Additive Manufacturing Applications and Implementation in Aerospace

by
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Abstract

Many aerospace companies are turning to additive manufacturing solutions to streamline current production processes and open opportunities for on-demand producibility. While many OEMs are drawn to the appeal of the benefits that additive manufacturing brings, they are beginning to understand the difficulties in what it takes to realize those benefits. This paper analyzes additive manufacturing from an industry perspective down to a company perspective to develop a deeper understanding of the practical use cases as well as the various challenges a company faces should they choose to enter this market.

This study begins with market research on the additive manufacturing and aerospace industry before honing in on a several use-case parts from rotary aircraft. Selection criterion were created and applied to analyze the value that additive manufacturing would bring in comparison to that of conventional methods, ultimately determining its feasibility for additive manufacturing. This study applied the selection criterion to various parts of differing functions among the aircraft, resulting in a group of candidate parts. An evaluation method was created and applied to provide an objective assessment on the candidate parts. Initial insights show that additive manufacturing favor casted parts with features that can be optimized to increase performance and reduce costs and weight. In addition, aerospace has the best product mix of low volume parts that are advantageous to the economies of scale for additive manufacturing.

Additionally, this study analyzes a company's organization and previous additive manufacturing efforts to propose ways to approach future development. Venturing through the various road maps that lead to the final goal of certification and addressing organizational barriers generate momentum for continuous development. These road maps, selection criterion, and evaluation method can be applied through many applications within the general aerospace industry.

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Contents

1 Introduction **15**

1.1 Motivation 15

1.2 Problem Statement 16

1.3 Problem Approach and Hypothesis 17

1.4 Thesis Overview and Organization 18

2 Literature Review **21**

2.1 State of Additive Manufacturing 21

2.1.1 Overview and History of Additive Manufacturing 21

2.1.2 The Additive Manufacturing Process 22

2.1.3 Materials and Processes 24

2.1.4 Economics of Additive Manufacturing 26

2.1.5 Additive Manufacturing Market and Trends 27

2.1.6 Competition in the Additive Manufacturing Industry 28

2.1.7 Applications and Industries 30

2.2 Additive Manufacturing in Aerospace 31

2.2.1 Additive Manufacturing Market Growth in Aerospace 31

2.2.2 Applications and Competitor Scope in the Aerospace Industry 32

3 Additive Manufacturing at Bell Textron Inc. **35**

3.1 Background on Company 35

3.2 Early Processes and Applications 36

3.3 Current State 37

3.4 Additive Manufacturing Needs at Bell Textron Inc. 38

4 Methodology **41**

4.1 Internal Data Collection Methods 41

4.2 External Research 42

4.3 Candidate Part Evaluation 42

4.4 Developing the Road map 43

5 Selection Criteria and Evaluation **45**

5.1 Application Breakdown 45

5.2 Selection criteria 51

5.2.1 Candidate Parts 53

5.3 Value Propositions 53

5.3.1 Cost Reduction 54

5.3.2 Speed and Lead Time Reduction 55

5.3.3 Material and Weight Reduction 55

5.3.4 Performance Gains 57

5.3.5 Supply Chain 57

5.4 Additive Manufacturing Evaluation Score 57

5.4.1 Score Breakdown 58

5.4.2 Application of AMES at Bell Textron Inc. 59

5.5 Business Case 59

5.5.1 Short-Term Wins 61

5.5.2 Long-Term Wins 62

6 Engineering and Design for Additive Manufacturing **63**

6.1 Design for Additive Manufacturing Overview 63

6.2 Topology Optimization 64

6.2.1 Topology Optimization Part Characteristics 65

6.2.2 Topology Optimization Process 66

6.2.3 Intermediate Gearbox Topology Optimization Case 67

6.3 Materials, Processes, and Machines 69
6.3.1 MMPDS and Material Development 69
6.3.2 MMPDS and Additive Manufacturing 71
6.3.3 Process and Machine Control 71
6.4 Quality Inspection 72
6.4.1 In-Process Monitoring 73
6.4.2 Nondestructive Testing 73
6.5 Certification 74
6.5.1 Current Standards 75
6.5.2 FAA Certification 75
6.5.3 Military Certification 75

7 Additive Manufacturing Road Map and Challenges 77
7.1 Additive Manufacturing Road map 77
7.1.1 Development Road Map 79
7.1.2 Engineering Road Map 80
7.2 Additive Manufacturing Challenges 82
7.2.1 Industry-Wide Challenges 82
7.2.2 Engineering Challenges 83
7.2.3 Certification Challenges 84
7.2.4 Cybersecurity 85
7.2.5 Organization Challenges for Adoption 85

8 Conclusions and Future Work 89
8.1 Key Findings and Conclusions 89
8.2 Future Work 90

A List of Acronyms 93

B Figures 95

C Tables 101

List of Figures

2-1 The five steps of additive manufacturing. 22
2-2 Powder Bed Fusion Additive Technology 24
2-3 Sheet Lamination Additive Technology[1] 25
2-4 Economies of Scale - Additive vs. Conventional[2] 27
2-5 Global Additive Manufacturing Market Growth[3] 28
2-6 Additive Manufacturing Material Growth 28
2-7 Additive Manufacturing Competitor Landscape[4] 29
2-8 Breakdown of Market Goods and Services[4] 29
2-9 Additive Manufacturing Market by Industry[5] 31
2-10 Market Projections for Additive in Aerospace[6] 32
2-11 Metals Growth by Industry[7] 32
2-12 Players in Aerospace with Additive Manufacturing 34

3-1 Timeline of Bell's Additive Manufacturing Development 37
3-2 Early Printed Parts at Bell Textron Inc. 38

4-1 Project Evaluation Flow 43

5-1 Model of the Bell Nexus[8] 47
5-2 Model of the Bell APT-70[9] 47
5-3 LSAM Printed Blade Tool 48
5-4 Rapid Prototyping and Tooling Applications 51
5-5 Spares and Production Applications 52
5-6 Speed Comparison - Additive vs Conventional 56

5-7 Material Usage Comparison - Additive vs Conventional[10] 56
5-8 Additive Manufacturing Supply Chain Streamline 58
5-9 Product and Supply Chain Transformation 61

6-1 Complexity Comparison - Additive vs Conventional 65
6-2 Topology Optimization Iteration Cycle 67
6-3 Overview of the Intermediate Gearbox Housing (IGB)[11] 68
6-4 Internal Features in the IGB[12] 69
6-5 Thermal Features on the IGB[13] 70
6-6 Control Factors for Additive Manufacturing 72
6-7 Example of In-Process Monitoring 73
6-8 Factors for FAA Certification 76
6-9 Factors for Military Certification 76

7-1 Overall Road Map for Additive Manufacturing 79
7-2 Development Road Map for Different Value Parts 80
7-3 Pre-DFAM Road Map 81
7-4 Post-DFAM Road Map 82
7-5 Example of Internal Lattice Structure[14] 84
7-6 Bell Engineering Organizational Structure 86
7-7 Organizational Additive Manufacturing Stakeholders 87

B-1 Calculation of Additive Manufacturing Evaluation Score (AMES) . . 96
B-2 Calculation of Additive Manufacturing Evaluation Score (AMES) . . 97
B-3 Calculation of Additive Manufacturing Evaluation Score (AMES) . . 98
B-4 Calculation of Additive Manufacturing Evaluation Score (AMES) . . 99

List of Tables

2.1 Additive Process and Compatible Materials[15] 26

2.2 Milestones of Additive in the Aerospace Industry[16][17] 33

5.1 Blank Selection Criteria 53

5.2 Example Selection Criteria Application 54

5.3 Additive Manufacturing Evaluation Score Sheet 60

5.4 AMES Application Summary 60

C.1 AMES - Part 1 102

C.2 AMES - Part 2 102

C.3 AMES - Part 3 103

C.4 AMES - Part 4 103

C.5 AMES - Part 5 104

C.6 AMES - Part 6 104

C.7 AMES - Part 7 105

C.8 AMES - Part 8 105

Chapter 1

Introduction

Parts for air and spacecrafts are complex, often needing long lead times to manufacture. This leads to higher inventory investments and creates difficulties for the planning team to ensure parts are delivered in time for production. As a result, the aerospace industry has been exploring the use of additive manufacturing to overcome supply chain hurdles and provide additional benefits to the produced part. Bell Textron Inc. is one such aerospace company that seeks to integrate additive manufacturing into existing and new programs to explore the limits within the industry.

1.1 Motivation

Additive manufacturing or (AM) for short, is a manufacturing process that joins materials to make objects from 3D model data. Additive, by fusing material layer by layer, as opposed to subtractive manufacturing that removes material.[18] Additive manufacturing has been around as early as the 1980s and emerged as a new method for manufacturing that promised to revolutionize industries. Additive manufacturing has been on the aerospace industry's radar since the beginning with a lot of hype on opportunities to reduce weight, cost, and manufacturing time as well as producing parts that can only be produced using additive manufacturing.

Bell Textron Inc. is one of many aerospace companies that have begun researching additive manufacturing and applying the technology to their products. The aerospace industry is gaining traction with AM and customers are beginning to drive companies like Bell to begin diving deeper into additive manufacturing. While Bell has previously researched additive manufacturing in the past, new technologies and the changing additive manufacturing industry is forcing a second look and new efforts to understand the current state of additive manufacturing and the practical uses within the company to benefit the company its customer base. This thesis is designed address the many benefits of additive manufacturing and steer toward the practical uses for the aerospace industry. In addition, this thesis will provide an applicable methodology that will provide objective assessments for the feasibility for additive manufacturing for parts. Furthermore, this thesis will highlight several key barriers to overcome, technically and as an organization. Finally, this thesis will provide a roadmap for adopting additive manufacturing for short- and long-term outlooks.

1.2 Problem Statement

Additive manufacturing provides many benefits and is widely touted as being the next revolutionary method for manufacturing. It has been a hot word that many Original Equipment Manufacturers (OEM) like to use in public articles to showcase innovation. However, beneath the glamorous surface of the perceived benefits of additive manufacturing lies the reality that practical uses of additive manufacturing are limited within the aerospace industry. Even further beneath that are the many challenges that are involved with the adoption of additive manufacturing.

Bell's products are focused primarily in rotary aircraft for the military, like the Department of Defense (DOD), and commercial customers. The military operates on a 24/7/365 days schedule and they need aircraft to be operational at all times. With aircraft usage, when a spare part is needed, depending on the specific part, the aircraft can be grounded for weeks due to the time it takes to procure the spare part. The military is looking to additive manufacturing for faster response time applications as such. As a result, they are turning to Bell to drive the requirements for additive manufacturing in their products. On the commercial side, Bell prides itself on its customer service and as a result maintains its entire product line. As long as a single vehicle in that product line is operating, Bell will continue to maintain that product. In that respect, Bell is faced with challenges of providing service for parts with outdated designs.

The initial thought of additive manufacturing sounds appealing, but the questions that are being asked are, "What are the applications for which additive manufacturing is useful?", "What are the challenges?", and "How do we do it, and where do we start?" Keeping these questions in mind, this project seeks to breakdown Bell's products and assess respective opportunities for additive manufacturing and understanding the external and internal dynamics that needs to be addressed in order to adopt and integrate additive manufacturing.

1.3 Problem Approach and Hypothesis

In order to provide a final road map to additive manufacturing adoption, this thesis begins with evaluating the value propositions for additive manufacturing before applying methodologies to assess feasibility for parts within Bell Textron Inc. Following, this thesis dives into the largest barriers to entry, including organizational challenges for adoption. Finally, this thesis culminates into an applicable road map. In researching additive manufacturing for this thesis, it is hypothesized that the additive manufacturing industry is not yet set up to support aerospace OEMs' push for adoption and certification, due to high investment costs and a rapidly changing industry. However, there are steps as an OEM, to be made without large investment costs that will provide long-term benefits and position for success when additive manufacturing is standardized for the industry.

The first step in assessing the feasibility for additive manufacturing is to understand the current state of AM. The additive manufacturing industry is quickly changing with new materials, technology, and players constantly being introduced. This fast-moving industry makes any past work potentially obsolete. Analyzing the markets and organizing the various processes and materials helps Bell to know which, out of all of the many combinations, is the most applicable and has the best opportunity to make impacts.

The next step is to evaluate the products and applications for Bell. The applications range from rapid prototyping to production to one-off spares, but within each category, there are other subcategories that different combinations of additive manufacturing can find value in. The goal through this phase is to understand that AM should not be used for every part, but rather for parts that can exploit the benefits of additive manufacturing. Complemented with the first step, it is possible to identify the process and material that would have the most opportunities. Following that, would be a business case study to understand the tangible benefits that could be applied.

Finally, this project looks dives deeper into the engineering capabilities and challenges to understand how to develop a road map to create the most value added while reducing the cost and effort needed to be invested. The traditional methods of qualifying new materials and processes for an OEM is a long process with high costs associated. Many OEMs are afraid to enter additive manufacturing due to those factors, but through this project, this road map will show that there are other ways to benefit and push additive manufacturing continuously without the high associated costs.

1.4 Thesis Overview and Organization

This thesis was organized to provide context to the benefits and challenges of additive manufacturing through the applicable lens of an aerospace OEM. Throughout this thesis, OEMs can view the provided framework as a basis on evaluating the current state of additive manufacturing and understanding how to position itself for AM implementation in the future. Chapter 2 depicts the additive manufacturing journey to its current state and touches on the AM market in the aerospace industry. Background on Bell Textron Inc. and its previous efforts with additive manufacturing are covered in Chapter 3. Chapter 4 briefly describe the methodology in evaluating additive manufacturing feasibility and the company leading up to the road map framework for AM adoption. Chapter 5 categorizes Bell's product applications and discusses the value propositions offered by additive manufacturing. Included in Chapter 5 will also be an example of applying a scorecard to objectively evaluate a part for additive manufacturing. The engineering and design aspects, from materials through inspection of additive manufacturing is outlined in Chapter 6. Chapter 7 lays out the foundation for an additive manufacturing road map OEMs can use for additive manufacturing adoption. Finally, Chapter 8 will highlight overall key points as well as providing final recommendations for future additive manufacturing work for OEMs.

Chapter 2

Literature Review

This chapter journeys through the historical rise of additive manufacturing to its current state by providing background on additive manufacturing as well as the market trends in the industry. In order to appropriately scope this thesis, this chapter will also provide context of the additive manufacturing industry specific to aerospace. Through this chapter, additive manufacturing concepts will be described and key industry aerospace players in today's state of additive manufacturing will be highlighted.

2.1 State of Additive Manufacturing

This section provides an overview of the entire additive manufacturing industry, beginning with its history, then the various processes and materials, and thereafter, the economics associated with additive manufacturing. Later, an analysis on the market and competition will provide the basis for various industries that which additive manufacturing is being applied.

2.1.1 Overview and History of Additive Manufacturing

Additive manufacturing is a term used to describe utilizing 3D-printing technologies for a production scale purpose. Additive manufacturing is different than conventional methods of manufacturing such as machining, casting, stamping, etc. in that material is being added rather than subtracted from a larger piece of material. 3D-printing has been around since 1987 originating in the labs of MIT with initial applications utilizing polymers and plastics for rapid prototyping. Presently, there exists many different technologies for additive manufacturing as well as the material choices compatible with each technology.

2.1.2 The Additive Manufacturing Process

Although additive manufacturing has many process types that will be discussed later on, all follow a generic procedure from design to build. Deloitte depicts a 5-step process for additive manufacturing as shown in Figure 2-1.[19]

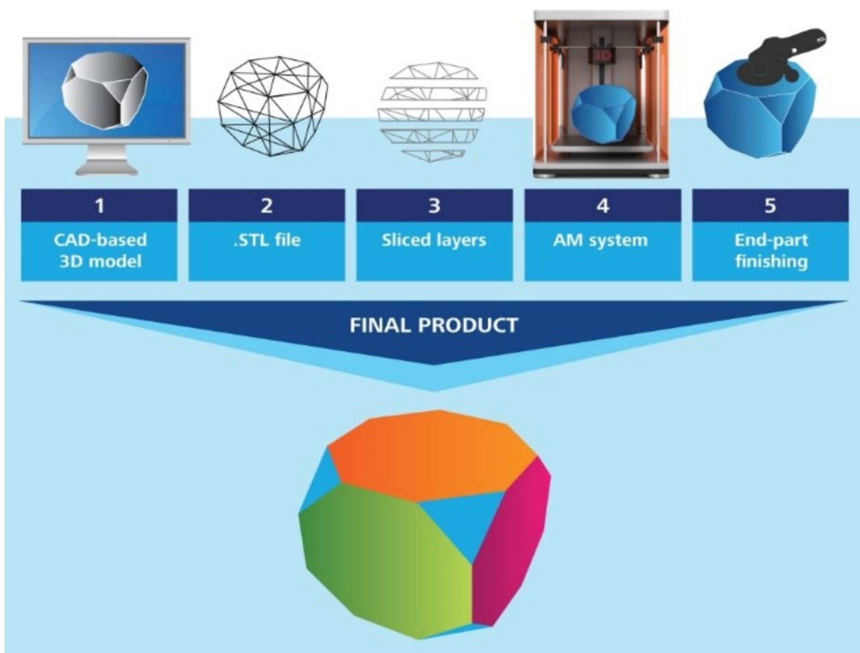

Figure 2-1: The five steps of additive manufacturing.

1. CAD Design – The first input for an additive manufacturing part is the 3D model or computer-aided design (CAD) model. This model defines the surface boundaries, tolerances, and internal geometry of a part. Material choice could be defined at this point, but is not necessary for build.

