified was called **embedded design** (Figure 10c), where foreign components are embedded in a part (Gao et al., 2015; Gibson et al., 2015). Even though embedded electronics through polymer AM have successfully been launched into space (Espalin et al., 2014), more research is needed in order to autonomously embed components (Ma et al., 2015). Today, the machine operator needs to temporarily interrupt the AM process to manually insert the component in the build before restarting the process, and it is important for engineers to have this action taken into account in their design. Since the AM process needs to be interrupted in order to insert electronics, systems and technologies have been developed to avoid this step (e.g. Espalin et al., 2014; Ma et al., 2015). Embedded components could reduce the need of fasteners since small metal components such as bolts or nuts could be embedded into the part (Gibson et al., 2015; Thompson et al., 2016).

*Figure 10, illustration of AM design area consolidation with a) integrated design (elimination of assembly features), b) internal design (internal channels) and c) embedded design (embedded heating system)*

The idea of the second design area was identified after realising that a majority of the literature discusses the possibilities of printing connecting elements directly in one build (e.g. Thompson et al., 2016; Gibson, 2017). Two design heuristics evolved from the investigations, where the first one is interlocking features. **Interlocking features** (Figure 11a) is a method for connecting components that are assembled and disassembled on a regular basis (Song et al., 2015). Since the volume of AM builds is limited, big parts might still need to be divided into several parts and assembled
(Gibson et al., 2015). Therefore, it is important for engineers to have this in mind while designing in order to facilitate an assembly. In the end, this design approach also enables the possibility of connecting components that are strengthened by the part’s own geometry (Song et al., 2015). It can also be important to acknowledge that there might be a value in interlocking features, even if the part fits in the build chamber (Gibson et al., 2015). For example, in some cases support material can be inconvenient, and dividing the part into sub-parts would help overcome this issue. To assist engineers in designing components with such features, a system with automatic generation of interlocking joints has been developed (Chen & Sass, 2015). The second design heuristic for AM in the design area of connection elements is the possibility of embedding joints in a build. Embedded joints (Figure 11b) are the possibility of having moving parts within one printed part. While utilising AM, joints such as hinges and slider mechanics can be printed fully assembled in one build (Gibson et al., 2015; Thompson et al., 2016). It is, however, important for engineers to know that these structures need a distance between the parts during the build (Thompson et al., 2016).

![Figure 11, illustration of AM design area connecting elements with a) interlocking features (finger joints) and b) embedded joints (ball joint)](image)

The third design area structure design was also identified in the literature where these aspects in design were frequently discussed (e.g. Thompson et al., 2016; Gibson et al., 2015). This design area consists of five design heuristics for AM that are of interest when designing structural perspectives of a part. The first identified heuristic is form synthesis (Figure 12a), where parts and elements are combined into a possible design shape for AM (Gibson et al., 2015). These designs are often formed in organic shapes where a software program can assist engineers create these new possible shapes (e.g. Autodesk, n.d.). It can help engineers comparing alternative designs to each other and explore the new design space. The second design heuristic topology optimisation (Figure 12b) is a similar design perspective, where a computational mathematical approach is used with given loads and boundary conditions (Leary et al., 2014; Gardan, 2016). The software then calculates the optimal design in the given design space that can withstand the given loads. When looking closer into material structure, the third heuristic anisotropic structures (Figure 12c) offers the possibility of processing materials at certain points or layers at a time (Yang & Zhao, 2015). Such an approach can have several material properties that are graded along a part (Gibson et al., 2015; Vayre et al., 2012).
This approach is best suited for powder processes, where the specific powder combination can be changed over the production time (Gao et al., 2015). The fourth heuristic under the structural design is identified as multiscale structures (Figure 12d), which can be beneficial in many cases where such structures can ensure strength, flexibility and lighter weight (Vayre et al., 2012). It can be composed in a way that the part is shape optimized (Gao et al., 2015), which allows for the possibility of creating the desired properties and functions within a product. These structures can reduce material use and decrease mass of the printed parts. The last design heuristic for AM is called mutli-materials (Figure 12e), which makes it possible to combine materials in a part. Products can therefore have several materials in one single part (Gibson et al., 2015).

Figure 12. Illustration of AM design area structure design with a) form synthesis (organic shape of bike design), b) topology optimisation (optimised design of hooks with loads), c) anisotropic design (graded material properties in a part), d) multiscale structures (cube with lattice structure) and e) multimaterial design (harder material at sharp edges)

6.3.2 Involving design heuristics for additive manufacturing in design practices
After identifying the 10 design heuristics though literature, the heuristics were tested in a workshop with engineers from the space industry. Observations from the workshop showed that a majority of the design heuristics for AM were utilised in the idea generation phase, even though it was a bit different between the cases. A matrix presented in Paper C shows how the heuristics were discussed in the ideation activities for each case. In summary (Table 9), 30% was discussed in all three cases, while 20% was not discussed at all. Furthermore, 30% of the heuristics was discussed in two of the cases, while 20% was discussed in only one case.

Table 9, percentage of used and not used design heuristics for AM in the workshop

<table>
<thead>
<tr>
<th>Percentage of heuristics used</th>
<th>Product A</th>
<th>Product B</th>
<th>Product C</th>
<th>All products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of heuristics used</td>
<td>60%</td>
<td>60%</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>Percentage of heuristics not used, but used by the other cases</td>
<td>20%</td>
<td>20%</td>
<td>30%</td>
<td>-</td>
</tr>
</tbody>
</table>

35
**Product A** involved integrated design, internal design, form synthesis, anisotropic structures, multiscale structures and multi-materials. This case was the only one that had discussions on form synthesis, with the ideas to use different shapes in internal and external parts in relation to each other. Since it early on was suggested to combine all parts into one, discussions on interlocking features did not seem to be relevant. Ideation discussions for **Product B** used integrated design, internal design, interlocking features, anisotropic structures, multiscale structures and multi-materials. This case showed great potential in involving internal design though integrating parts internally and having internal supports instead of solid pieces. **Product C** involved integrated design, interlocking features, topology optimisation, anisotropic structures and multi-materials. This case was the only one that had discussions on topology optimisation with an optimisation of material use and design for some elements in the part. Paper C suggested that the reason why embedded design and embedded joints were not included in the discussions at all was because the three cases had mainly static parts with few or no moving parts.
7 Discussion

This chapter discusses the presented findings in relation to the theoretical framework with the aim of addressing the research questions. The discussion is split into two subchapters, that aims to contribute to answering the two research questions.

