

MASTER

**Additive manufacturing : will it be a potential game changer for the aerospace manufacturing industry?
a qualitative study of technology adoption**

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Additive Manufacturing: Will it be a potential game changer for the aerospace manufacturing industry?

A qualitative study of technology adoption

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Abstract

Additive manufacturing has the ability to transform traditional manufacturing. AM facilitates manufacturing complex and internal structures, providing more product performance and reducing component weight, as well as allow for high volume customization due to the removal of tooling. Due to the continual desire to reduce the weight of an aircraft, in order to improve fuel efficiency, there is a drive demand for 3D-printed products in the upcoming future for this industry. 3D printing's impact on economies of scale and scope make it a natural fit for aerospace, which, in contrast to other mass production industries, is largely geared toward customized production. It is an expensive game buying new equipment to fulfill each small contract. The technology seems to have found its place for the prototyping business, however the transition to part production is still stalled.

The main contribution of this paper is to propose the additive manufacturing aerospace adoption model (AAMAM) for modelling the acceptance process, which is driven by factors that influence additive manufacturing adoption by the aerospace industry for production.

This research is performed at Vaupell, a market leader in aerospace interiors industry. Twelve experts within the industry provided input, and added insight into the industry for the adoption process within the aerospace industry. In general, the findings revealed four additional variables for Davis and Venkatesh' (1996) TAM that can (in)directly influence the aerospace organizations' intentions to adopt additive manufacturing for production. This research does not aim to validate the modified version of TAM as the majority of existing TAM studies does, but will apply TAM in a qualitative way. Additional findings of this study indicate barriers to adoption, as well benefits of the technology. To be successful however, the right target market has to be selected which fit within the benefits and limitations of the technology. A potential market strategy is formulated for Vaupell, regarding the use of additive manufacturing within aerospace.

This research aims to create an understanding of the found adoption variables and their relation in the specific context of the phenomenon. Consequently, the outcome of this study aims to provide a starting point for future quantitative studies that could test and validate the findings as well as the modified TAM.

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Additive Manufacturing: Will it be a potential game changer for the aerospace manufacturing industry?

A qualitative study of technology adoption



Keywords: Technology Adoption Model; TAM; Aerospace Sector; Additive Manufacturing; Advanced Manufacturing Technology

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List of Abbreviations

Generally Used Terms	Abbr.
Additive Manufacturing	AM
Advanced Manufacturing Technology	AMT
Behavioral Intention	BI
Original Equipment Manufacturer	OEM
Maintenance, Repair and Overhaul	MRO
Perceived Behavioral Control	PBC
Perceived Ease of Use	PEU
Perceived Usefulness	PU

Theories and Models	Abbr.	Author
Diffusion of Innovation	IDT	(Rogers, 1995)
Technology-Organization-Environment	TOE	(Tornatzky & Fleischer, 1990)
Technology Adoption Model	TAM	(Davis, Bagozzi, & Warshaw, 1989)
Theory of Reasoned Action	TRA	(Ajzen & Fishbein, 1975; 1980)
Theory of Planned behavior	TPB	(Ajzen, 1991)
Aerospace Advanced Manufacturing Technology Adoption Model	AAMTAM	
Aerospace Additive Manufacturing Adoption Model	AAMAM	

3D Print Technologies	Abbr.	Technology Name	Material Used
Material Extrusion	FDM	Fused filament fabrication	Thermoplastic
VAT polymerization	SLA	Stereolithography	Thermoset
Powder bed fusion	SLS	Selective laser sintering	Thermoplastic
	DMLS	Direct metal laser sintering	Metal powder
	SLM	Selective laser melting	Metal powder
	EBM	Electron beam melting	Metal powder
	WAAM	Wire-arc additive manufacturing	Metal wire
Direct energy deposition	DED	Direct energy deposition	Metal wire
	MD	Metal Deposition	Metal wire

1. Introduction

General Electric is making a radical departure from the way it has traditionally manufactured things. Its aviation division, the world's largest supplier of jet engines, is preparing to produce a fuel nozzle for a new aircraft engine by 3d printing some of the parts with lasers rather than casting and welding the metal. The technique, known as additive manufacturing has been crowned as the start of a third industrial revolution (The Economist, 2012) and the market is predicted to have a possibly huge growth potential (see Appendix B, section B.1). It could transform how companies design and make many of the complex parts that go into everything from gas turbines to ultrasound machines. Additive manufacturing (AM) and 3D printing will be used as synonyms throughout this report. With the technology available today, it is already possible to 3D print plastics, metals, composites and ceramics¹, and there are six different types of technologies (see Appendix A).

1.1. Industry Context

Vaupell, (an aerospace interior manufacturing company based in Seattle Washington) wants to sustain a competitive position in the market, and a possibility could be by adopting additive manufacturing within the next 5 years. Vaupell also has a rapid prototyping facility located in Hudson, Massachusetts which has multiple additive manufacturing technologies available (SLA, SLA, DMLS and Urethane Casting) which are currently solely being used for prototypes. However, "Production is where the money is": Terry Wohlers² (2014b). Vaupell has close connections to other manufacturing companies within the aerospace industry. For a company like Vaupell, it is important to figure out whether adopting 3D printing technology will have benefits for the organization and increase its productivity, or risk lagging behind the competition that might find the right applications. "It's whoever can come up with the right innovation for the right market, being very strategic and picking a niche": Dr. C. MacCormack (2015) of Mcor technologies.

Additive manufacturing promises to wipe out the need for specialist machines for one-off jobs. Due to the continual desire to reduce the weight of an aircraft in order to improve fuel efficiency, there is a drive demand for 3D-printed products in the upcoming future for this industry. 3D printing's impact on economies of scale and scope make it a natural fit for aerospace, which, in contrast to other mass production industries, is largely geared toward customized production. It is an expensive game buying new equipment however (PwC, 2013; European Space Agency, 2014; Bagley, 2014; Campbell, Williams, Ivanova, & Garret, 2011; Elwell, 2014; Cohen, D.; George, K.; Shaw, C., 2015). Many of the technologies are limited to rapid prototyping (Mellor, Hao, & Zhang, 2014) as they do not allow common engineering materials to be processed with sufficient mechanical properties (Kruth, Levy, & Klocke, 2007). Multiple surveys have been done to ask manufacturing companies if they were planning to use the technology (see section B.1), and results are mixed. According to Gartner's (2014b) study, 19% of the machines are being used for functional part production. This is also in accordance with the PwC (2014) study done, which results in that 19% of additive manufacturing users would use it for production. The Wohlers (2014a) report shows that 29% of the industry is for functional parts (including tooling). In

¹ See (Additively, 2015) for a description of the technologies

² Terry Wohlers, president of Wohlers Associates, a 3-D printing insights firm (Heller, 2014) and writer of the Wohler's Report (known as the additive manufacturing industry 'bible').

conclusion, about 80% of these are used for prototypes and non-functional parts. However, great impact on aerospace is expected (SmarTech, 2014a; PwC, 2013; Coykendall, Cotteleer, Holdowsky, & Mahto, 2014; Roland Berger, 2013; Cohen, Sargeant, & Somers, 3-D printing takes shape, 2014). According to Terry Wohlers (2015), “we have only seen the tip of the iceberg of what is possible”. The concept of rapid manufacturing (RM): “the production of end-use parts from additive manufacturing systems” (Hague, Mansour, & Saleh, 2007) is emerging today; though its economic impact remains modest (Levy, Schindel, & Kruth, 2003). According to Terry Wohlers, the 3-D printing industry is nearing Moore’s (1992) chasm in terms of manufacturing adoption rates.

1.2. Problem statement

When looking to use this new technology for production purposes, there are still a lot of uncertainties. The firms today are facing a reality where “flexibility,” “quality,” “time” and “innovativeness,” along with “cost,” are the competitive factors that define the competition pattern (Yousafzai, Foxall, & Pallister, 2007). Additive manufacturing has been found to increase a companies’ productivity³ (Achillas et al., 2014) which has been found to lead to a competitive advantage in the marketplace (Stevenson, 2012). The managers in adopter firms want to make appropriate purchasing decisions, however they are not given an easy task, having to keep in mind many views whether to implement or not. Vaupell is unsure whether to further invest in the additive manufacturing technology and adopt it for production. The technology price for professional production machines today is still quite steep ranging from \$500.000 to more than \$1.000.000, so the investment will have to be justified by enough payback (Huang, Liu, Mokasdar, & Hou, 2013). Business performance has been found to be closely related with a company’s manufacturing and business strategy (Sun & Hong, 2002). The technology is still improving, and the finish and durability of some printed items can still fall short of what producers require (Mellor, Hao, & Zhang, 2014; Roland Berger, 2013; The Economist, 2013; Achillas, Aidonis, Iakovou, Thymianidis, & Tzetzis, 2014). Additionally, due to the high quality standards set by the Federal Aviation Administration (FAA, 2015) and aerospace companies themselves (Boeing, 2015; Airbus, 2015) the potential of AM for production in the aerospace industry is not entirely clear.

Additive manufacturing is a new advanced manufacturing technology, and it is unclear to what extent it will be adopted as a production technology within the aerospace industry.

³ Stevenson (2012): A measure of the effective use of resources, usually expressed as the ratio of output to input

1.3. Research Problems

Aerospace organizations, like any others, are motivated to adopt technology in an attempt to achieve a competitive advantage. Yet in the attempt to attain a competitive advantage through technology, not all organizations are necessarily created equal. Whilst in the past competitiveness in the sector was principally based on differentiation and technical issues, in recent years, a series of competitive priorities have arisen that are turning into an enabling factor for competing in this (Martinez-Jurado & Moyano-Fuentes, 2014). The technology has been around since 1980, and aerospace has been an early adopter of the technology, but mainly for prototypes and models. It has not been able to cross the chasm up to this point for a production technology however (Heller, 2014). The industry environment is characterized by highly differentiated and hugely complex products, low production volumes and low repeatability (Martinez-Jurado & Moyano-Fuentes, 2014). Additionally, it is regulated by strict national and international standards (Benner & Tushman, 2003). Several theories have been proposed to explain user adoption and acceptance of new technologies. Some of these are based on socio-physiological contexts and focus on the adoption of innovation such as the Theory of Reasoned Action (Ajzen & Fishbein, 1975; 1980) or the Technology Adoption Model (Davis, 1989). Conversely, others have focused on features of innovation such as Diffusion of Innovation Theory (Rogers, 1995). The majority of existing research, (using a model to predict adoption behavior) is based on the use of internet technology and mainly in a “Business to Consumer” construct (Straub, 2009; Yousafzai, Foxall, & Pallister, 2007; Sahin, 2006; Bagozzi, 2007). In the “Business to Business” context, it is important to understand the diffusion of technology among professional in order to further understand the effects of external variables and use this to assist the organization’s implementation and application of a technology system (Lee, Li, & Huang, 2010). In the aerospace industry the decision to adopt a manufacturing technology is expected to undergo a complex decision making process. Additionally, the additive manufacturing is an advanced manufacturing technology and thus an entirely different technology than information systems. The knowledge level of engineers, managers and workers may also differ regarding specific technologies and industry (Mazzucato & Tancioni, 2008). Currently, no adoption models are available, which have been tailored to this specific context thus current models could additionally benefit from further expansion to other industries (Legris, Ingham, & Collette, 2003; Raida & Néji, 2013).

Which models are capable predicting the technology adoption of additive manufacturing for production within the aerospace industry?

Rich Merlino, a former Pratt and Whitney employee said: *“The aerospace industry is increasingly looking to utilize additive manufactured parts in R&D projects and eventually in production. Very few additive manufacturing companies have the deep level of understanding about what is involved in aerospace matched with additive manufacturing expertise.”* (Molitch-Hou, 2015). By researching the positive and negative factors that affect adoption, more insight regarding the aerospace industry could be gained, reducing some of the uncertainties regarding the use of this technology. The barriers of adoption, as well as the benefits of the 3D printing technology can be identified using a model of technology acceptance, as done by e.g. BenMessaoud et al. (2011) or Yarbrough and Smith (2007). This leads to the following research question:

What are the main barriers for adopting additive manufacturing as a production technology within aerospace?

Explorative research is done, guided by a modified technology adoption model in order to investigate the barriers to adoption, as well as other potential factors that affect the decision to adoption. This will be used to create a fitting marketing strategy for Vaupell. According to Baker (2003) a formalized planning procedures generally result in greater profitability and stability in the long term and also help to reduce friction and operational difficulties within organizations. Marketing strategy includes all basic, short-term, and long-term activities in the field of marketing that deal with the analysis of the strategic initial situation of a company and the formulation, evaluation and selection of market-oriented strategies (Homburg, Kuester, & Krohmer, 2008).

What is a fitting marketing strategy for Vaupell, concerning the use of additive manufacturing for production?

1.4. Research Contribution

Towards solving the research problem, this research will try to reduce some of the uncertainties of additive manufacturing in aerospace and find to what extend the technology will be adopted for production. This research aims to examine the decision process for adopting additive manufacturing technology within the aerospace industry, and to create an understanding of the found adoption variables and their relation in the specific context of the phenomenon. This research Measures for predicting and explaining a new technology use has great practical value, both for vendors who would like to assess user demand for new design ideas, and for supplier managers within user organizations who would like to evaluate these vendor offerings (Davis, 1989). A modified technology adoption model (TAM) is created for predicting the adoption of additive manufacturing technologies within aerospace. Following Sun and Zhang's (2006) suggestions to apply the TAM in a qualitative direction. This research does not aim to validate the modified version of TAM as the majority of existing TAM studies does, but the outcome of this study aims to provide a starting point for future quantitative studies to validate the created model.

1.5. Research Structure

The structure of this thesis is depicted in Figure 1.1 below. Subsequent to ‘introduction’ section that deals with motivation and research problems, chapter 1 details the theoretical background, including the development of a conceptual technology adoption model, entitled the “Aerospace Advanced Manufacturing Technology Adoption Model” or AAMTAM in short. Chapter 3 includes the research design/methodology, including the research approach, data collection and quality criteria. Chapter 4 presents the results and discussion with key findings. The first, second and third research question will be answered in the discussion section (chapter 5). Based off of the research results, the barriers of adoption for additive manufacturing are found, which are explained in section 5.2. During the qualitative analysis of the interviews, additional factors that could affect adoption are uncovered, which had not been taken into account in the model created in chapter 2. The proposed model, created based off of the research findings (the Aerospace Additive Manufacturing Adoption Model) follows, and is shown in paragraph 5.3. The created market strategy for Vaupell is presented throughout section 5.4. Finally, this thesis’ conclusion will be presented in chapter 6.

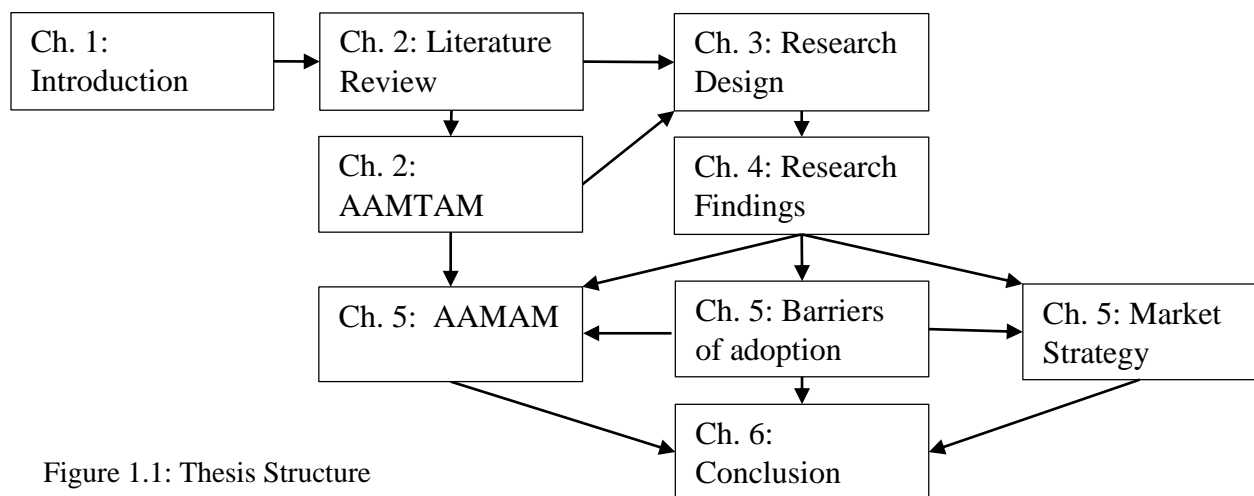


Figure 1.1: Thesis Structure

2. Literature Review

This literature review chapter concludes with a conceptual model to predict the adoption of additive manufacturing aerospace. Since there are six different AM technologies, first it will be investigated which can be used for production in section 2.1. Before a fitting theory of adoption is chosen, the specific context is analyzed in section 2.2. It is decided to compare additive manufacturing to advanced manufacturing technologies, and to explore the adoption of AMTs. Sections 2.3 until 2.5 are aimed at examining the different adoption theories, and modifying them to fit AMT adoption within aerospace. Section 0 shows the final conceptual model.

2.1. Plastic and Metal Additive manufacturing for Production

There is a wide range of technologies accommodated under the umbrella of AM, with varying benefits, disadvantages and potential. An analysis of the sector must differentiate between the kinds of technologies used and the value they can create. AM service providers were asked which machine they were using most, and which machine they were likely to buy next (shown in Figure 2.1). Almost 50% of them said powder based technologies. This includes plastic as well as metal powder bed fusion. In conclusion for plastics, three different 3d printing technologies appear to be the most widely used within the manufacturing industry: selective laser sintering, fused deposition modeling and stereolithography (Wohlers, 2014a; Huang, Liu, Mokasdar, & Hou, 2013).

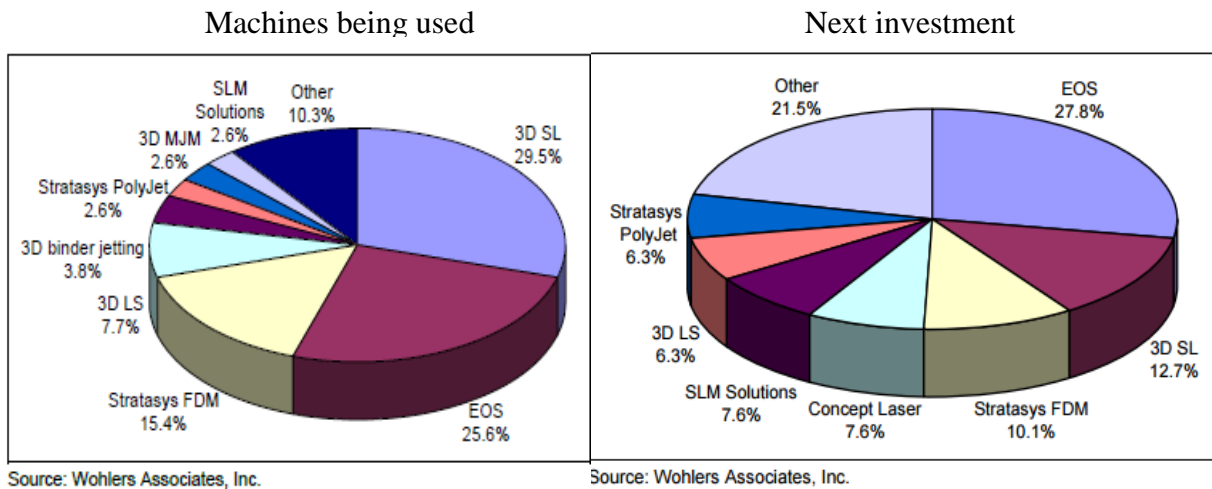


Figure 2.1: Machines Used for Manufacturing. *Source:* (Wohlers, 2014a)

Some parts are known which have been produced for the aerospace industry using additive manufacturing equipment including FDM and SLS (Wooten, 2006; Catalano, 2015; Lyons, 2012; Dickey, 2013; Wohlers & Caffrey, 2015). VAT polymerization technologies have primary been used for indirect production such as tooling (also see 0 for applications of the different technologies). The parts made in SLA are better suited for casting purposes (so-called rapid manufacturing) in the aerospace industry. The main application fields for SLA are the construction of functional and aesthetic prototypes, construction of models for VC and tooling or mold inserts for the injection of certain polymers (Angrish, 2014; Petrovic, Gonzalez, Ferrando, Gordillo, & Puchades, 2011). FDM and SLS will be the primary AM technologies for plastic part production.

In Appendix C, both FDM (section C.1) and SLS (section C.2) are explained further in-depth including the process, material characterization, part strengths and cost.