2. STL File – The next step is to convert the 3D CAD model into a stereolithography (STL) file. The STL file is the most common file format for additive manufacturing software compatibility. STL files contain the information of 3D models that describe the surface geometry without any other model attributes. The STL conversion is a checkpoint to ensure that all surfaces are fully defined and enclosed.

3. Slicing – The slicing step involves taking the STL file information and "slicing" the model into layers of appropriate and uniform thickness. Recall the definition of additive manufacturing involves adding material "layer by layer". In each slice, the STL file creates new model information for each slice. The slice thickness is determined by the range of material that can be deposited during the print process. Another important factor in this step is taking into account the orientation by which the part is going to be printed. The model slices and the part's features are two of several determinants as to which orientation for print will be the best.

4. AM System – After the model has been sliced into its appropriate layers, this new STL file is sent to the additive manufacturing system. This additive manufacturing system includes the software and machine associated with the print process. In this step, the part can be oriented and configured in the machine with respect to other parts that will be involved in the same print batch. Additionally, this step is also where the printed material will be defined. Other manipulative variables that can be configured in this step include power output, material feed speed, and print factors that determine structural supports and warping. At this point, once the base parameters are set, the part is off to print.

5. Post Processing – The last step of the additive manufacturing process is post processing. After the part is printed, there are several optional "post-processing" steps that can range from simple machining to surface treatments all the way to heat treatments. This process is dependent on the final, as-designed CAD model, the additive manufacturing process, and the functional requirements of

the printed part.

2.1.3 Materials and Processes

Additive manufacturing began with a concept where heat energy was directed toward a selected area. This heat energy was focused at a selected singular point to melt powder material to fuse together. That process today is known as powder bed fusion (PBF). In addition to PBF, there exists 6 other categories of additive manufacturing processes for a total of 7. Some of the processes have subcategories with different attributes, but the main technology is defined.

1. Powder Bed Fusion (PBF) – This method of additive manufacturing uses a laser or an electron beam to melt and fuse material powder together. PBF spreads a layer of powder material over previous layers and uses an energy source to fuse the material in specific locations. Common PBF methods are Electron Beam Melting (EBM), Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS). Figure 2-2 graphically displays the PBF process.

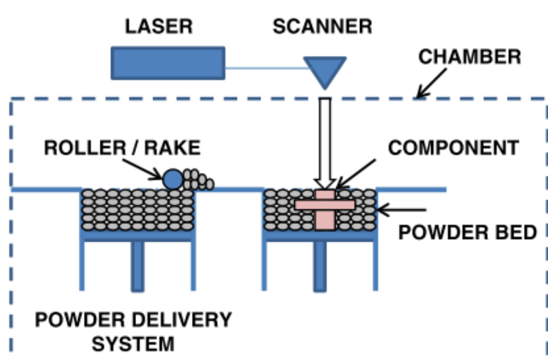

Figure 2-2: Powder Bed Fusion Additive Technology

2. Directed Energy Deposition (DED) – DED method for additive manufacturing utilizes a multi-axis arm to deposit powder or wire-fed material while an energy source melts and fuses the material to an existing part or layer. This method is commonly used for repairs or to add material to an existing part.

3. Vat Polymerization – Vat polymerization uses an ultraviolet light to cure required areas of resin layer by layer. This method does not require the use of structural supports and the process for curing is through photo polymerization.

4. Sheet Lamination – Sheet Lamination takes layers of sheet metal and uses an ultrasonic weld to bind layers together. In this method, a near-net shape of the finished part is created, thus final machining and post processing is usually required.

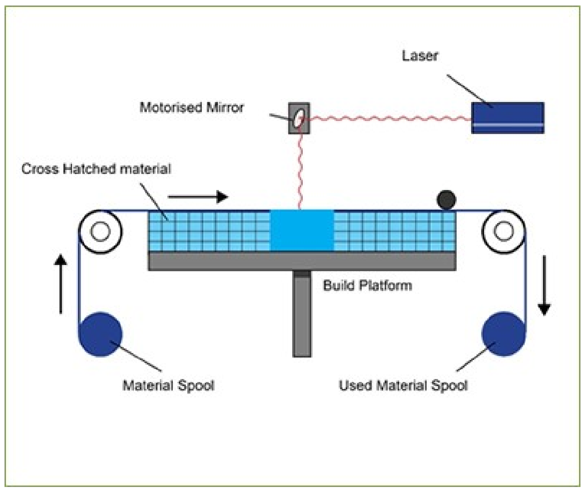

Figure 2-3: Sheet Lamination Additive Technology[1]

5. Binder Jetting – This family of additive manufacturing is similar to PBF, but instead of an energy source to fuse the material together, a binder material is dropped into the powder bed to form a solid part after the binder is cured. This method is commonly used for low-cost 3D parts and sand casted cores and molds. Metal Jetting is a new technology within binder jetting that utilizes metals.

6. Material Jetting – Material jetting deposits photopolymer liquid material onto the build tray while an ultraviolet light cures the layers. The UV light and material jet moves simultaneously for instantaneous curing.

7. Material Extrusion – Material Extrusion is one of the most common methods for additive manufacturing that draws material through a nozzle where it is

heated and deposited layer by layer. The finished quality of the part depends on many factors such as the use of support material for the part. In addition, a constant flow of heated material and pressure is needed for accurate results. The most common process within this method is Fused Deposition Modeling or FDM.

Within each family of additive manufacturing, are the different materials that are compatible for the specified process for an additive print. The most common materials to be used are plastics and polymers. As technologies mature, more methods are beginning to utilize ceramics and metals to expand the applications for additive. Table 2.1 summarizes the different materials that are compatible for each method.

Table 2.1: Additive Process and Compatible Materials[15]

Additive manufacturing processes

Process	Laser-based?	Materials
Powder bed fusion	Yes	Metal, polymer, *ceramic
Directed energy deposition	Yes	Metal
Vat polymerization	Yes	Polymer, *metal, *ceramic
Sheet lamination	**	Metal, polymer, *ceramic
Binder jetting	No	Polymer, metal, *ceramic
Material jetting	No	Polymer
Material extrusion	No	Polymer

* Indirect approaches.
** Sheet lamination has historically used a laser, but current processes use a cutting blade.

2.1.4 Economics of Additive Manufacturing

A key component of additive manufacturing is the study of the economies of scale for production and how it compares to that of conventional methods for manufacturing. Within a production run, cost per unit for conventional methods are quite large for the initial parts due to the high cost for development and procurement for tools needed to produce the part. However, as the number of parts produced increases, the cost per unit decreases significantly. In this thesis, the most commonly compared conventional methods are casting and machining. For additive manufacturing, the initial cost per unit is lower than that of conventional methods, but as the number of parts produced increases, the cost per unit stays flat. Figure 2-4 below depicts the economies of scale in comparison. It is noted that after a certain number of units, the conventional manufacturing method is more cost effective than that of additive manufacturing. If only comparing manufacturing economics, a challenge for Original Equipment Manufactures or OEMs in all industries is to find the equilibrium point to know when additive manufacturing is favorable. However, many other benefits from additive manufacturing arise that can further justify the use of additive manufacturing. Chapter 5 will describe those benefits in detail.

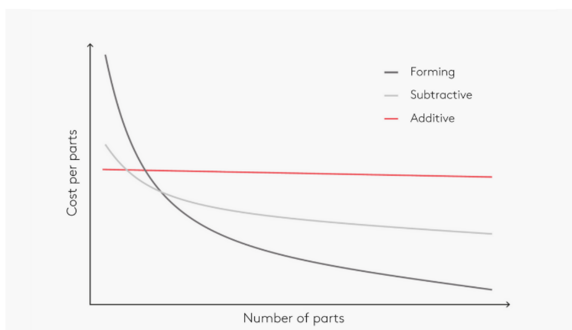

Figure 2-4: Economies of Scale - Additive vs. Conventional[2]

2.1.5 Additive Manufacturing Market and Trends

The global additive manufacturing market cap was valued at $9.03 in 2018 with a growth of 18% from the previous year. The growth trend in the last decade has been exponential with global estimates for additive manufacturing to exceed $30B by 2025. Reasons for this growth can be attributed to technological advances, material expansion, and driving customer needs. In addition, certification agencies are beginning to see the value of additive manufacturing thus enabling OEMs to begin integrating additive manufacturing processes into production.

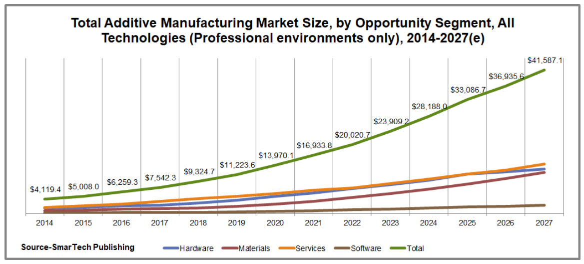

Figure 2-5: Global Additive Manufacturing Market Growth[3]

A large driving factor for additive manufacturing adoption in industries are the growth of the available materials able to be used for additive manufacturing. It is important to note that the additive manufacturing industry has been mainly focused on the applicable uses for photopolymers and plastic filaments. However, more recent trends are showing the growth for those materials to be slowing down, but metals appear to be experiencing the exponential growth for the last five years and is expected to continue said trend for the next five.

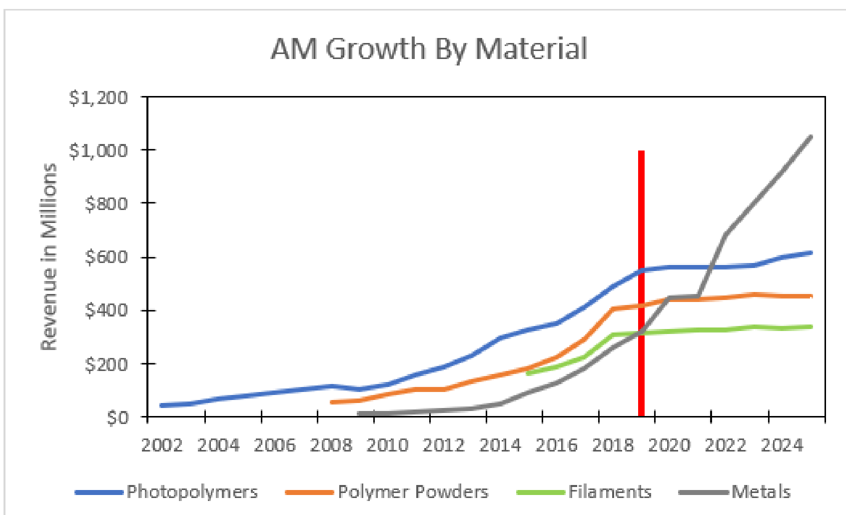

Figure 2-6: Additive Manufacturing Material Growth

2.1.6 Competition in the Additive Manufacturing Industry

Within the additive manufacturing industry, the amount of companies that are involved directly with additive manufacturing, has grown significantly. As of April 2019, it has been estimated that there are over 170 companies in additive manufacturing that cover hardware, software, materials, and post-processing. Figure 2-7 shows the landscape of companies that are involved with additive manufacturing.

Figure 2-7: Additive Manufacturing Competitor Landscape[4]

Figure 2-8 also breaks down the intended additive focus for each company. A key takeaway from this figure is that most companies are focusing on hardware. More than two-thirds of the companies are developing hardware while a little more than a quarter are involved with the software for additive manufacturing. Post-processing rounds out the rest of the companies, but its presence is significantly smaller than that of hardware and software.

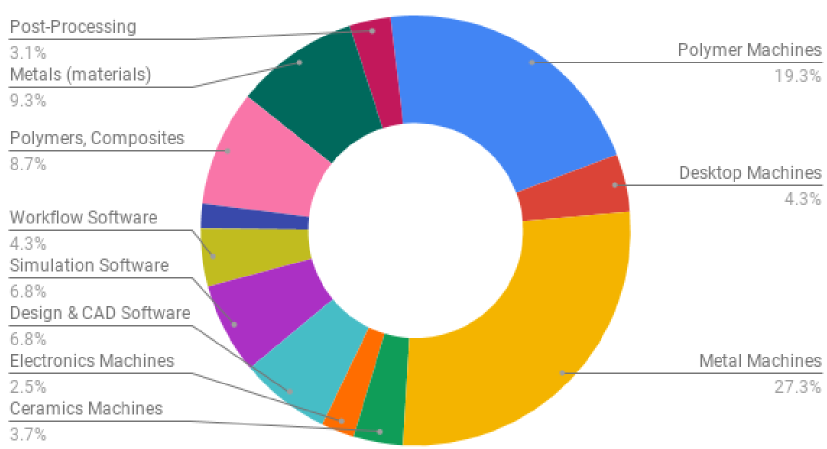

Figure 2-8: Breakdown of Market Goods and Services[4]

While there are many companies involved with additive manufacturing, it is expected that the number will fluctuate as larger companies acquire smaller companies and as new companies enter the market. According to Emerging Tech[20], as of November 2019, the largest companies in the additive manufacturing market are:

1. Hewlett-Packard (HP) – Multi/Metal Jet Fusion
2. Proto Labs – SLS/DMLS
3. 3D Systems – Printers and Services
4. Stratasys – FDM and Services
5. Materialise – 3D Printing Services
6. SLM Solutions Group – SLM
7. Nano Dimension – 3D Electronics Printing
8. ExOne – Binder Jetting
9. Organovo – Medical 3D Printing
10. Voxeljet – 3D Printing Services

2.1.7 Applications and Industries

Additive manufacturing began with creating rapid prototypes on a small desktop-size scale. Today, the applications have expanded to various industries for use in everyday products. Consumer products and industrial businesses have accounted for a large portion of the market due to its small size and risk applications. The automotive and aerospace industry has taken a larger stance to developing additive manufacturing for its products. The figure below highlights the various industries that additive manufacturing is being applied.

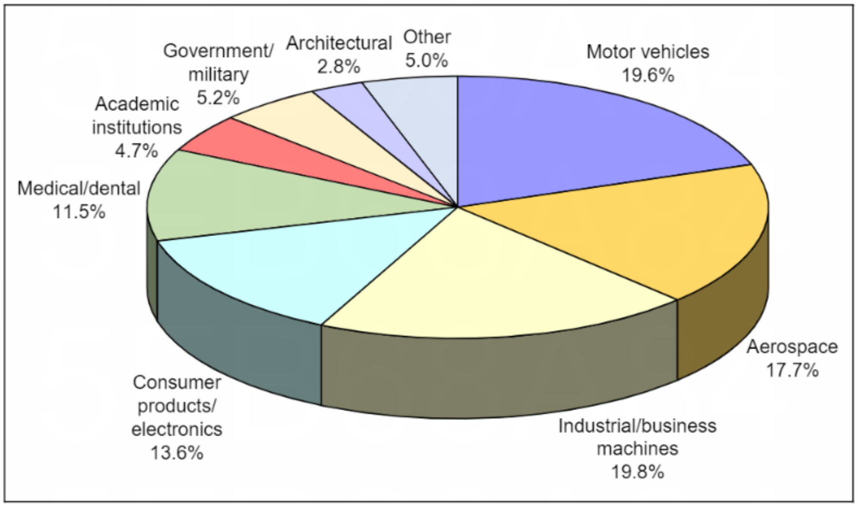

Figure 2-9: Additive Manufacturing Market by Industry[5]

2.2 Additive Manufacturing in Aerospace

This section is intended to provide insight to the additive manufacturing industry as applied to the aerospace industry. The current market, competitors, and applications will be briefly discussed. Furthermore, this section will outline the industry growth as well as highlight some of the major milestones and investments for additive manufacturing in aerospace.

2.2.1 Additive Manufacturing Market Growth in Aerospace

In discussing the industry applications for additive manufacturing, it was noted that the aerospace industry accounts for almost 18% of the entire global additive manufacturing market. In the figures below, additive manufacturing in aerospace is projected to grow at a rate of 23% between 2017 and 2021. As more applications become identified within aerospace, the need for additive will also increase. Likewise, as metal additive manufacturing develops and matures, the usage in aerospace will greatly increase.

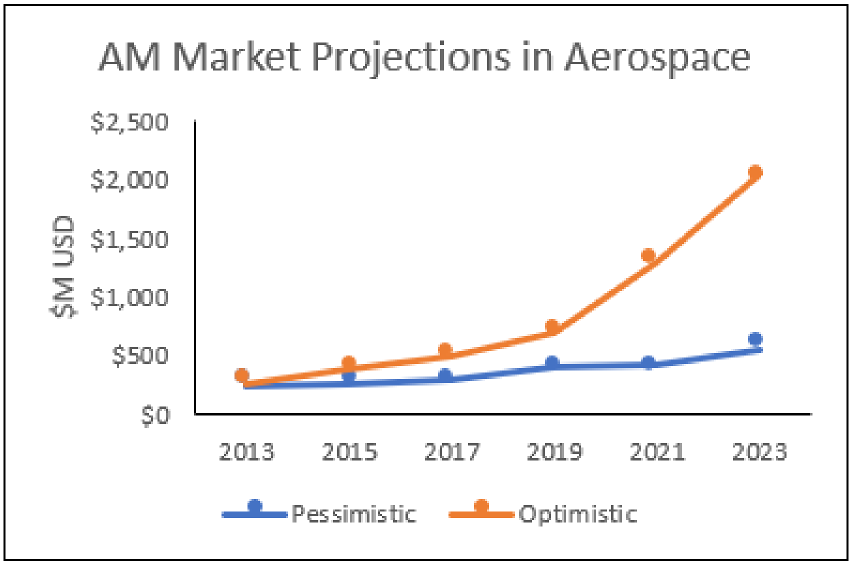

Figure 2-10: Market Projections for Additive in Aerospace[6]

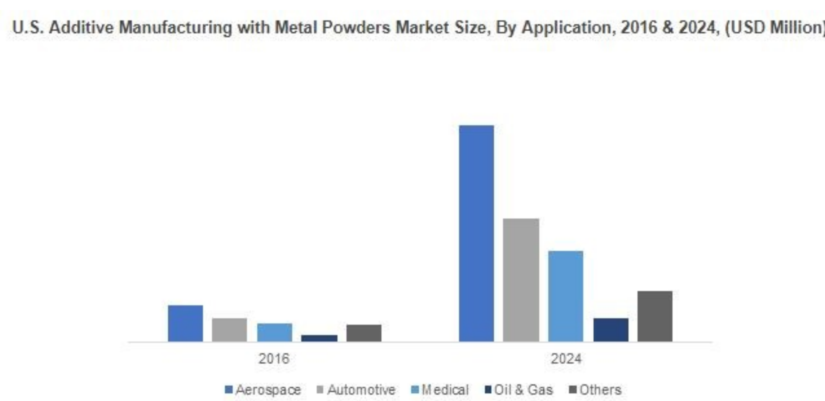

Figure 2-11: Metals Growth by Industry[7]

2.2.2 Applications and Competitor Scope in the Aerospace Industry

Many aerospace companies began researching additive manufacturing shortly after it was introduced. As mentioned earlier, the initial applications for additive manufacturing were mainly for rapid prototyping as a way to quickly iterate and lower development costs. From there, the aerospace companies turned to tooling applications for jigs and fixtures in order to lower the cost for tools. Following that, the aerospace industry began to find "low risk" applications for additive manufacturing.