7.1 Opportunities and challenges for engineers in design

Two main opportunities have been identified. Engineers who seek to advance their understanding of AM in design, and to investigate the possibility of including AM in their design practices, can get extensive supports from management levels. Since AM is highly desirable to implement, management seems to have a tendency to give extensive supports and hence increasing the possibility for engineers to adopt the knowledge needed for AM. Such supports from management levels is considered to affect successful design practices (e.g. Dostaler, 2010; Lukumon 2010) and hence can be a great opportunity when it comes to including AM in design. This support is something that can open up opportunities to expand knowledge and can assist engineers in continuing to developing their design capabilities. Strong supports from management can also enhance dedication in design teams and encourage a progress of experience, which is also considered to be of great importance for design practices (e.g. Chen et al., 2010).

The second opportunity that has been identified comprises the new possibilities in design that can give engineers new design and solutions spaces to explore. Engineers have shown a dedication to increase their experience with AM in design (in main study I), which has been shown to affect design practices in a positive perspective (e.g. Chen et al., 2010). The new possibilities in design increase the opportunities for engineers and change boundaries in the design space. Since AM brings new boundaries in design, it puts engineers in a new situation with new product definitions, which is another aspect that needs to be considered in design practices. Therefore, the new boundaries in design affect the opportunity to design products that can bring new benefits to design.

When it comes to challenges, there are mainly four areas that have been detected. First of all, there are generally high expectations of what AM can bring to design (Pre-study and main study I). It seems as if it is experienced that these high expectations could be hard to match, which makes engineers magnify the usage of AM in design. Engineers ask for more knowledge, tools and methods when it comes to AM since “it is very hard to fully utilise the design freedom”. One respondent expressed that the design freedom is the main incentive for introducing AM to design, but that there are insufficient supports for engineers to really utilise it fully. Instead of applying a “trial and error” approach, which novice engineers often do (as discussed in Ahmed et al., 2003), experienced engineers with limited knowledge of AM are a bit cautious towards AM processes and the new design freedom. Therefore, engineers request new tools and methods for design and claim that there are not enough support tools to assist them in
their early encounters with AM (main study I). This is seen as the second challenge for engineers in adopting AM, where expert engineers feel uncertain with the limited support tools available. However, even though there has been some research made on strategies in design that can assist engineers (e.g. Klahn et al. 2015), engineers included in these studies did not seem to have had contact with these. Engineers seem to request something more comprehensive, that is, something to serve as a “guiding book”, showing them the possibilities and limitations with AM in design.

The third identified challenge was the cautiousness towards the maturity and quality of each AM process. Since the space industry is in such a high-performance and high-demanding design atmosphere due to complex product systems and a demanding environment (e.g. vacuum, temperature and radiation), every step in the design process is very important to verify. Even though AM processes have matured rapidly during the past few decades and are used in many industries today, the space industry still perceives the processes to be a bit too immature when it comes to understanding material- and process properties. This assessment has put engineers on the edge, where they wonder if they really can ensure the quality that is needed for a launch into space. This leads to the fourth challenge, where this insecurity with ensuring quality of the product affects engineers in their design practices also comes from customers. Customers in a large and complex product system are the ones that have the last say in what processes that is accepted as production approaches, and which ones that do not reach the right maturity for the system requirements. This seems to put yet even greater pressure on engineers, as they try to adopt an understanding of AM in design. They not only need to ensure their own insecurities with quality control, but they also need ‘external’ stakeholders to approve of their choices before the choice can be final.

7.2 Introducing additive manufacturing in design practices
Studies presented in this thesis have not only resulted in a description of the opportunities and challenges that engineers can encounter in design, but also directions on how AM can be introduced in design practices. The pre-study showed that there are few tools and methods available for design engineers when introducing AM in design practices, and in the main study I showed that this is something that also is requested by engineers in the industry. It is implied that such tools and methods are needed for engineers to really adopt an understanding of utilising AM in design. When it comes to what kind of tools or methods that are needed, some literature (e.g. Gao et al., 2015; Gibson et al., 2015) and respondents discussed the need to develop CAD programs to address an understanding of an additive approach instead of the traditional subtractive understanding in design. In paper A, we proposed a CAE system with integrated topology optimisation perspectives. However, many CAD software programs have been developed since then and are now, to some extent, considering topology optimisation, form synthesis and a top-down approach in adding material rather than subtracting. As discussed in paper C, many topology optimisation programs are often considered to be useful after the first ideation activities. Therefore, it is suggested that many software programs with, e.g., topology optimisation or form synthesis are further
and continuously developed to assist engineers in earlier phases to find an optimal design. However, these kinds of software programs cannot replace engineers, and since redesign and alterations of the design are to some extent needed after such an approach (e.g. Gibson et al., 2015), many aspects in design need to be considered in earlier design phases. Instead, tools that can assist engineers to adopt AM in early phases of design need to be introduced in the ideation phase.

One example is to have AM desktop machines available in engineers’ daily work, to increase the possibilities of exploring new designs. Desktop machines can assist engineers in understanding the 3D-design space that is now available with AM, and increase design iterations in the early design phases (in ideation and/or conceptualisation). This approach can lead to increased uses of parallel designs, and hence create the opportunities for saving designs for a longer period of time in the process, which, perhaps in traditional design activities, would have to be discarded due to tight time frames. It is therefore proposed that the involvement of AM desktop machines is iteratively included throughout a typical design process (Figure 13).