There are a large number of AM technologies that can produce metal components, but not all of them can achieve the same quality of the final part. EBM, SLM and some MD processes look to be the most applicable technologies for high technical requirement parts (Uriondo, Esperon-Miguez, & Perinpanyagam, 2015). Looking at the current technologies being used however, mainly the powder based technologies are being used for production. The powder based metal AM systems are fairly similar to the SLS process. Thomas Prete, Pratt's head of engineering, noted that 25 components for its latest quiet and fuel-efficient PurePower will be made using the DMLS, SLM and EBM technologies (McKenna, 2014). GE is known to be using Arcam's EBM technologies to create full nozzles (Kellner, 2014). Lastly Airbus and EOS are collaborating to create metal hinges and brackets (EOS, 2014). Thus for metals, there are currently three different technologies being adopted, namely DMLS, SLM and EBM for part production (see 0 for more information). It is difficult to predict which technology is being used for the manufacturing of metal parts. There is a lot of confusion about the difference between Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), LaserCusing and Electron Beam melting (EBM). In fact, some vendors of these technologies themselves do not always draw clear distinctions between their capabilities. Joris Peels⁴: *“Some people use the terms SLM, SLS and DMLS interchangeably, others maintain that there are sharp differences between them and others think that it is just a bunch of Germans who used to all be friends playing word games in English.”* These three powder bed technologies are further investigated in Appendix C. The differences between the processes are shown in section C.3, based on the material characterization.

2.2. Additive Manufacturing: An Advanced Manufacturing Technology

It is important to select the context of a technology because it matters when exploring technology adoption (Hsiao & Yang, 2001). This is in line with Fenn and Bruce (2003) whom suggest that technological heterogeneity is important when modelling firms' investment decisions. Additive manufacturing processes (as a manufacturing technology) requires designers and engineers to re-think design-for-manufacturing attitude to a more design-for-function mindset (Mellor, Hao, & Zhang, 2014). Hyman (2011) names it among the top-10 technologies that will transform the next decade. Due to the changes it bring to the manufacturing industry, 3D printing could be considered a disruptive technology (Grynol, 2013; Dawson, 2014). A disruptive innovation describes the phenomenon by which an innovation transforms an existing market or sector by introducing simplicity, convenience, accessibility, and affordability where complication and high cost are the status quo. Initially, a disruptive innovation is formed in a niche market that may appear unattractive or inconsequential to industry incumbents, but eventually the new product or idea completely redefines the industry (Christensen C. , 1997).

Furthermore, additive manufacturing could be considered an advanced manufacturing technology (AMT). Advanced manufacturing technologies serve a wide range of users and purposes, and include any computer-based equipment used to design, manufacture or control information related to the development and production of a product (Lewis & Boyer, 2002; Small, 2007). In a broad

⁴ Joris Peels is a 3D printing community manager, consultant & blogger

sense, AMT suggests both soft and hard technologies which are being employed to enhance manufacturing competencies (Chung & Swink, 2009). Boyer et al. (1997) suggest there to be three categories within the advanced manufacturing technologies: design, administrative and manufacturing. Additive manufacturing will belong to the latter category, since it is essentially a machine used to fabricate products. Additive manufacturing can also be considered to be a ‘radical manufacturing technology’: Manufacturing tools and technologies that have the potential to redefine an industry through the disruption of existing competitive advantages, reducing the leverage of established firms and creating opportunities for the entry of new competitors (Sinha & Noble, 2008). Explaining and predicting user adoption of new technology enjoy a long history of attention in both academia and practice. Some of these are based on socio-physiological contexts and focus on the adoption of innovation such as the Theory of Reasoned Action (Ajzen & Fishbein, 1975; 1980), the Theory of Planned Behavior (Ajzen, 1991), or the Technology Adoption Model (Davis, 1989). Conversely, others have focused on features of innovation such as Diffusion of Innovation Theory (Rogers, 1995) or the Technology-Organization-Environment (TOE) framework (Tornatzky & Fleischer, 1990). These different models are compared in the next section, to find an appropriate model for predicting AMT adoption in aerospace.

2.3. A Comparison of Different Adoption Theories

The TOE framework (Tornatzky & Fleischer, 1990), integrates three contexts which are technological contexts, organizational contexts and environmental contexts. The theory postulates that these contexts influence the process which innovations are adopted and implemented in organizations. To this point, the majority of the theoretical development that has taken place related to the TOE framework has been limited to enumerating the different factors that are relevant in various adoption contexts. No new constructs have been added to the framework. Little theoretical synthesis has occurred, and thus has evolved very little since its original development (Baker, 2012). There may be multiple reasons for the relative lack of evolution and change in the TOE framework since its initial development. First, the TOE framework has been described as a “generic” theory (Zhu & Kraemer, 2005). This assessment seems appropriate considering that the theory has come to be used as a framework within which a host of various factors can be placed. Additionally, according to Baker (2012) the TOE framework may have seen relatively little evolution because it has been viewed as aligned with other explanations of innovation adoption, rather than offering a competing explanation to them. Tension between the TOE framework and other theories has been seen as slight, and this tension has, at this point, to be resolved by allowing the TOE framework to subsume competing ideas, rather than respond to them (Baker, 2012).

Rogers’ (1995) Innovation Diffusion Theory (IDT) is a theory of how, why, and at what rate new ideas and technology spread through cultures, operating at the individual and firm level. The theory sees innovations as being communicated through certain channels over time and within a particular social system. IDT is probably the most influential theory in this research, however, it is not practical to use in all situations (Straub, 2009). IDT provides a framework, but the breadth and depth of the theory makes it difficult to frame a single study within the structure (Greenhalgh, Robert, MacFarlane, Bate, & Kyriakidou, 2004). In addition, as it is primarily descriptive rather than prescriptive, it does not tell how to facilitate adoption but rather why adoption occurs (Straub, 2009). Roger’s theory is consistent with the TOE framework which both emphasized individual

characteristics, and both the internal and external characteristics of the organization, as drivers for organizational innovativeness. Both theories however fail to consider the unique characteristics of SMEs or individual organizations and the importance of people aspects (Straub, 2009). A review of these theories indicates the presence of various factors affecting technology adoption. Some of the factors are more salient than others in terms of their recurrence in various models (Straub, 2009; Wang & Qualls, 2007). According to Hwang (2005) quoting Tornatzky & Klein (1982), only three of Rogers' innovation characteristics (relative advantage, complexity, and compatibility) are being consistently related to adoption behavior. Relative advantage is similar to the notion of usefulness, and complexity is similar to ease of use, thus, TAM captures the core dimension of IDT (Hwang, 2005).

TRA, TAM or TPB have shown some promise in previous research done using the model in manufacturing context (Scannell, Calantone, & Melnyk, 2012; 2011; Dimnik & Johnston, 1993; Tjahjono, 2009; Ivan, Connie, & Walter, 2010). In 3D printing context, the TAM has been adapted for the acceptance of 3D printers as a training tool for neurosurgeon students (Ryan, Chen, Nakaji, Frakes, & Gonzalez, 2015), and used to test participation in web-based co-creation platforms (Jung & Ju, 2014). Meta-analyses of TPB and TAM research concluded that the model has strong predictive validity and is robust even in research situations that do not fall within the boundary conditions originally defined by the model (Sheppard, Hartwick, & Warshaw, 1988; Armitage & Conner, 2001). Past studies have found inconsistent findings however as regards to the relationship of perceived behavior control and intention. In a direct test, Mathieson (1991) found that PBC did have a significant relationship with behavioral intention, though it did not provide substantial explanatory power. George (2002; 2004) did not find perceived behavior control to be a significant predictor of intention or behavior. Scannell et al. (2011; 2012) tested the effect of PBC in their model for shop for manufacturing technologies in two different cases. Both times PBC was not found to have a significant effect on behavioral intention to adopt. Hwang (2005), preferred using the TAM over the TRA and TPB in explaining specific systems adoption, such as ERP systems, with the parsimonious constructs. For the TRA and TPB models, the difficulties associated with establishing a set of salient beliefs may be one reason why Davis et al. (1989) and Mathieson (1991) found that TRA and TPB did not explain usage intentions as well as TAM.

Despite other available theoretical models that can be used for testing technology acceptance, TAM remains the model most used and tested in various settings (Straub, 2009). The TAM has been widely used as the theoretical basis for many empirical studies of user technology acceptance (Bagozzi, 2007; Yousafzai, Foxall, & Pallister, 2007), it is consistent with Everett Roger's theory since they are similar in some constructs and complement each other to examine the adoption of IS/IT (Lee, Hsieh, & Hsu, 2011; Taylor & Todd, 1995). From multiple disciplinary vantage points, perceived usefulness and perceived ease of use are chosen in multiple cases as a theoretical basis for its parsimonious yet powerful capability to explain technology usage (Legris, Ingham, & Collette, 2003; Bagozzi, 2007; Davis, 1989). Legris et al. (2003), Serenko et al. (2007) and Sun & Zhang (2006) suggest that TAM can be adapted to situation or technology-specific constructs, making it useful beyond end-user and software acceptance (Agarwal et al., 2000).

2.4. The Basic Construction of Organizational Use

Multiple studies have thus been done incorporating extra factors which will help explain behavior. TAM 2 for instance has an explanatory power of 60%, and TAM 3 reaches 70%. Even though they have a higher explanatory power, they have only been used in information technology context. They could thus differ substantially from the factors which need to be researched for adopting advanced manufacturing technologies. As researchers began empirically testing the TAM, the attitudinal construct was removed in efforts to achieve a more parsimonious model (Simon & Paper, 2007). Venkatesh and Davis (1996) argue that the role of attitude in explaining behavioral intention or actual adoption behavior is very limited and is at best a partial mediator in the relationship between salient beliefs and the adopter's behavioral intention. At the same time, removing the attitude variable eliminates any unexplained direct influence observed from the system characteristics to the attitude variable (Davis & Venkatesh, 1996). It is thus concluded to use the theoretical basis of TAM (Figure 2.2

Figure 2.2) for its parsimonious yet powerful predicting constructs. An additional change brought to the original TAM, was the consideration of other factors, referred to as external variables that might influence the beliefs. Examples for the use of this version of TAM can be identified, including qualitative and quantitative studies (David, Poissant, & Rochette, 2012; Tobbin, 2012; Hwang, 2005; Wang & Qualls, 2007).

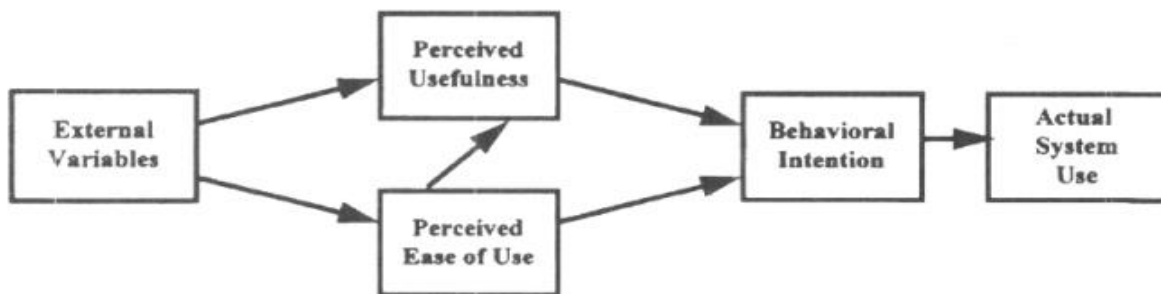


Figure 2.2: Davis & Venkatesh (1996) TAM model

A number of measures have been used for the Perceived Usefulness (PU), Perceived Ease of Use (PEOU) and Behavioral Intention (BI) constructs (Davis, 1989; Legris, Ingham, & Collette, 2003; Venkatesh, Morris, Davis, & Davis, 2003) which have been well validated in a number of studies (Mathieson, 1991; Taylor & Todd, 1995; Hsu & Lin, 2008). Research in psychology and TAM itself suggest that users' intention to use is the single best predictor of actual system usage (Davis & Venkatesh, 1996). The application of the TAM framework to organizations rather than individuals requires reconsideration of the model's key variables, though the organization-level acceptance process is similar to that for individuals' acceptance. At the organizational-level of analysis, the dependent variable reflecting acceptance is operationalized as the intention of the organization to use a specific technology (Autrya, Graweb, Daugherty, & Richeyd, 2010). The literature in organizational dynamics has noted key differences in group decision making processes versus those of individuals. Whereas individuals make decisions by resolving cognitive or affective conflict internally to create a unitary self-perception, group perceptions form via the synthesis and resolution of multiple feelings or beliefs across multiple individuals (Bartel &

Saavedra, 2000; Kelly & Barsade, 2001). Given the financial magnitude of the typical an advanced manufacturing technology decision, firms generally allocate significant personnel meeting time and resource support to such decisions. TAM has been successfully applied to predict adoption within organizations as well industry adoption (Benedetto, Calantone, & Zhang, 2003; Chatzoglou, Vraimaki, Diamantidis, & Sarigiannidis, 2010; Kim, 2009; Lin, 2003; Yarbrough & Smith, 2007; Calantone, Griffiths, & Yalcinakaya, 2006; Richey, Tokman, & Skinner, 2008). It can provide an organization the ability to further understand the effects of external variables regarding the causal relationship and interaction level between perceived usefulness, perceived ease of use and behavioral intention, to assist the organization's implementation and application of a technology system (Lee, Li, & Huang, 2010).

Perceived usefulness can be considered a summary measure of all benefits related to a technology (Davis, 1989). To the adopting organization, the perceived benefits entail both economic and qualitative benefits resulting from adopting the technology (Wang & Qualls, 2007). In terms of advanced manufacturing technology adoption, the greater the perceived benefits of the manufacturing technology, the more a decision-maker will develop a positive attitude towards adopting the technology. The measures of PU include performance increase, productivity increase, effectiveness, overall usefulness, time saving and increased job performance (Davis, 1989; Legris et al, 2003; Venkatesh et al., 2003; Wang & Qualls, 2007). However, it is equally important that the adopting firm also understands the trade-offs in using a new manufacturing technology (Mellor, Hao, & Zhang, 2014). There has been wide support for the hypotheses that PU positively relates to the behavioral intention to adopt in computer and technology adoption research.

Perceived ease of use is one of the most studied technology characteristics. It concerns a potential adopter's perception of the ease of use of the technology. The perceived ease of use is defined as the degree to which the potential adopter expects a technological innovation to be free of effort in use (Davis & Venkatesh, 1996; Moore & Benbasat, 1991). Measures for PEOU have included, ease of control, ease of use, clarity, and flexibility of use (Dahlber, Dahlberg, & Nyström, 2008). The general accepted finding is that the acceptance and perceived usefulness increase with an increase in the perceived ease of use (Davis & Venkatesh, 1996; Davis, 1989; Kaasinen, 2005). Perceived ease of use has sometimes been found to be more important than perceived usefulness (Heijden, 2004). However, the general consensus is that perceived usefulness is more important than ease of use (Davis, 1993; Davis, Bagozzi, & Warshaw, 1989).

2.5. Additional Variables of the Technology Adoption Model

Through integration with other acceptance models or by expanding the factors, the model can be adopted to specific systems, ameliorating the power of prediction and explanation (Legris, Ingham, & Collerette, 2003; Gounaris & Koritos, 2008; Wang & Qualls, 2007). Attempts to extend TAM have generally taken one of three approaches: by introducing factors from related models, by introducing additional or alternative belief factors, and by examining antecedents and moderators of Perceived Usefulness and Perceived Ease of Use (Wixom & Todd, 2005). A multitude of factors affecting manufacturing adoption (>10 internal and external factors) have been found (Small, 2007; Das & Nair, 2010; Baldwin & Lin, 2002; Bartoloni & Baussola, 2001; Sohal et al., 2006) but two factors were chosen. Lack of available evidence from a reliable adapted TAM or lack of

evidence explaining which factors definitely effect AMTs adoption within this specific context, caused other factors to be left out.

2.5.1. Perceived Technological Uncertainty

The combination of technologies used in space usually configure to a system that requires a high level of technical and scientific performance. Therefore the technologies that make up such a system meet particular chemical and physical standards, and at the same time have to be complementary to one another to ensure integration among the different parts of the system (Petroni, Venturini, & Santini, 2010). Results of several empirical studies indicate that implementing AMT has often not been either as successful or as straightforward as expected (see Small, 2007). Some failures have been blamed on the inability of firms to integrate their advanced and conventional technologies effectively (Beauty, 1990). It has also been suggested that infrastructural problems such as inadequate organizational planning and preparation for the adoption of AMT have contributed to this failure to achieve the potential benefits (Small & Yasin, 1997; Hayes & Jaikumar, 1991). In space activities the cost of a technical breakdown is generally very expensive for organizations involved, since space products are relatively expensive. Reliability and certainty about the capabilities is a highly rated attribute with the aerospace industry, as shown by Petroni et al. (2010) whom researched technology transfer within aerospace. It is so intertwined with coverage and ability to provide continual service (Pagani, 2006) and if airplanes parts fail to deliver what was expected, consequences can be severe. Emerging technologies, show types of behavior and performance that are not always well defined at the technical-scientific level and are therefore not fully understood. Garsombke and Garsombke (1989) note that managers who have feelings of complacency and satisfaction with the status quo create a barrier to modernization of technology. Schroeder et al. (1989) stated that some managers classified as "traditional" may exhibit a fear of technology, which may cause them to create a barrier to the adoption of AMT. For example, with additive manufacturing, there is an inherent rapid-prototyping legacy, which may result in a psychological barrier to adoption, as management only see the technology-class as being suitable for RP applications (Mellor et al., 2014). The AM technology is still constantly improving (Srinivasa, Gary, & Rangaswamy, 2002), and has not been accepted as a production technology for a large part of the global manufacturing industry (Mellor, Hao, & Zhang, 2014) including aerospace (Wohlers, 2014a). If a technology fails to deliver its expected outcome, it will result in a loss to the user (financial, psychological, physical, or social) (Im, Kim, & Han, 2008). Research shows that technical knowledge at all levels of an organization is crucial for AMT acceptance and implementation by reducing uncertainties about the technology (Marri, Gunasekeran, & Sohag, 2007; Jonsson, 2000; Tjahjono, 2009; Zhao & Co, 1997).

Perceived technological uncertainty is defined as the uncertainty about the technological capabilities, and future improvements. Due to lack of knowledge regarding the new technology, it has been found that users often reject systems that enhance their performance in favor of systems with less pronounced benefits (El Jaafari, Forzy, Navarro, Mars, & Hoc, 2008; Inagki, Itoh, & Nagai, 2007; Navarro, Mars, Forzy, El-Jaafari, & Hoc, 2010; Ghazizadeh, Lee, & Boyle, 2012). The factor is expected to have an impact on PU. Uncertainty about the technology will affects people's confidence in their decisions, as well as the perceived characteristics of the technology (Im, Kim, & Han, 2008). Reliability of a technology is a determinant for technology transfer in

aerospace (Petroni et al. 2010), thus uncertainty regarding the capabilities is expected to effect the decision to adopt. As the overall rate of invention across industries increases, so does technological uncertainty (Dyer, Furr, & Lefrandt, 2014). Uncertainty about the benefits of a new technology is a factors slowing down the speed of diffusion (Dorfman, 1987). The uncertainty of how much the technology will improve in the upcoming years is also likely to effect the decision to adopt, since it could results in uncertainty about future benefits. For this reasoning, it is proposed that the technological uncertainty will have a direct (negative) effect on the perceived usefulness.

2.5.2. Process Management Regulations

As shown in a study based manufacturing technologies, the structure of the company plays a crucial role in the implementation process of advanced manufacturing technology adoption (Song, Dai, & Song, 2007; Yu, Shen, & Lewark, 2011). Successfully implementing a new technology not only requires mastery of the technology itself, but also calls for modifications in existing organizational routines, by responding to changes in the environment (Ettlie, Bridges, & O'Keefe, 1984; Baldwin & Lin, 2002). According to Elsbach (2002), organizations can be viewed as micro-institutions that involve formal structures and procedures to achieve organizational goals, and are also infused with values and vested interests. Within aerospace, these formal structures and procedures exist in the form of process management practices, like the ISO 9000. Institutional forces constrain innovators in established companies to what is legitimate within existing institutional logics and structures, thereby inhibiting radical innovation (Dijk, Berends, Jelinek, Romme, & Weggeman, 2011). Innovating actors may also find themselves pitted against existing institutional structures, because radical innovations often lack legitimacy (see Dijk et al. 2011). Legitimacy is a generalized perception or assumption that actions are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs and definitions (Suchman, 1995). Dougherty and Heller (1994) found that product innovations in established firms frequently faced legitimacy crises regarding connections of new products to firm strategies and structures, collaboration across departments, and links between technological opportunities and market needs. Innovations that lack legitimacy may fail to acquire resources and be abandoned altogether (Dougherty & Heller, 1994; Zimmerman & Zeitz, 2002). This is of importance for AM, since it has not been accepted as a production technology for a large part of the aerospace manufacturing industry (Mellor et al. 2014; Wohlers, 2014a).