"Low risk" has various definitions but range from a non-critical part for flight to low cost, low function parts. Items such as brackets, hinges, handles, and ducts were great applications for quick, on-demand, single use parts. However, aerospace OEMs were realizing the economies of scale for additive manufacturing were not favorable for low risk parts, but rather for complex and primary-structure parts. Consequently, they were also realizing the monumental effort and cost needed to reach additive manufacturing with higher risk parts. Within this past decade, aerospace companies have been increasingly exploring the use of additive manufacturing in production parts subject to higher structural loads. Table 2.2 shows a few milestones from various companies within the last decade.

Table 2.2: Milestones of Additive in the Aerospace Industry[16][17]

Year	Company	Material	Application	Milestone
2012	Airbus	Plastic	Rapid Prototyping	First 3D printer
2013	Boeing	Plastic	Production	First use of additive parts
2013	Lockheed	Metal	Production	Wing Spar Additive Build
2014	GE	Metal	Production	First LEAP Fuel Nozzle
2014	Bell	Plastic	Production	Ducting Systems Production
2014	Airbus	Plastic	Production	First plastic part on Airbus plane
2014	SpaceX	Metal	Production	Flown first engine component on Falcon 9
2014	AJR	Metal	Production	Tested entirely 3D-printed engine
2015	Relativity	Metal	Production	First Rocket to be entirely 3D printed
2017	Boeing	Metal	Production	AM for Spacecraft Part
2017	Airbus	Metal	Production	First metal part on Airbus plane
2018	GE	Metal	Production	30,000th LEAP Fuel Nozzle
2018	Boeing	Plastic	Tooling	Large Scale Additive Manufacturing
2019	Bell	Plastic	Tooling	Large Scale Additive Manufacturing

Within the aerospace industry, the largest players working with additive manufacturing are GE, Boeing, Lockheed Martin, United Technologies Corporation (UTC) and Airbus. These companies have created departments within their existing organization dedicated to additive manufacturing development. In addition, these main players have also made significant investments in purchasing additive manufacturing machines as well as partnerships with service providers. Lastly, in order to further advance their positions with additive manufacturing, these companies have made acquisitions of several smaller additive manufacturing companies. Figure X shows a snapshot of the major players of additive manufacturing in the aerospace industry.

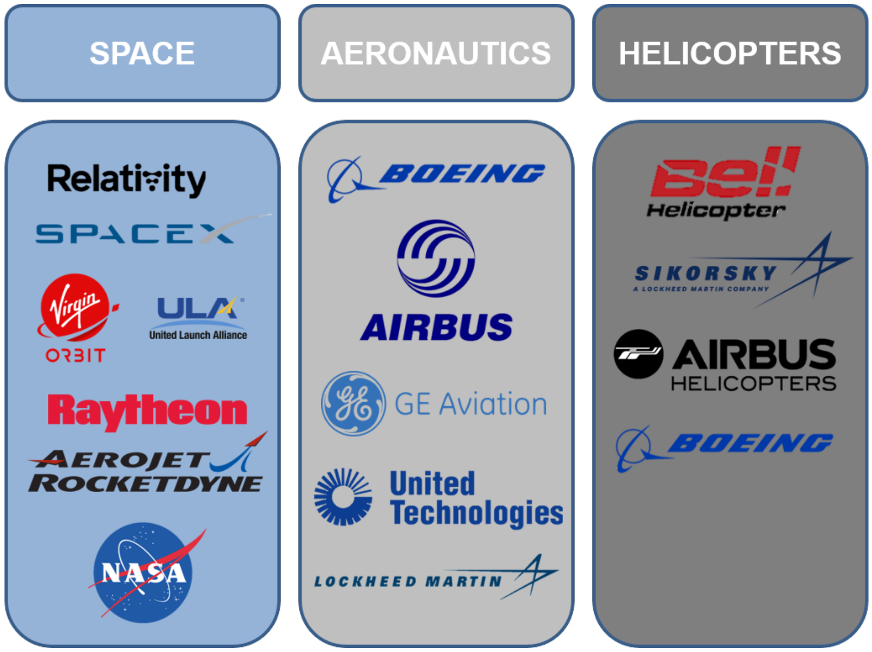

Figure 2-12: Players in Aerospace with Additive Manufacturing

Chapter 3

Additive Manufacturing at Bell Textron Inc.

This chapter introduces and provides background on Bell Textron Inc., an American aerospace company that serves as the basis of this thesis' study. This chapter will begin with a brief history on the company and proceed through early efforts and current needs of additive manufacturing as it pertains to Bell Textron Inc.

3.1 Background on Company

Bell Textron Inc., a wholly subsidiary company to the larger parent company Textron Inc, is an aerospace company that specializes in providing rotor systems and aircraft to commercial customers and military customers for the US federal government and various agencies around the world. The company was founded in 1935 in Buffalo, New York initially designing fighter aircraft. The company changed focus to helicopters and when Textron bought Bell, its only focus became helicopters and rotary aircraft. Today, the company employs over 7500 people with most employees at headquarters in Fort Worth, TX. Bell Textron Inc. has a majority of its operations in the Dallas-Fort Worth Metroplex, but also operates satellite locations out of Amarillo, TX, Mirabel (Quebec, Canada), and Mexico City (Mexico). On the commercial side, Bell Textron Inc. produces over 15 different commercial-use helicopters that range in applications from logging, firefighting, to tourism. Most of the commercial helicopters are produced in Mirabel, Quebec. On the military side, Bell Textron Inc. maintains a portfolio of helicopters and tiltrotor aircraft. The most prominent vehicles the military uses are the UH-1 and AH-1 Huey and the V-22 Osprey tiltrotor. The V-22 Osprey was the first of its kind for the vertical take-off and landing (VTOL) aircraft. To this day, Bell Textron Inc. has produced over 200 V-22s for the military.

3.2 Early Processes and Applications

Starting in the early 1990s, Bell Textron Inc. was one of the first aerospace companies to experiment with additive manufacturing. The first use of Selective Laser Sintering (SLS) was for quick prototypes of tooling and experimental parts. However, as the additive manufacturing industry progressed, Bell understood the need to allow the additive manufacturing industry to mature. In 2007, a larger initiative to begin additive manufacturing of production parts was enacted. It was at this point when environmental control systems were the target applications for plastic and polymers additive manufacturing. These parts did not carry any structural loads critical to flight, thus making for a prime, low-risk candidate for additive manufacturing. Bell also pushed for internal qualification of two subset of polymer materials: PEEK and PEKK. Polyether ether ketone or PEEK is a thermoplastic that has excellent mechanical and chemical properties for heat resistance. Polyetherketoneketone or PEKK is also another heat resistant thermoplastic. Toward the end of 2007, Bell had begun production of its ECS ducting with PEEK and PEKK materials.

Up until 2013, Bell had been focused primarily on plastic/polymer additive manufacturing. 2013 introduced electron beam melting for a special titanium allow, Ti-6Al-4V or Ti-64 for short. In this short period, Bell had a preliminary effort for Ti-64 qualification for electron beam melting. Following that, Bell began partnerships and case studies with a larger initiative for additive. The V280 program was a new military product that had opportunities for additive manufacturing. Bell's most recent additive manufacturing venture lies with large scale additive manufacturing (LSAM).

In the summer of 2019, Bell partnered with Thermwood to 3D print a to-scale blade bond tool.

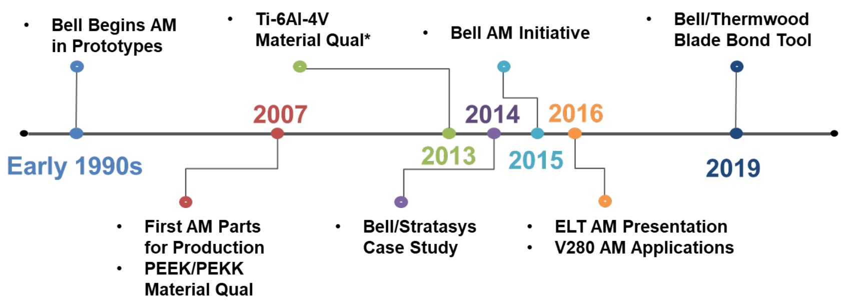

Figure 3-1: Timeline of Bell's Additive Manufacturing Development

3.3 Current State

At its current state, Bell outsources all of its additive production manufacturing while operating four machines in-house dedicated for research and development. All of the outsourced and in-house machines utilize plastics and polymers. Since the start of additive efforts, Bell has produced over 550 parts widely spread among its products with just Selective Laser Sintering (SLS). While a majority of parts produced are experimental, it is worth noting that over 200 of those 550 parts are for production purposes. Bell has normally followed the additive industry and because the industry began with thermoplastic and polymer materials, Bell has followed suit with most of its additive contributions through thermoplastic and polymer materials. In its most recent initiative, Bell has begun to focus more so on metal specific additive manufacturing and with titanium alloys.

The progress that Bell has made with additive manufacturing has been done through internal committees comprised of subject matter experts (SME). Residual budgets from programs have contributed to the efforts of learning more about additive manufacturing and its applications for Bell. Partnerships have also played a major factor in the progression of additive. Previous joint efforts with big additive manufacturing players such as Stratasys, EOS, and Thermwood have enabled Bell to establish lessons learned and baseline metrics for internal development.

Figure 3-2: Early Printed Parts at Bell Textron Inc.

3.4 Additive Manufacturing Needs at Bell Textron Inc.

As the additive manufacturing industry continually develops, especially among metals, the pressure on OEMs like Bell to respond accordingly is increasing. The main concerns that Bell is looking to overcome can be broken down into four categories.

1. Past Efforts vs. Today – One of the biggest challenges with a rapidly developing industry is the notion that past efforts may be obsolete in the face of newer technologies and materials. For example, data that was collected through an Electron Beam process with a titanium alloy may not represent the characteristics at which parts may be printed now. This challenge makes it difficult for OEMs to commit to additive manufacturing due to the fact that time and investments may be wasted efforts and thus may resort to a "waiting game" as the alternative.

2. Design for Additive Manufacturing – The early efforts at Bell have helped the company learn the capabilities of printers and how to print certain parts. However, aside from printing, there needs to be an understanding for designing for additive. There are many benefits that only a part designed for additive can achieve but the industry lacks documentation on how to design for additive to achieve those benefits.

3. Methodology to Choose Parts – When looking at products and parts, it is difficult to understand which parts are great for additive and which are not. A selection criterion will help to determine a baseline on separating the feasible parts from parts that are best fit with conventional means of manufacturing. OEMs, in all industries, struggle to determine where and what to start with for additive manufacturing.

4. Development is Costly – The biggest challenge in aerospace is that additive manufacturing development requires a substantial amount of monetary investments and time for qualification. This, combined with a rapidly changing industry create a lose-lose situation that smaller aerospace OEMs are not willing to risk. This creates an ever-increasing gap in the additive race between the smaller OEMs and the larger OEMs with larger dedicated funding sources.

These main issues especially the development cost culminate the need for a roadmap for aerospace companies, that do not have access to large resources, to plan for continuous development. The goal is to provide cost effective ways to learn quicker and determine areas of need for additive manufacturing to be successful within respective organizations.

Chapter 4

Methodology

This chapter details the methods used to collect information internally within Bell as well as the external market research. Furthermore, this chapter also describes the methodology of identifying the candidate part for further study during the developmental phase. The scoring system for candidate parts will also be described briefly. Finally, this chapter concludes with an overview of the structure for the road map proposed for additive manufacturing adoption.

4.1 Internal Data Collection Methods

The majority of data for this project was collected internally through Bell Textron Inc. resources. The qualitative data were collected in three ways: internal documentation, employee interviews, and site visits. Internal documentation was helpful to understand Bell's prior efforts with additive manufacturing and pinpoint its current state. Interviews with employees revealed motivations for the efforts in the past, but more importantly, also to outline the largest systemic barriers to entry for additive to be adopted within the organization and industry as a whole. The last internal source for data came from site visits to view the manufacturing processes. This method quickly showed areas where additive manufacturing can provide immediate benefits and areas that can benefit from a longer-term development effort. The learnings from this step would help form the strategies in the road map.

4.2 External Research

While the majority of data came from internal sources, external data was equally important to understand the industry trends and competitive landscape. Market research was crucial to identify the market trends for the industry as well as filtering out which process and material had the best opportunity at Bell. Sources such as published additive manufacturing industry reports also provided insight to future projections. Competitor research served to evaluate the larger players in the aerospace industry working with additive manufacturing to confirm the processes and materials being favored in aerospace. Secondly, a look into the major players helped to identify potential third-party service bureaus that would be advantageous for OEMs like Bell, to partner with. Other sources for external research were through online sources, vendor visits, and conferences. Vendor visits and conferences provided the most up-to-date insight on the industry and technologies related to additive manufacturing hardware, software, and post processing.

4.3 Candidate Part Evaluation

One of the fundamental processes in the development of additive manufacturing is being able to identify the candidate parts that would showcase the benefits and provide the foundation for future development for additive manufacturing. A selection criterion must be created to identify the candidate parts and the evaluation must be as objective as possible. With a set of candidate parts, a business case will be conducted to provide scope as to which material and processes candidate parts favor for development. In previous efforts, lists of candidate parts have been identified, but this thesis also aims to improve the methodology to provide objective selection based on specific characteristics, material, and functions.

4.4 Developing the Road map

Once the candidate parts are identified and both the material and process have been chosen, a road map would be developed to identify the future steps needed for the organization to fully realize the beneficial gains for additive. This road map splits into two key factors in parallel to the candidate part: Design for Additive Manufacturing or DFAM and Materials and Processes or M&P. Both need a plan and each plan would help dictate the necessary phases for execution. The end goal for the road map is certification of the material and process to enable full use for production flight hardware. However, a key differentiator would be ensuring the certification is not for one piece-part, but rather the general process and material in its entirety.

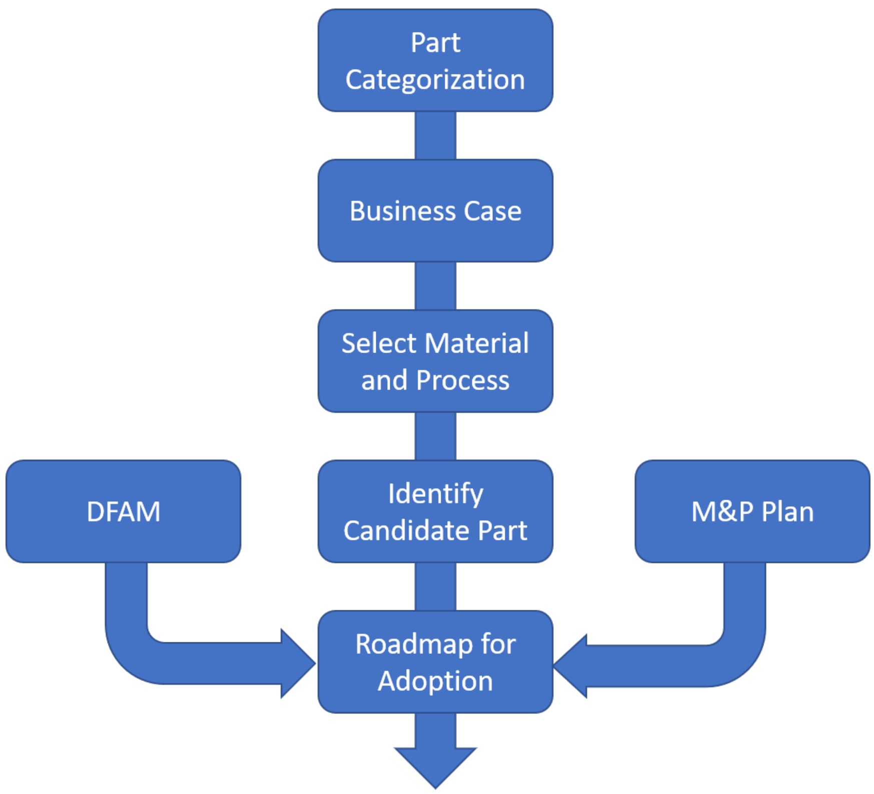

Figure 4-1: Project Evaluation Flow

Chapter 5

Selection Criteria and Evaluation

In any organization looking to develop and adopt new technology, an evaluation into the benefits and applications is a must. Consequently, a business case follows suit. In the case with Bell Textron Inc. and additive manufacturing, this chapter walks through the process of selecting candidate parts through building the business case. The selection criteria and evaluation are heavily focused to stress the importance of applying parts to additive manufacturing in a systematic way. In doing so, parts of different sizes and characteristics can be compared side by side. Further along the chapter, the business case will present the value propositions and how an organization can situate itself for short or long-term success. An important assumption to note in making the business case, is the technology and process has already been developed. This helps to simplify the business case, but is not representative of the upfront and recurring costs needed to develop the technology. More information on the complexities of the development process will be covered in Chapters 6 and 7 and aggregated into the proposed road map in Chapter 8.