The suggestion is that after an initial ideation phase, continue developing a limited amount of ideas (e.g. in the figure 5 ideas) with the assistance of simple desktop polymer machines. In this way, there is a possibility for engineers to understand the design in 3D early in the design process, which was something that some respondents expressed to be hard to grasp even with 3D software programs. After evaluating ideas, the suggestion is to limit these ideas as a smaller number of concepts (e.g. in the figure 3 concepts). In this part of the design process, there could be a possibility of test printing the concepts in the proposed materials (e.g. metals) and evaluate them, not only in relation to the design, but also material and process parameters. The last step in Figure 13 is the one that more clearly stands out in comparison to how the design process normally can be performed. Since AM can have a shorter production time (Gibson et al., 2015) in comparison to, e.g., casting, there is a possibility of including multi-designs later in in the design process. Therefore, it is suggested to include several designs (e.g. in the figure 2 designs) when entering the detail design phase. Thus, engineers have the possibility of fully evaluating each design and avoiding discarding those ideas too early, concepts or designs too early, that perhaps could have resulted in radically improved performances.
Another suggestion is to integrate support from AM experts while the design team learns to utilise AM in design. This can be made through workshop activities, such as the ones made in study I or II, with experts that assist design teams in an early encounter with AM. According to feedback given by participants, such workshops have been great support for understanding the new possibilities that AM can bring. However, after working with AM for a while, and the individuals who are in an advanced beginner- or competent level (Cheetam & Chivers, 2005), there is probably a greater need to have experts in support of specific problems through meetings or e-mail conversations. Such an expert asset could either be an external- or internal representative, depending on the size of the company. Larger companies might have greater possibilities for providing internal experts than smaller companies, which perhaps could buy such knowledge and support from external experts.

7.2.1 Design heuristics for additive manufacturing as a support tool
While the pre-study showed that there are few supports for AM in design, and the main study I showed that this is something requested by engineers, a possible support tool though design heuristics (“rules of thumb”) was designed for main study II. Ten design heuristics for AM have been designed to assist engineers in an early encounter with AM. The main target group for these heuristics is engineers who have reached the higher steps in skills, e.g., proficient or expert level (Cheetam & Chivers, 2005) when it comes to design, but are in the lower steps (e.g. novice) when it comes to AM. The identified design heuristics are a collection of possibilities in design that AM can bring, and are something that aims to assist engineers to really adopt an understanding of these various benefits that can be created for each product. A majority of the heuristics were used in the early ideation phases in a creative workshop (Study II), even though some of them were relatively unknown by the respondents before the workshop. Involving design heuristics in early phases of design can assist engineers with limited experience in AM (but high experience in product design) to manage the new design space that is considered to be unimaginable. Without support in design for AM, the difficulty of absorbing a new design space and design freedom could hinder the possibility of reaching new solutions in design.
Conclusions

This final chapter presents conclusions drawn based on research presented in this thesis. The chapter begins by presenting the main conclusions with short answers on each research question, followed by a presentation of research contributions, both to academia and industry. The chapter concludes with suggestions for further research.

8.1 Additive manufacturing in product design

The objective of this research was to advance the understanding of the effect that AM technologies have on product design practices. Since this thesis has a particular emphasis on a space industry context, conclusions given in here are mainly directed towards the space industry. Most of the results can, however, also be transferred to other, similar industries. To reach the objective of this thesis, AM has been studied through observing and discussing with engineers who operate in the space industry. This has led to two main conclusions, where the first one is that the novel opportunities and challenges created by AM put engineers in a new position, where they feel insecure and request more support than what has previously been stated. The second conclusion is that there is a hype regarding AM that can make it easier for engineers to start up investigations on what benefits AM can give their products (e.g. support from management). This hype brings both confidence in AM and insecurities on how to fully take advantage of the possibilities that AM bring in design. One way to address these insecurities is to buy desktop machines for engineers to “play with” and develop their individual and team understanding of AM possibilities and limitations.

8.1.1 Research question 1

The first research question was described in the introduction as “What opportunities and challenges can design engineers encounter when introducing additive manufacturing in design practices?”. From the results and discussions presented in this thesis, the following opportunities and challenges have been identified:

- AM seems to bring high support for engineers from management levels, which can increase the possibilities for successful design practices. (Opportunity)
- New possibilities in design can bring higher dedication among engineers and new boundaries to relate to. (Opportunity)
- High expectations of what AM can bring in design, which, in practice, can be hard to match. (Challenge)
- Engineers feel that there are limited tools and methods available for learning how to design for AM. (Challenge)
- Engineers are being cautious with regard to the maturity and quality of AM processes, which hinders them to fully adopt and understand AM. (Challenge)
- There is a need to convince customers that the new products produced with AM really do reach high quality, which brings additional insecurities. (Challenge)
8.1.2 Research question 2

The second research question was described in the introduction as “How can additive manufacturing be introduced in product design practices?”. From the results and discussions presented in this thesis, three areas have been shown to assist engineers to introduce AM in design practices:

- Increase availability to methods and tools for AM in design to improve AM design understanding (CAD tools have today increased their applicability through, e.g., topology optimisation and form synthesis perspectives).
- Involve desktop machines for exploration of a new design space and hence increase the usage of prototypes.
- Include AM experts in design practices as support when introducing AM in design activities.

Ten design heuristics for AM have also been developed throughout research presented in this thesis, which have been shown to assist engineers to initiate their AM design understanding.

8.2 Research contribution

Academically, results of this research contribute to an increase in the understanding of the phenomenon AM and the new design space that is opened by it. This thesis also contributes with insights on what to expect when something is considered to radically change the design work that is known, and how attitudes can affect further understanding of design. The theoretical contribution is mainly situated in product design literature, where this thesis brings insights on effects given by a new technology incorporated in the design process. However, the results also give an industrial contribution, where the gathered design heuristics are considered to bring engineers in the industry a platform of where they can start evaluating their possibilities for involving new design features through AM. Therefore, this thesis contributes supports when evaluating AM in specific designs.

8.3 Further research

This licentiate thesis provides a clear understanding of what areas of AM design need to be researched further. The discussion shows that supports in design for AM need to be further developed. It is also shown that supports available today also needs greater availability amongst engineers for them to fully utilise the new design- and solution space. More research on the effect that human qualities such as insecurity and attitudes about technology have on design practices needs to be considered in the continuing development of design for AM.