Process management practices, like the ISO 9000 in the aerospace industry, focus on reducing variation and increasing efficiency in organizational routines (ISO 9000, 2015). These practices have spread beyond their origins in manufacturing and operations into other activities, such as processes for selecting and developing technological innovations. As these variation-decreasing activities spread to centers of innovation, or variation-creation activity in organizations, they increasingly affect an organization's dynamic capabilities. The effects of process management on technological innovations arise in several ways (Benner & Tushman, 2003). First they stabilize the resource allocation and decision processes that determine which technological projects will be supported. Secondly, process management techniques also tighten internal communication linkages and affect the types of technological changes that are recognized and addressed. Lastly, process management activities also influence technological innovation directly through adherence to particular product development or design processes. For example, the ISO 9000 program has an

explicit focus on adherence to documented processes, entailing in a certifications in product design and development. (Benner & Tushman, 2003). With a focus on refining project selection processes to yield continuous improvement in the speed or success rates of new products, using ISO 9000 practices for example tip the project selection toward those with greater predictability, lower variation, and increased certainty (Heras-Saizarbitoria, Cilleruelo, & Zamanillo, 2013). As the reach of process management activities extends further into research, R&D project selection activities, or product development, radical innovation projects increasingly give way to more certain, incremental activities (Benner & Tushman, 2002; 2003; Benner, 2009). Tightly coordinated and streamlined processes in product development and manufacturing may allow for rapid response with extensions and enhancements of current capabilities, but the associated inertia is likely to make such an organization slower to respond to radical technological change (Benner, 2009). For radical innovation, process management activities are less conducive to organizational effectiveness (Benner & Tushman, 2003). Benner and Tushman (2002) found increasing process management practices in a firm associated with increases in exploitative patents that used familiar to the firm knowledge but with decreases in more exploratory innovations that relied on new knowledge. McMillan and McGrath (2000) and Gautignon et al. (2002) state that radical innovations are associated with organizations that have experimental cultures, entrepreneurial climate, loose, decentralized structure, flexible work processes, heterogeneous human resource profiles, and strong technical competencies.

The external variable “process management regulations” is expected to moderate the relation between the behavioral intention to adopt, and the actual system use. A moderator is a variable that affects the direction and/or strength of the relation between an independent or predictor variable and a dependent or criterion variable (Baron & Kenny, 1986). The whole industry is guarded by process management regulations, set by either the FAA or the OEMs themselves which govern all technologies that can be used for production in aerospace. Before aircraft components can be used within an airplane, the technology and components have to undergo a qualification and certification process⁵, a so called airworthiness qualification. The restrictiveness in regulations and policies is predictive of adoption tendencies, and tend companies to select less radical technologies with increased certainty (Lin, 2003; Baldwin & Lin, 2002). Tellis et al. (2009) stated that tolerance for risk is an essential attitude to adoption. Loukis et al. (2011) investigated adoption in het Hellenic industry and came to a similar conclusion, stating difficulties concerning integration of new technologies within the current systems. Companies might have the intention to adopt AM for production, however due to the fact that AM is still a new technology, and possibly without OEM or FAA approval, companies might be discredited to do so.

⁵ The FAA and Industry Guide to Product Certification – www.faa.gov

2.6. Final Aerospace Manufacturing Technology Adoption Model

Factors which have been found to affect the adoption of disruptive innovations or AMTs include: perceived product network (Moore, 1992), environmental influences (Christensen & Bower, 1996; Pfeffer & Salancik, 1978), supplier support (Zhao & Co, 1997; Saleh, Hacker, & Randhawa, 2001; Lager & Horte, 2002; Rahman & Bennett, 2009) or organization size (Das & Nair, 2010; Jonsson, 2000; Dewar & Dutton, 1986). It could be argued that important independent variables have been left out. No other research has applied the TAM to additive manufacturing for aerospace, thus there are few predictors which are fundamental or generic. Testing a model including all factors would become very ‘chaotic’, thus solely these two additional factors were added since previous research had included them in either manufacturing or aerospace context. Sohal et al. (2006) suggest that the adoption of AMT is primarily a function of a firm’s assets for AMT, which comprise of the resources, capabilities, and competences for developing and using AMT. Overall, assets for AMT represent the knowledge base of a firm. Combining the additional factors with Davis’ (1996) model, a firm’s knowledge base, capabilities and competences can be accounted for. This leads the model which will be used to test the adoption of AM in aerospace (Figure 2.3); the Aerospace Advanced Manufacturing Technology Adoption Model (AAMTAM).

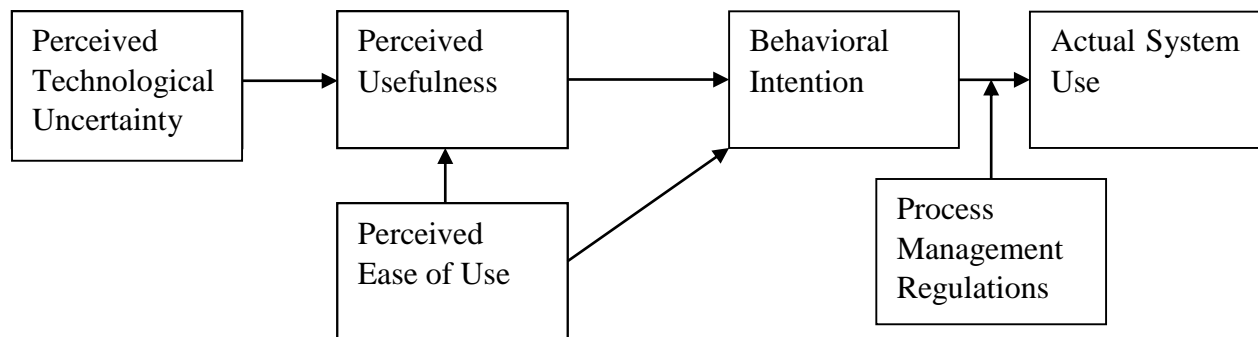


Figure 2.3: Aerospace Advanced Manufacturing Technology Adoption Model

3. Research Design

Since no other research has applied the TAM to additive manufacturing for aerospace, there are few predictors which are fundamental or generic. Due to the scarcity of theory (and hence the relevant variables) in extension literature, exploratory research is considered as the most appropriate for this current research. Review of all the various literatures indicates a wide spectrum of determinants for technology adoptions for AMTs (Yu, Shen, & Lewark, 2011; Small, 2007; Mellor, Hao, & Zhang, 2014; Bartoloni & Baussola, 2001). It is thus necessary to delineate factors that have the most significant effects. As this paper aimed to identify common, but most significant determinants of technology adoption in the aerospace industry, further exploration is warranted.

3.1. Explorative Qualitative TAM research

As TAM in this master's thesis is mainly used to answer a "why" question, specifically to analyze human behavior and the activities that affect this behavior, it seems to be more appropriate to use a qualitative research method. Qualitative methods can be used to understand complex social processes, to capture essential aspects of a phenomenon from the perspective of the studied participants, and to uncover beliefs, values, and motivations that underlie individual health behaviors. Such research can also illuminate aspects of organizational context that influence organizational performance (Curry, Nembhard, & Bradley, 2009). Existing quantitative research has focused on studying perceived ease of use and perceived usefulness, which does not allow for expanding the determinants of technology use. While this existing research is beneficial it provides a snapshot, where incorporating qualitative methodology is better suited to address processes as it is focused on explaining certain aspects of the particular subject of study (Cormack, 1991; Charmaz, 2000). In conclusion, a qualitative research method aims to gain a detailed understanding about implementation of AMT, discover what the main usage motivators for professionals were and analyze them using TAM and its extensions. The studies where acceptance is investigated with qualitative methods show that results can be achieved which move beyond well-known theory, and potentially uncover new constructs (Tobbin, 2012; BenMessaoud et al., 2011; Mallat, 2007).

The AAMTAM has not been validated in the specific context. This research does not aim to validate the modified version of TAM as the majority of existing TAM studies does, but rather to contextualize it. This study will thus apply TAM in a qualitative way and thereby following Sun and Zhang's (2006) suggestions. This research aims to create an understanding of the five constructs and their relation in the specific context of the phenomenon. Consequently, the outcome of this study aims to provide a starting point for future quantitative studies that could test and validate the findings as well as the modified TAM. This overall research approach follows the typical exploratory research paradigm, which very often marks the beginning of total research.

3.2. Sources of Data

Three different data sources are used: in-depth interviews, industry literature and observations.

3.2.1. Gathering information through interviews

Primary data for qualitative analysis can be gathered through observation or interviewing (Patton, 2001). Both are able to generate textual data that can be analyzed, but for this thesis, the first and most important source (primary data) are the interviews with the aerospace industry professionals. The aim of the interviews with the professionals is to gather information about the professionals'

experiences with the AM technology, how they started to use it, the usefulness and benefits offered by technology, what products they were creating, and the barriers/facilitators related to the use or adoption of the technology. The interview structure is based on the modified TAM approach, where the questions relate to the concepts of the adapted model. Semi-structured interviews gather detailed information without preconceived factors; the method provides opportunities for identifying unanticipated outcomes and is effective in understanding attitudinal and behavioral nuances in the situated context (Creswell, 2003; Palvia, Mao, Salam, & Soliman, 2003; Yarbrough & Smith, 2007). This is similar to the methods used by BenMessaoud et al. (2011) and Tjahjono (2009). It proved to be sufficiently open to the extent that it was consistent with the inductive method for analyzing information chosen, which as a result, did not distort the evidence obtained. In this respect, the aim of the interviews and consultation involved obtaining narratives from the interlocutors, rather than obtaining specific responses (Yin, 2003). The interviews also provide an opportunity for the moderator to know the underlying motives which guide a person’s attitude that might be ignored in the literature.

Table 3.1. Interviewed Companies and Different Job Positions of Interviewed Professionals

Companies	Positions
AIM	Business Developer
Boeing	Researcher
Deloitte	Manufacturing Application Manager
GoEngineer	Materials Manger
Roland Berger	Vice-President
SLM solution	
Stratasys	
Vaupell Holdings inc.	
Vaupell Rapid Solutions	

The interviewees are shown in Table 3.1, with the different companies on the left, and the different job positions are shown on the right. The columns are not directly related, in order to keep the interviewees anonymous, however both columns show the diversity of the contacted people. Contacts consist of equipment providers whom have sold AM systems to aerospace and defense manufacturers, personnel of current aerospace and defense manufacturers or the personnel of consultancy firms whom have done research on AM. Potential respondents were mainly approached through Vaupell’s network referrals within prior-selected respondent’s social network or through so-called “snowball” process (Gubrium & Holstein, 2001). In total more than twenty firms within the aerospace industry were contacted in order to hold on interview. Not all potential candidates wanted to be interviewed however, and they did not respond to the call request. Two consultant firms were interviewed, whom had already done research concerning additive manufacturing within aerospace, and whom were willing to participate for this research. The chosen equipment providers had been known to sell to aerospace companies. In the end, eleven professionals were interviewed, and one interviewee sent answers electronically due to unavailability for a call.

Researching based on qualitative interviewing can get enough information from a small number of participants. This of course relies on the research design as well as on the knowledge and contribution of participants (Patton, 2001). In order to fit the situation, questions were adapted or added and some of the professionals were asked more specific questions based on the information given during the discussion or email exchange before the interview. The AAMTAM was used when constructing interview questions in order to get as much information regarding adoption in aerospace. In order to get diversify the information, multiple persons from different parts of the industry are interviewed. All interviews were recorded and transcribed. Notes were also taken along the side the interviews. Most of the interviews were about thirty minutes, the longest being almost 1.5 hours and the shortest 16 minutes.

3.2.2. Industry Literature and Observations

Most information about where additive manufacturing is being applied not openly published. An important asset will be the *Wohlers Report 2014*. This report gives an in-depth analysis of the past, present and future of the additive manufacturing industry. Additional information about the industry can be found in consultancy reports concerning the AM or aerospace industry. Reliable sources of information about the aerospace and defense or additive manufacturing industry are: Deloitte, PwC, McKinsey and Roland Berger. These are all respectable companies (Vault, 2015; Firms Consulting, 2015) which have provided valuable research and insights regarding the industry (see Table 3.2). In order to ensure data validity from the gathered information, multiple sources of evidence will have to be used. Information will be deemed as valid when there are multiple occurrences and it has a basis in proven reliable sources.

Table 3.2. Aerospace or Additive Manufacturing consultants

Source of Report	
Wohlers	(Wohlers, 2014a)
Deloitte	(Coykendall, Cotteleer, Holdowsky, & Mahto, 2014; Cotteleer & Joyce, 2014)
PwC	(PwC, 2014)
Roland Berger	(Roland Berger, 2013)
McKinsey	(Cohen, Sargeant, & Somers, 3-D printing takes shape, 2014)

This research is performed at Vaupell’s locations, informal conversations provided insight in the processes of the aerospace industry. The researcher assumed a participatory-observant role by becoming an intern within the organization. Observations also provided information about the people working at different positions in the firm and the projects in which the firm participated. In addition, the researcher was invited to observe meetings concerning the technology and obtain additionally knowledge, through participation in additive manufacturing projects. Throughout the research phase for this thesis, every other week meetings were held with a business developer from Vaupell, and with a strategy consultant from Future Materials Group (FMG). FMG is an independent strategic advisory firm based in Essex UK, with specialized expertise in the advanced materials and high value manufacturing sectors. They agreed to aid and guide the additive manufacturing research and provide feedback whenever necessary. These meetings served to validate the obtained data as well as give input on industry or technological developments.

3.2.3. Data Validity

The quality of good research is judged by reliability and validity of the research design and analysis. Four common measures to determine the quality of empirical research that are often used are construct validity, internal validity, external validity and reliability (Yin, 2003).

Construct validity examines how well a given measure is measuring the theoretical construct it is supposed to measure (Bhattacharjee, 2012; Yin, 2003). This research aims to identify the factors that influence the adoption of additive manufacturing within aerospace. Yin (2003) gives three principles of data collection which help to establish construct validity. The first principle is using multiple sources of evidence. This is done in this thesis by triangulating data from multiple data sources. This research gathers its data from three different sources: interviews, literature and industry observations. Secondly, multiple persons from different parts of the industry are interviewed, thereby triangulating the interview results. The second principle is having informants review the data draft. During the research process, weekly meetings are held with two parties to discuss the research results, one informant from Vaupell, the other from Future Materials Group. The third principle is to maintain a chain of evidence, this allows the reader to follow the derivation of any evidence from the initial research questions to the ultimate conclusions. This principle is adhered to by demonstrating actual interview quotes, allowing the reader to see the logic that was used to draw conclusions for each topic.

Internal validity examines whether the change in the dependent variable (in this case the adoption) is indeed caused by the hypothesized independent variables (Bhattacharjee, 2012; Yin, 2003). It was tested by constructing a detailed research framework ahead of time. Pattern-matching is a logic that compares an empirically based pattern with a predicted one (Yin, 2003). The development process will be studied in multiple different projects and compared with processes from theory. If the same pattern of problems and causes will be found, the analysis and diagnosis of the problem is internally valid.

External validity deals with the problem of knowing whether a study's findings are generalizable beyond the immediate case study" (Yin, 2003). Although results of the study are not generalizable to other populations, the uniqueness of the experiences described provide rich detail for those who want to understand the lived experiences of professionals within the aerospace industry who are looking to adopt/ have adopted the technology.

Finally, reliability is to be sure that if another researcher follows the same procedures as described and conducted the same study all over again he would arrive at the same findings and conclusions (Yin, 2003). To ensure reliability of this research for every interview the audio was recorded and interview notes were saved together. Afterwards, the interview notes were coded in QDA miner⁶.

3.3. Data Analysis

Qualitative content analysis pays attention to unique themes that illustrate the range of the meanings of the phenomenon rather than statistical significances of the occurrence of particular

⁶ QDA Miner is a qualitative data analysis software package used for coding, annotating, retrieving and analyzing.

texts or concepts (Patton, 2001). Deductive reasoning is employed when the construction of the study is based on previous knowledge, and it is used to test theory (Patton, 2001).

Content analysis is a research analysis method that is used to interpret data from its context. It provides novel perceptions and enhances the researchers' understanding of specific phenomena (Krippendorff, 2013). Content analysis is a method that concentrates on the content and patterns of the data, allowing justification of the context to avoid researcher bias (Neuendorf, 2002). It is employed to identify the actual meaning of words, concepts, phrases or sentences within the data (Krippendorff, 2013). Tentative linkages are developed between the theoretical core concepts and the data. The strategy that can be used in deductive⁷ content analysis is to begin coding immediately with the predetermined codes based on the predetermined theoretical model. Data that cannot be coded are identified and analyzed later to determine if they represent a new category or a subcategory of an existing code (Hsieh & Shannon, 2005). The findings from a deductive content analysis offer supporting and non-supporting evidence for a theory. This evidence can be presented by showing codes with exemplars and by offering descriptive evidence. Because the study design and analysis are unlikely to result in coded data that can be compared meaningfully using statistical tests of difference, the use of rank order comparisons of frequency of codes can be used (Hsieh & Shannon, 2005). The prior research will guide the discussion of findings. After coding completion, conclusions are drawn from data and finally reported as a concept. The participants (interviewees) are individuals. They have different backgrounds and varying opinions. This research acknowledges the individual background and considers the individual aspects for data analysis, but an individual case by case comparison is not the research focus. Following Patton's (2002) recommendation, a cross interview analysis is applied in the case of this research.

3.3.1. Coding Notations

The interviewee notations are given in Table 3.3. As can be seen, there are 4 different groups including consultants (C), personnel from R&D (R), equipment providers (S) and (potential) users (U). The U's are aerospace manufacturing companies whom are looking to invest in AM, and implement it for production parts. Equipment providers give information regarding their experience with previous (non)sales to aerospace manufacturing companies. The contacted consultants have been researching the industry (including AM) and will thus be able to provide a good overview of the facilitators and barrier for adoption. The R group has experience with the technology, and are looking for ways to further develop AM capabilities. The contacted R&D personnel are working within the aerospace industry, and are thus also able to identify some barriers and facilitators as well. The model is aimed at predicting the adoption of AM by aerospace firms, thus the U group will be the primary target of this study. The C, S and R groups however, add valuable insight, to this qualitative study, due to their expertise of the industry.

Table 3.3: Interviewee notations

Notation	Group type	Notation	Group type
C	Consultant	S	Equipment Provider (Seller)
R	Research and Development	U	(potential) User

⁷ Hsieh and Shannon (2005) refer to deductive coding as 'direct' coding

4. Research findings: Additive Manufacturing in Aerospace

In this section the results are presented. Quotations from the interviews are displayed to give a richer example about the found phenomenon.

4.1. Perceived Usefulness of the Technology

The first variable which was tested is the PU, which could be considered as a summary measure of all benefits related to a technology. When creating the concepts for the factors which the interviews found most beneficial, Holmström et al.'s (2010)⁸ suggestions were used. The ideas however were simplified to three concepts however, namely: ability to create complex shapes, removal of tooling and less waste. In Table 4.1, a summary of the different categories are presented.

Table 4.1: Perceived Usefulness Variables

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Able create Complex shapes	X	X	X	X	X	X	X		X	X	X	X
Parts that would be difficult to be created otherwise	X						X		X	X	X	X
Reduce the weight of the part		X		X	X					X		X
Combining parts into one			X			X					X	X
Performance optimization		X		X					X			X
Removal of tooling	X	X	X	X	X		X	X	X	X	X	X
High customization/ low volume production			X	X	X		X				X	
No tooling cost		X			X			X	X	X		
On-demand production less inventory	X	X	X	X			X		X			X
Less Waste					X				X			X

The aerospace industry is known for its high standards and product requirements. When researching the usefulness of the technology, several categories were used by the interviewees in order to compare/describe the technology with other production methods (see Table 4.2). These are described as the performance parameters.

⁸Holmström et al. (2010): (1) No tooling is needed significantly reducing production ramp-up time and expense. (2) Small production batches are feasible and economical. (3) Possibility to quickly change design. (4) Allows product to be optimized for function. (5) Allows economical custom products (batch of one). (6) Possibility to reduce waste. (7) Potential for simpler supply chains; shorter lead times, lower inventories. (8) Design customization.

Table 4.2: Performance of the Technology

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Part Performance Parameters		X	X	X	X	X	X	X	X		X	X
Part strengths		X	X		X	X	X		X			X
(An)Isotropic properties			X	X		X	X				X	X
Ductility					X		X					
Durability							X					X
Cosmetics			X					X			X	
Process Performance Parameters	X	X	X	X	X	X	X				X	X
Build size					X							
Build speed/ Production output	X	X	X	X	X	X	X				X	X
Inconsistency/reliability			X	X		X	X				X	
Aerospace Material Availability	X	X	X	X	X	X		X	X	X	X	X
Plastic	X	X	X	X	X			X	X	X	X	X
Metal						X						

4.1.1. Designing of complex structures

As seen in Table 4.1, 11 out of 12 interviewees named the ability to create complex shapes as a main benefit of AM. This ability to create complex shapes are categorized to lead to four main outcomes. AM provides the flexibility to create complex part geometries that are difficult to build using traditional manufacturing. It can build parts with designs such as internal cavities and lattice structures that help reduce parts' weight. Additionally, the ability to manufacture metal objects without virtually no limitations on geometry and without tools offers the opportunity to create new products that help boost product performance (e.g. tool inserts with cooling channels or highly efficient injection nozzles) (Roland Berger, 2013; Cotteleer, Neier, & Crane, 2014). It could also lead to costs decrease through bill of materials decrease. Previously multiple parts could be combined into one piece (Cotteleer & Joyce, 2014).