5.1 Application Breakdown

The additive manufacturing selection process is a series of four steps. The first is the application breakdown. The second and third steps are the selection criteria and evaluation, respectively. Lastly, the part is selected for additive manufacturing.

As mentioned in earlier chapters, there is a need to identify the applicable areas for additive manufacturing. In doing so, an organization can determine which areas of a part or product line are more favorable for additive manufacturing and as a result can use these identified areas as starting points for additive manufacturing plans. For Bell Textron Inc., the product lines involve large scale assemblies that can be broken down into four process categories. They are rapid prototyping, tooling, spares, and production. Breaking down applications helps to develop an appropriate scope and determine the value drivers associated with each process category.

Rapid Prototyping - The earliest use of additive manufacturing was applied toward rapid prototyping. This category of part processes involves the quick fabrication of physical parts or models from computer aided designs (CAD). Rapid prototyping is not meant to produce the end design, but rather to demonstrate key concepts or designs to be validated. The rapid prototype model is usually designed to have multiple iterations in quick succession, Additive manufacturing brings value with speed because rapid prototyping needs to be quick. An additive manufacturing solution will not only be quick, but potentially more cost effective to allow for more iterations. Designers are held up, waiting for prototypes to validate a design metric. Additive manufacturing can turn these validation exercises around much quicker. The powder bed fusion (PBF) process is highly popular for prototypes that need higher fidelity or quality. However, because the product is not a final product piece and the risks are low, the most common material choice would plastics and polymers for its availability and low prices. At Bell Textron Inc., the Rapid Prototyping team is constantly aiming to utilize additive manufacturing for validation and demonstration of their products. Therefore, their main use for additive manufacturing lies with mock-ups on new products. Bell has recently announced new products in the vertical takeoff and landing (VTOL) realm where additive manufacturing rapid prototyping would be of use. The Nexus is an air-taxi that aims to provide quick point-to-point transportation services in partnerships with Uber. In the mock-up that was unveiled at the Consumer Electronics Show (CES)[21], many parts in the mock up were made using additive manufacturing methods. In parallel, the Autonomous Pod Transport or APT for short, is a large-scale commercial drone used to provide last-mile delivery services for various industries. Rapid prototyping has played a large role in validating weight requirements and providing quick solutions for design iterations through the use of additive manufacturing.

Figure 5-1: Model of the Bell Nexus[8]

Figure 5-2: Model of the Bell APT-70[9]

Tooling - In order to manufacture and assemble any product, tools are needed. Tools or tooling (noun) can be anything from material handling pallets to jigs and so on. Tools show great promise for additive manufacturing due to its lack of risk for flight. Like rapid prototyping, tooling applications take a long time to manufacture and once a tool has been ordered, designs are locked down to the tool. Furthermore, tooling costs are also high thus additive manufacturing can be a quick and cost-effective alternative. At Bell, tooling can be broken down into four subcategories:

Bond Tools, Jigs and Fixtures, Tables and Pallets, and Surrogates. Most of Bell's rotor blades are made with composite material and a bond tool is required to mate the two sides of the blade together and to cure the blade in an autoclave oven. This tool is large, heavy, and has to meet requirements specific process requirements. Jigs and fixtures, pallets and tables are involved in the manufacturing process by either hold a part in place or aiding a machine for precision manufacturing. Bell has many applications with drive systems that utilize tables and fixtures for every step of the manufacturing process for every part, thus a large inventory of tools sits idle until it is needed. The last category within tooling is for surrogate parts. These tools are used as substitutes for higher value, long lead time sub-assemblies. Additive manufacturing solutions present opportunities to replace long lead tools and create tools with better properties. A majority of larger tools are metallic, but additive manufacturing has opportunities to utilize a wide range of tools to achieve similar functions. A promising solution Bell Textron Inc. is looking into is Large Scale Additive Manufacturing (LSAM). LSAM aims to provide quicker, cheaper, and lighter solutions for large tools. Bell has worked with the manufacturer, Thermwood to explore LSAM opportunities for a blade bond tool. The figure below summarizes applicable tooling areas for additive manufacturing at Bell.

Figure 5-3: LSAM Printed Blade Tool

Production Spares - Spares to maintain aircraft are critical to keeping an aircraft ready to be flown. Design planning helps to ensure an inventory of critical spares are on hand to prevent aircraft from staying grounded. Bell identifies two areas where additive manufacturing can help to improve the production of spares. The first area lies with grounded aircraft. Although there is an inventory of critical spare parts, benign parts such as door handle or a hinge can prevent an aircraft to be cleared for flight. The second area involves legacy aircraft that require parts that are obsolete to the production process. Parts may have been designed prior to the use of computer-aided designs (CAD) and original suppliers may not exist anymore. Additive manufacturing creates an on-demand service that can provide one-off parts. This use of additive manufacturing within spares aims to transform the supply chain process. For the benign and wide range of applications involved in the spares process, there is an equally wide range of processes and materials of additive manufacturing that can be used. However, the combination of fidelity and speed has powder bed fusion and material extrusion emerging as the best processes for spares at Bell Textron Inc.

Production Spares - The largest and most highly sought application base is geared toward production of parts for primary and secondary structure. The Federal Aviation Administration (FAA) defines Primary Structure as “structure which carries flight, ground, or pressurization loads, and whose failure would reduce the structural integrity of the aircraft.”[22] Secondary structure “carries air or inertial loads” or in ordinary speak, “less risky”[23]. At Bell Textron Inc., production parts can be broken down into categories of functions with the aircraft. The subcategories are the following:

1. Drive Systems
2. Rotor Systems
3. Propulsion
4. Structures

5. Avionics

6. Miscellaneous

Drive Systems are the combination of gears and gearbox housing that transfers power to various areas of the aircraft from the engine. In helicopters at Bell Textron Inc., the number of major assemblies for its drive systems can vary due to the number of rotor systems. The part components range from shafts to gears to gearbox cases, also respectively in order from critical to non-critical parts.

Rotor Systems involve the helicopter blades and the assemblies that connect the drive systems to the blades. One such assembly is the yoke that aggregates the blades and interfaces with the drive system. This category of parts involves a high number of critical parts for flight.

Propulsion Systems contain the main engine systems that provides the power to the drive systems. Major critical components are involved in this category of parts that the vehicle is reliant upon for successful flight.

Structures refer mainly to the airframe of the helicopter body. This system comprises of the main skeletal frame of the vehicle that is responsible for absorbing the majority of the aerodynamic and in-flight loads. The airframe is a critical piece to flight as it holds many different structures and sub-assemblies in place.

Avionics are the flight electronics associated with the aircraft during flight. Avionics components involve flight controllers and any instrumentation needed to ensure flight safety. Components are also critical for communication between aircraft and ground systems. Most avionics components are housed in boxes that are attached to the airframe, but carry no structural loads.

Miscellaneous parts involve anything that are not categorized above. Parts in this category can be unique and may not be attributed to primary structure, thus also not carrying critical flight loads.

Depending on the application, there are various uses and applicable methods for additive manufacturing at Bell. Along with the other categories, upon interviews with employees in these categories, the most promising technology is powder bed fusion within metals. There is a trade off in metallic material choice, however, that depends on the maturity of the material and the number of applicable parts on the aircraft. For example, at Bell Textron Inc., titanium is not attributed to a large percentage of the material make up, but is the most mature material in the industry. However, aluminum and steel have numerous applications, but have not developed maturity levels to be readily used.

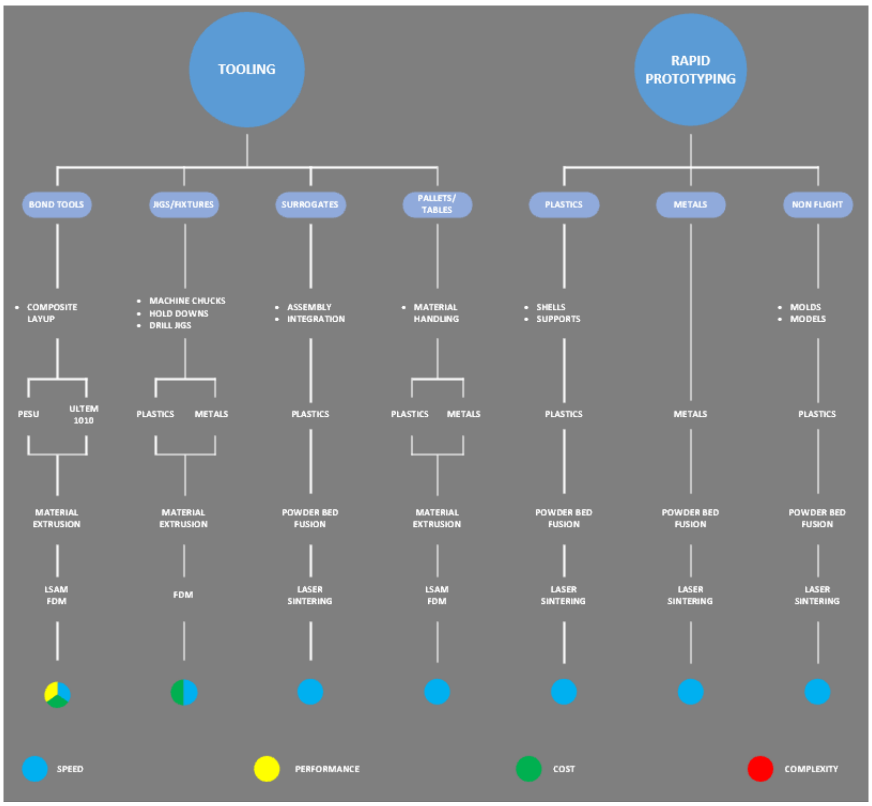

Figure 5-4: Rapid Prototyping and Tooling Applications

5.2 Selection criteria

The second step in the additive manufacturing selection process is the selection criteria. This step serves as a quick, first-order, assessment to determine if a part would be a great part for additive manufacturing. In this assessment, a part would be analyzed on certain characteristics and a final aggregate of the responses at the end would determine if the part would benefit from additive manufacturing. Parts at Bell

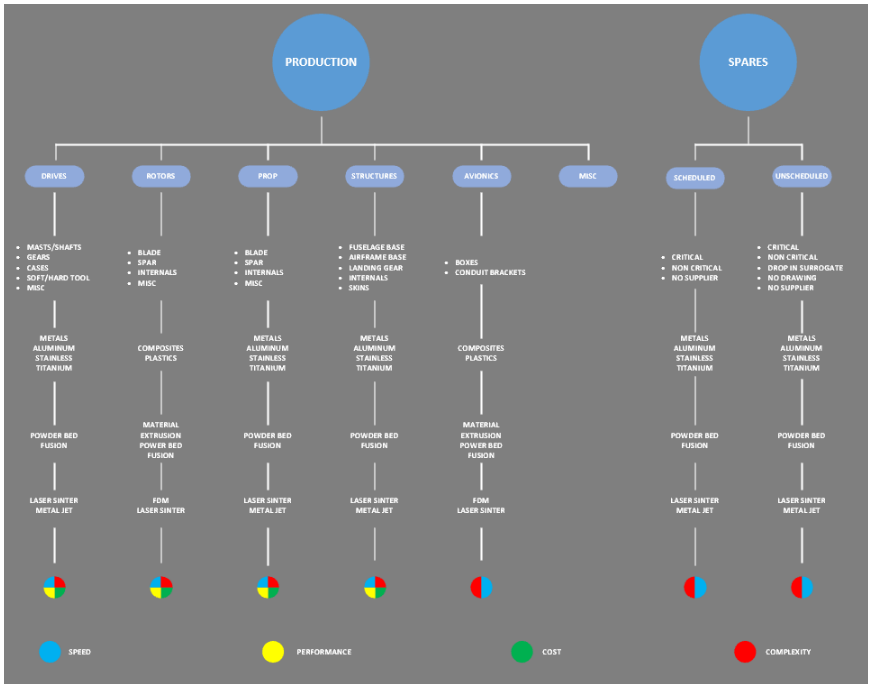

Figure 5-5: Spares and Production Applications

Textron Inc. were analyzed on major characteristics of load path, merged assemblies, wall thickness, internal features, and surface finishes. In addition, the part was assessed with its current method of manufacturing to determine if any post processing would be needed. For most of the criteria, the answers would be either yes or no. A few answers required more detail such as to what degree of surface finish the part expected to have. In this evaluation, it is important to note that because this is a first order evaluation, the criteria carry equal weight when the answers would be tallied. The evaluation would be pitted against an "ideal" scenario and if the number of matches were more than half for the yes/no characteristics and the numerical answers exceeded half the that of the ideal, then the part was expected to be great for additive manufacturing.

In Figure 5.2, an example of the use of the selection criteria is shown below with the Intermediate Gearbox or IGB. In the evaluation, the IGB exhibited many characteristics that are favorable for additive manufacturing. In addition, the numerical score also supports the IGB to be a favorable candidate part.

Table 5.1: Blank Selection Criteria

Criteria	Type	Score
Load Path	Function	Y/N
Merged Assemblies	Function	Y/N
Internal Channels	Characteristic	Y/N
Heat Management	Characteristic	Y/N
Wall Thickness, 5 being very thick	Characteristic	1-5
Internal Supports	Characteristic	Y/N
Complex Geometry, 10 being complex	Characteristic	1-10
Casting	Manufacturing	Y/N
Machining	Manufacturing	Y/N
Surface Finish, 5 being machined	Characteristic	1-5
Surface Finish for Fatigue/Perfomance	Function	Y/N
High Stress/High Fatigue	Function	Y/N
Access to internal surface	Function	Y/N
Subject to Iterative Change	Characteristic	Y/N
Forgings	Manufacturing	Y/N
Post Processing needed	Manufacturing	Y/N

5.2.1 Candidate Parts

Once a part has passed through the selection criteria, the parts that have been passed are placed in a list of candidate parts for evaluation. In this exercise, candidate parts from prior efforts and newer candidate parts were aggregated. It is important to maintain the part categories as mentioned in the earlier sections. For example, the IGB was identified as a candidate part. The part was part of the production process that was in the subcategory of drive systems. Among the candidate parts in the production process, the majority favored drive systems that carried lower risks. Chapter 6 will take the IGB and further discuss its characteristics that made it a candidate part.

5.3 Value Propositions

A discussion of the additive manufacturing value propositions will bring context to the evaluation process the candidate parts will be evaluated against. This section will describe the various value propositions that aerospace OEMs are interested in

Table 5.2: Example Selection Criteria Application

Criteria	Type	Ideal	Actual
Load Path	Function	Y	N
Merged Assemblies	Function	Y	Y
Internal Channels	Characteristic	Y	Y
Heat Management	Characteristic	Y	Y
Wall Thickness, 5 being very thick	Characteristic	5	2
Internal Supports	Characteristic	Y	Y
Complex Geometry, 10 being complex	Characteristic	10	6
Casting	Manufacturing	Y	Y
Machining	Manufacturing	N	N
Surface Finish, 5 being machined	Characteristic	1	2
Surface Finish for Fatigue/Perfomance	Function	N	N
High Stress/High Fatigue	Function	N	N
Access to internal surface	Function	Y	N
Subject to Iterative Change	Characteristic	N	N
Forgings	Manufacturing	Y	N
Post Processing needed	Manufacturing	N	Y
Intermediate Gearbox Housing (IGB)	Matches		9/13
	Numerics		10/16

exploiting. While this section discretely describes each proposition, the evaluation will collectively address them all.

5.3.1 Cost Reduction

An immediate value proposition that additive manufacturing has to offer is the reduction in cost. Cost reduction is applied to the unit cost and does not include the development and non-recurring engineering (NRE) associated with the part. Recalling earlier in the economics of manufacturing, additive manufacturing has lower startup costs, thus the per unit cost in the beginning is lower. However, in conventional methods there exists higher upfront costs, thus in the beginning conventional manufacturing has much higher costs per unit. However, as the number of units increases, conventional manufacturing surpasses additive manufacturing in becoming more cost effective. In the aerospace industry, parts are considered to be low volume and low rate and fall and the number of units produced are favorable for additive manufacturing. Therefore, an opportunity to lower costs for production and likewise tooling for production, presents itself. So long as the number of units produced does not exceed the equilibrium point for additive and conventional manufacturing, the case can be made to use additive manufacturing as the primary means of manufacturing.

5.3.2 Speed and Lead Time Reduction

Perhaps the most discussed value proposition that additive manufacturing has to offer is the speed at which machines can take designs and print parts. Similar to the economics of additive versus conventional manufacturing, there too is a comparison with respect to speed and the number of parts that are produced. Conventional manufacturing utilizes large upfront time to set up the machine and produce parts. However, once in a large production phase, conventional manufacturing time decreases per part. Additive manufacturing has much less set up time and therefore does has less time per part. Parts can become batched in a print run, decreasing the time per part by a small amount, eventually flattening out. As the number of parts produced increases, conventional manufacturing will surpass additive in terms of speed. In Figure 5-6 below, the number of parts for rapid prototypes, spares, and tools are minimal and additive manufacturing has the advantage. In aerospace production where the volume is low, additive manufacturing is favorable as long as the number of parts produced are below the equilibrium point.