Finally, the design heuristics for AM that have been presented in this thesis need to be further evaluated in terms of usefulness in design practices. This should be made with engineers ranging from novice to experts on AM and in various industries.
References


ESA, (2017a, June 16), Ariane 6, Retrieved [online] 2018-01-16 from: http://www.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_6

Angelica Lindwall, Additive Manufacturing in Product Design for Space Applications

ESA, (2013, October 16), 3D printing for space: the additive revolution, Retrieved [2018-01-25] from: http://www.esa.int/Our_Activities/Human_Spaceflight/Research/3D_printing_for_space_the_additive_revolution


InssTek, (n.d.), MX-100: The system is to manufacture mid-large sized products, Retrieved [2018-02-09] from: http://www.insstek.com/content/standard/mx100


References


Appendix A

Appendix A present a map with the visited sites for the Swedish AM tour in the pre-study. Most field meetings were conducted in Swedish, with a few exceptions at e.g. universities such as Chalmers and Lund.

<table>
<thead>
<tr>
<th>Visited universities</th>
<th>Visited industries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luleå university of technology</td>
<td>Sandvik</td>
</tr>
<tr>
<td>Mid Sweden university</td>
<td>Tillverknings tekniskt centrum (TTC)</td>
</tr>
<tr>
<td>Orebro university</td>
<td>Siemens</td>
</tr>
<tr>
<td>University West</td>
<td>GKN</td>
</tr>
<tr>
<td>Chalmers university of technology</td>
<td>Arcam</td>
</tr>
<tr>
<td>Lund university</td>
<td>Höganas</td>
</tr>
<tr>
<td></td>
<td>Digital metal</td>
</tr>
</tbody>
</table>
Appendix B

Appendix B present the interview guide used in main study I, and was initially designed in Swedish since the interviews were conducted with Swedish respondents. The interview guide has been translated to English 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) Do 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 to for use in space products?
14. A) Do you perceive that there is a 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 that additive manufacturing can influence 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 C

Appendix C presents the agenda used for the workshop series described in main study I. All workshops were conducted in Swedish.
Appendix D

Appendix D presents the agenda used for the workshop described in main study II. The workshop was conducted in Swedish.
Opportunities and Challenges for Additive Manufacturing in Space Applications

Proceedings of NordDesign 2016

Christo Dordlofva, Angelica Lindwall & Peter Törlind
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.

![Image of AM methods for space applications]

**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 ID 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.](image)

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 Sciaxy 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 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.

Acknowledgement

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Citations and References


Additive Manufacturing and the Product Development Process: Insights from the Space Industry

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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 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 (subsystmes) (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

<table>
<thead>
<tr>
<th>General description of the companies included in the study</th>
<th>Company</th>
<th>Study of Internal documents</th>
<th>Interview respondents</th>
<th>Workshop participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td>A</td>
<td>Yes</td>
<td>Eight engineers within different roles in the product development organisation, including chief engineer, design leader, design engineer and manufacturing engineer.</td>
<td>Roles from different levels of the company, including department manager, quality manager, design leader, manufacturing engineer and design engineer.</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>No</td>
<td>N/A</td>
<td>Roles from different levels of the company, including department manager, chief engineer and design engineer.</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>No</td>
<td>N/A</td>
<td>Roles from different levels of the company, including company management, subsidiary CEO and design engineer.</td>
</tr>
</tbody>
</table>
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

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

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 customer 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 of 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.

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.

REFERENCES


Evaluating Design Heuristics for Additive Manufacturing as an Explorative Workshop Method

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Angelica Lindwall & Peter Törlind
EVALUATING DESIGN HEURISTICS FOR ADDITIVE MANUFACTURING AS AN EXPLORATIVE WORKSHOP METHOD

Lindwall A., Törlind P.

Abstract
It is suggested that the space industry is an ideal case for Additive Manufacturing (AM), with a low production volume and need for complex geometries. However, few engineers have experience of AM design. One way to support design engineers with limited experience of AM is the use of design heuristics, to enhance variety, quality and creativity of potential designs. This paper is based on literature studies and observations of creative workshops with companies from the space industry. Results showed that heuristics assisted designers and 8/10 heuristics was utilised during the ideation phase.

Keywords: additive manufacturing, case study, product development, design for space, design heuristics

1. Introduction
The interest in additive manufacturing (AM), a collection of layer-upon-layer manufacturing processes, has lately increased due to the improved quality of metal AM processes (Wohlers & Caffrey, 2015). It is suggested that AM can bring various benefits to design (Gibson, 2017; Thompson et al., 2016), but it is also argued that there is generally insufficient understanding on how to design for AM (Gibson, 2017; Thompson et al., 2016; Yang & Zhao, 2015; Klahn et al., 2015; Campbell et al., 2012). When new products are designed through new technologies that design engineers have limited experience with, design teams need support in design to show the limitations of the new technology as well as the opportunities it offers. It is therefore argued that various heuristics need to be developed for additive manufacturing to help design engineers to explore the solution space (Gao et al., 2015). Such design heuristics are aimed to help design engineers to navigate in a possible concept space and to help them find non-obvious ideas (Daly et al., 2012). By combining different solution areas, the total solution space can become significantly increased. There is therefore a need to explore what possible design heuristics for AM there are that can be presented to design engineers. These heuristics aim to increase the possibility to create innovative solutions and assist designers in adopting an understanding of AM in design. The interest in designing products with complex geometries for metal AM has increased within aerospace industries (Gibson, 2017). Products for space applications such as satellites and rockets have a great potential to adopt AM technologies, since parts with complex geometries that are produced...
in low volumes are ideal for AM (Wohlers & Caffrey, 2015). Therefore, the study presented in this paper is performed in a space industry context, with design engineers that have high experience in product development and limited experience in AM. The study initially evaluates design heuristics for AM that can be of assistance for design engineers, through traditional DFM/A guidelines and current literature in AM design to limit the number of design heuristics. The study aims to (1) identify design heuristics on a higher level, which can then be presented to design engineers in the space industry with limited knowledge of AM, and (2) explore the usage of such heuristics in a creative workshop, with space-related products, that includes design engineers with limited previous experience in design for AM.