Parts that would be impossible/difficult to be created otherwise

C2: "Right now there is a space between the fabricated parts between the world, where AM is not just a good design solution, because it can create parts that can't be created with other manufacturing technologies."

U3: "You can produce parts which can normally not be manufactured by any other means."

Complexity is free, implicitly recognizing that AM technology can be incredibly versatile. AM enables the creation of freeform designs that would be difficult or impossible to produce with traditional machining techniques, because it generally produces objects "layer by layer".

Reduce the weight of the part

U5: "Increased design freedom leads to reduced weight of end use parts"

S1: “You can custom engineer a high complex monolithic parts, that using traditional technologies would have resulted in significant weight penalty, you have solution that has a lot of potential value”

Use of AM technology for different application has resulted in a decrease of material waste in the form of machining from the casts, but also improved design (Achillas et al., 2014). Industry executives claim the ability to reduce component weight by 30–55 percent and eliminate up to 90 percent of material used (Cotteleer & Joyce, 2014). Since a weight decrease will result in saving fuel, millions of euros could be saved in an aircraft’s lifetime (Roland Berger, 2013).

Combining parts into one

U5: “Increased part complexity has naturally progressed into bill-of-material (BOM) simplification. The ability to replace 20+ components within a BOM with a single part, while simultaneously eliminating assembly, is an advantage that A&D companies have publicly celebrated”

S1: “You can obtain a high level of complexity, you can combine multiple parts into one.”

An example of this is given by GE aviation, which has created a fuel nozzle for its next generation LEAP engine. The part was previously created by combining 18 different part. Using AM, the company was able to do it in just one part (Cotteleer, Neier, & Crane, 2014).

Performance optimization

C1: “Using components with additive manufacturing basically addresses 2 levers. Weight reduction and performance improvements for allowing more efficient processes.”

R2: “You can optimize the design, for the specific application.”

For example, AM enables tooling to be manufactured with free-form cooling channels that can provide more homogeneous heat transfer, yielding improved cooling characteristics and, ultimately, higher-quality parts (Petrovic, Gonzalez, Ferrando, Gordillo, & Puchades, 2011). Through faster heat removal, some companies have seen a 60 percent reduction in the cycle time for injection molding (Bobby & Singamneni, 2013).

4.1.2. Removal of Tooling

No tooling cost

R3: “Injection molding is a very expensive venture, tooling cost and process costs are very high. Even for the 737 with 30 planes per month, and you will make 1 part, that is 30 parts per month. The whole benefit is that you do not have to invest in tooling. You can download the drawing, and send it to your printer. With the same part and IM, you have to build the tool and this can be, even for small parts, 25000 dollars.

U1: “The opportunity is going to be, as the tools wear out for replacement parts, [The OEM] will look more at the SLS process to see if it is a viable opportunity instead of having to refurbish the tool, or maybe invest in a new one”

U3: “Taking a part that you would normally manufacturing with another tool process, that you remove the tool. So for low volume parts, your total cost of production is much lower”

Potential cost savings are offered by the 3D technology since no tooling is required. Reducing the reliance on hard tooling (which facilitates the manufacture of thousands of identical items) creates an opportunity to offer customized or bespoke designs at lower cost or allow for on-demand manufacturing (Cohen et al., 2014; Cotteleer et al., 2014; Roland Berger, 2013).

High customization/ low volume production

U2: “If you need to have multiple parts, but you don’t want to tool up, or if you lost that tool, you could cover yourself in that way as well.”

U3: “Taking a part that you would normally manufacturing with another tool process, that you remove the tool. So for low volume parts, your total cost of production is much lower.”

C2: “The low volumes of aerospace are friendlier for a technology like AM, compared to the complexity of setting up and running a machine center to produce a handful of parts. These things are big and expensive, and complex to program, and when they are up and running you don’t want to run them for 100 parts, but for thousands of parts like in automotive. In aerospace, because of its volumes, it’s a more attractive space for 3d printing equipment.”

The ability to manufacture objects without tools offers practitioners the ability to manufacturing batch sizes consisting of just one item and thus tailor the production process to each specific object.

On-demand production/less inventory

C2: “They want fabricate spare parts on demand, and reduce the inventory they need to carry.”

C1: “The aerospace industry is dreaming of small decentralized systems where you can print on remote locations. Just having a printer, and if you need a spare part, you just print it.”

U2: “They tracked a part for a Boeing airplane, and the part traveled more before it went into the airplane, then it would do its first year of being in function. It was going around to world, from manufacturing to manufacturing, polishing, finishing, sub-assembly, assembly. This happens all the time. Why couldn’t 3d printers become the emergent manufacturing in a MROs back shop?”

R1: “Low volume, high customization and quick response time.”

Currently, traditionally manufactured parts and components are purchased and shipped to the depot to be stored in a large inventory center until they are needed. These parts can simply be 3D printed on demand, which would reduce costs, the space needed for part storage and the dependency on part availability. Where traditional production methods may require centralized, even offshore, production (where transit times can stretch into weeks or months), the ability to take advantage of superior scale economics may position AM-enabled manufacturers to respond more quickly to customer demand (Cotteleer & Joyce, 2014). Some AM equipment providers claim that their systems can be used to reduce lead times for the fabrication of tooling by 40–90 percent. Fewer labor inputs are needed. Ford Motor Company e.g. successfully used AM to reduce tooling

fabrication lead times by in-housing its fabrication operations. The company uses AM to rapidly create the sand molds and cores used for casting prototype parts (Cotteleer, Neier, & Crane, 2014).

4.1.3. Low waste

Not only can material be saved in the end part, but during manufacturing as well. AM machines produce less scrap than traditional machines which is a critical attribute when using expensive aerospace materials such as titanium (AirbusVoice Team, 2014; Cotteleer et al., 2014; Cohen et al., 2014; Roland Berger, 2013). In order to produce the end-product, subtractive technologies often produce large quantities of material waste (Achillas et al., 2014). Oppositely to subtractive equipment, modern AM techniques are up to 97% material efficient, wasting only a fraction of raw material. Aerospace is the most cited relevant example. In this industrial sector, buy-to-fly ratios are approximately 20:1, i.e. 20 kg are required to produce 1 kg of end-product. The remaining 19 kg are waste requiring reprocessing or recycling (Achillas et al., 2014).

R3: “And at low volume, your scrap rate can be quite high, so when you finished your run, you have to shut it down and purge your machine. Then you have to waste material and labor on that, making the cost per part quite expensive.”

U2: “There is an advantage for the 3d printers, because you have a lot less waste of material.”

4.1.4. Process Performance Parameters

The speed of production forms can be slow—taking five hours to print a hand rest. Speed is relative however, and based on the part being produced (Sun & Zhang, 2006). Nicolas Vortmeyer, chief technology officer at Siemens’ power generation division said: “You can make one part in, say, 10 hours. If you have an individual part it’s economical but if you have 10,000 parts to make, milling or casting is probably better. In my opinion slow build-up rates are the biggest obstacle to overcome.” (Powley, 2013). Parameters concerning the metal process was less apparent during the interview. Most interviewees were specialized in the plastic side of AM.

C2: “For plastic parts, when you get about a certain production volume, injection molding is most likely going to be the preferred choice. For metals, additive manufacturing competes with other process technologies. ”

C1: “Boeing is not active in metal. They are very good in plastics. The other way around with Airbus. Airbus has a very aggressive growth strategy for the future. But of course, nobody is releasing numbers.”

S1: “The product is in the category of an investment casting, and in that way we kick their butt. Investment casting can reach about 91, 92% strength of wrought material, while we can reach 96, 97%. If you compare us to a machined part, we get about the same percentage. We are a more precise casting, this is a way you can look at our machine. There is still some weakness in the perpendicular direction to the weld. In that direction, we are comparable to casting. ”

Most interviewees named the production speed/output as a parameter. Less named, but other limitations include the build size, and the print consistency.

S2: “Sometimes for specific applications, the build size could be limiting as well.”

C1: “As you move more main stream production for high values and standard parts, that are not so complex, it becomes more and more difficult to compete with traditional manufacturing.”

S2: “You will get inconsistency while laying down the material.”

R2: “We have seen issues where there is machine to machine variation”

U4: “It will be a long time before it will be used for high reliability and structural parts.”

4.1.5. Product Performance Parameters

The parameters concerning part performance are mainly for the end part strength and the anisotropic properties. The z-axis of the print tend to be much weaker. During the interviews, plastic AM was compared to injection molding multiple times.

R3: “From a technological standpoint, AM couldn’t meet most of the requirements. Only at low volume will you be able to compete with injection molding for certain application.”

S2: “Either the z or y axis are going to be weaker than the other.”

R1: “Even the best 3d technology don’t compete with IM in a structural. IM outperforms 3d printing almost every time. The z axis will be the of most concerns within the aerospace industry”

U1: “I think it has possibilities, it will take an improvement in the technology and in the materials for it to be a viable replacement for the injection molded parts.”

For the metal AM systems (the powder bed systems) many of the same process limitations exist in comparison with the plastic systems. The build volumes, production speed, product volume output and part cosmetics have been named a process limitation for the metal machines. With the metal however, similar properties to cast metal can be achieved, opening up to more opportunities within the industry.

C1: “So for metals the printers meet the requirement. For metals, the quality of the parts is not a big problem right now.”

S2: “For metals, they are more useful for smaller parts. With the bigger parts, there have been some difficulties with obtain a certain constancy and quality with each part. Additionally, the powder requires a clean room, so that is something that has to be handled.”

4.1.6. Available Materials

Ryan Sybrant (2015), Stratasys' senior manager of manufacturing solutions said: “*The materials drive applications, applications obviously drive the industry and drive sales for our machines*”.

R3: “Well depending on the material, there are more applications.”

In today's world however, 3D printers are currently limited to using only a handful of engineered materials, mostly plastics and a few metals and it is well known that materials drive applications. Ten out of 12 interviewees, have named that the limited number of available materials for plastic AM systems, forms a barrier.

C1: "Not all materials are suitable for AM, as more material become possible to use, more applications will become available for its use."

R1: "The FDM Ultem 9085 is the only qualified 3d printing material for aerospace. Right now there are 2 materials which are qualified, the Ultem and the Nylon 11."

U2: "Then a lot of these material used in aerospace, at least from a structural perspective, are going to have to have some type of reinforcement in them, and you are not going to print that with the technology today."

Most plastic materials are generally of low quality and not suitable for most production products due to their limited strength, toughness, surface quality, and UV degradation properties (PwC, 2013). Stratasys' Fortus machines are the only production grade FDM machines available today. The most common material Ultem 9085 (since the resin complies with FAR 25.853), is made by Sabic for Stratasys. For the selective laser sintering technology, multiple professional grade machines exist namely the German EOS machines, Japanese TPM machines and multiple 3D systems machines. The most popular (for producing parts) has been the EOS machines (section 2.1). The only qualified SLS material is PA 11 FR-106, a nylon.

S1: "There are about 10 metal powder providers, it (the metal powder price) should go down in the next 10 years. Right now the powder that is being sold, is basically waste from other applications that require massive amounts of metal powder. After that application is done, then they sell the remaining powder. If you use the umbrella of a weld-able material, those materials you can probably use."

For metal the materials world look differently, with EOS claiming to have Nickey-alloy, Stainless Steel-alloys, Al/Mg alloys and Titanium available in aerospace grades (EOS, 2015).

4.2. Perceived Ease of Use

Based on the PEU factor, two categories came to light (Table 4.3). The first contained an extra skill was needed to be learned before the technology can be used. The second variable which became visible during the data analysis was the OEM (e.g. Boeing or Airbus) control. The process management regulations variable is also shown in this table, but this is explained in 4.3.

Table 4.3: Perceived Ease of Use Variables

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Extra skill needed	X	X	X	X		X	X		X	X	X	X
Missing tools/knowledge about using the technology	X	X	X	X		X						X
No issue for implementation					X		X		X	X	X	
Process Management Regulations	X	X	X	X	X	X	X	X	X	X	X	X

There are mixed results about whether requiring a new skill will have an effect adoption.

No issue for implementation

U2: “The process you have to learn is pretty straight forward. Anyone who has done any level of modeling is going to be able to learn working with this technology. The CAD companies have done such a good job in creating a common 3d modeling platform, this will keep the doors open for this technology”

U3: “The software needed in order to work with the technology can be figured out.”

R3: “Most of the engineers were looking for ways to get promoted, and looked for techniques that were novel to save weight or cost. So if there were cost to be saved with SLS, the engineers would just try it. They would download the CAD drawing, and do whatever they do with the program to get it compatible.”

There are missing tools/knowledge about using the technology

S1: “You will need to have an engineer with experience about design for manufacturing in order to use the technology. Really nobody today is designing the components to take full advantage of the additive manufacturing technologies. You will need to have the extra expertise.”

C1: “The industry needs to understand the process, you can’t print the part and put it in an airplane.”

R1: “They don’t know the technology well enough, but they don’t know or have the right tools for Additive manufacture. Like Cad software, integration of additive manufacturing design principles within the CAD software.”

S2: “3d printer will require some additionally design principles when constructing your build file, but I don’t see the software really being an issue. They are still going to use the same type of software to do the design, like Katia. These days, most software is able to convert the build file into a .STL file right away. Engineers do need to be mindful about the build direction they choose, since this can have an effect on the build properties. ”

4.3. Process Management Regulations

During the interview process, it became clear that one of the biggest variables slowing down the adoption of new technologies, is the process and material certification. The process management

regulations, also includes the cost of qualification. In order to qualify a material or a process, the supplier will have to pay a certain fee (Table 4.4).

U3: “The regulatory barriers are by far the biggest barriers. Getting it approved for production (by the FAA), there is a whole laundry list of regulatory approvals. Then at the OEM level, there is another list of certification”

The Federal aviation regulations cover a wide variety of activities are regulated, such as aircraft design and maintenance, typical airline flights, man-made structure heights, obstruction lighting and marking. The rules are designed to promote safe aviation, protecting pilots, flight attendants, passengers and the general public from unnecessary risk (FAA, 2015). After getting a part proved for production, the part will have to be qualified according to the OEM (e.g. Boeing or Airbus) standards. Every person interviewed name the certification process as a barrier of adoption for the 3d printing technology.

Table 4.4: Process Management Regulation

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Process management Regulations	X	X	X	X	X	X	X	X	X	X	X	X
The OEM decides what technology will be used		X	X		X	X		X		X		
Cost of Part qualification process	X		X		X				X	X	X	
Certification of process and material	X	X	X	X	X	X	X	X	X	X	X	X

4.3.1. OEM Decision to Use a Technology

The OEM mainly decides what technologies can be used. Before any company within the supply chain can use a technology to produce parts, the OEM has to allow this supplier to use this particular technology for a part.

S1: “The printers are now mainly being adopted by the tier 1. A company like Vaupell is a supply chain member. You link contracts from larger OEMs and deliver parts and systems.”

U3: “The OEM is in control of the decisions being made about what technologies to use. The FAA has regulations which flow down to the OEMs. The OEMs will then make decision according to their assessment, engineering and risk tolerances where opportunities are.”

R3: “Well there will have to be a substantial improvement in weight or cost. But this would be a [OEM] decision, and not a vendor decision. There has to be an advantage for some part for them to consider switching the process or the material.”

U1: “The implication of a new technology is primarily driven by [The OEM]. So when they have a part that they have decided they want to do it with 3d printing. That will be the process for which they specify how the part will be produced, and companies within the

supply chain will follow the process as instructed upon on their drawing or parts list from [The OEM].”

C2: “OEMs will simplify the design the requirements and software to make it easier to use technology as well (for the rest of the supply chain).”

An important aspect thus within aerospace, is that the OEM has accepted the technology, and has written process management regulations on how the new technology will be used, and with what materials. When the OEM has accepted a technology for production, it will then qualify it, allowing parts to be made with the technology. Afterwards, the supplier whom make the parts will then use the technologies which have been qualified by the OEM. It is possible that the same part can be produced using two different (certified) technologies. Then the supplier will decide, in according with the OEM on which to use.

R3: “What many people don’t realize is that [The OEM] doesn’t own 99% of the technology it uses. [The OEM] doesn’t own any injection molding technology.”

U1: “The way they operate is that they develop a relationship with Harvest or some others, and they may be doing some research, and [The OEM] might be funding it.”

Research done about which technologies and materials to use does not come solely from the OEM. Organizations within the industry do independent research concerning technology changes or improvements, which the OEM could allow to be used for production parts.

4.3.2. Part and Material Qualification

R3: “You have a material and a process qualification. Now for the material qualification, if you are going to make the material, then you become the material supplier. You have to qualify that material to the OEM’s material standard. If you also have the equipment to make the part, than you also have to qualify to the process standards, the BACs.

R3: “If you make a different part on the same machine, then you go through a first-part qualification. This is true for everything, you are qualified for the BAC but there is still a lot of paperwork. You have to make a run, and do your dimensional, and there are probably some mechanical test you still have to do. You are then not qualifying the process, but more qualifying the part to the drawing.”

Getting the process and material certified

U5: “Aerospace and defense applications are demanding and must meet certification and air-worthiness requirements”

C1: “Another whole area that needs to be figured out is the qualification. Especially in the aerospace industry, certifying the process and the material. ”

R1: “In order for the companies to use the material, they will have to certify their end product which is a big effort.

S2: “You will need to qualify the process, so the parts can additionally do, what they are supposed to do. The FAA regulations however are slowing down the whole adoption process within aerospace. ”

Cost of qualification

U4: “Think about it, if you only need 10 parts, but you need 30 to validate the process, then you can better build the mold. After qualification, each part after it will be cheap. On the other side, 3d printing is nimble. You need to have a validated production parts. You cannot make a quick change without change. The process is that you will have to re-qualify the product. The economics could be a problem because validation can be expensive.”

R1: “It (process qualification) is expensive, it costs time, money, and it slows down the whole innovation process.”

U2: “The biggest impediment is going to be the cost of change. The qualification costs money”

From the point of view of the qualification of AM in the aerospace industry, there are significant challenges because standardization is not yet well established. However, the ASTM F42 Committee is working to overcome this challenge. This committee meets twice a year to discuss the qualification process for AM in aerospace (ASTM, 2015). ASTM has identified priority topics for standardization, in particular: qualification and certification methods, design guidelines, test methods for characteristics of raw materials, material recycling guidelines and standards protocols for round robin testing standard test artefact, requirements for purchased AM parts, harmonization of existing ISO/ASTM terminology standards and testing of finished parts (Uriondo et al., 2015).

U4: “In aerospace the biggest issues is validating the process. Making it repeatability this is the biggest problem. The whole qualification process is difficult and expensive.”

R2: “We have seen issues where there is machine to machine variation, and we still don’t understand how much there is, and why the variation is there. There are multiple parameters that can affect it. There is a concern that just because you build and certify on one machine, it can change. And that is just between the same types of machine. Think about changing from a Fortus 900 to a Fortus 400.”

R2: “The average time to qualify material is 8-16 months, and it’s one of those thing, that we have to do, to ensure that we have a robust material and process. That has stumped the industry so far.”

R3: “I don’t have a dollar figure (concerning qualification), but it is an expensive process. It is in the 1000 and 1000 of dollars. Between the 50 and 100 thousand dollars range I would guess.”

The conventional certification processes for aircraft components is very costly and lengthy. Adaptations, such as the use of new material, can require up to one year of development time.

R2: “Everyone wants to shove the technology into prime time, but the engineering hasn’t been done to put it there. And that is a big thing people have to take a step back, and do the

base line engineering work. When we do that, then we can apply it. But nobody want to wait for that.”

4.4. Perceived Technological Uncertainty

The results concerning the perceived technological uncertainty is shown below (Table 4.5).

Table 4.5: Perceived Technological Uncertainty

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Perceived Technological Uncertainty	X	X	X	X	X	X	X	X		X	X	X
Unfamiliar with capabilities	X	X	X	X		X	X				X	X
Immature/Not well defined - technology			X	X	X			X		X	X	

The majority (11/12 interviewees) named uncertainty about the technology as a barrier to adoption.

U1: “This is a new technology, and [...] is still dabbling in it, but at some point when they decide that it is a mature technology to really make some cosmetic parts, like interiors, then you will see them start to look to replace a lot of the injection molded parts.”

S1: “Frankly, most people are not aware of where we are at. Everybody needs to start with a service bureau, so the customer can have some parts made and get used to the technology. When people see what the printers are capable of, then they will further investigate whether to buy the machine for themselves.”

U3: “You have got to get the technology (additive manufacturing) well defined, and approved before it will be adopted. The industry as a whole is pretty risk averse.”

U4: “The biggest problems for using it in production are: familiarity with materials, qualification materials, accuracy, feature definition and cost. Same for the metal machines. Any of the 3d printing process are not the standards, engineers are used to.”