5.3.3 Material and Weight Reduction

Aerospace is an industry where vehicle weight and payload weight are critical attributes that military and commercial customers take into account when choosing an aircraft for usage. Additive manufacturing produces parts that can be printed with significantly less upfront material usage. In Figure 5-7 below, it is shown that there is a significant decrease in material usage for various part geometries with different features where additive manufacturing was used. With new design software, parts can be simplified into organic shapes that can reduce the weight and mass of the overall finished part using topology optimization. Topology optimization will be discussed

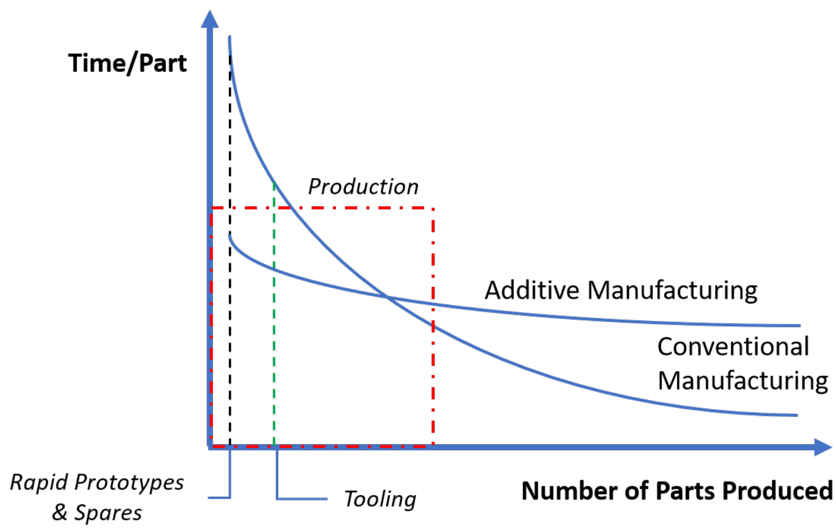

Figure 5-6: Speed Comparison - Additive vs Conventional

in greater detail in Chapter 6. Customers are interested in the overall decrease of final weight reductions in order to increase the overall payload accommodations. In simple terms, the lighter the aircraft, the more the aircraft can carry.

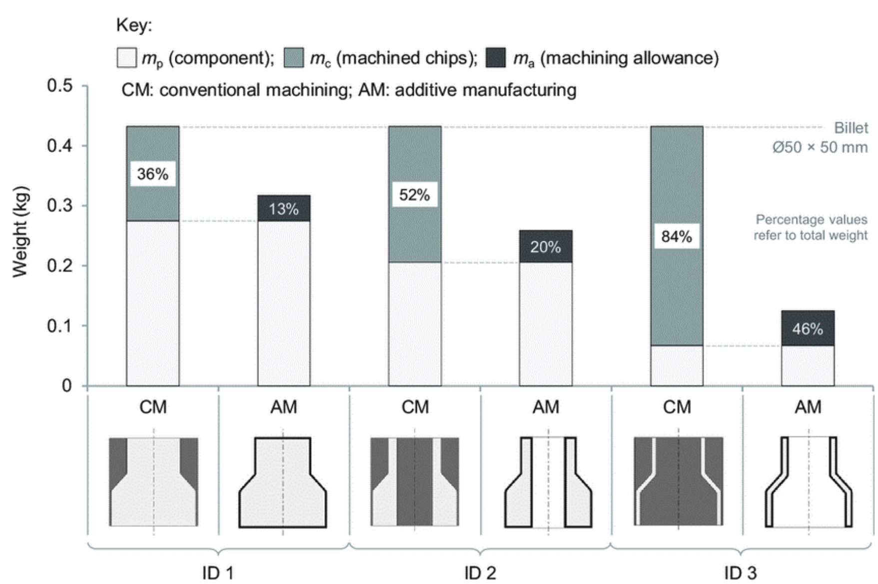

Figure 5-7: Material Usage Comparison - Additive vs Conventional[10]

5.3.4 Performance Gains

A part is designed with certain features that handle mechanical and thermal loads. The most difficult value proposition to quantify that additive manufacturing brings is performance gains. Performance gains can be classified using materials or optimization. On the materials side, parts can now be produced using new materials and alloys that have better mechanical properties. For example, a part that was previously manufactured out of magnesium can now be printed with aluminum or titanium without any significant weight additions, and still perform better than magnesium. Along the lines of optimization, software included in additive design can create and improve designs that are built around specific load paths. As such, designs can be optimized to support the load path without added mass and weight.

5.3.5 Supply Chain

The ability to print on demand creates an opportunity to simplify the supply chain for aerospace OEMs. The additive process is self-contained in the print that eliminates many middle steps for production. In addition, if a local shop or an in house printer is used, the process is on-demand so inventory is almost entirely eliminated. Furthermore, because the on-demand print is offered, planners do not need to plan for inventory and the process is as simple as sending the CAD file to the printer.

5.4 Additive Manufacturing Evaluation Score

The third step of the selection process is the evaluation step. As mentioned earlier, the evaluation step takes candidate parts and evaluates them individually across the value propositions. Currently there are no standard evaluation processes for candidate parts, but the goal is to objectively assess a part's additive manufacturing feasibility and to compare against other candidate parts.

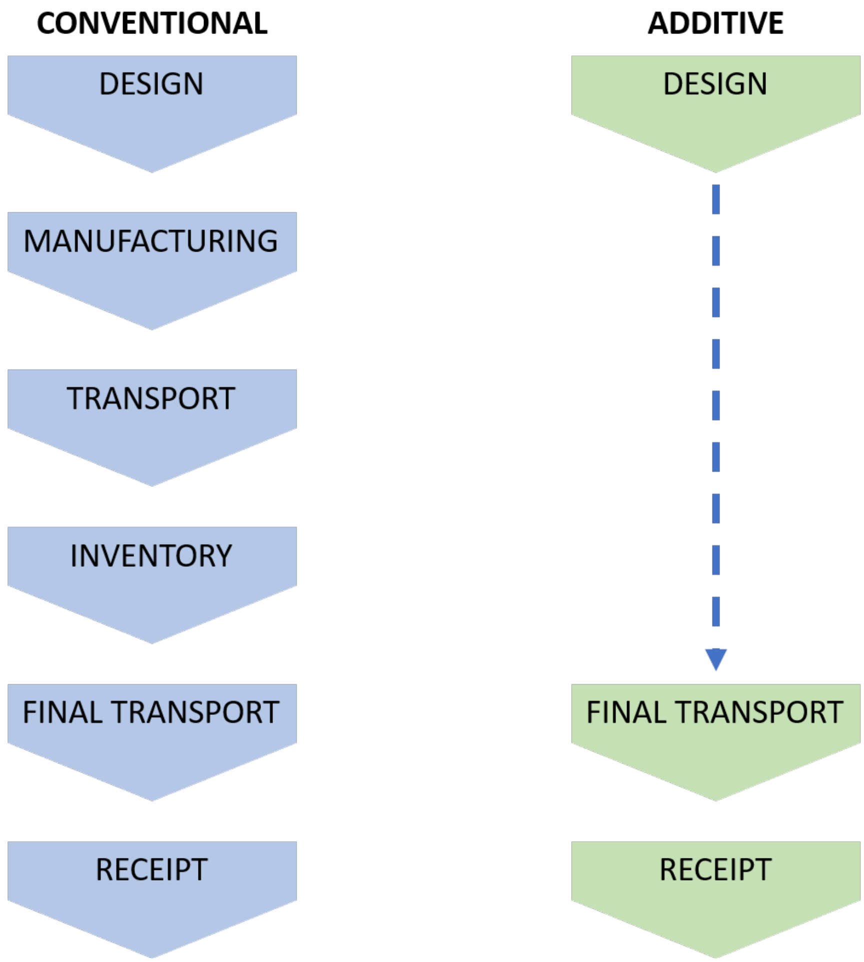

Figure 5-8: Additive Manufacturing Supply Chain Streamline

5.4.1 Score Breakdown

In the assessment, an Additive Manufacturing Evaluation Score or AMES was established. This score would be used by subject matter experts in the development phase for each part in accordance to the scorecard. AMES was comprised of five key components: cost reduction, lead time reduction, supply chain, Design for Additive Manufacturing (DFAM), and Performance. Cost, lead time, and supply chain took into account the percentage savings that the part would assume given additive manufacturing methods. DFAM was broken up into a few sub components of material, waste, weight, and post processing. The performance score was divided between ability for topology optimization and part consolidation. The final evaluation took a weighted average of the five components into a single, comparable score. Exhibits

B-1 to B-4 provide more details on the breakdown of each scoring component.

5.4.2 Application of AMES at Bell Textron Inc.

The Additive Manufacturing Evaluation Score was applied to several candidate parts at Bell Textron Inc. In the figure below, an example of the scorecard as applied to a candidate part. From initial scores, most candidate parts landed in the 35-55% range. Furthermore, among the candidate parts, it seems that additive manufacturing has more potential among production parts in drive systems and rotors. Candidate parts with structures, particularly airframe did not exhibit strong scores to support additive manufacturing. The AMES method is important to take a candidate part list, remove any subjective bias, and create a rank of feasibility and potential for additive manufacturing on parts. There are limitations to consider, however. This model assumes the five main factors carry equal weight that exhibit equal importance. If an evaluator wishes to apply a secondary weight, an additional factor must be accounted for. This model also assumes certain cost savings and time savings from the model. As the industry creates more accurate models for cost and time estimates for additive manufactured parts, so too will the AMES model increase in accuracy. Refer to Exhibits C.1 to C.8 for additional information to the cumulative model and evaluated parts.

5.5 Business Case

Before discussing the business aspects of additive manufacturing for Bell Textron Inc., it is worth noting the additive manufacturing state can be described by a combination of the intended product and supply chain changes. Deloitte[19] outlines the relationship into four states of additive manufacturing: stasis, supply chain evolution, product evolution, and new business. Stasis is described as “no change” where the product and supply chain are “as-is”. In this position, rapid prototyping and tooling applications are favored because of the lack of impedance on the product and supply chain. In evolving the supply chain, this is where the supply chain is transformed by

Table 5.3: Additive Manufacturing Evaluation Score Sheet

Part Name	Score	Notes
Category		
Manufacturing Method		
Materials		
Part Size		
Cost Score		
Lead Time Score		
Supply Chain Score		
DFAM Score		
Material Maturity Score		
Waste Score		
Weight Score		
Post Process Score		
Performance Score		
Topology Optimization Score		
Part Consolidation Score		
Total Score		

Table 5.4: AMES Application Summary

Candidate	Category	Size	Cost Score	LT Score	SC Score	DFAM Sc.	Perf. Sc.	Total Sc.
Part 1	Production - Drives - Cases	Medium	30%	50%	75%	45%	75%	55%
Part 4	Production - Rotors	Small	20%	45%	55%	55%	75%	50%
Part 3	Production - Rotors	Small	15%	80%	55%	55%	38%	49%
Part 2	Production - Drives - Cases	Large	30%	48%	55%	45%	63%	48%
Part 5	Production - Rotors - Others	Small	20%	29%	55%	48%	63%	43%
Part 6	Production - Structures - Airframe	Med	10%	45%	55%	39%	50%	40%
Part 7	Production - Structures - Airframe	Med	10%	45%	55%	34%	50%	39%
Part 8	Production - Structures - Airframe	Med	0%	45%	55%	34%	38%	36%

consolidating vendors and removing middle steps. Spares and one-off products excel in this area because the supply chain can improve while the produce stays the same. As for product evolution, in order to change the product for additive manufacturing, design benefits must be applied such as topology optimization and DFAM. Lastly, evolving both the product and supply chain creates a “new business” where only additive manufacturing is the sought-out method for producing parts. In assessing additive manufacturing, Aerospace OEMs are looking to improve existing operations and products to create products focused around additive manufacturing.

In assessing Bell Textron Inc., the company is situated comfortably within “stasis” and is looking to utilize the AMES evaluation process to determine how to create “new business”. Bell Textron Inc. has experimented with the supply chain evolution path

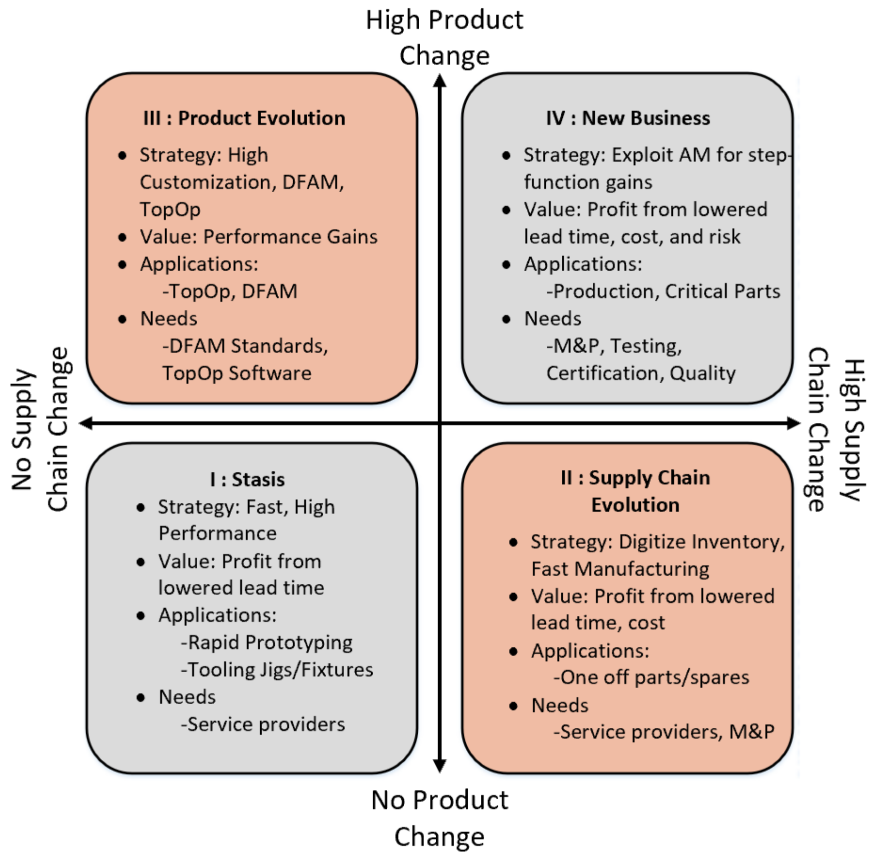

Figure 5-9: Product and Supply Chain Transformation

with spares, and is interested in pursuing a product evolution path in parallel. AMES is a starting point to aid designers with candidate parts to begin utilizing additive manufacturing design standards and software. Upon further review of Bell Textron Inc., the four states in the figure above can be classified as a short- or long-term wins. It is imperative for Bell Textron Inc. to commit to the long-term goal and leverage short-term wins for momentum.

5.5.1 Short-Term Wins

For Bell Textron Inc., short-term wins can be associated with anything related to time reductions. Rapid prototyping and tooling are both applications that need quick turnaround times and are usually lower risk items that can be tackled with the current additive manufacturing technology. As it stands today, there is not a lot of development that would be needed thus the upfront costs for development would be low. However, short-term wins will not produce cost nor performance benefits, but rather the focus is on speed and lead time reduction. Not to be overlooked, however, are the continued learnings from developmental projects to aid in the long-run. These short-term wins are essential to driving early momentum for additive manufacturing adoption within any organization.

5.5.2 Long-Term Wins

The remaining attributes of cost, material reduction, performance, and supply chain are long term business goals for additive manufacturing. Long term wins will take more than just a few years for the benefits to be realized. The industry has many barriers to overcome in order for standardized processes to be created and for Bell Textron Inc., a long-term commitment is hard to justify. A connection between a short-term win to a long-term goal must be established to generate a path forward for organizations to follow for development.

Chapter 6

Engineering and Design for Additive Manufacturing

Up until this chapter, this thesis has performed evaluations and discussed benefits pertaining to additive manufacturing under the assumption that the process, technology, and material has already been developed. However, today in the aerospace industry, that is not the case. This chapter serves to highlight the engineering process for additive manufacturing and material development. Toward the end of this chapter will be an overview of the inspection and certification processes, culminating this chapter with a stress on the engineering complexities aerospace OEMs have to consider, that make additive manufacturing so difficult to develop.

6.1 Design for Additive Manufacturing Overview

When engineering designers approach an initial design for a part, one of the philosophies that guide the design is called design for manufacturing or DFM. DFM is considered the best practices to allow for "optimal manufacture of parts with the goal of keeping costs down."[24] Take a part that is to be machined, for example. Based on the design requirements and the functions of the part, aluminum was chosen as the material of choice. In addition, aluminum was also chosen with the manufacturing process in mind, to reduce the wear and tear of the tools. This helps to reduce the total cost of machining, as money is saved from having to purchase new tools.

Design for additive manufacturing (DFAM) is a similar philosophy that is applied to reduce the cost for this particular method of manufacturing. DFAM reduces cost in three ways: part consolidation, design features, and orientation. Part consolidation aims to reduce the amount of parts needed for assembly. If there are several parts that will be assembled into a larger assembly, a DFAM solution would be to combine all of those parts into one. Savings will be found in less parts needing to be manufactured and less labor costs for assembly. Moving to design features, part characteristics such as internal structures and overhangs are focused areas for DFAM. These specific characteristics make traditional manufacturing methods highly expensive due to the difficulty manufacturing those features. Additive manufacturing solves these issues but utilize extra structure to achieve these features. The temporary structure adds cost and labor to remove the structure. Design features combined with orientation can help reduce the temporary structure costs. DFAM will take into account the way a part is envisioned to be printed. If there is an overhang, the part could potentially be printed upside down where supports are not needed at all. These factors generalize the philosophy of DFAM and is also dependent on the additive manufacturing process.