1.1. Research setting

The research is carried out as a demonstrator project between two Swedish universities (Luleå University of Technology and Chalmers) and three space-related companies (case companies). One of the goals is to challenge and identify alternative design solutions that utilise the potential AM has for space components. The demonstrator project uses a facilitated workshop approach that utilises the ‘Tiger Team’ approach. True to its name, the Tiger Team (Ashley 1992) approach is a powerful way of composing a special, multidisciplinary task force to rapidly solve a problem. The tiger teams aim to reach true collaboration, where diversity and competences of the whole team can be utilised. This leads to the possibility of team members to collaborate by using fragments of ideas from others as well as gestures and drawings to create new ideas rather than merely exchanging information or opinions and dividing work (Törlind, 2005). By bringing together external experts and innovators, existing working methods and obstacles, e.g., "we've always done it like this", will be questioned. In the workshop series (Figure 1) with academia and participating companies, the maturity of the concept is being developed in five steps planned to last for 18 months, from autumn 2017 until the end of 2018. The first two workshops focus on developing a conceptual design of each case product, while the final three workshops focus on verifying and qualifying the product through extensive testing of the printed designs. Design results from the first workshops highly affect work made in the final workshops, where the combined workshops and internal work in-between the workshops can determine workshop designs.

![Figure 1. Illustration of the workshop series](image-url)
The Tiger team consists of company experts that have an extensive experience in design for space; the researchers have a more general engineering knowledge as well as an expert knowledge in design processes. In the workshops, companies are expected to work intensively with each other's problems with the support of academic experts. After each workshop, challenges and unknowns are identified that companies and the participating experts need to explore on their own (with the support of the ordinary design teams) before the next workshop.

2. Additive manufacturing in the space industry

While the usage of AM has increased in several industries throughout the world (Wohlers & Caffrey, 2015), it has also been shown that aerospace industries (space included) have an increased interest in AM with an aim to create a higher product value (Steenhuis & Pretorius, 2017; Gibson, 2017). Products for space applications, such as satellites and rockets, are ideal for AM, since parts are produced in low volumes and are often difficult to manufacture with traditional processes (Wohlers & Caffrey, 2015). The products often have high safety requirements, where many of the system architectures have been established in the past and have barely been changed since (Fortescue et al., 2011). While introducing AM as a possible manufacturing method within the space industry, new values can be created through, for example, new geometries or lower weights. This seems to bring a hope to increase the design space and providing innovative possibilities for space products (Lindwall et al., 2017). Various examples of AM printed artefacts for space applications can be shown, such as a rocket engine for nanosatellites that have been printed as a whole through the powder bed fusion process (LLNL, 2017). The first prototype was printed in eight days with a total cost of $10,000, which makes it more cost effective than the traditional manufacturing processes. A study on the development process for antenna feed arrays has been made with the usage of certain AM design rules (Gill et al., 2017). The study also showed a comparison of the AM approach to the traditional manufacturing approach, which resulted in fewer parts, a lighter weight and a decreased manufacturing time by at least 20 hours. Such examples show that the specific interest of AM in the space industry introduces the possibility of adopting many of the benefits provided by AM. There are more examples illustrating the same effect on AM in design projects within the space industry. Lockheed Martin has printed a spherical titanium tank used for one of their satellite buses, with a decreased time span from 18 months to less than 6 months (Spacenews, 2017). At the same time, Aerojet Rocketdyne has successfully tested a full-scale thrust chamber with a part count reduced by more than 90 percent (Spacenews, 2017). It is hard to argue against the possibilities and benefits that AM can provide product design projects in the space industry. The special setting with high safety requirements and various stakeholders in design makes it important to explore AM in such a complex and special context.

3. Creativity and design heuristics

Often engineering design is focused on enhancing the performance of a product by giving them the ability to handle higher stresses (higher stress, less material), making them lighter (same stress, less material) or allowing for other design perspectives. These perspectives often include Design for X methods, such as design for manufacturing, where a reduction of complexity can reduce cost and at the same time bring improved performance (Ulrich & Eppinger, 2012). AM is considered to offer various benefits to design, such as a more extensive design space (Gibson et al., 2017; Thompson et al., 2016), which can increase the possibilities of being creative. However, it is argued that one of the ultimate limitations of AM in design is the imagination of the designer (Campbell et al., 2012). It has been shown that specified design heuristics support designers to explore the possible design space, where cognitive heuristics from the memories of designers are applied to the solution space (Yilmaz & Seifert, 2011). It is proposed that design heuristics can guide design engineers through the possible design space through several characteristics that can create new designs. Significant changes in the domain are often considered to be the most difficult to work with, due to its ambiguity, and it is argued that clearly defined goals and boundaries are of great importance to enhancing creativity (Csikszentmihalyi, 1996). Such boundaries are today considered to have been changed through AM, due to the new and wider possible solution space. Therefore, designers with expert knowledge in product design, but limited knowledge of AM in design, need support through design heuristics specifically for AM (Gao et al., 2015). A person
with high expertise in an area can more easily explore and solve problems through creativity (Amabile, 1998), and designers with expert knowledge in design are argued to utilise heuristics more fully than novices (Yilmaz & Seifert, 2011). Hence, design strategies for AM, such as design heuristics, have recently gained an increased interest and are considered helpful for design engineers to fully utilise the new design space (Gao et al., 2015; Blösch-Paidosh & Shea, 2017). In this paper, design heuristics are defined as a cognitive help to point designers towards the exploration of design variations (Daly et al., 2012). Heuristics are aimed to create endless variations of ideas, through new combinations as well as developments in new and unknown directions. Design heuristics are argued to enhance variety, quality and creativity for the potential designs of the solution space (Yilmaz & Seifert, 2011) and could increase the number of possibilities for innovative solutions (Daly et al., 2012).