R2: “If you ask Stratasys what happens when you change the raster pattern, they can’t tell you the affect it has on the properties. So how can aerospace adopt that as a technology when even the machine supplier can’t tell you what will happen to the integrity of the part?”

R1: “The smaller companies watching waiting to see what technologies to adopt and where to adopt so there all less uncertainties about the capabilities.”

The technology is still fairly new, and there is still a lot of development being done. An interviewee commented on that the larger corporations were funding the research. During the interviews, an additional factor was found when asking about the technological uncertainty, namely knowledge sharing. It seems that the corporations who have been doing the research share limited information regarding the technology. Further details regarding knowledge sharing are given in section 4.5.1.

C2: “(The larger companies have) Engineering resource, to have a few people to work with the technology to see where it can be applied. The smaller companies are aware of this, they want to learn how it is developing, but they are less at the forefront because they have smaller budgets to focus on this. ”

U4: “Additionally they (companies within the aerospace industry) are not sharing any of the information about the material data, or the qualification process which can slow down the process.”

C1: “All material property data for printed with a laser components is not publically available. If you want to have this data, you need to make the test for yourself, GE won’t pass that to you.”

4.5. Additional factors for adoption

During the data analysis, as of a result the examined variables, three other variables came to light. These factors are knowledge sharing, the machine cost and intellectual property.

4.5.1. Knowledge Sharing

During the analysis of technological uncertainty, it became apparent that there is limited knowledge sharing within the industry. As can be seen in Table 4.6, nine respondents named that the limited knowledge sharing within the aerospace industry had an impact on adoption.

Table 4.6: Knowledge Sharing in Aerospace

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Knowledge Sharing	X	X	X	X	X	X	X	X			X	
Amerika Makes group shares information				X								
Limited to keep competitive advantage	X	X			X							
Limited Knowledge sharing	X			X		X	X	X			X	

U4: “Additionally they (companies within the aerospace industry) are not sharing any of the information about the material data, or the qualification process which can slow down the process.”

S2: “not a lot is being shared within the aerospace industry.”

C1: “The manufacturing process technology tends to be knowledge that companies like to keep. Many companies for instance do not take out patents on certain types of technology in order to keep it a trade secret. ”

R1: “The technology is slow because everyone is a little protective of what they are doing. They don’t want to give up any advantage”

Companies within the industry are reluctant to share information considering the material data, or qualification process. Three interviewees said that this was done to keep a competitive advantage.

R2: “Yes and no. As part of the Amerika Makes, a lot of aerospace companies, Boeing, GE, Northrup, lockheed was involves, all of them got together and did some work on FDM in the course of 2 years.” (In response to whether knowledge sharing effects adoption)

President Obama started the National Additive and Manufacturing Innovation Institute, known as “America Makes,” created in 2012 to promote research and standards in the field of 3-D printing

(Jayakumar, 2014). So according to the interviewee, some of the data sharing is enforced through this Amerika Makes program, however this only complies with the companies within the party.

R2: “But I understand that there are parties who will be reluctant to share what they are doing.”

The same interviewee still acknowledges that there are companies unwilling to share knowledge.

4.5.2. Equipment Cost

Cost has been named on multiple occasions during the interviews, including cost of qualification, machine cost, or the cost-benefit for production. Machine costs tend to dominate cost structures for AM applications, representing 60–70 percent of total direct costs (Cotteleer & Joyce, 2014). The direct costs of this technology are thus significantly high, so it can be only justified by special benefits in the lifecycle or tooling costs (Roland Berger, 2013). For this reason, multiple respondents named the high equipment cost as a potential barrier to adoption (Table 4.7).

Table 4.7: Equipment Cost

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
High Machine cost		X			X	X	X		X	X	X	
Hard to justify investment						X	X				X	
Not enough resources		X									X	
Depends on price benefit		X			X		X		X	X	X	

U4: “The cost of the technology is really slowing down adoption. It is an R&D expense, and the bigger companies can afford to invest in the long term.”

S1: “It is hard to justify 800.000 dollars”

U3: “As long as you can prove that there is a promising value proposition, an idea that has some legs, that it in the future, might get to a point where it will provide a real benefit. Then we will be willing to invest and go through”

C2: “The smaller companies are aware of this (additive manufacturing), they want to learn how it is developing, but they are less at the forefront because they have smaller budgets to focus on this.”

The machines costs between 0.5 and 1 million dollars, thus companies could be reluctant to invest since the costs are high. If the industry does not see enough potential value to invest in such a large amount, adoption will be slow. Additionally, not all companies are able to invest such an amount.

U2: “Even if you have the qualification in place, is it cost effective for moderate to high volumes, or is it destined to only be applicable for part with less than 50, to make sense for a run standpoint. So it will come down to cost. At the end of the day, this is the most important. Follow the money.”

4.5.3. Intellectual Property

If a 3D printer made a copy of an object and that copy included a trademark, the copy would infringe on the trademark. However, the specificity of 3D printing would allow an individual to replicate an object without replicating the trademark. If you like a given product, and do not feel passionately about having the logo attached to it, it will generally not be a violation of trademark law to reproduce it without the logo (Weinberg, 2012). Thus, making a bottle in the classic Coca-Cola shape may infringe on the trademark, although final judgment may be driven by how that AM produced bottle is used (Campbell & Ivanova, 2013). Copyrights protect original creative works that are “fixed in a tangible medium” (i.e., a term of art in copyright law and a critical prerequisite for copyright protection) (Weinberg, 2012). For example, a decorative display on the outside of a vase can be covered by copyright law, whereas the vase itself may not be (depending on the originality of the vase). One may thus encounter copyright law restrictions if 3D printing was used for both the vase and its decoration simultaneously (Campbell & Ivanova, 2013). Four interviewees commented on the potential of IP infringement Table 4.8.

Table 4.8: Creating Copied Parts Using 3D Printers and 3D Scanners

	C1	C2	R1	R2	R3	S1	S2	U1	U2	U3	U4	U5
Copying Parts												
Less of an issue at the time			X	X								
Aftermarket concern				X								
Potential risk		X										
More a consumer concern			X									
There are counter measures to prevent a big issues									X			

U2: “You can argue that 3d printing will allow people to knock parts of, but I think there is going to be a counter measure to limit the ability for those parts to migrate out, and certainly insertion in airplanes.”

R2: “The problem you will have is that you end up with somebody over in Asia who scans a part, builds a part and it get sold or repaired. I could see the problem occurring in China where you end up seeing counterfeit parts. When you buy parts through a reputable distributor that should be mitigated. But counterfeit parts make their way on aircraft. This is at the spares level, at production level I don’t see it being a problem at all. ”

C2: “For patented designs which cannot be manufactured any other way, for let’s say medical implants, there is a risk that this can be easily copied.”

Additive manufacturing itself is becoming heavily patented. In the past decade, there has been an almost exponential growth in both filed and approved patents for AM materials and systems (Wohlers, 2014). It is expected this to continue apace as new AM technologies come on-line (Campbell & Ivanova, 2013). In short, there is much that remains to be worked out in terms of the potentially disruptive effects from AM on IP law. The convergence of the Internet, digitized music and media players has had dramatic consequences for music copyright. 3D printing technology

may have similar implications for artistic copyright, design right, trademarks and patents, but in a rather more diverse legal framework (Bradshw, Bowyer, & Haufe, 2010; Palmquist, 2014). Technical measures would could founder on the problem that, unlike music files haring, personal 3D printing does not produce an exact copy that can be digitally signed or protected with digital rights management. It is the sharing of (as seen, legitimately) reverse engineered designs that is the issue, not original design documents (Weinberg, 2012).

R1: “3d scanning is not trivial, there is a lot that goes into capture high precision 3d data. This could become an issue, but less of issue at the current time. In the consumer world it could become a bigger problem.”

R2: “It will have to be considered for sure, but the biggest problem is dealing with the build. How to make sure not anybody can get that build files. I know some of the 3d printing systems use cloud based systems, and that could be a problem. I can’t see [...] ever going along with that.”

There is no consensus about what effect 3d printing could have an IP infringement laws in the future, however from the interview responses, it is not seen as a major barrier right now.

U2: “At the end of the day, whoever is installing that part, is putting their FAA manufacturing ticket on the line if they put a fake or knock-off part inside the plane.”

5. Discussion: Additive Manufacturing for Aerospace Production

The aim of this research is to identify the benefits for adopting this technology, but also the main barriers which are inhibiting further adoption in the industry. This could provide a starting point for future implementations of solutions similar to the additive manufacturing technology, as well as explore the possibility of using the technology adoption model in the aerospace context. It is important to figure out whether adopting 3D printing technology will have benefits for an organization within the aerospace industry, in order to justify the investment. The concepts based from the created model (AAMTAM) were tested within the aerospace industry however due to insufficiency of previous research done in this area, variables had not been taken into account. The research lead by the conceptual model, identified barriers of adoption within the industry. Additional external variables are found to have an effect on adoption, which lead to a new proposed model, shown in 5.3. The propositions for the relations between the constructs are explained in sections 5.1 and 5.2. Lastly, a fitting market strategy for using this technology as a production method within the aerospace industry, based off of a proposition of benefits and drawbacks. This chapter therefore provides an answer for the third research questions.

5.1. Basic Model Construction

The variable in the concept model shown in Figure 2.3, have been tested, within the aerospace industry. During the qualitative analysis however, two additional constructs are detected, namely: knowledge sharing and the cost of equipment.

5.1.1. Behavioral Intention to Use

BI has been found to be the most reliable predictor of actual system use, which does not deviate from the Davis and Vekatesh's (1996) model. As explained in section 2.4, this formed the basic construction of the model, which has also been successfully tested within organizational and industrial contexts (also see section 4.3.1).

P1: Behavioral intention to use will have a positive effect on actual system use.

5.1.2. Perceived Usefulness

When studying the PU factor results from the interviews thus suggest that additive manufacturing on currently provides multiple benefits. The two most profound benefits are the (1) ability to create complex shapes and (2) that no tooling was required in order to make the parts. Since the technology uses a layer by layer addition of material, it does not require a premade tool (such as a mold or a casting pattern) in order to make the final part. Additionally, almost any geometry can be formed. According to the U group, the removal of tooling seems to be the biggest benefit, since all (potential) user named this aspect. A less named, but still present benefit was that the production technique produces generally less material wastage compared to CNC machined parts. Future research will need to measure "perceived usefulness" along multiple dimensions, since AM may provide a range of long- and short-term benefits similar to AMTs (Thomas, Barton, & John, 2008; Scannell, Melnyk, & Calantone, 2011). Several prior studies have shown that perceived usefulness as important antecedent to intention to adopt and use a technology (Davis, 1989; Legris et al., 2003; Venkatesh et al., 2003). The more benefits organizations can foresee from using the technology, the more likely they are to adopt the technology given sufficient support and facilitation (Wang & Qualls, 2007). This relationship has also been found by Scannell et al. (2011;

2012) when he tested it for shop floor manufacturing technologies. The proposed relationship between PU and BI does not deviate from the Davis and Venkatesh's (1996) model. As explained in section 2.4, this relationship has been successfully tested in industry/organizational context.

P2: Perceived usefulness will have a positive effect on the behavioral intention to use additive manufacturing technologies for aerospace production.

5.1.3. Perceived Ease of Use

Perceived ease of use is the extent to which an individual believes that using a technology will be free of effort. The current study found the PEU for AM to affect the adoption for aerospace companies. Based off of the interviews it was determined that the PEU of a technology is determined by two factors: (1) additional skill needed to use the technology and (2) the process management regulations (this factor is further explained in section 5.2.1). AMTs generally expand the technical complexity of the jobs, while relieving workers of the routine tasks. This often translates into a change in the skill requirements of the workers, necessitating extensive technical retraining (Co, Patuwo, & Hu, 1998). This could result in labor-related problems arise from a shortage of skills, training difficulties, and labor contracts (Baldwin & Lin, 2002; Yu, Shen, & Lewark, 2011).

There were some mixed statements regarding how easy it would be to use the new technology. Four out of twelve participants did not see the extra skill needed as a barrier, since the required software is or 'pretty straight forward' to learn. Three of these interviewees were part of the U group, demonstrating that manufacturing firms find that learning the new technology will not be a big issue for implementation. The other respondent however (the majority including one U) commented that 'education is needed' and that 'nobody today is designing the components to take full advantage of the additive manufacturing technologies'. This is in line with Taylor and Tod's (1995) conclusion, and with Machuca et al. (2004) who found that 95% of asked aeronautical organizations took personnel training in consideration during AMT adoption and implementation. AM works with 3d modeling software such as SolidWorks or Katia. Many of the engineers within the industry have previous experience with the modeling software. It was mentioned by a researcher during an interview that more expertise was needed about build direction and orientation. As of today, there is no complete set of design, layout, material, machine and process rules about how to construct with the technology. According to Roland Berger (2013), more experience is needed in the next years before new objects can be made with less effort.

Prior studies has shown while the direct effects of perceived ease on perceived usefulness, as well as the behavioral intention (see section 2.4). This can be found within one of the quotes, stating that general design principles for 3D printing are missing, and that "nobody is taking full advantage". Once engineers learn to use the new technologies, then they will be able to reach the full benefits of the technology. In conclusion the proposed relationships between PU and PEU does not deviate from the Davis and Venkatesh's (1996) model. No all U personnel agree with that additional skill needed will affect the adoption, but the results were mixed for the manufacturing companies. Additionally, the majority of the interviewees, said that the additional skill needed to use the technology was effecting AM implementation. Therefore the proposed relation between PEU and BI will also be similar to the original model.

P3a: Perceived ease of use will have a positive effect on the behavioral intention to use additive manufacturing technologies for aerospace production.

P3b: Perceived ease of use will have a positive effect on the perceived usefulness.

5.2. Barriers of Adoption

Based off of section 4.5 it was decided to add the additional factors of knowledge sharing and cost of equipment to the adoption model. Nine respondents named that the limited knowledge sharing within the aerospace industry effects the adoption. The equipment cost was stated less times (seven respondents), but it is proposed it does effect a company's decision to adopt. In total, four barriers of adoption were defined during the qualitative analysis, which will be explained in this section. Additionally their proposed effect on the factors in the modified TAM model is explained. Based off on section 4.5.3, the IP factor is not taken into the final model. From the four respondents who named IP during the interview, the general conclusion is drawn that it is not a serious issue today. The 3D scanning technology is not trivial, and there are countermeasures in place to keep 'fake' parts out of an airplane such as the FAR and the process management regulation set by the OEMs.

5.2.1. Process management regulations

The qualification of the 3d printing technology was a predicted barrier (section 2.5.2), and it was also mentioned by all respondents. There is an issue of part to part variability, as well as machine to machine variability, which is hindering the qualification process. Unlike other manufacturing processes, AM is neither adequately understood nor characterized to establish a combination of fixed process parameters, acceptance testing, non-destructive inspection, and destructive coupon testing, to confirm if it complies with all requirements. With the current state of this technology in terms of design, qualification, process specifications and standardization, it is difficult for the aerospace industry to develop a single specification and associated database for AM for a material (Uriondo et al., 2015). When AM parts are used in critical applications where they have a direct impact on the safety and success of a project, ensuring their quality and reliability is of paramount importance. Since these parts are often complex and built as one-piece in one-go, inspecting or testing them using traditional methods without compromising the part is difficult (Tampi, 2015). In other words, when all variables in the AM process are fixed and the process becomes stable and controlled, the resulting mechanical properties are well characterized and sufficiently invariable, the structural performance of AM parts is predictable using conventional design tools, and the ability to accomplish post processes is demonstrated (like machining or drilling), then only can AM be considered a viable option in the aerospace industry. The unique problem which companies are facing with their high-value additively manufactured parts is that the technology is not just redefining the way objects are made, it is redefining the way in which such objects are tested and evaluated, as well. There are very few tools currently available to track what's going on inside AM equipment. This increases lot sizes of test components and requires expensive post-manufacturing checks. Aerospace has not defined its exact requirements from AM equipment suppliers, leaving them to guess in many situation what type of build process is needed. Consistency of outputs remain barriers to using 3D printers and many customers have not put their full trust into these products (Coykendall, Cotteleer, Holdowsky, & Mahto, 2014).

The moderating factor is kept within the proposed model. There are many regulations in place, which do not fit with, as explained above, how 3d printing manufactures parts. So even if a company has the intention to use a technology, the certification process can limit the actual use of the technology. The restrictiveness in regulations and policies is predictive of adoption tendencies (Lin, 2003; Baldwin & Lin, 2002). Besides from the OEM control over the suppliers via process management regulations, the FAA also provides regulations to which the process and materials have to comply for they have achieved ‘airworthiness’, which are expected to moderate to what extend the technology can be used.

The process management regulations are also expected to effect the PEU. If there is not certification in place for a certain manufacturing technology, the technology cannot be used. The OEM is in control of these qualification standards and if a supplier wants to use a certain technology, it will have to certify to the specification. For Boeing these certifications include: the Boeing Material Spec (BMS), the process specification (BAC). Before a material can be used, it has to be qualified to a BMS standard. Different applications require different BMS qualifications, so one material could be qualified for multiple applications. Secondly, the process of manufacturing (BAC) has to be qualified. This process is part specific. The BAC defines how a part can be made, and with what material. For instance it defines that an air-duct can be created using selective laser sintering and PA11 FR-106. If either the method of manufacturing, or the material changes, a new BAC qualification process takes place. If a part design is changed, then both new BMS and BAC have to be re-qualified for this new part.

- P4a: The process management regulations (negatively) moderate the relation between behavioral intention to use and actual system use.
- P4b: The process management regulations will have a negative effect on the perceived ease of use.

5.2.2. Perceived Technological Uncertainty

During the interviews, ten out of twelve respondents named that the industry was unfamiliar with the new technology. Uncertainty resides with the structural integrity of the final build. There are many factors that come into play for the final part properties, such as raster pattern and build orientation, which are not fully understood. Due to lack of knowledge regarding the new technology, it has been found that users often reject systems that enhance their performance in favor of systems with less pronounced benefits (El Jaafari, Forzy, Navarro, Mars, & Hoc, 2008; Inagki, Itoh, & Nagai, 2007; Navarro, Mars, Forzy, El-Jaafari, & Hoc, 2010). Four out of five manufacturing companies noted that uncertainty was slowing down the adoption. They were “unfamiliar with the technology or the machine” and that the technology had not been defined well. The technology has not been deemed as U1: “mature” so these manufacturing companies are not yet sure concerning the capabilities. There is an inherent rapid-prototyping legacy with AM system which may result in a psychological barrier to adoption, as management only see the technology-class as being suitable for RP applications (Mellor et al., 2014). U3: “the whole industry is pretty risk averse”. It was mentioned that smaller companies tend to wait for larger companies, whom are researching the technology to reduce these uncertainties. In total, ten respondents named uncertainties concerning the technology as a factor slowing down adoption.

The parts of the factor were found to be: unfamiliarity with the capabilities and the second was that the technology was still not well defined. The adopting organizations ability to present benefits of AM as a manufacturing process in a clear and balanced way will determine the success of implementation (Mellor, et al., 2014). The factor is expected to have an impact on PU as well as PEU, since uncertainty about the technology will affects people's confidence in their decisions, as well as the perceived characteristics of the technology (Im, Kim, & Han, 2008). Due to the unfamiliarity with the technology, the PU is thus expected to be affected. Since it was named that the technology was not yet mature or well defined, it could therefore also have an effect on the PEU, e.g. perceiving more expertise is required (then actually needed) to use the technology, or that it will be more difficult to implement the technology within the industry, with regard to passing the regulations and certifications.

P5a: The perceived technological uncertainty and limitations will have a negative effect on the perceived usefulness.

P5b: The perceived technological uncertainty and limitations will have a negative effect on the perceived ease of use.

5.2.3. Cost of Equipment

The additive manufacturing machines are between \$500.000 and \$1.000.000. The equipment cost was stated seven times (out of twelve respondents) to have an effect a company's decision to adopt. Hall and Khan (2003) stated that diffusion can be seen as the cumulative or aggregate result of a series of individual calculations that weigh the incremental benefits of adopting a new technology against the costs of change. In order to recoup costly investments in new production technologies, firms want to be assured that there will be income in the future to pay for the investment, as a way of reducing the risk inherent in the adoption decision. Because of investments in existing technology, switching cost imposed by radical technologies retard a firm's responsiveness to emerging technologies (Moriarty & Kosnik, 1989). As one might expect, the greater the sunk costs will be the rate of adoption of an innovation (Asteberto, 2004). From a traditional economic point of view, the acceptance of technological developments in society has been approached as an economic cost/benefit analysis, where a trade-off is made between societal benefits and economic costs associated with a certain technology or activity (Starr, 1969; Ronteltap, Trijp, Renes, & Frewer, 2007). Customers compare the benefit from the service to the cost of using the service. If the cost exceeds the benefit, they do not subscribe to the service (Shin, 2009).