6.2 Topology Optimization

Besides DFAM, another philosophy pertaining to additive manufacturing is topology optimization. This method of design takes into account several design constraints and mathematically optimizes a geometric layout. The optimized objective can vary around mechanical loads or minimal material usage. A single part can be optimized for both, but one objective function would prioritize the other and would need separate iterations for each function. A uniqueness of topology optimization is the ability to do so on complex geometries. Furthermore, because additive manufacturing prints in a layer-by-layer method, complex shapes can be printed at no additional cost to the designer.

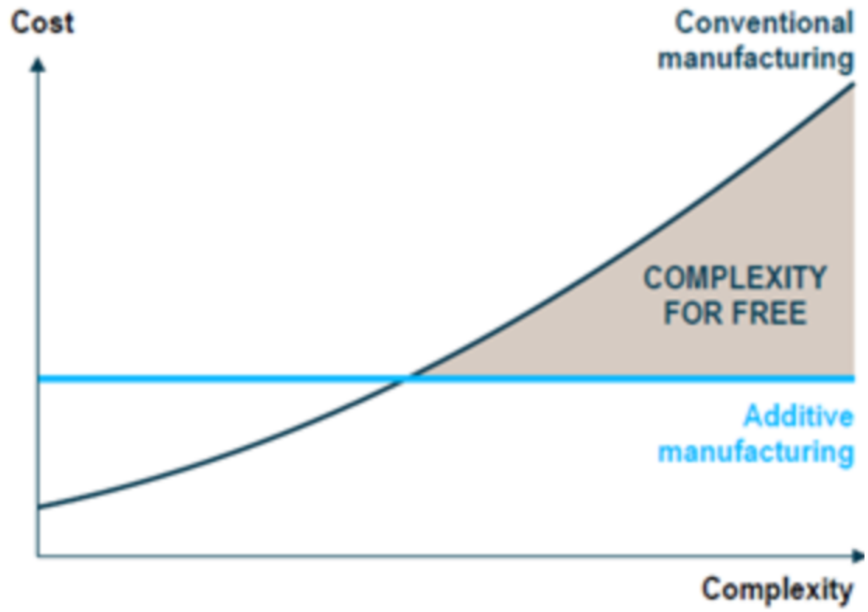

Figure 6-1: Complexity Comparison - Additive vs Conventional

6.2.1 Topology Optimization Part Characteristics

As with most processes within additive manufacturing, a selection criteria would be needed to determine if a part would benefit from being optimized. The list of criteria is comprised of characteristics that were discussed earlier for applications for additive manufacturing. The relevant characteristics for topology optimization are the following:

1. Load Paths
2. Internal Structure
3. Thin/Thick Walls
4. Thermal Management
5. Surface Finish

The first characteristic to analyze is the intended structural load paths the part is expected to experience. A load path can be simplified and described in a linear path; thus, a geometry can be built around the path. The next feature to evaluate is the internal structures. Topology optimization can create designs that optimize the internal functions of a part. Next, thick and thin walls in certain parts exist because of the way a part is conventionally manufactured. For example, a thick wall does not provide mechanical support and is not needed, but because the part is casted, the thick wall is needed. Topology optimization can reduce the thickness and as a result weight can also be reduced. Occasionally a part will have a thermal requirement such as heat dissipation via a heat sink. Most manufacturing methods have a basic fin geometry, but topology optimization can utilize the entire surface and create geometry to maximize surface area for heat transfer. Lastly, the surface finish requirement must be evaluated for the function of the part. Additive manufacturing has limited fidelity, so the ability to have certain surface requirements, especially internally will determine the feasibility. In performing an optimization, it is important to define the boundary constraints. If the requirements tightly set, the optimization would not be able to have freedom for design. However, if the requirements are not tightly set, the optimization will have too much freedom and can produce an undesired part.

6.2.2 Topology Optimization Process

With a candidate part is identified, the first step in the optimization is to establish the base requirements. These requirements are vague but are used to describe a part in its 3D space. Furthermore, the requirements are broken down into physical and mechanical properties. The physical requirements dictate the spatial limitations that limit the amount of freedom the optimizing software has. On the contrary, the mechanical requirements are guidelines the software has to abide by.

Once the requirements are defined, an initial design model is selected. Currently, there is no standardized design guidelines for the initial design. However, the more detailed the initial design is, the less freedom the optimization software has to work with. The key component in the initial design nonetheless, is the fixed hard points. These points can be surfaces or interface points where other parts are expected to mate at these locations. With the base requirements and initial design, a part can proceed through the optimization cycle.

In each iteration of the optimization cycle, an optimized objective is chosen, such as "minimize total material mass". From the model, the design space can be defined to allow the optimizing software know what areas of the part can be optimized. After the optimization has been run, the output of the model needs smoothing in areas such as intersecting joints and surfaces. The model is reanalyzed for performance and subject matter experts (SME) would provide additional guidance for next iterations. Figure 6-2 summarizes the topology optimization process and cycle.

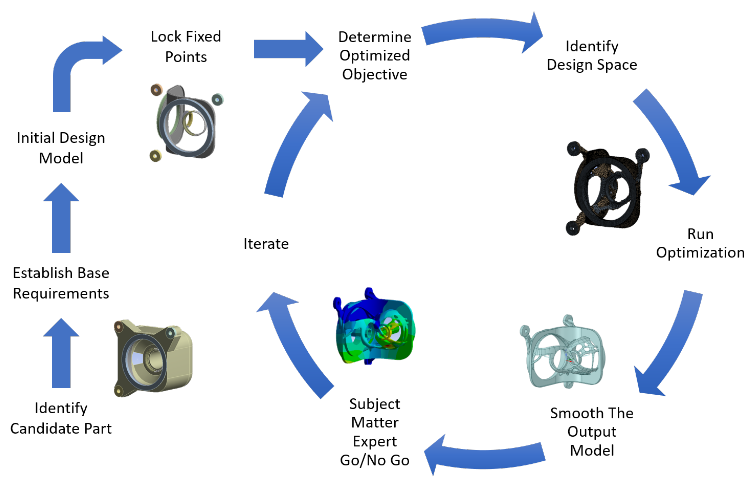

Figure 6-2: Topology Optimization Iteration Cycle

6.2.3 Intermediate Gearbox Topology Optimization Case

Through the selection criteria as discussed in Chapter 5, the Intermediate Gearbox Housing was shown to be a fitting candidate for additive manufacturing. In addition, the IGB was also assessed for topology optimization. It was revealed that the IGB exhibited the following characteristics that made it an ideal candidate for topology optimization development.

1. The IGB carries no significant loads critical to flight

2. There are internal channels and structures to support the gears

3. The material currently used is magnesium

4. There is a thermal management feature

5. There are thick walls due to casting constraints

Figure 6-3: Overview of the Intermediate Gearbox Housing (IGB)[11]

As mentioned, the IGB is a prime candidate for topology optimization because it carries little risk, but exhibits internal and thermal features that can be optimized. The objective function would be to reduce material and weight. Furthermore, the original material is magnesium, and the additive manufactured material would be aluminum. Lastly, because the IGB is a casted part, there exists thick walled areas that do not carry structural loads.

Through this example case, discussions on the possibilities of additive manufacturing through topology optimization have given rise to new paths to development. Topology optimization on the IGB has developed ideas on optimizing for different materials that have better mechanical properties with marginal cost downsides. In addition, the IGB is an existing part, and the potential to run an optimization and perform fatigue tests on the printed part would be a first at Bell Textron Inc. and provide valuable data. This is possible because the interface points are fixed to be exactly the same as the original part thus interfacing with existing test stands. The IGB has shown potential for many additive manufacturing benefits that utilize topology optimization, but still there are limitations and challenges that will be further discussed in Chapter 7.

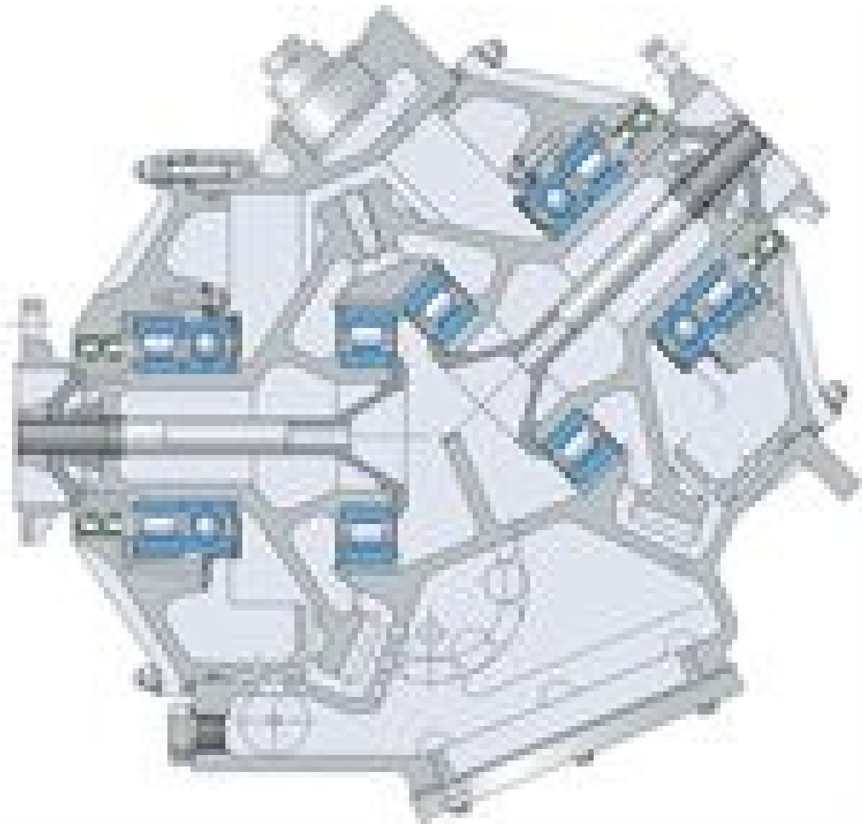

Figure 6-4: Internal Features in the IGB[12]

6.3 Materials, Processes, and Machines

In any manufacturing process, a proven standard of materials and processes must be met. This section describes the monumental task of qualifying a new material and procedure as well as summarizing the agencies that must approve the overall process. In addition, this section also details the parameters that must be controlled in each given machine, an added level of control to ensure consistency throughout the print process.

6.3.1 MMPDS and Material Development

MMPDS stands for Metallic Materials Properties Development and Standardization. According to its website, MMPDS is the primary source of statistically-based design allowable properties for metallic materials. MMPDS standards are widely followed in commercial and military aerospace applications. In addition, many certifying agencies

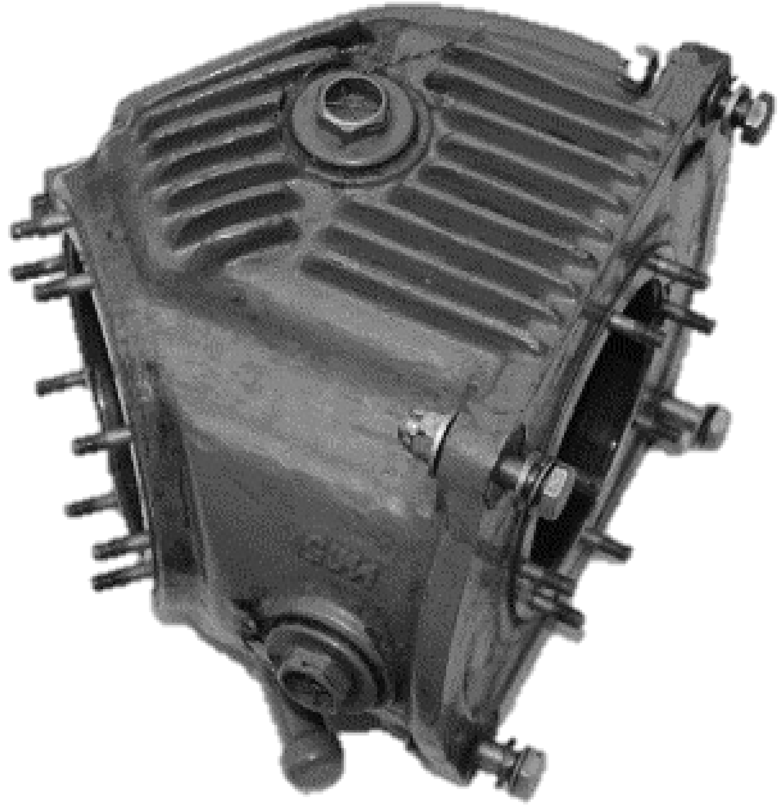

Figure 6-5: Thermal Features on the IGB[13]

such as the FAA and Department of Defense utilize MMPDS as the primary source of reference when deciding allowable loads for design.

A Design Allowable is a statistical value at which a certain percentage of measured values will exceed with a certain confidence level. This design allowable can be either a physical property or a mechanical property of a given material. The aerospace industry has two classifications of an allowable. An "A" basis allowable pertains to 99% of population equals or exceeds value with 95% confidence or the specification minimum when it is lower. A "B" basis allowable states that 90% of population equals or exceeds value with 95% confidence.

In order to attain these values, MMPDS requires tests to be conducted for physical properties (hardness, density, composition, etc.), mechanical properties (stress/strain, tension/compression, fatigue, etc.), and thermal properties (specific heat, thermal conductivity, etc.). To get a material into MMPDS, each material must have an

Aerospace Materials Specification or an AMS. In addition, the required tests that are needed are:

1. Tensile
2. Compression
3. Shear
4. Bearing
5. Stress-Strain Curves
6. Modulus
7. Physical Properties

Recommended additional tests include temperature elevation, fatigue, and toughness. Each specific test requires a sample size of 100 specimens from 10 lots. The aerospace industry generally follows the MMPDS analysis for qualifying materials.

6.3.2 MMPDS and Additive Manufacturing

Additive manufacturing material development will fall under MMPDS when undergoing qualification. Additive manufacturing faces two challenges in material qualification. The first is the state at which the material is injected into the machine can be a powder or wire or solid rod. There is a lack of standards for additive material qualification and at this moment, a separate qualification would be needed for each state. The second challenge is that a machine can print in all X-Y-Z axes. The mechanical properties can differ on each direction of print. Like the different material states, the material must also be separately assessed on each orientation of print.

6.3.3 Process and Machine Control

Consistency is all about controlling the parameters of the process. There are many parameters in the print process that affect the resulting quality of the part. External from the machine, the material needs to be consistent. In powder bed fusion, the size of the particles must be consistent. Likewise, the powder must have the same concentration of material at all times. The machine itself will have to be situated on a calibrated, level surface.

Internal to the machine, there are also many parameters that affect the quality of the print. The material injection, power output of the laser, internal environments all contribute to small deviations to the print such as layer thickness, fuse capabilities, density, and so on. In the aerospace industry the criticality of its applications requires a high level of consistency in order to prove safety for flight.

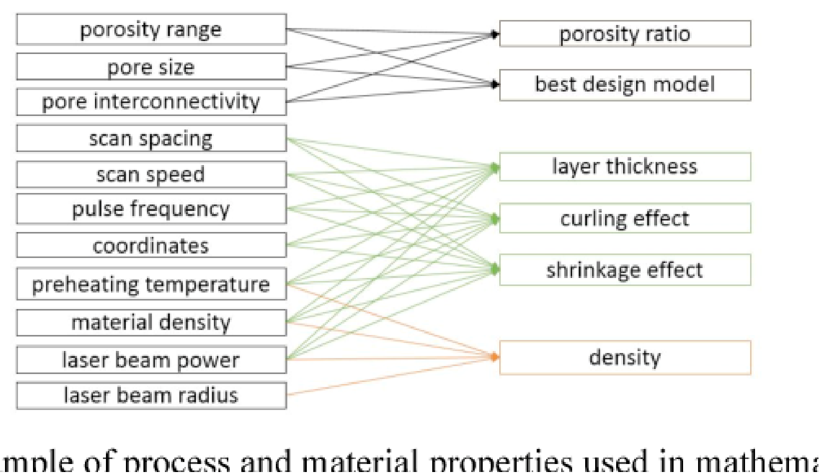

Figure 6-6: Control Factors for Additive Manufacturing

6.4 Quality Inspection

The last piece of the engineering process that is often overlooked is the inspection process. This section discusses the current means of inspection in the aerospace industry as well as proposed methods of in-process monitoring for additive manufacturing. Quality inspection exists to verify the consistency in the as-designed process. Furthermore, this section describes a few testing methods that current metallic parts undergo that would also be applied for metals additive manufactured parts.

6.4.1 In-Process Monitoring

In-process monitoring is a method used to aid in ensuring consistency during the print process. While the machine itself can monitor outputted parameters, there is no telling how the quality of the print really is. Visual inspection is usually applied after the print is completed. In-process monitoring generally comprises of a thermal system that monitors the melt pool of the printed material. The melt pool is the heated material that fuses to the previous layer. Melt pool physics are complex, but this method provides a simple way to ensure the output parameters of the machine are outputting a quality print. Furthermore, machines are being implemented with software and algorithms to utilize the feedback from thermal scans to perform live course correction to the print. While this concept is in its early stages, utilizing live data analytics will be crucial to ensuring the quality printed part.