4. Identifying design heuristics for additive manufacturing

To identify design heuristics that can be of interest in the space industry, the work was initiated with literature investigations on design strategies for AM. The study included the work conducted by Blösch-Paidosh & Shea (2017) when it was published, that had derived 29 design heuristics for AM from a pool of over 200 AM artefacts. It was judged that the number of design heuristics presented to design engineers needed to be limited, to make sure that it was possible to go through all heuristics during a one-day workshop. The heuristics were therefore first categorised into areas that are expected to fulfil the same or similar action. Three main design areas were identified with the assistance of a list of traditional DFM/A guidelines that was collected through the literature (Figure 2).

Each design area and its design heuristics was therefore developed through finding literature that discussed similar aspects in design of interest or importance when designing for AM. These were put into a table to provide an overview of what areas could be compiled and had similar aspects (Table 1). For example, DFM/A guidelines that included reducing part count, simplifying design and designing multifunctional parts was related to design heuristics presented in the literature and categorised under the design area of part consolidation. Blösch-Paidosh & Shea (2017) had heuristics such as ‘consolidate parts for better functional performance’ and ‘embed functional component’ that was also categorised under consolidation. The three design areas for AM were also studied through literature (e.g. Thompson et al., 2016; Gao et al., 2015; Gibson et al., 2015) to gain an understanding of what perspectives could be taken into account in such areas and to identify the design heuristics.

Part consolidation is aimed at enabling the production of a part that with traditional manufacturing methods would require an assembly of several parts (Thompson et al., 2016). Some of these parts can be combined with each other with AM through integrated designs (Gao et al., 2015). Consolidating parts and limiting assemblies can assist design by keeping the product compact and avoiding leakage. Another way to consolidate is to manage internal designs through the inner part (Gibson et al., 2015). In many cases, it also brings greater value to the end product with specific inner features such as cooling channels. For example, a method has been developed to assist the design of optimal internal channels and ultimately to address pressure losses and heat transfers (Pietrolaoli et al., 2017).
Table 1. Overview of design heuristics and their characteristics

<table>
<thead>
<tr>
<th>Design heuristic</th>
<th>DFMA guideline</th>
<th>AM literature discussions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated design</td>
<td>reduce part count; simplify design; design multi-functional parts; reduce assembly time</td>
<td>elimination of assembly features including new possible design features; produce less parts; increase functional performance with integrated designs; remove material and design lightweight parts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>involve complex internal structures; customisation of internal geometry; increase functional performance with internal designs; design multiple functions</td>
</tr>
<tr>
<td>Internal design</td>
<td>reduce part count; simplify design; design multi-functional parts; minimise systemic complexity; reduce assembly time</td>
<td>embed functional components; design multiple functions; reduce number of parts to assemble; include external functions embedded in parts; reduce the need for fasteners</td>
</tr>
<tr>
<td></td>
<td></td>
<td>involve complex internal structures; customisation of internal geometry; increase functional performance with internal designs; design multiple functions</td>
</tr>
<tr>
<td>Embedded design</td>
<td>reduce part count; simplify design; design multi-functional parts; reduce assembly time</td>
<td>embed functional components; design multiple functions; reduce number of parts to assemble; include external functions embedded in parts; reduce the need for fasteners</td>
</tr>
<tr>
<td>Interlocking features</td>
<td>reduce assembly time; minimise assembly directions; design a mistake-proof assembly; reduce manual handling time</td>
<td>simplify assembly and disassembly; limited build chamber can require division of parts; strengthen part through its own geometry</td>
</tr>
<tr>
<td>Embedded joints</td>
<td>reduce assembly time; minimise assembly directions; design a mistake-proof assembly; reduce manual handling time</td>
<td>use enclosed and functional parts; have moving parts in one artefact; reduce assembly with print-ready assembly</td>
</tr>
<tr>
<td>Form synthesis</td>
<td>minimise systemic complexity; reduce part count; minimise systemic complexity; reduce manufacturing time; simplify the design; design multi-functional parts</td>
<td>optimise design shapes for a certain purpose; design new organic shapes; customise shapes; design multi-functional parts</td>
</tr>
<tr>
<td>Topology optimisation</td>
<td>minimise systemic complexity; reduce part count; minimise systemic complexity; reduce manufacturing time; simplify the design; design multi-functional parts</td>
<td>optimise geometry through mathematical software calculations; design completely based on given loads and boundaries; design multi-functional parts; reduce weight through optimised geometries</td>
</tr>
<tr>
<td>Anisotropic structures</td>
<td>design multi-functional parts; minimise systemic complexity, Process controllability</td>
<td>optimise material properties; design materials varying along a part; produce functional materials; embed functional material; process materials at certain points or layers</td>
</tr>
<tr>
<td>Multiscale structures</td>
<td>minimise secondary &amp; finishing operations; design multi-functional parts; minimise systemic complexity, Process controllability</td>
<td>create a multi-functional part; replace internal structures with lattice structures; ensure strength and flexibility through structures; reduce weight with less material; distribute material to get desired properties</td>
</tr>
<tr>
<td>Multi-materials</td>
<td>design multi-functional parts; minimise systemic complexity, Process controllability</td>
<td>use multi-materials to increase material properties and vary materials along a part; embed functional material; combine materials in a part</td>
</tr>
</tbody>
</table>

Embedding external components such as electronics in a mechanical part can bring many values to end products. Embedded designs can also reduce the need for fasteners by embedding bolts or nuts into the part (Gibson et al., 2015). Another design area identified for AM was named connection elements, where heuristics such as ‘use enclosed, functional parts’ and ‘absorb energy with small interconnected parts’
(Blösch-Paidosh & Shea, 2017) were categorised together. Since the volume of AM builds is limited, large parts might still need to be divided into several parts (Gibson et al., 2015). One way to address this is to design connecting components that can be assembled and disassembled on a regular basis (Song et al., 2015) through interlocking features. However, it could also be important to acknowledge that there might be a value in interlocking features even if the part fits in the build chamber. There can also be a value in including moving parts in a component, such as joints. AM can build these, fully assembled, in one build (Gibson et al., 2015).