The cost of the equipment is proposed to negatively affect the behavioral intentional to use a technology. One manufacturing firm stated that the cost of equipment is a barrier to industry adoption, and the two other stated it depended on the value proposition of the technology. Firms will want to be assured of a high pay-back because the switching cost are higher, and they will have to invest a lot of money, it will be S1: "hard to justify the investment". This is in compliance with Baldwin and Lin (2002) whom state that the cost of acquisition is found to be an impediment to manufacturing technology adoption. Larger and more profitable firms are more likely to have the financial resources required for purchasing and installing a new technology, as well have additional resources for R&D expenditures (Jaffe, Newell, & Stavins, 2003; Das & Nair, 2010;

Sohal, Sarros, Schroder, & O'Neill, 2006). Since large investments are required, not all companies will be able to make use AM due to lack of funds.

P6a: The cost of equipment will have a negative effect on the behavioral intention to use AM as a production technology within aerospace.

Griliches (1957) presumes that the primary factor limiting diffusion is information, and that the most important source of information about a new technology is people or firms who have tried it. According to Bessant and Haywood (1986), the time lag between initial adoption and cost recovery can often exceed five years. Managers who are risk averse are less likely to adopt AMT and expose themselves to such high levels of uncertainty. The cost of the innovation is high, making it more expensive to test or try-out the technology. As stated in the interviews, the smaller companies are waiting for the bigger ones to reduce the uncertainties of the technology. C2: “they (the smaller companies) want to learn how it is developing, but they are less at the forefront because they have smaller budgets to focus on this.” According to Rogers’ (2003): trialability positively correlated with the rate of adoption, and is the degree to which an innovation may be experimented with on a limited basis. The personal trying-out of an innovation is a way to give meaning to an innovation, to find out how it works under one's own conditions. This trial is a means to dispel uncertainty about the new idea. The following proposition is thus formulated:

P6b: The cost of equipment increases the perceived technological uncertainty

5.2.4. Limited Knowledge Sharing in Aerospace

When researching the technological uncertainty, a recurring factor seemed to be the limited knowledge sharing within aerospace. Nine out of twelve respondents named that the limited knowledge sharing within the aerospace industry effects the adoption. The collaboration of prime aerospace manufacturers may provide new industry standards and quality criteria for future development (McAdam, O'Hare, & Moffett, 2008) which is happening through the Amerika Makes initiative, also named by R2. However, most companies within the industry are not sharing any of the information about the material data, the qualification process or parts being produced. Two manufacturing companies named that the limited knowledge sharing is slowing down the process since the industry is not willing to share any information regarding part/material qualification. Corporations are found to be reluctant to share information regarding the new technology, in fear of losing competitive advantage. Communication or knowledge sharing is a process in which participants create and share information with one another to reach a mutual understanding, thus the limited knowledge sharing will thus inhibit the diffusion of innovation (Rogers, 1995) Technological uncertainty results from unknowns regarding the technologies that might emerge from limited knowledge sharing (Sinha & Noble, 2008). Experimenting with a technology is found to reduce uncertainty regarding a technology (see section 5.2.3), so if companies whom are testing the technology, openly share their research results, it is expected that this will reduce the eventual uncertainty of the technology.

P7: Knowledge sharing concerning additive manufacturing will decrease the perceived technological uncertainty

5.3. Aerospace Additive Manufacturing Adoption Model

Adding the propositions, which have been explained in the previous 2 paragraphs, the Aerospace Additive Manufacturing Adoption Model (Figure 5.1) is created.

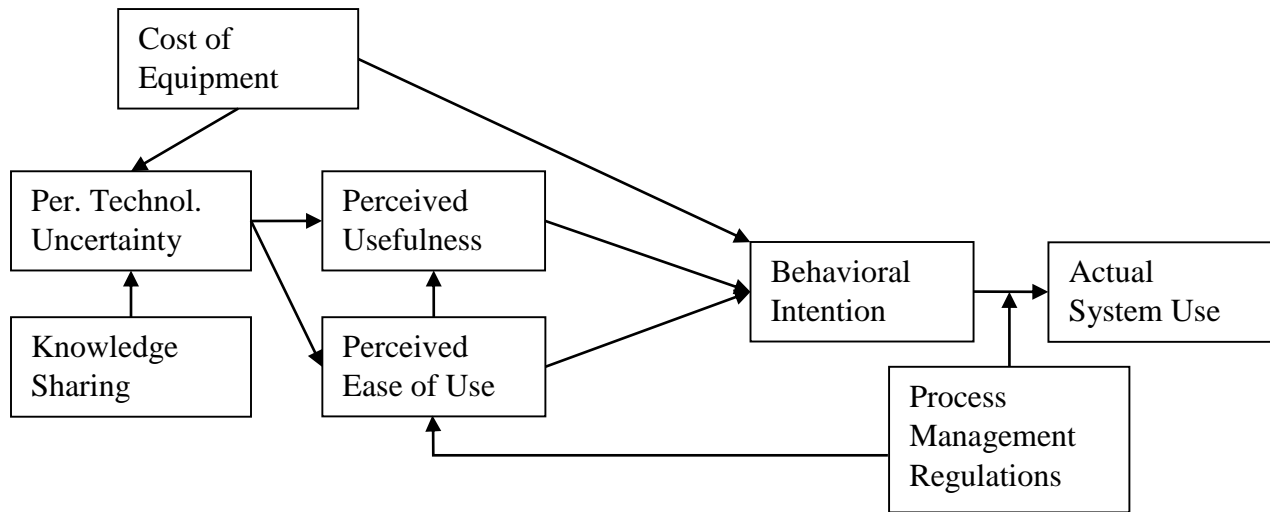


Figure 5.1: Aerospace Additive Manufacturing Adoption Model

The exploratory field study within the aerospace industry provided some important additional explanations to the industry’s adoption of additive manufacturing for adoption. Although a qualitative data cannot be used to test statistically the TAM model, the findings support the explanatory prowess of its PU and PEU constructs. Also, the findings provide indications of additional factors that may affect the industry’s behavioral intentions towards additive manufacturing which is in support of Sun and Zhang (2006) and Legris et al. (2003) about the need for TAM to be extended to include additional factors for specific context.

The proposed factors are unique to this model, meaning that the factors cannot simply be positioned within other adoption theories (for instance Rogers’ diffusion of innovation theory). Rogers defines five factors namely the: relative advantage, compatibility, complexity, triability and obserseabilty. Hwang (2005) stated that relative advantage is similar to the notion of usefulness, and complexity is similar to ease of use. Lastly knowledge sharing could be considered similar to obserseabilty. The difference between applying the factors in this TAM and to the IDT is that the inter-relationships defined in Figure 5.1, are unique to this model. IDT provides a framework, but the breadth and depth of the theory makes it difficult to frame a single study within the structure (Greenhalgh, Robert, MacFarlane, Bate, & Kyriakidou, 2004; Straub, 2009). Within the aerospace industry, there is a complex decision making process, where deciding to use a technology is not solely affected by the interested firm but also by the regulations that govern the industry. The effects of the process management regulations for instance, which have been modeled in AAMAM, will be hard to define within the IDT, since they do not solely affect adoption, but also variables within the model itself. Similar constructs could be added to the basic TPB framework, however, as explained in 2.3, the PU and PEU constructs have consistently outperformed the TPB. Additionally, inconsistency remain regarding the PBC factor, (also see Scannel et al. 2011; 2012 for the use of PBC in predicting shop floor manufacturing adoption.

In conclusion, the adapted TAM (AAMAM) is decided to fit best in predicting AM use for aerospace production, in regard to other adoption theories. The proposed model to prediction AM use (for production) within aerospace is given in Figure 5.1, answering the first research question. The barriers of adoption for the use of AM within aerospace have been explained in the previous section for 5.2.1 until 5.2.4., giving answer to the second research question.

5.4. Vaupell’s Additive Manufacturing Marketing Strategy

The last research question involves creating a marketing strategy for Vaupell. This is a system which will help Vaupell to think in a structured way and also make explicit their intuitive economic models of the business (Baker, 2003).

5.4.1. Additive Manufacturing Uses in Aerospace

During the interviews, participants were asked where the current technology was being used. The results from the interview are shown in Table 5.1. In Table 5.2, actual parts which are being created, are shown. The main use for 3D printing today in the aerospace and defense industry is making prototypes (Cohen, Sargeant, & Somers, 2014). Prototypes made by 3D printing, particularly in plastic, have matured into a mainstream, also known as rapid prototype fabrication methodology (Wohlens, 2014a). Much like CAD/CAM, additive manufacturing greatly increases the feasibility of designing, leading to the attitude of: “Let’s just 3D print it,” (Hiemenenz, 2013). The use of AM to produce tooling such as cast patterns, mods and dies is especially advantageous at low production volumes, as it can eliminate some of the expensive up-front costs caused by design changes tooling (Cotteleer, Neier, & Crane, 2014).

Table 5.1: Additive Manufacturing System Use

Plastics		
	Non-critical / non-structural components	C1, R1, R3, S2, U2, U4
	Interiors	R1, U1, U4
Metals		
	Engine applications	C1, S1, S2
	Structural	C1, C2, S1, U4
General		
	Tools (incl. molds), jigs and fixtures	R1, R2, S2, U2, U4
	Prototypes	C1, U2, S2, U4, R3
	Business/Luxury jet	U4, R1, R2
	Aerospace aftermarket/ MRO	C1, C2, U2, R2, R3, S2

Table 5.2: Parts Created Using Additive Manufacturing (interviews)

Plastic	
	Busing, Bearing (potential)
	Electronic cooling system/ Duct work
	Avionics
	Wingtips (potential)
	Storage racks
	Lavatory applications
Metal	
	Engine applications: fuel nozzle. (Potentially: rocket burners, blades, vanes)
	Brackets, valves

For plastic production applications two different technologies are used within the industry, selective laser sintering and fused deposition modeling. For the SLS technology, currently the only aerospace qualified materials is Nylon 11 (FR-106), however as mentioned in section 2.1, multiple production grade machines exist. Stratasy's Fortus machines are the only production grade FDM machines available today. Additionally, the most common material (Ultem 9085, since the resin delivers compliance with FAA FAR 25.853), is made by Sabic for Stratasy's. The companies have a collaboration, the Ultem filament spool is specifically created for the Fortus machines. Many of the parts manufacturing with SLS and FDM are similar parts. Due to the fact most of the produced parts are hidden parts (non-cosmetic surfaces), and do not need to carry a high load. Both SLS and FDM are not capable of producing structurally sound parts due to the lack of mechanical properties. This makes the options very limited, thus similar parts arise. For FDM however, desired cosmetics have been achieved with 9085 by filling, sanding and painting the rough (stepping) surface. The company *Custom Control Concepts* (e.g.) uses FDM in order to create video housings for private jets.

For metal production applications it is difficult to predict which technology is being used for the manufacturing of metal parts since the terms are used interchangeably. The most popular for creating engine parts has most definitely been EBM since GE, P&W and Rolls Royce have stated to use the EBM technology. For other applications within the aerospace industry it is more difficult to predict however. LaserCusing announced in a new report that they had been working together with NASA, Honeywell and Lockheed martin. The most popular material that has been used for the powder bed system is Ti6Al4V.

5.4.2. Vaupell's Marketing Strategy

From the interviews it was found that there were performance parameters which the companies look at to compare a technology (see Table 4.2). The most stated parameter by the manufacturing companies was the materials the technology was able to use. The aerospace industry is known for its high standards and product requirements. For some applications, the AM systems cannot produce parts that pass the requirements. In Appendix C, the AM technologies are explained in more detail, additionally showing the process and part performance per 3D technology. For plastics, there are currently two materials that can be used.

Vaupell is a plastics injection molding company, who are specialized in aerospace interiors, which is shows that there is an opportunity for them with plastic additive manufacturing systems. The additive manufacturing industry has a huge potential growth according to many consultants (B.1). The aerospace industry is about 12.3% of the total AM industry, and this part of the sector is also expected to grow within the next years, averaging a CAGR of about 20% (see B.2). The technology thus has a large grow potential, but high utilization underpins any technology investment (Hill, 2000). To be successful, the right target market has to be selected which fit within the benefits and limitations of the technology. The implementation of AM must be preceded by strategic alignment of the business, manufacturing and R&D strategy. The technology benefits must be linked to the capabilities required of the manufacturing unit, capabilities derived from the business strategy, viewed as the market-pull strategy to AM implementation. However, it is also proposed in line with the current resource-based view of the firm that investment in AM may be seen as a structural investment which will build new manufacturing capabilities, creating new business opportunities for the enterprise, the technology-push strategy.

The biggest barrier of adoption has been noted as the process management regulations, which are (partly) controlled by the OEMs. To Vaupell it is proposed to make contact with OEM in order to combine their efforts in order to explore the full use of AM within aerospace. If there are no process regulations in place for the technology, it can simply not be used. Combining efforts with an OEM allows for simultaneously expanding the range of available process management regulations, as well as explore possible parts to produce. This could also possible increase the knowledge sharing between these two companies. If both companies are open about their findings regarding the AM technology, both companies would benefit at reducing more uncertainties regarding the technology. Another proposition is to make a contractual partnership with an AM service/equipment provider within the industry. They have experience with the technology and are familiar with the capabilities and the materials it can use. Combined efforts of Vaupell and the service/equipment provider can uncover additional parts to be made with the technology. Vaupell has contacts within the interiors industry, and can present possible parts which could be produced by the technology, while the AM service provider can reduce uncertainties regarding the capabilities and thus state which opportunities are feasible.

6. Conclusion

Additive manufacturing has the ability to transform traditional manufacturing. AM facilitates manufacturing complex and internal structures, providing more product performance and reducing component weight, as well as allow for high volume customization due to the removal of tooling. There has been much development within the industry, in some sections more than other. The technology seems to have found its place for the prototyping business, however the transition to part production is still stalled.

Academic implications - For this research it was chosen to extend Davis' (1989) technology adoption model in order research the factors effecting the use of additive manufacturing as a production technology within the aerospace industry. Explorative qualitative research is done, by means of interviewing aerospace experts, in order to investigate the barriers and drivers of the adoption process within the aerospace industry. Currently, no TAM exist which has been validated in this specific context, therefore this research is aimed at proposing a model for researching AM use in aerospace. This research does not aim to validate the modified version of TAM as the majority of existing TAM studies does, but will apply TAM in a qualitative way and thereby following Sun and Zhang's (2006) suggestions. This research aims to create an understanding of the found adoption variables and their relation in the specific context of the phenomenon. Consequently, the outcome of this study aims to provide a starting point for future quantitative studies that could test and validate the findings as well as the modified TAM. This overall research approach follows the typical exploratory research paradigm, which very often marks the beginning of total research.

Managerial implications – Measures for predicting and explaining a new technology use has great practical value, both for vendors who would like to assess user demand for new design ideas, and for supplier managers within user organizations who would like to evaluate these vendor offerings (Davis, 1989). Towards solving the research problem, this research will try to reduce some of the uncertainties of additive manufacturing in aerospace and find barriers of adoption for using the technology in this industry. By doing more in-depth research about the market and technology, there will be more certainty about the return of investment for the technology and discover the future possibilities. A proposed market strategy based off of the research finding, has also be defined for Vaupell.

6.1. Limitations and Further Research

This research aims to create an understanding of the found adoption variables and their relation in the specific context. Consequently, the outcome of this study aims to provide a starting point for future quantitative studies that could test and validate the findings, the modified TAM, and additionally identify the most important factors that are influencing adoption. The conceptual model is based on the technology adoption model and the opinion of multiple industry experts. However, since this research targeted only additive manufacturing usage for production, further research involving all applications would be required to fully characterize the current additive manufacturing adoption scene in aerospace. The model is not quantified in the sense that the factors have not gotten any weights and the model has not been quantitatively tested. Therefore a possibility for future research is to quantitatively test the model with a larger sample size.

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Appendix A. Available 3D Printing Technologies

The ASTM international Committee F42 on additive manufacturing technologies defines additive manufacturing as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods (Wohlers, 2014a).

Additive manufacturing, in a nutshell, is the process of adding layer upon layer to create 3-dimensional objects. Using 3D modeling software, a model can be created which is sent to the printer. Advanced manufacturing technologies serve a wide range of users and purposes, and include any computer-based equipment used to design, manufacture or control information related to the development and production of a product (Lewis & Boyer, 2002; Small, Planning, justifying and installing advanced manufacturing technology: a managerial framework, 2007).

With the technology available today, it is already possible to 3D print plastics, metals, composites and ceramics. Terry Wohlers classifies the different printing technologies in 6 different groups (see the list below).

1. Material extrusion: An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
2. Material jetting: Inkjet print heads are used to jet melted wax materials onto a build platform. The material cools and solidifies which allows to build layers on top of each other.
3. Binding jetting: Inkjet print heads apply a liquid bonding agent onto thin layers of powder. By gluing the particles together, the part is built up layer by layer.
4. VAT photopolymerization: an additive manufacturing process in which sheets of material are bonded to form an object.
5. Powder bed fusion: an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
6. Directed energy deposition: An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as the material is being deposited.

Appendix B. The promise of this new technology

In this appendix, figures from multiple sources are shown, depicting the total size of the additive manufacturing market, as well as the growing interest in the technology.

B.1. Additive Manufacturing: A Growing Industry

The additive manufacturing is getting increased attention, not only from the media but market researches, journal articles and kick-starter projects as well (as seen in Figure B. 1).

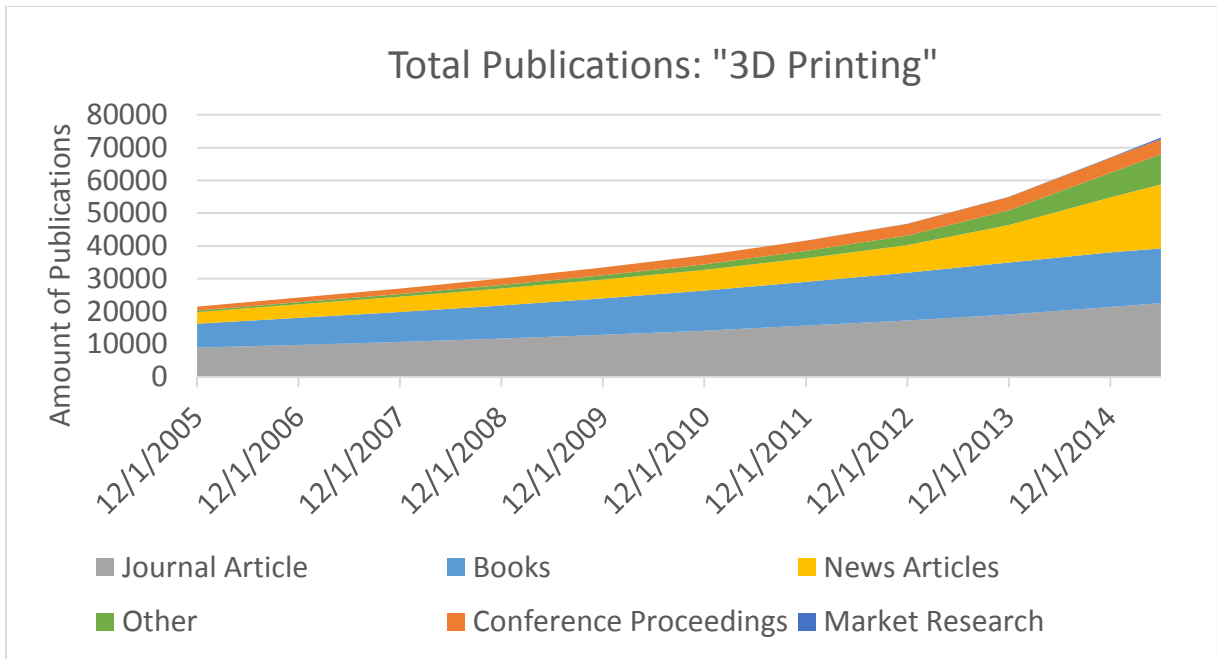


Figure B. 1: Total publications containing “3D printing” – based on TU/e online library

Interestingly, the amount of metal 3d printing publications has increased compared to the amount of polymer 3d printing publications the last few years (Figure B. 2).