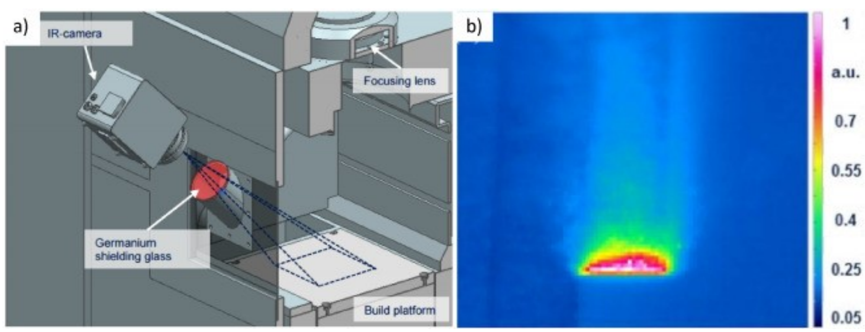

Figure 6-7: Example of In-Process Monitoring

6.4.2 Nondestructive Testing

According to the American Society for Nondestructive Testing or ASNT, nondestructive testing or NDT is the process of inspecting and testing for discontinuities, or differences in characteristics without destroying the serviceability of the part or system.[25] NDT is an important step in ensuring that each produced part is printed to the intended design. Furthermore, with additive manufacturing offering different orientations and batching, NDT becomes critical in determining consistency no matter the orientation or placement within the printer. NDT does not focus on physical properties such as strength and toughness, but rather on surface and internal integrity. The destructive tests are usually used in material development described in the MMPDS process. The main methods of NDT usually use a penetrating medium along with equipment to observe any discontinuities in the product. Some of the most common NDT methods in the aerospace industry are[26]:

1. Visual Testing (VT)
2. Magnetic Particle Testing (MT)
3. Liquid Penetrant Testing (PT)
4. Acoustic Emission Testing (AE)
5. Leak Testing (LT)
6. Radiographic Testing (RT)
7. Ultrasonic Testing (UT)
8. Thermal/Infrared Testing (IR)

At the moment, typical standards for NDT are being applied to additive manufacturing, while lessons learned are being used to develop specific standards for additive manufacturing. The standards being used and developed apply to as-printed parts as well as post-processed printed parts.

6.5 Certification

The last gate a part has to pass through before being capable of flight is certification. In the military, there are several agencies that award certification. As for commercial products, the FAA is in charge. This section will provide an overview of the FAA and military methods for standardization as well as current standards for certification.

6.5.1 Current Standards

While standards are currently being developed for certification, there is still the need to define qualification and certification meaning in the additive manufacturing industry. The aerospace industry understands the need to collaborate to have general standards, but it requires data and contributions from every entity. Efforts from third party aerospace companies and partnerships with Standards Agencies are being used to lay the groundwork for developing standards. In short, there are no standards, but there exists a long process of creating those standards today. Without the qualification and certification standards, additive manufacturing will continue to present itself as an ideal technology, rather than practical, method for manufacturing.

6.5.2 FAA Certification

As stated before, the Federal Aviation Administration or FAA, is the governmental body for regulation of civil aviation within the United States. This includes the power to certify and qualify a process and/or material for additive manufacturing for use in commercial aerospace products. The FAA scrutinizes processes due to the unique safety concerns with humans in particular environments. The FAA has announced a collaborative effort in 2017 to create a roadmap for additive manufacturing. However, the effort has been halted with very little recent progress. Programs that have been successful with piece-part certification have normally underwent a general list of proving a level of understanding on materials, products, procedures, personnel, equipment, and models that ensure consistency as defined by standards from MMPDS, ASTM, and AWS.

6.5.3 Military Certification

The military has its own set of internal agencies that regulate certification for use of additive manufactured parts on their aircraft. Like the commercial side, the military has a basic set of requirements that need to be proven before use on the aircraft. The military carries a more structured method in ensuring the standards are applicable for

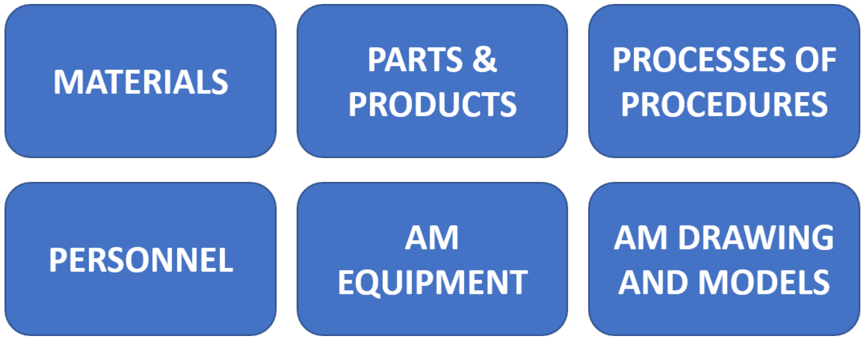

Figure 6-8: Factors for FAA Certification

all of additive manufacturing including the terminology and training that is involved in the process. Lastly, the additive manufactured part has to be an approved part by the Department of Defense in order to be considered for approval.

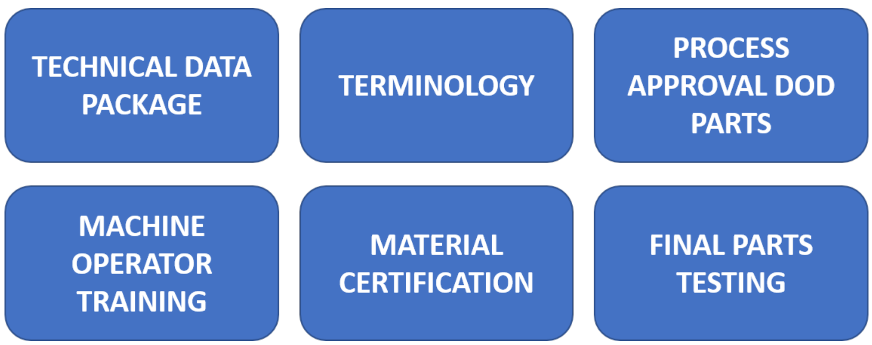

Figure 6-9: Factors for Military Certification

Chapter 7

Additive Manufacturing Road Map and Challenges

This chapter is an aggregate of the previously discussed aspects of additive manufacturing applied to a strategic road map for an aerospace OEM. This road map is structured to focus on the higher-level company needs to establish and maintain momentum for adoption of additive manufacturing. This chapter also provides example paths for engineering development for low- and high-value parts. The road map serves as an ideal yet practical path for adoption. However, challenges exist within additive manufacturing development and this chapter will be address these challenges from an industry, company, and engineering perspective.

7.1 Additive Manufacturing Road map

The roadmap for additive manufacturing is a combination of four main components progressing together in parallel. It is broken down by the enterprise, engineering, supply chain, and education. The enterprise side of the roadmap is responsible for establishing the driving direction for additive manufacturing and creating a dedicated team and budget to move forward. This area also focuses on the changing needs that constantly arises from changes in the market. Furthermore, this part of the roadmap manages the partnerships and assesses the plans that will be implemented for certification and customer use. Targeted value parts and new areas for business and intellectual property will also be discussed here. Lastly, the overall production strategy and any potential mergers and acquisitions of smaller additive manufacturing companies will be evaluated among the enterprise.

The engineering roadmap covers the majority of development for design and materials. The material test matrix and plan will be created in this function as well as the creation of the selection criteria as applied to the existing and future products of the enterprise. This path also documents the design and engineering best practices that will be the foundation for development. The engineering roadmap will work with agencies to establish the design-allowable(s) and also to merge quality and inspection plans into a greater certification plan.

The supply chains main focus lies with creating partnerships with service bureaus in merged efforts from the enterprise. In addition, material suppliers and machine vendors will be identified, and either integrated in existing, or set aside for dedicated supply chain networks. Aside from the suppliers, the supply chain will also focus on integrating additive manufacturing into larger production processes and merging additive manufacturing capabilities with existing workflows.

An often-overlooked function of the roadmap, but equally as important, is the educational side of additive manufacturing. This involves learning and documenting additive manufacturing best practices from external experts at conferences, universities, and partners. As information is flowing from external sources into the additive manufacturing team, the team faces a larger challenge of diffusing the knowledge to the designers and engineers to provide the tools needed to utilize additive manufacturing for their use. The education roadmap looks for creative ways to pass knowledge among the company through activities such as lunch and learns, design days, etc.

It is important to understand that the four areas for the roadmap are not discrete within its respective functions, but rather work dynamically with each other. For example, the supply chain function works with the enterprise on partnerships, but the information that the partnerships yield flows into the engineering and educational side. Likewise, the engineering team will define the requirements for development, and work with the enterprise and supply chain to purchase machines or identify service bureaus to partner and conduct tests to gather data. If any one of the four areas of the additive manufacturing roadmap are neglected, momentum for adoption will quickly be lost.

	PHASE 1	PHASE 2	PHASE 3
ENTERPRISE	• Create Dedicated AM Group • Centralize AM Database • Join AmericaMakes • Monitor the Industry/FAA • Bridge RP/Spares to Production • Secure incremental funding • Target low value part	• Certification Plan • Cybersecurity Plan • Purchase AM Machine • IP/Patents • Target hi-value part • New target areas	• Evaluate M&A • PR • Production Strategy
ENGINEERING	• Material Qual Doc/Template • Gather/Create Data • Coupon Test Matrix • Create Design/TopOp Spec • Selection Criteria • AM Process Flow, test with secondary structure parts, XX/year	• Quality Inspection Plan/Tools • Part plan for primary structure • Establish Design Allowables • New Materials	
EDUCATION	• Training workshops for DFAM with program designers • Lunch & Learns • Conferences • AM Design Challenge/Hackathon • Establish University Partnerships		
MANUFACTURING & SUPPLY CHAIN	• Partnerships with service bureaus • Identify material suppliers • Consolidate suppliers/vendors • Workflow integration	• Plan Future Supply Chain	

Figure 7-1: Overall Road Map for Additive Manufacturing

7.1.1 Development Road Map

The development roadmap is a separate roadmap to highlight the differences for development of a low-value part versus a high-value part. The low-value part refers to a low-risk, low-complexity part that does not exhibit many characteristics of additive manufacturing that would exploit the benefits. In contrast, a high-value part is a part that could be flight critical, a production part, and would have characteristics that is advantageous for additive manufacturing. Both roadmaps consist of a candidate part selection, engineering design, material and process development, and testing to certification. The low-value part follows the development timeline in a relatively short amount of time, with a limited amount of needed budget; a relatively small and manageable amount for a development budget. The timeline for a low-value part is potentially a three to five-year process, with three being an optimistic prediction with continual efforts throughout the company. The high-value part, in comparison, shows exactly the same path, but in an elongated timeline. This means that the development time is just an extended path of that of the low-value part. The amount of funding budgeted can be similar or slightly higher in the high-value development, but for a much longer time frame. In additive manufacturing, there are many uncertainties which make it difficult to quantify the exact timeline for development for a high-value part. It is worth noting, however, a high-value part can be developed in the same amount of time as a low-value part, but the cost for development will be greater by several magnitudes.

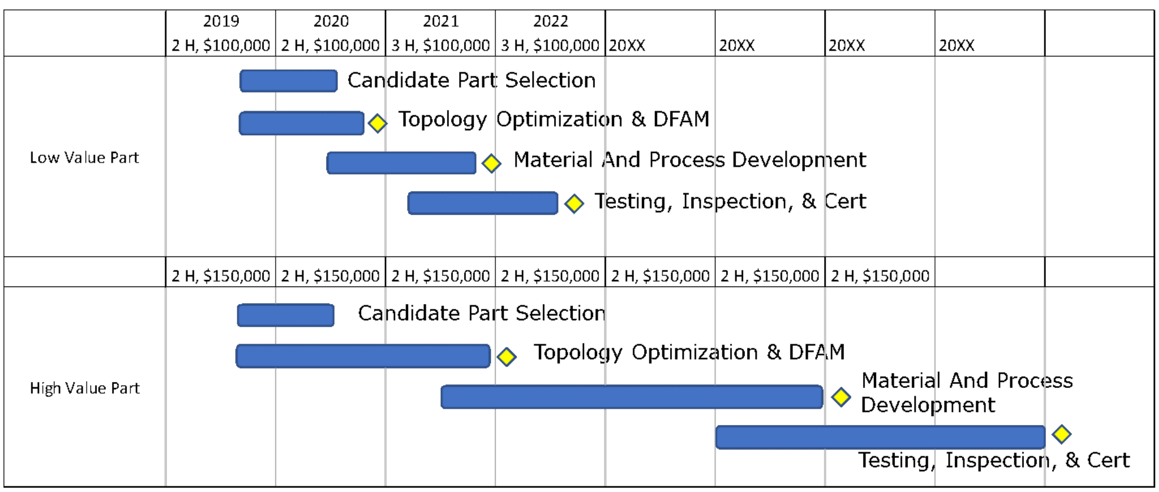

Figure 7-2: Development Road Map for Different Value Parts

7.1.2 Engineering Road Map

As discussed in earlier chapters on the engineering roadmap is split into design and material development. The two converge in Design for Additive Manufacturing, all the way through certification. In material development, the process begins with identifying a material, the suppliers of that material, and test campaign for in-house development. The major milestone that results from this effort is the first order design allowable that flow into DFAM. On the design side, a part runs through multiple iterations of topology optimization to establish a best practices guideline that feeds into DFAM.

After the part reaches DFAM, in parallel, a print supplier is sourced and a material plan is created. The part is produced in the print phase and is post-processed if needed. Afterwards, the part enters a test plan dictated by the engineering team. Subsequently, a certification plan takes the part forward toward approved production and certified flight. Additive manufacturing development is a series of trials and errors, and this roadmap is constantly iterating, redefining design metrics, updating best practices, and retesting for certification.

The engineering roadmap carries a majority of the development effort and cost needed to adopt additive manufacturing. In the figure below, most aerospace OEMs are at the highlighted stages and stagnate in those phases due to the high costs associated with the next steps in the development roadmap.

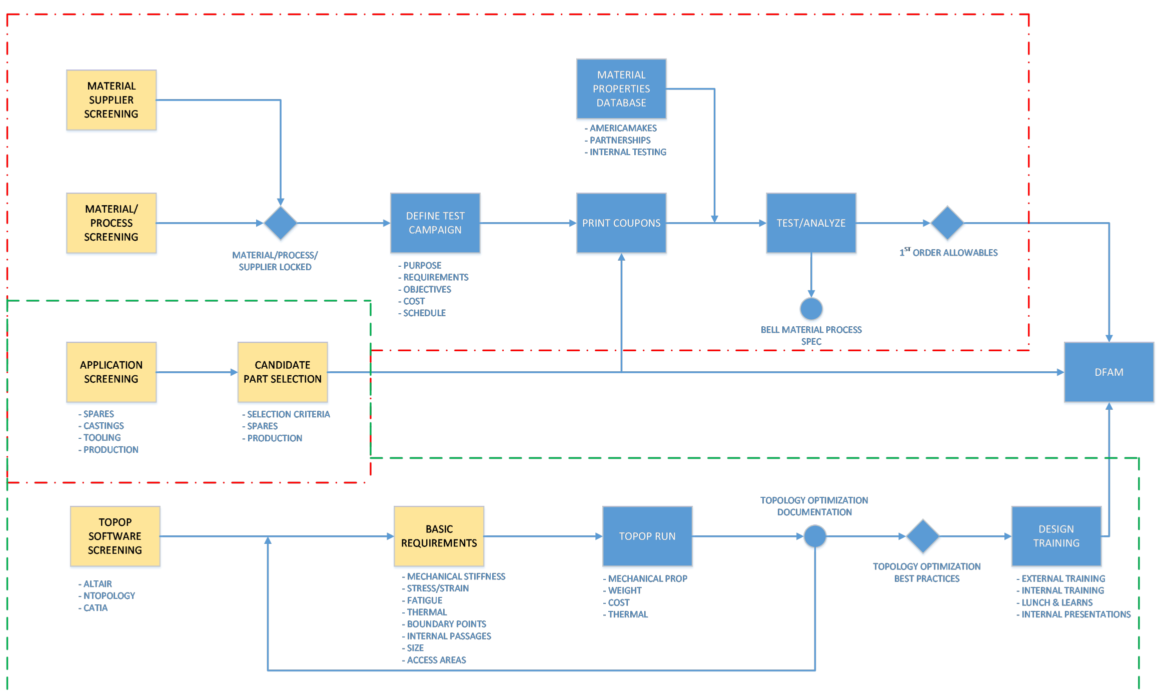

Figure 7-3: Pre-DFAM Road Map

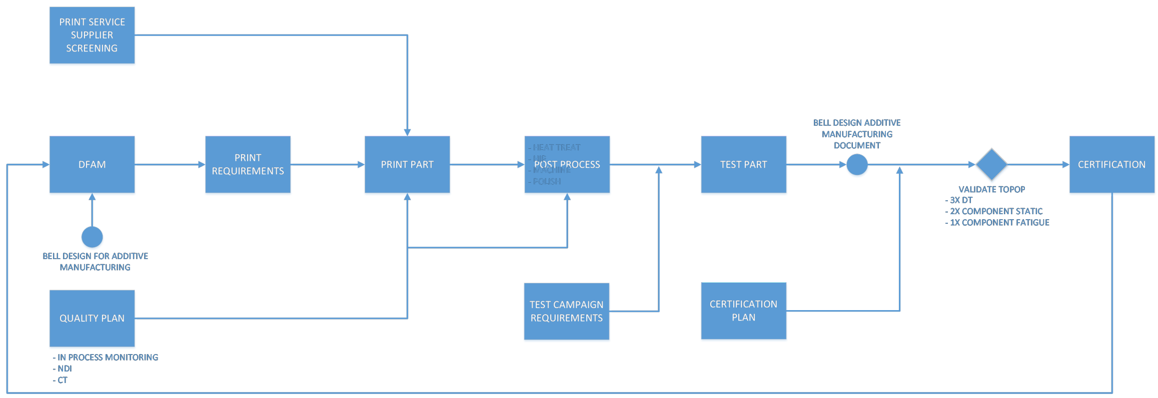

Figure 7-4: Post-DFAM Road Map

7.2 Additive Manufacturing Challenges

Additive manufacturing is a technology that has been around for several decades, yet it still seems to be a novel method of manufacturing to OEMs in the aerospace industry. This is due to the many challenges associated with additive manufacturing that raise skepticism among executive leaders in these OEMs. This section provides details on the three biggest challenges among the industry, companies, and engineering. Furthermore, this section concludes with insight on the certification challenges and cyber security involved with additive manufacturing adoption.