The third design area identified for AM includes a variety of perspectives and has been called structure design. This one includes heuristics such as ‘hollow out artefact to reduce weight’ and ‘embed functional material’ (Blösch-Paidosh & Shea, 2017) in its categorisation. One structural perspective that can assist designers is the usage of form synthesis design tools. Such tools are designed to synthesise various design solutions in organic viewpoints and one example of such a program is ‘project dreamcatcher’ (Autodesk, 2017). This approach helps designers to explore alternative designs and compare them to each other. Another perspective that also has emerged for assistance in design is computational topology optimisations (Leary et al., 2014). The topological optimisation method uses the mathematical approach within a specified design space, given load and boundary conditions (Gardan, 2016). In some products, there is a need for specific properties on one part of the article and other properties in another part, which can be feasible with AM through anisotropic structures. The material complexity available with AM makes it possible to process the material at one point or layer at a time, enabling complex material compositions (Yang & Zhao, 2015). Multiscale complexities can also bring values to a component through ensuring strength, flexibility and lighter weight. The structural design can be composed in such a way that the part is shape-optimised (Gao et al., 2015), which creates the possibility of creating the desired properties and functions of a product (Gardan, 2016). A final perspective within the structure design is the possibility of including multi-material designs, where the article can have several materials within one article (Gibson et al., 2015). The various perspectives within the three design areas are distinguished as the design heuristics used in the empirical study included in this paper (Figure 3).

### Figure 3. Illustration of the design areas and their design heuristics

#### 5. A creative workshop with space-related cases

In September 2017, the design heuristics were evaluated for nine participants in a creative workshop managed by the authors. The participants were engineers working with product development for space applications who were employed at one of the three case companies (Table 2). All participants of the workshop had 12-30 years of experience in product development. Some of them had worked with classical engineering design such as CAD and mechanical engineering, but others worked in areas such as simulation and material engineering. Also, approximately 45% of the participants reported having, to various degrees, experience in AM before the workshop. Each case company had been assigned to bring an example of a product intended to be redesigned for AM, which in this paper will be referred to as case products.
Table 2. Presentation of case companies and participants of the workshop

<table>
<thead>
<tr>
<th>Company</th>
<th>Company description</th>
<th>Participants</th>
<th>Roles of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The company is developing complex and high-performance components for the aerospace sector.</td>
<td>4</td>
<td>Design leaders and design engineers</td>
</tr>
<tr>
<td>B</td>
<td>The company operates in Low Earth Orbit constellation programs. Responsibility includes the whole chain, from R&amp;D to sales for several product areas.</td>
<td>2</td>
<td>Design engineer and simulation expert</td>
</tr>
<tr>
<td>C</td>
<td>A company that focuses on product development for space systems and satellites, and is involved in several highly critical projects.</td>
<td>3</td>
<td>System engineer, project manager and chief technology officer</td>
</tr>
</tbody>
</table>

This first workshop was performed during one and a half days at case company C and was initiated with a presentation of the company and a tour of their facilities. For a simplified presentation of the workshop schedule, see Figure 4.

![Figure 4. The workshop process for workshop 1](image)

The participants filled in a survey on their own perceived experience with the identified design heuristics, before any one of them was presented or discussed. Such information was obtained to see the pre-knowledge of the participants in relation to the discussions of the design heuristics. The authors presented the design heuristics together with inspirational examples of AM artefacts from the space sector (e.g., satellite parts, rocket propulsion systems). Discussions were held during the presentation regarding some of the heuristics, such as the possibility of printing embedded joints directly in one build. An example of embedded joints for space applications that was brought up was the possibility of having a structure that unfolds itself due to a response to temperature changes. Participants were interested in this example, since some functions are not needed until the product is already launched into space.

After the presentation, participants were encouraged to describe the context, expectations, known requirements and black box decomposition to the other participants. The second day consisted of the ideation phase, where each case product was the focus for 45 minutes, with the intention of each to include the design heuristics. Each case had a general discussion with the entire group and briefer ideation activities in smaller groups (approximately three persons in each group). The workshop was finished with a conclusion of the two days and an evaluation of the workshop. Discussions from each day were documented at the workshop by one of the authors, while two other colleagues made notes and took pictures. Participants made sketches and drawings of their ideas during the workshop, which were also included in the documentation. A final document was designed with the ongoing documentation, notes, pictures, sketches and drawings included. The discussions from the ideation phase have been analysed through a form of content analysis, where written data were sorted into categories to arrive at an understanding of the information conveyed by the participants (Krippendorff, 2004). These categories were pre-decided in a coding matrix (Flick, 2014), with the case products in one axis and the design heuristics in the other.
6. Empirical results

This section presents the empirical results provided by the conducted workshop. The implications are organised according to each case product, with a description of ideas given in the ideation phase. While the documentation of the discussions in the ideation phase was analysed, the ideas were categorised into a matrix (Table 3) for a general overview. Overall, the discussions in the workshop showed that the design engineers had their own perceptions on some of the design heuristics that were presented. Most of the general discussions, both during the presentation of design heuristics and the presentations of each case product, was focused on topological optimisation and anisotropic structures. Even though the participants did not necessarily use the term 'anisotropic structures', they knew the concept of developing the material properties needed for a specific point in a part.

<table>
<thead>
<tr>
<th>Table 3. Matrix analysis</th>
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</thead>
<tbody>
<tr>
<td><strong>Integrated design</strong></td>
</tr>
<tr>
<td>✅ Integrating new geometries for functional purpose</td>
</tr>
<tr>
<td>✅ Combining all parts into one article</td>
</tr>
<tr>
<td><strong>Internal design</strong></td>
</tr>
<tr>
<td><strong>Embedded design</strong></td>
</tr>
<tr>
<td><strong>Embedded joints</strong></td>
</tr>
<tr>
<td><strong>Topology optimisation</strong></td>
</tr>
<tr>
<td><strong>Anisotropic structures</strong></td>
</tr>
<tr>
<td><strong>Multiscale structures</strong></td>
</tr>
<tr>
<td><strong>Multi-materials</strong></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Ideation for **Case Product A** illustrated various opportunities for redesigning the product for AM, where the discussions initially covered questions on where the boundaries were. Design engineers from case company A initiated a preparation for AM, but the original design required a greater support structure.
than they had anticipated. Therefore, the participants from the case company specifically asked the workshop participants to contribute insights on new geometries and to avoid traditional manufacturing thinking. The workshop activities resulted in ideas covering designs where all parts would be integrated into one article, including internal structures, rethinking internal and external shapes, and using graded or porous material, ceramic surfaces and including lattice structures. There were similar discussions regarding Case Product B, where the participants immediately saw the potential to integrate parts and support in the design. The desire was that AM would create the possibility to design as needed, instead of being limited by traditional manufacturing constraints. The ideation phase resulted in such ideas as having simple and cheap supports entirely for the launch, as the support is unnecessary while in space and can, therefore, be discarded. Some design features on the original design could also be eliminated, according to other discussions. Participants from case company C were hopeful that AM could result in the design of Case Product C having fewer interfaces and weight reductions. Other ideas that emerged through the discussions were to include interlocking features through locking rotations or keyhole slots.