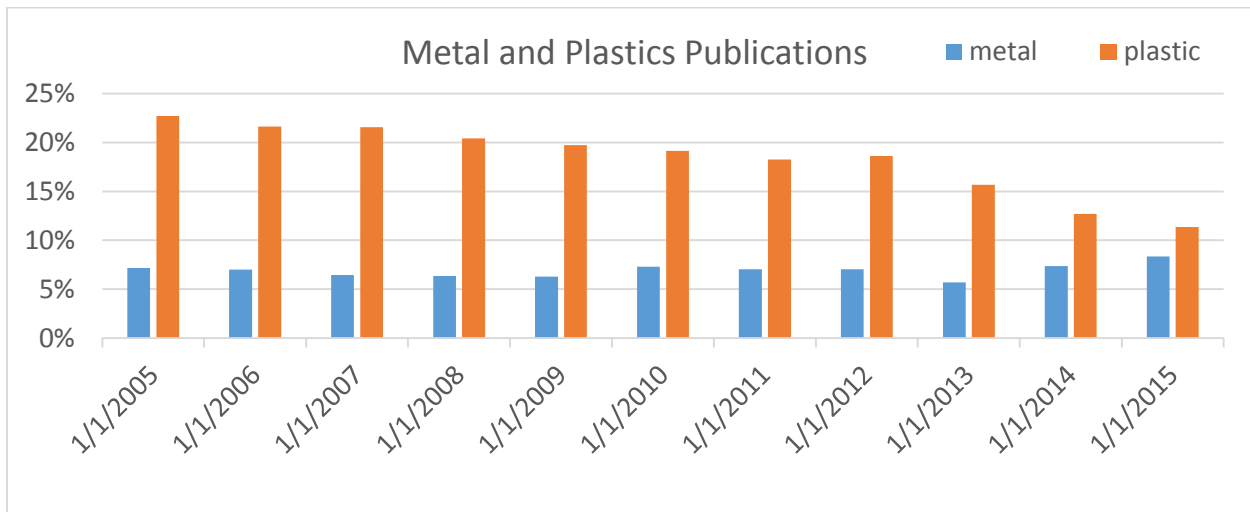


Figure B. 2: Metal vs plastic 3D printing publications – based on TU/e online library

The publication growth trend can also be related to the growth of the industry itself. Over the past 25 years, the industry has seen a 27% CAGR with an average 32.3% growth the last three years (Reuters, 2015). McKinsey and PwC have done surveys asking manufacturing firms about their predictions for 3D printing (Table B. 1 and Table B. 2). Both surveys show that most companies think the importance of additive manufacturing will increase in the next couple years.

Table B. 1: PwC survey for the adoption of 3D printing for production (n=114)

	Low volume	High volume
Very unlikely	18%	33%
Slightly unlikely	8%	29%
Moderately likely	25%	17%
Likely	34%	13%
Very likely	15%	8%

- (PwC, 2014)

Table B. 2: McKinsey 3D printing survey for manufacturing firms (n=100)

Highly relevant today	10%
No highly relevant today, but will gain relevance within 3 years	33%
Might be relevant, but will need more information.	12%
Not relevant now, and won't be in the next 3 years	5%

- (Cohen, D.; George, K.; Shaw, C., 2015)

*Of all respondents 40% were not familiar with 3D printing beyond press coverage

In multiple reports, the market is said to have enormous growth potential with predicted CAGR levels fluctuation between 15 and 47 percent until 2020, now that the main barriers of entry for 3D printing are being addressed (Canalys, 2013; Gartner, 2014a; IDC, 2014; McCue, 2012; IBISWorld, 2014; Coykendall, Cotteleer, Holdowsky, & Mahto, 2014). In order to get an estimation of the total market size, the prediction of multiple sources were used⁹. The market estimations of the current and future situation are given in

Table B. 3.

⁹ Sources: AMR, CCS, IDC - (Columbus, 2015); (Canalys, 2013); Credit Suisse - (Wile, 2013) (Gartner, 2014a); (JP Morgan Research, 2013); (Market and Markets, 2014); (Morgan Stanley Research, 2013); (SmarTech, 2014b); (Vicari, 2015); (Wells Fargo, 2014).

Table B. 3: Forecast of AM market size [Billion \$]

Billion [\$]	2012	2013	2014	2015	2016	2017	2018	2020	Growth	CAGR up to
AMR	2.3						12.8	21.0	33.0%	2020
Canalys		2.5					16.2		45.7%	2018
CCS		1.2					4.8		33.0%	2018
Credit Suisse	2.2	3	3.6	4.3	4.9	6.7	7.5	11.5	22.9%	2020
Gartner				1.6			13.4		103%	2018
IDC	1.5					5.4			29%	2017
JP Morgan								7	18.0%	2020
Market and Markets	1.841		3.77					8.43	14.4%	2020
Morgan Stanley								21.3	34.0%	2020
SmarTech		2	2.4	3	3.95	5	6.8	10	25.8%	2020
Vicari		2.25	2.6	3.05	3.65	4.3	4.75	6.5	16.4%	2020
Wells Fargo	.225	2.2				5.7			26.9%	2017
Wohlers	2.28	3.07	4.08	5.43	7.22	9.70	12.8	21.0	33.0%	2020

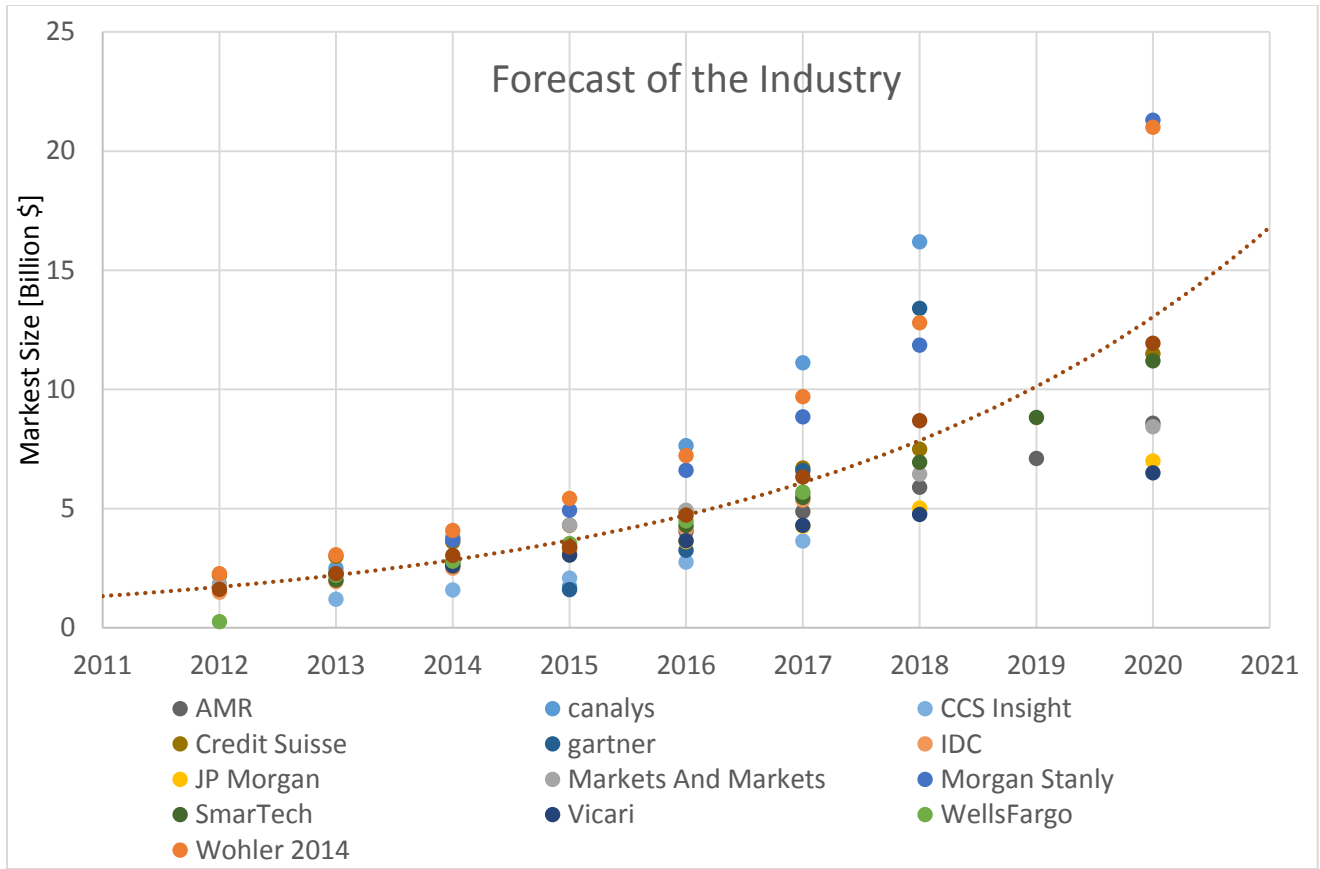
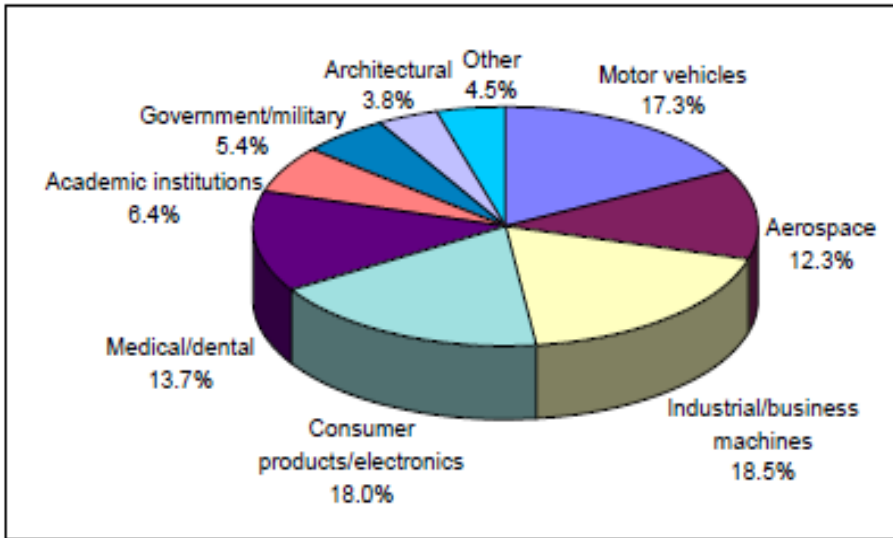


Figure B. 3: Forecast of the Industry

The actual market size was created by taking the average of all prediction values per year. In order to make sure all different sources had the same input power, the ‘missing’ data points were calculated by applying the average (or give) CAGR. Morgan Stanly for instance only provided the market size for 2020. Using the CAGR, the data points up till 2014 could be calculated. All points, were thereafter plotted in Figure B. 3 combined with a trend line. The trend line was calculated by going through the calculated averages with as result that the market has a size of 2.86 Billion dollars in 2014, with a CAGR of 28.7% until 2020.

B.2. Additive Manufacturing in Aerospace

The market segmentation (according to Wohlers) is given in Figure B. 4. The aerospace and defense industry recorded to account for 10.2% of the total 3D printing revenue of 2.2 billion dollar in 2012, and grew to 12.3% of the industry in 2013, with increased funds being put into research and development (3ders, 2014; Mitchel, 2013; Powley, 2013; 3ders, 2013). The global economy is worth about \$70 trillion, and manufacturing accounts for more than 15%, which is \$10.5tn. If AM grows to capture just 2% of this global manufacturing market, that’s \$21bn (Wohlers, 2014a).



Source: Wohlers Associates, Inc.

Figure B. 4: Market Segmentation according to Wohlers

In Figure B. 5 below, four different consultancy firms have made a prediction about the average market growth for additive manufacturing.

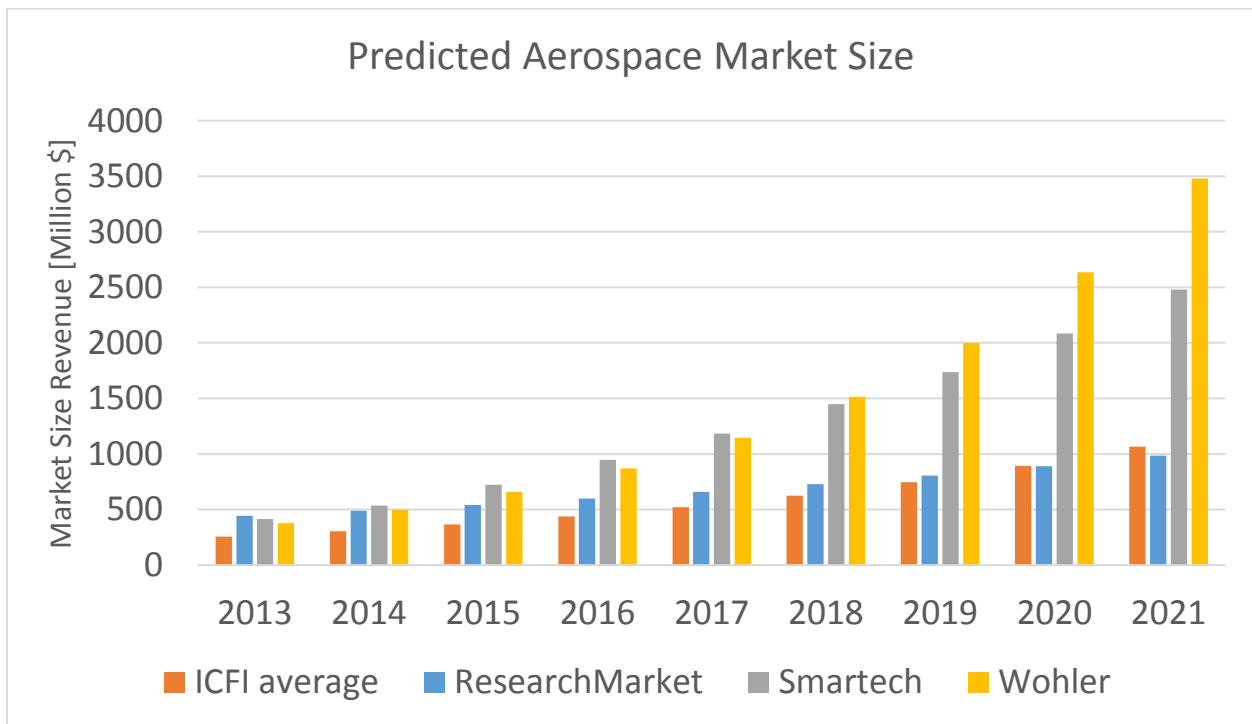


Figure B. 5: Prediction of Additive Manufacturing (in Aerospace) Market Size

There is a general overlap between the predictions that the overall market size (in 2014) was estimated to be 500.000 in general. Except for ICF international whom is well below (note that two different prediction were given pessimistic and optimistic and an average was chosen). Little consensus for the CAGR however, ranging from 10% to 32%. According to Wohlers, the aerospace industry has grown 42% since 2011, but the average industry growth is taken to predict the market size in 2014 (Table B. 4).

Table B. 4: Consultant AM Market Size Predictions

	Market Size 2014	% of market	CAGR Aero	CAGR All
ICF international (2014) at: Singapore Airshow	\$304,932,000		19.6%	
SmarTech (2014c) at: Cellular3D	\$535,600,000	20.0%	25.1%	27.0%
Research and Markets (2014) in: Materials Today	\$488,725,000	13.0%	10.5%	14.4%
Wohlers (2014)	\$498,445,000	12.3%	42%	32.0%

An interesting comparison can be made to see how big of a part aerospace play in the entire AM industry. This is given in the table above.

Appendix C. AM production technologies: In depth

C.1. FDM

The process and material characterization is explained below.

C.1.1. The process

Parts created with fused deposition modeling are made through an extrusion process. The extrusion means that the build material is forced out through the nozzle in a semi-solid state by using pressure. After the extrusion, the material fully solidifies in order to remain its shape. In addition, the material bonds with the preceding material that has already been extruded. During the part fabrication, material flow is stopped while scanning across the build platform and started again after that. After the layer is completed, either the extruder system moves upwards or the build platform moves downwards before the next layer is built (Gibson, Rosen, & Stucker, 2010); (Kruth, Mercelis, Froyen, & Robmouts, 2005); (Peltola, Melchels, Grijpman, & Kellomaki, 2008). The material inside the chamber is kept in a semi-solid state. However, the temperature should be kept as low as possible. The reason for that is that some polymers degrade quickly at high temperatures and they could also burn, leaving a residue inside the chamber. This residue may contaminate the upcoming materials. The high temperature inside the chamber also requires additional cooling after the extrusion to ensure the quick enough solidification (Gibson, Rosen, & Stucker, 2010). The main FDM disadvantages, include the seam line between layers, the required

supports, long build time, and delamination caused by temperature fluctuation (Huang, Liu, Mokasdar, & Hou, 2013).

C.1.2. Material characterization

Materials that are used with FDM machines should be polymers that are rather amorphous than crystalline (Table C.1). Amorphous polymers can be extruded as a viscous paste since there is not an exact melting point, leading to a semi-solid material that softens when the temperature is gradually increased. In other words, the material viscosity is suitable for the extrusion since the extruded material maintains its shape and size and solidifies fast enough. This also enables the bonding of the newly extruded material and previously extruded material. Another important benefit is the mechanical properties of the fabricated parts. The parts fabricated with FDM are the strongest inside the polymer-based AM processes (Gibson, Rosen, & Stucker, 2010).

Table C. 1: Available Aerospace Grade Materials for FDM

Material	Type	
Ultem (9085, 1010)	Amorphous	Sabic
Nylon 12	Semi-crystalline	Stratasys
PEEK	Semi-crystalline	INDMATEC

Unlike in most manufacturing technologies, the values of parameters of the additive manufacturing process can be more significant than the properties of the part material – two different sets of process parameters applied to the same geometry can result in obtaining two products of entirely different properties, e.g. strength or accuracy. Each set of the process parameters: orientation of the product in the working chamber, layer thickness and method of filling of the layer contour, will make the part structure look different, which will result in different values of coefficients such as strength, accuracy or surface quality

Moreover, the obtained properties can be much different if only one parameter of the process – e.g. the part orientation – is changed. There are two main reasons for this: the first one is the weak bond between layers in the FDM parts, which causes the strength characteristics to decrease, even dozens of times, in comparison to the injection molded samples. The second reason is the volume error, which is always present at the FDM samples, since they are not monolithic. The volume error is the main reason why even the best parts made by the FDM process will never be as strong as the injection molded parts out of the same material, even if the weak interlayer bond effect is reduced to a minimum, the volume errors still make the effective loaded area smaller than in case of the fully monolithic part, which increases the overall stress and decreases strength. This difference is the most visible for the impact strength tests. FDM products have many material discontinuities inside, which can act as notches during impact tests, this is why even the best FDM sample achieved cannot reach the impact strength of the monolithic sample produced by injection molding (Gorskim, Wichniarek, Kuzcko, Zawadzki, & Bun, 2015).

C.1.3. Test for Ultem 9085

To understand the comparative performance of AM parts to traditional injection molded specimens, the researchers at DMRC generated standard stress-strain curves. A stress-strain curve shows the relationship between the deformations (strain) of a material exhibited as a result of tensile loading (stress). The first chart shows the stress-strain relationship of Ultem 9085 test specimens printed with FDM versus the same test specimen manufactured with injection molding. The injection molded data is represented by the blue line, and the solid red line represents FDM data from a sample oriented in the X-direction during printing. The FDM part printed in the X-direction performed equivalently to the injection molded part in stress, but fractured at a much lower strain (Figure C.1). DMRC optimized the build for the x-tensile test, showing that build parameters definitely affect build strength.

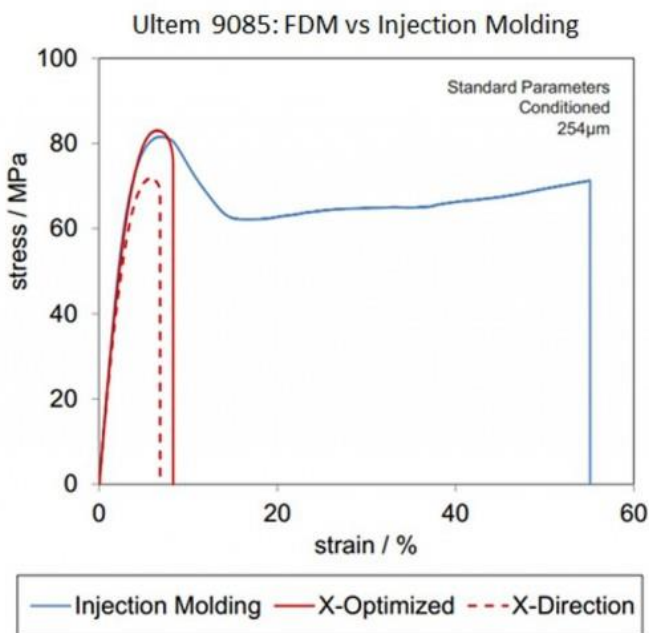


Figure C. 1: Tensile Strength vs Strain of Ultem 9085 – Injection Molded vs 3D Printed

Another study published in *Polymeric Materials* 2010 by DMRC also tested the part quality of Ultem 9085 material. The results are shown in Figure C.2 and Figure C.3. The parts produced are highly anisotropic and that the properties in z-direction are (ductility wise) less than half of the x direction. The experimental observations indicate reduction of strength, ductility, and toughness of FDM processed ULTEM 9085 compared with the injection molded ones. This fact might be due to the molecular deterioration of the polymer as result of heating during the deposition process.