However, a recurring obstacle was the pre-established boundaries of the product, which were given by customers.

By studying the generated matrix (Table 3), some connections can be drawn. All three case products have to some extent included integrated design, anisotropic structures and multi-materials in the ideation activities. However, the only design heuristic that was not included in any of the ideation activities was embedded joints, even though a discussion regarding its possibilities was brought up during the presentation of the heuristics. The survey that was filled in by the participants showed an average knowledge level (Table 4) and showed that topology optimisation and integrated design were the most well-known design heuristics before the workshop. However, even though topology optimisation was well-known, it was sparingly used in the case products during the creative activities of the workshop.

<table>
<thead>
<tr>
<th>Average knowledge of heuristics in relation to use in the cases</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Integrated Design</th>
<th>Internal Design</th>
<th>Embedded Design</th>
<th>Interlocking features</th>
<th>Embedded joints</th>
<th>Form synthesis</th>
<th>Topology optimisation</th>
<th>Anisotropic structures</th>
<th>Multiscale structures</th>
<th>Multi-materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Knowledge (max 7, min 1)</td>
<td>4.7</td>
<td>4</td>
<td>3.1</td>
<td>3.3</td>
<td>2</td>
<td>2</td>
<td>4.2</td>
<td>2.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

| Used in number of cases | 3 | 2 | 0 | 2 | 0 | 1 | 1 | 3 | 2 | 3 |

7. Concluding discussion

This study has identified ten design heuristics for AM on a higher level that can assist design engineers with high experience in product development, but limited experience in design for AM. These heuristics have been explored in a creative workshop together with design engineers from the space industry, with three case products in focus. The findings from this study suggest that many of the heuristics for AM can be useful for products designed for space applications. Therefore, we suggest that design heuristics for AM open up possibilities for engineers with limited experience in AM to clearly explore the new design space. Some of the heuristics were, however, not used to the same extent as others, such as embedded design, embedded joints, form synthesis and topology optimisation. Some heuristics where participants perceived a lower knowledge level, such as embedded joints or form synthesis, were not used to the same extent as some of the other heuristics. However, embedded joints have been suggested as having been excluded in the creative activities since the case products used in the creative workshop were all mainly static with either no or few moving parts. We also suggest that the exclusion of embedding external components could be for a similar reason: that is, that the case products were mainly static and did not have such functions. However, embedding components could still be of interest if the case companies would like to attach sensors for evaluating their product in use. The other two heuristics, topology optimisation and form synthesis, which were sparingly discussed in the creative activities, could have been excluded due to the possibility of using them in a later stage, since today they are...
included in many of the available CAD programs. They are therefore more suitable to use in detail design phases, when virtual models are more thoroughly designed.

The heuristics that were discussed primarily were either in the design areas of part consolidation or structure design. Table 4 suggests that design heuristics in the area of structure design that were perceived to be less known before the workshops, such as anisotropic structures, multiscale structures and multi-materials, were a major topic of the creative discussions. The focus on structure design is suggested to be of importance due to the identified risk of insufficient qualification or verification approaches for AM in an industry with such high requirements and risks (Lindwall et al., 2017; Dordlofva, 2018). Products launched into space can have high variations of temperatures, with the heat from the rocket engine being one issue and the coldness of space another. This put high demands on what materials need to withstand and, together with other aspects such as radiation hazards and vacuum, the design of product properties can be crucial. We suggest that the design heuristics for AM presented in this paper can assist designers in adopting an understanding of how to explore the design space through creative activities in design for AM. Since a majority of the heuristics (all but two) was discussed at some point during the creative activities of the workshop, it is suggested that engineers start to reflect on and use the presented heuristics in early encounters with the new solution space. Therefore, this study indicates that engineers find support in using design heuristics for AM when exploring new possible design spaces with this new manufacturing technology.

The study of design heuristics was based on the literature and was adapted to the space industry. Each heuristic was researched through the literature and presented during the workshop to enhance the possibilities that participants would arrive at a general idea and be similarly exposed to each heuristic. Presenting the design heuristics in relation to the current literature was done to increase the shared knowledge level of participants in the workshop and to raise the level of the creative discussions and related activities. However, there was no testing on whether the participants had the same or a similar understanding and knowledge of the heuristics. The space industry is today exploring the possibilities of including AM benefits in their designs, and there are many examples of space-related companies with printed and tested designs. However, since there are no known reports of AM printed parts that have been deemed ‘critical’, e.g. with loads that make the part necessary for the primary purpose of the product, many are still hesitant towards adopting AM for all components in the space industry (Dordlofva, 2018). Such discussion relates back to the insecurity of not having sufficient approaches to qualify or verify products and their durability.

Overall, this study suggests that design heuristics for AM can be useful in the creative phases of product development toward expanding design. Not all heuristics are useful for every single product, but the heuristics can give a hint on what designs can be used and how they can be combined.

8. Future work

The authors of this paper will continue following the development of the case products for four more workshops with various focuses, such as conceptualisation, where the case companies will have continued working on their designs between the meetings. Further discussions and conclusions can therefore be presented later on in the project, with respect to the full utilisation of the design heuristics in the concept development phase of product design for space applications.

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References

Dordlofva C., (To be published), Towards qualification for additive manufacturing in space industry, Licentiate thesis, Luleå university of technology