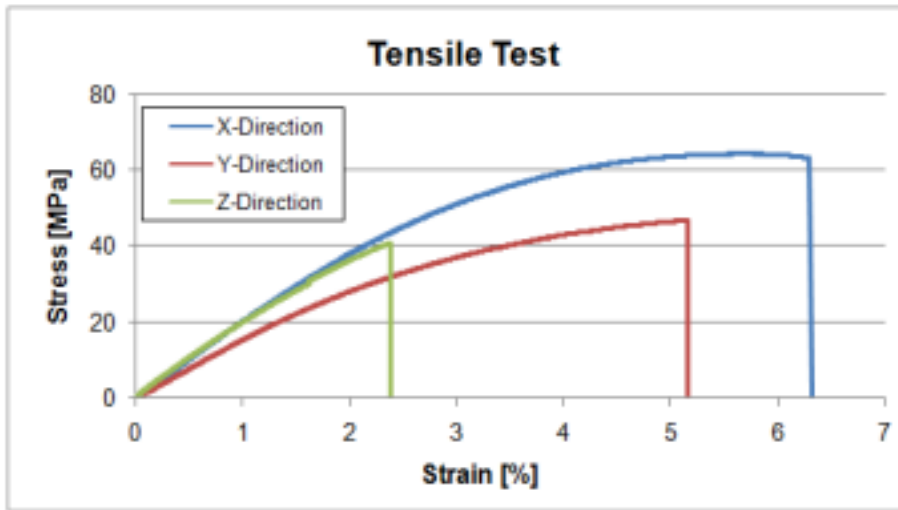


Figure C. 2: Tensile Strength vs. Strain of 3D Printed Ultem 9085

<i>Direction (tested parts)</i>	<i>X (12)</i>	<i>Y (12)</i>	<i>Z (40)</i>
Young's modulus [MPa]	2033,54 ± 64,73	1461,41 ± 194,40	2092,26 ± 129,92
Tensile stress at break σ_B [MPa]	61,34 ± 1,31	45,67 ± 1,38	40,71 ± 2,07
Tensile strength σ_M [MPa]	63,25 ± 1,07	45,87 ± 1,32	40,75 ± 2,06
Tensile strain at break ϵ_B [%]	6,35 ± 0,28	5,0 ± 0,45	2,29 ± 0,19
Tensile strain ϵ_M [%]	5,65 ± 0,08	4,99 ± 0,44	2,29 ± 0,19

Figure C. 3: Mechanical Properties of 3D Printed Ultem 9085

C.2. Selective Laser Sintering

C.2.1. The process

Laser sintering (LS) of polymer materials is a process that has been developed over the last two decades and has been applied in industries ranging from aerospace to sporting goods. The build takes place inside a nitrogen controlled atmosphere on a heated platform that indexes down about 0.1–0.15 mm after each layer is sintered. During a typical PA-12 build the part bed is heated to a point about 12 °C below the crystalline melting endotherm temperature. This is to prevent steep thermal gradients that would occur when the laser melts the material, which can lead to distortion of sintered parts and build failure. A direct beam CO₂ laser applies energy to the material to take it above the endothermic melting range to a point where the material is able to flow under low stress, to facilitate sintering. The un-sintered powder surrounding the part acts as support. This loose material is brushed off the part when it is cleaned following completion of the build cycle. Some of the more important process variables affecting the development of sintering include bed temperature, layer thickness, laser power, scan speed and scan spacing (Vasquez, Majewski, Haworth, & Hopkinson, 2014).

C.2.2. Material characterization

LS polymer feedstock materials tend to be semi-crystalline polymers such as polyamide (PA, or “nylon”), and more recently polystyrene (PS), polyetheretherketone (PEEK), and polyether block amide (PEBA). Semi-crystalline polymers have large regions of crystalline order connected by short amorphous regions. Crystallites usually take the form of spherical crystals termed “spherulites” which grow out of distinct nuclei during solidification, with the number of nuclei increasing with increasing undercooling below the melting point as discussed by (Argon, 2013)

Amorphous Laser Sintering: The relatively sharp melting endotherm of PA12 allows the polymer powder to be heated to just below the melting point throughout the build process cycle. This is more difficult for amorphous materials because of the more gradual transition towards the required, predominantly viscous deformation behavior during sintering, as temperature increases. Amorphous materials do not show distinct transitions, so that changes in thermal and flow behavior are more gradual. This can make laser sintering much more challenging because small percentages of the material may start to flow at lower and more variable temperatures, which could inhibit powder flow across the part bed due to the temperature sensitivity of thermal and viscous characteristics. Thus for amorphous polymers, the relative densities of the SLS parts are very low, and there are many voids inside the SLS parts.

Semi-crystalline sintering: For semi-crystalline polymers, the relative densities of the SLS parts are relative higher, and the loosely packed powder is sintered into a near-fully dense part. Both LS and injection molding (IM) produce parts with similar yield strengths, though the ductility of LS is generally an order of magnitude lower than IM parts as shown by Ajoku et al. (2006) and Griessbach et al. (2010). IM parts have a fundamentally different microstructure than LS parts, since IM parts experience shear stresses during processing that result in aligned lamellar crystalline regions and inter-twined molecular chains, see Zhou (2013). Rapid cooling in IM also results in reduced crystallinity compared to LS parts, as discussed by Hooreweder et al. (2013). Other phenomena that occur in LS are the formation of porosity, regular porosity between powder layers resulting in weak planar interfaces, and the presence of particle “cores” of a different crystallographic nature than the surrounding crystal structure; see Majewski et al. (2008). (Bourell, Watt, Leigh, & Fulcher, 2014)

Elongation at fracture data for Z tensile bars show significant scatter, and the values are about an order of magnitude lower than typical values for IM parts. Most researchers attribute this behavior to particle coring, periodic porosity, and inter-layer porosity that can result in particularly poor properties in the Z direction. These problems primarily arise as a result of inconsistent powder deposition and incomplete particle melting. Incomplete melting is complicated by the fact that commercial LS machines often have uneven heating and cooling of the powder bed surface. This gives rise to local hot and cold spots that can result in insufficient heating (porosity, particle coring), or excessive heating (thermal degradation). (Bourell, Watt, Leigh, & Fulcher, 2014)

C.2.3. Tests with Nylon 12

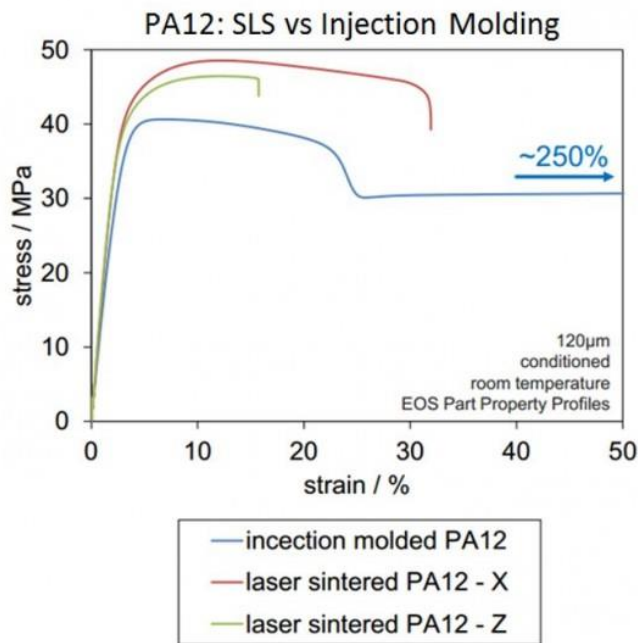


Figure C. 4: Tensile Strength vs Strain for Nylon 12 – Injection Molded vs 3D Printed

Figure C.4 compares the tensile properties of PA12 fabricated via SLS versus parts manufactured with injection molding from a study done by DMRC. The data representing the sample printed in the X-direction is shown in red, the sample printed in the Z-direction is shown in green, and the injection molded sample is in blue. Both the SLS print orientations demonstrated higher stress than the injection molded part, but, like the FDM part, ruptured at far lower strains. SLS however does show increased isotropic properties however.

C.3. Metal AM

For metals there are currently three different technologies being adopted, namely DMLS, SLM and EBM from respectively EOS; SLM solutions and Concept Laser; Electron Beam melting. In short, these are the main differences:

- **DMLS** refers to the process as applied to metal alloys. But what sets sintering apart from melting or "Cusing" is that the sintering processes do not fully *melt* the powder, but heat it to the point that the powder can fuse together on a molecular level.
- **Selective Laser Melting or Laser Cusing** can do the same as sintering--and go one further, by using the laser to achieve a full melt. Meaning the powder is not merely fused together, but is actually melted into a homogenous part.
- **EBM** is very similar to selective laser melting. Like SLM, it produces models that are very dense. The difference between the two techniques is that EBM uses an electron beam rather than a laser to melt the metal powder.

3D printing of metal can result in uniform microstructures due to rapid solidification, in contrast to the traditional metal casting and forging that require metal to cool from the outer surface to the core. This allows engineers to control the object's strength, hardness, springiness, flexibility and ability to support stress. As a rule of thumb, with decreasing width of α -lamellae, yield strength increases and with increasing yield strength fatigue limit increases. In general, all microstructural parameters that increase yield strength and/or reduce slip length should improve the part strength (Welsch & Boyer, 1998). Annealed samples can reach in properties of wrought material z-direction, the samples tested in x-direction and the as-built samples tested in z-direction are comparable to cast material.

C.3.1. DMLS

The general idea of DMLS is that fine metallic powders are sintered together using a laser beam. This happens in an inert environment (argon gas for instance) in order to prevent oxidation. Below, studies examining the microstructure of DMLS parts are investigated.

Investigating Porosity: Comparing the laser spot size (0.4 mm) with the maximum particle size (0.178 mm), it is recognized that both are of the same order. After a local fusion of particles, the heterogeneity cannot be eliminated for that the diffusion region is too small and the existence time of liquid phase is too short. Some unmelted particles are often found in the sintered body. When the laser beam melts a layer of powder to the lower layer, seams between two layers are created. These seams, in the presented study (of iron-based material), were rich of pores and contaminations giving the evidence of obvious interface boundaries and the layer texture (Wang, Bergstrm, & Burman, Characterization of an iron-based laser sintered material, 2006). The investigation of DMLS copper alloys (Khaing, Fuh, & Lu, 2001) showed the same phenomenon, but with much higher porosity 30–45%, and 23% (Yang, Loh, Wong, Fuh, & Lu, 2003).

The influence of particle packing on the heterogeneous microstructure could be minimized by refining the metal powder, increasing laser power and decreasing scan speed to provide more fusion heat and keep elemental diffusion faster and longer. Increasing the beam size could also make the material more homogenous, but at the cost of dimensional accuracy (Wang, Bergstrm, & Burman, Characterization of an iron-based laser sintered material, 2006). As observed by Simchi (2006), finer particles provide a larger surface area to absorb more laser energy, leading to a higher sintering rate. However, before starting the additive process, it is fundamental to sieve the powder to ensure a maximum particle size in agreement with the layer thickness when filling the DMLS machine. During the DMLS process, on account of the short interaction times and high conductive heat transfer rate, a very fine microstructure originates (Manfredi, et al., 2013).

Mechanical properties of DMLS samples: It was observed that the AlSiMg DMLS samples have isotropic properties when built on the xy-plane, as expected from the scanning strategy adopted in Manfredi et al.'s study. Considering the samples built along the z axis direction, there are some differences, but they could be considered negligible. Compared to investment casted metals, the ultimate tensile strength is a little higher, while for the elongation at break, there is an enhancement on the xy-plane and a decrease along the build direction. It is well known that this is the weakest direction for samples produced by DMLS. However, the elongation at break is only slightly lower than conventionally processed material (Manfredi, et al., 2013). A study conducted by (Brandl,

Leyens, & Palm, 2009) showed that all as-built powder-bed samples and the annealed samples tested in xy-direction met properties of wrought material. The annealed samples tested in z-direction did not meet properties of cast material. Yu et al. (2012) have studied the mechanical properties of Ti6Al4V for a laser based powder deposition process and discovered similar material properties as for the DMLS sample. The microstructure showed α' -martensite phase with a high strength ($R_{p0.2} = 976$ MPa, $R_m = 1099$ MPa) but poor elongation to fracture (4.9 %). Parts made using DMLS in Ti6Al4V showed (Chauke, Mutombo, & Kgomom, 2013): Yield and ultimate yield strength of about 60%, and elongation of about 20% compared to traditional manufactured metal parts in a different study down however.

In conclusion, the parts created with DMLS are not fully dense due to the porosity. The properties of the parts can reach cast-metal properties after annealing the parts. The z-direction is (in general) weaker than the xy plane, have worse ductility than cast meta.

C.3.2. SLM

(Campanelli, Contuzzi, Angelastro, & Ludovico, 2010) The laser must have a greater power than with DMLS and at the end of the process the manufactured objects are quite similar to series production. Some claim it does not require special surface finishes and may be subjected quietly at conventional machining. In order to reach a high density, the metallic powder particles are fully molten, laser melting process is accompanied by the development of residual stresses, that derive from high thermal gradients in the material. These stresses can cause distortion of the part, cracks or delaminations ((Fishcer, et al., 2003); (Pohl, Simchi, Issa, & Dias, 2001); (Nickel, Barnett, & Prinz, 2001)). Another undesirable phenomenon is the vaporization that occurs when the bed of powder is irradiated with high energy intensity. During the laser melting process, the temperature of the powder particles exposed to the laser beam exceed the melting temperature of the material. A further increase in temperature (about twice the material melting temperature) causes the evaporation of the powder, so, there are a fast-moving expansion of evaporated particles, which generate an overpressure on the melted zone and the material is ejected from its bed (Hauser, Childs, Taylor, & Badrossamay, 2001).

Another problem that may occur during the SLM process is the "balling" or spheroidization phenomenon, i.e. the formation of isolated spheres with a diameter equal to the laser beam focus, which inhibits deposition and decreases the density of produced part. It occurs when the molten material is unable to fully wet the substrate because of surface tension. The phenomenon is caused by an excessive amount of energy, which gives to the melted powder a too low value in viscosity ((Nickel, Barnett, & Prinz, 2001); (Kannatey-Asibu, 2009); (Niu & Chang, 1999)

Recently, metal additive-manufacturing machines have become available with powers up to 1000W, as described in the work of Niendorf et al. (2013) on the microstructure and mechanical properties of 316L stainless steel at powers of 400W and 1000W. But, this increasing laser power is accompanied with the increasing likelihood that the mechanism for melting of the powder in the powder bed and the fusion of that molten material to underlying material could transition from being controlled by thermal conduction to being controlled by the so-called keyhole mode melting as described in Rai et al. (2007). In keyhole-mode laser melting, the power density of the laser beam is sufficient to cause evaporation of the metal and formation of plasma. Metal evaporation

causes the development of a vapor cavity that enhances the laser absorption. This enables the laser beam to drill to a far deeper depth than is possible in conduction controlled mode. Collapse of the cavity can leave voids in the wake of the laser beam, as shown in Madison and Aagesen (Madison & Aagesen, 2012).

Reaching full density requires balancing laser power, scan speed, beam size, and layer thickness to ensure on one hand that the layer fully melts and on the other hand that the melting does not result in development of a large amount of voids due to the keyhole mode mechanism. Results show (for 316L steel) that, at higher power values, there is a large range of scan speeds over which the relative density remains >99%, with the density reducing rapidly at high speeds due to insufficient melting, and less rapidly at low speeds due to the effect of voids created as the process enters keyhole mode (Kamth, El-dasher, Gallegos, King, & Sisto, 2014).

C.3.3. EBM

EBM produced surfaces are reported to have a quite rough morphology, containing a rippled structure with visible sintered powder grains. For products where a smooth surface is essential, the as-produced surface roughness resulting from EBM may be unfavorable. The reason for the rougher surface morphology in the EBM process is that it is also affected by the spot size (Safdar, 2012). The spot size is in turn affected by the functionality of the electron gun and the magnetic coils that shape the ebeam (Goldsteinm, 2003). The size of the e-beam will also be affected by the negative charge build up that is taking place in the process.

When producing smaller components (<1) with high levels of detailing the accuracy of the product dimensions will be affected and details might be lost. Since EBM uses fused layers stacked on top of each other to buildup parts, the layer thickness influences the resolution of the build. Early versions of EBM process equipment used 100 μm as the standard layer thickness. The current standard layer thickness has been reduced to 50–70 μm . A powder particle size of 45-100 μm is currently used (ArcamAB, 2015). For Selective Laser Melting (SLM), which is an AM process that uses a laser as the energy source, a finer surface morphology can currently be obtained than with EBM. Murr et al. have compared surfaces from both EBM and laser manufactured parts (Murr, 2009). In SLM a thinner layer thickness compared to EBM, normally 20-30 μm is used together with a powder size of 25-45 μm . The use of powders with smaller sizes will make it possible to use a thinner layer thickness and thereby obtain a finer surface morphology.

Increasing the melt scan rate from 100 to 1000 $\text{mm}\cdot\text{s}^{-1}$ in the EBM fabrication of oriented Ti-6Al-4V cylinders increases the cooling (solidification) rate and this results in a decreasing α -phase acicular grain width as well as an increasing proportion of α' -martensite plate production. This decreasing microstructure dimension (or refinement) increases the microindentation hardness (HV) for the horizontal built cylinders. Correspondingly, increasing melt scan rate increases the porosity by creating unsintered powder volumes within the layers (Puebla, et al., 2012). After HIPping, wrought like properties can be obtained (Rengers, 2012) for xy and z plane. Elongation is usually a little worse, however this shows the promise of this new technology.

C.3.4. Comparative Studies

In both the SLM/DMLS process, because of rapid heating and cooling of the powder layer, residual stresses are developed. In EBM, high build chamber temperature (typically 700- 9000C) is maintained by preheating the powder bed layer. This preheating reduces the thermal gradient in the powder bed and the scanned layer which reduces residual stresses in the part and eliminates post heat treatment required. Preheating also holds powder particles together which can acts as supports for overhanging structural members. So, supports required in the EBM are only for heat conduction and not for structural support. This reduces the number of supports required and allows manufacturing of more complex geometries. Powder preheating feature is available in very few laser based systems where it is achieved by platform heating. In addition, entire EBM process takes place under vacuum since, it is necessary for the quality of the electron beam. Vacuum environment reduces thermal convection, thermal gradients and contamination and oxidation of parts like titanium alloys. In SLM, part manufacturing takes place under argon gas environment for reactive materials to avoid contamination and oxidation whereas non-reactive materials can be processed under nitrogen environment. So it can be expected that EBM manufactured parts have lower oxygen content than SLM manufactured parts. In spite of having these advantages, EBM is not as popular as SLM because of its higher machine cost, low accuracy and non-availability of large build up volumes.

This study (Rafi, Karthik, Gong, Starr, & Stucker, 2013) compared the microstructure and mechanical properties of Ti6AL4V made in a DMLS process (EOS M270) and an EBM process (Arcam S400). The microstructure in the DMLS samples were martensite structure, so called α' (α'')-phase. The material shows excellent strength but poor elongation in fracture. When using EBM each layer is pre-heated with the electron beam to keep an even temperature of 600-650°C. Even though the electron beam intensity is higher than the laser beam, and the scanning speed is faster, it will still cool down slower because of the elevated temperature. This provides a different microstructure, so called α and β phase in a Widmanstätten structure. The as built material from the EBM process is not as strong as the laser material, but the fracture elongation is higher. However, both techniques showed better strength than the minimum requirements in AMS 4911 but to low fracture elongation especially for DSML samples. The DMLS samples showed a bigger spread in quality than the EBM samples. For both techniques the material was slightly stronger in the plane perpendicular to the building direction.

The most popular for creating engine parts has most definitely been EBM since GE, P&W and Rolls Royce have stated to use the EBM technology. For other applications within the aerospace industry it is more difficult to predict however. LaserCusing announced in a new report that they had been working together with NASA, Honeywell and Lockheed martin. Among the available metals for additive manufacturing are aluminum alloys, titanium alloys, nickel-based superalloys, and a range of steels. A summary comparison between DMLS, SLM and EBM is shown in Table C.2.

Table C. 2: Comparison of Metal Powder Bed Fusion

DMLS	SLM	EBM
Sintering of metals	Melting of metals	Melting of metals
Cheapest		Little residual stress due to elevated room temperatures
Mainly alloys	mainly pure parts	Mainly pure parts
200-400w laser	400w - 1000w laser	3000w laser
		Fastest
95% - 99%	99-99.9%	99-99.9%
Main Problems		
Porosity	Spheriodization	Worst cosmetics
Stresses during melt	High cooling rates, high residual stresses	Most expensive of the three

- Powder melting vs. powder sintering
 - Actual melting creates less porosity, and better part properties (Tensile strength, Ductility)
 - This makes the technology more expensive due to higher laser requirements and energy consumption.
 - Spheriodization and metal evaporation can also occur due to higher temperatures compared to DML
- EBM has the highest energy source, an electron beam
 - Metal melts faster than the SLM and DMLS processes
 - After HIPing, the parts can have wrought metal characteristics
 - Worse Cosmetics than SLM and DMLS, due to higher concentrated energy (more rippling in the metal)
 - Technology is more expensive

In spite of having these advantages, EBM is not as popular as SLM because of its higher machine cost, low accuracy and non-availability of large build up volumes.