7.2.1 Industry-Wide Challenges

As mentioned, several times in previous sections, additive manufacturing is a constantly changing industry. The technology and material offerings have not been standardized and any new variation or added parameter prevent continual development from OEMs. Furthermore, machine manufacturers haven't reached a production point where their parts are standardized and consistent. Any customization in the machine adds increased challenges in the certification process. The fear is that any development being made today will not be valid for the next machine, the next alloy, or the newest process. Until the industry matures among its materials, machines, and technologies, aerospace OEMs will be hesitant to fully push forward with additive manufacturing development and adoption.

7.2.2 Engineering Challenges

The main engineering challenges for additive manufacturing can be associated with development and its physics. This thesis has mentioned many times that development for additive manufacturing is a major barrier to entry for most aerospace OEMs due to its large associated costs. For example, the qualification of a single metallic material in one orientation can be upwards of ten million dollars due to the number of specimens, post processing, and tests. This estimate is simplified to only account for printing the specimens and the number of specimens to account for the material scope. This does not take into account the testing costs nor the labor costs associated with material development. At an initial and simplified estimate of ten million just for the specimens, aerospace OEMs are hesitant to commit such a large amount of funding. Furthermore, it is easy to see costs continually pile on as the industry isn't standardized. The ten-million-dollar estimate can be multiplied by each machine or process or even the number of materials being qualified. Finally, because the industry is also changing, the development efforts can be rendered obsolete as the technology progresses. The high costs and changing industry explain why most aerospace OEMs choose elongate the development process.

On the finer engineering side, there are challenges attributed to the physical part and the inspection processes. The challenges on the physical part are mainly focused on the fidelity of the print. Fidelity refers to the quality of the printed part. Many aerospace OEMs are attracted to the opportunity of ready-to-fly parts for additive manufacturing. But the surface qualities or the mechanical properties may not be ready for flight. The surface quality on external and internal surfaces are critical for performance and for a helicopter manufacturer like Bell Textron Inc., this poses a huge risk. Helicopters operate in a high-cycle, high-fatigue environment. Surface quality must be extremely smooth to minimize, if not eliminate, stress concentrations. In a topology optimized part with internal structures, it is hard to machine the internal surfaces to meet that requirement.

Extending past the physical part, the inspection process is an equally challenging

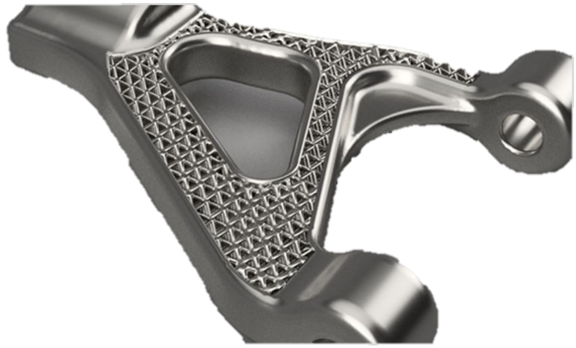

Figure 7-5: Example of Internal Lattice Structure[14]

step that is often overlooked. Just like the fidelity of the part finish, the fidelity of the inspection process also poses a risk for additive manufacturing development. The concern is how to fully verify if the part that was printed is the actual as-designed part. Furthermore, with a structure like the figure above with internal lattices, it is hard to pinpoint where defects are and if defects are found, methods for correction are also limited with a structure such as this example.

7.2.3 Certification Challenges

The desire for a part that is designed and printed with additive manufacturing is certification for flight. The challenges that are associated with certification are hand-in-hand with the development and engineering challenges. The two biggest challenges surrounding certification are (1) there are no current standards and (2) current certification is piece parts. For the lack of standards, the certification agencies such as the FAA rely on OEM data to be able to create the standards and data for additive manufacturing material development is proprietary and public data is limited. Furthermore, the FAA does not have a clear roadmap for general certification. This leads to the current method of piece part certification. This means a certified part is tied to the process, machine, and material that was involved in the certification. Any changes to the process or material or machine requires another certification. The process is lengthy and performing re-certifications for each part and each change is not desirable for any OEM developing additive manufacturing.

7.2.4 Cybersecurity

When a part is sent to the machine, many times it is transferred electronically and through the internet. This feature raises cybersecurity concerns among the aerospace industry. The obvious concern is that part models can be stolen from the machine or during the file transfer process. Another concern is that the machine could be compromised and the machine will not produce quality parts as it should be. Lastly, machines are operated by software that can be updated through pushed updates from the manufacturer. This can compromise the current process and force a need for recertification. Cyber security concerns are not as big of a concern as other challenges, but will be when production and flight critical parts are in question.

7.2.5 Organization Challenges for Adoption

As an aerospace OEM looks to adopt additive manufacturing into its organization, it is important to assess where the team plans to exist. An analysis on the internal organization is needed to review the stakeholder, cultural, and system level barriers.

Organizational Analysis - Looking at Bell Textron Inc. as an example, the organization is set up in a matrix organization where functions support multiple product lines. At Bell Textron Inc., within engineering, multiple functions such as supply chain, manufacturing ops, propulsion, and structures report to a program manager and a chief engineer for each product line.

The matrix organization creates a difficult scenario as to where additive manufacturing should belong. At Bell Textron Inc., the additive manufacturing efforts are in an overarching function of Manufacturing Innovation. This allows rapid prototyping and different programs to tap into additive manufacturing efforts. However, the number of stakeholders also increases. This first stakeholder is the champion for additive manufacturing that is able to push from the top-down. The other stakeholders come from program and supply chain teams. The last stakeholders are external to the company and this involves partnerships. In the figure below of Bell Textron Inc.'s organization, the stakeholders are categorized in different groups that all feed into

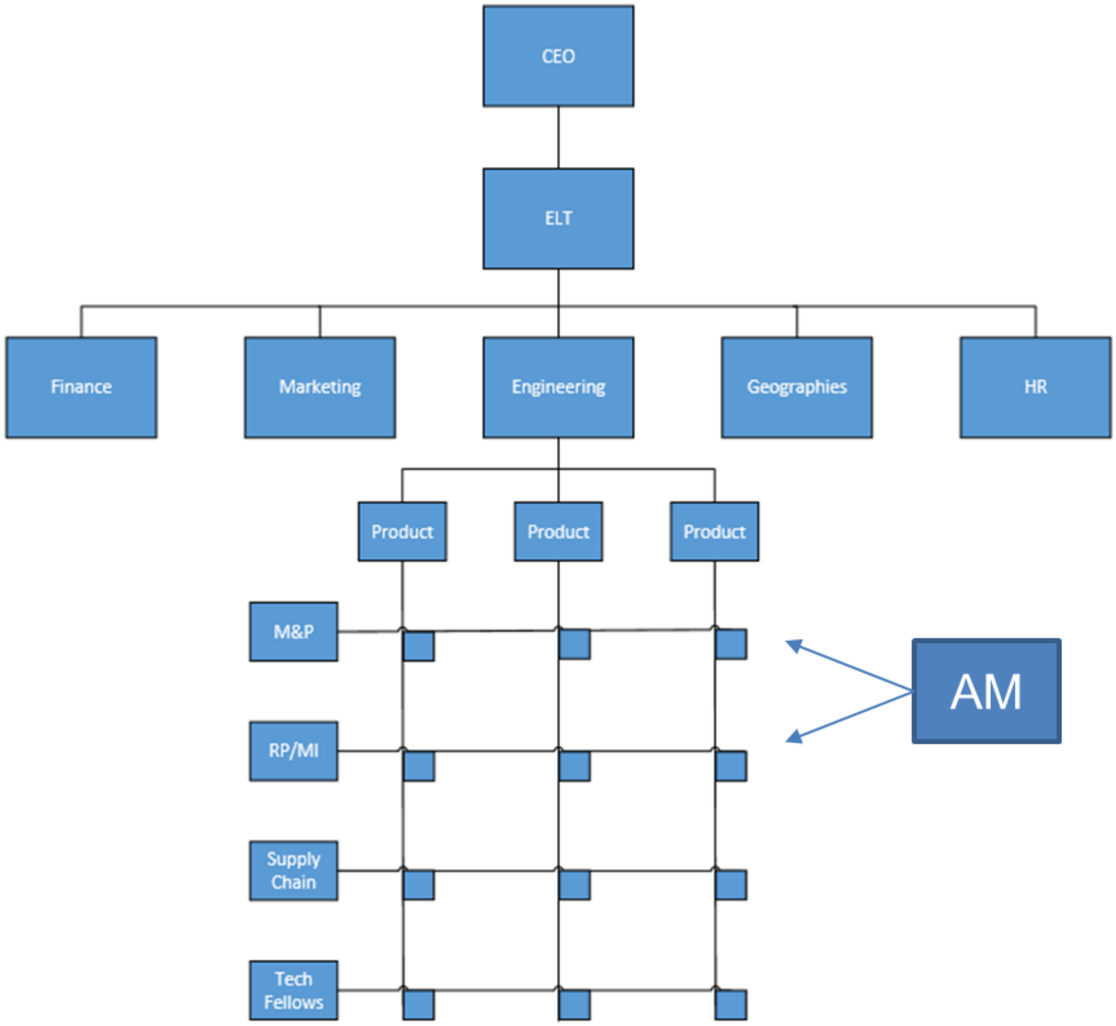

Figure 7-6: Bell Engineering Organizational Structure

the additive manufacturing effort. The observation that there are many stakeholders in various functions and groups creates political divisiveness toward development due to multiple respective goals trying to be met simultaneously.

The last organizational barrier is the culture. Bell Textron Inc. is an aerospace OEM that has existed for many decades and are not receptive to major changes. Conventional manufacturing methods have existed since the beginning and the introduction of a new method for design and manufacturing are not appealing to engineers as a tool for future designs. Knowledge diffusion and education is a must to tackle this internal barrier as well as a high-level directive from additive manufacturing

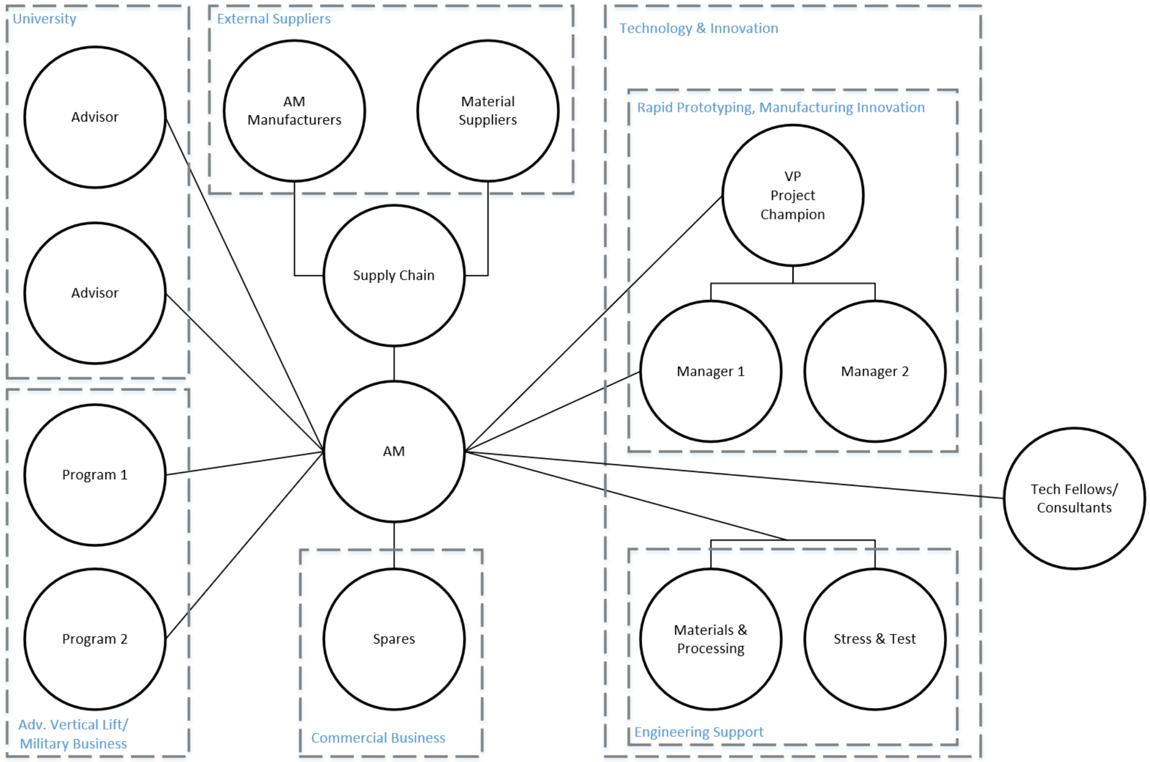

Figure 7-7: Organizational Additive Manufacturing Stakeholders

champions within the company.

Systemic Challenges - Apart from the organization, the systemic challenges that additive manufacturing faces are the tools to enable, partnerships, and funding. Additive manufacturing technology is a broad topic and companies lack the best practices, expertise, machines, and software to enable adoption. Likewise, aerospace OEMs are also afraid to dedicate personnel to understanding and developing additive manufacturing. Partnerships are preferred outlets to quickly gain information quickly, but vendors and manufacturers look for long-term commitment from OEMs to secure business. As the industry has not yet matured, aerospace OEMs are not keen on such a long-term commitment. Lastly, funding within an OEM is difficult for research and development. For an OEM such as Bell that operates in a matrix organization, funding for Internal Research and Development or IRAD is split among the different programs. Each program has specific performance goals they are trying to achieve and additive manufacturing development is not a priority to help programs reach those short-term goals. As such, programs would rather spend the funding in other areas that directly contribute to achieving program targets.

Chapter 8

Conclusions and Future Work

8.1 Key Findings and Conclusions

This thesis has exhibited the benefits and opportunities that additive manufacturing has in rotary aircraft as well as the larger aerospace industry. The analysis detailed the benefits, risks, and organizational challenges that arise with implementation. While the aerospace industry has some of the most impactful opportunities for additive manufacturing, it is important to note three key realities:

1. Additive manufacturing can print anything, but should not print everything
2. The additive manufacturing industry is slow to consolidate and standardize
3. Existing development methods are not ideal for adoption and implementation

The evaluation process has shown the many criterium that parts are subject to in order to be eligible for additive manufacturing. Even after verifying the characteristics and perceived benefits additive manufacturing brings to a specific part, there exists many internal and external factors that force development into an uphill battle.

3D printing has been around for more than 30 years, yet the technology has not taken off in the aerospace industry thus far. The additive manufacturing industry is constantly developing new technologies as well as incorporating new forms of materials and alloys. The constant influx of new methods and companies prohibits the consolidation of the industry as well as the standardization of methods for the industry to adopt. This creates too many variables that are difficult for industries and companies to manage.

Lastly, the aerospace industry is inundated with regulations and standards that were put in place due to many unknowns in production and design within the industry in the past. Many developmental methods end up becoming too costly and drawn out such that companies are discouraged from development. With the aerospace industry entering a digital age, there arises a new opportunity to revisit the needs for such strict guidelines that inhibit the possibility of new processes.

8.2 Future Work

There is a significant need to push the development of additive manufacturing on a holistic level. The aerospace industry must collectively work with agencies to create the standards needed to adopt and implement additive manufacturing. There have been studies that exhibit the need for additive manufacturing as well as the various applications, thus ensuring the demand for the technology.

As a company, an effort must be made to gain momentum for additive manufacturing development. This involves the creation of a dedicated team, identifying a champion, and securing incremental funding. In addition, while a design and process development plan are needed, a plan to diffuse knowledge to the working teams is equally important. There is no set method to researching and developing additive manufacturing, but companies can focus on developing their design for additive manufacturing (DFAM) and evaluation processes.

Lastly, additive manufacturing is so broad that there is not one set path forward. There can be a path that a company can take to learn at minimal costs, and a path headed toward material development for another company. Even a path through the military is a feasible option. The beauty of additive manufacturing is that there are so many factors that enable all the freedom associated with the technology. However, those same factors are the ones that create difficulty in developing the technology.

Companies need to work together to overcome traditional mindsets and hurdles to enable engineers and designers the freedom to utilize additive manufacturing within the aerospace industry.

Appendix A

List of Acronyms

AM – Additive Manufacturing

ASTM – American Society for Testing and Materials

AWS – American Welding Society

BHTI – Bell Helicopter Textron Incorporated

BPS – Bell Process Spec

CAD – Computer-Aided Design

CMM – Coordinate-Measuring Machine

CT – Computed Tomography

DFAM – Design for Additive Manufacturing

DED – Directed Energy Deposition

DOD – Department of Defense

EB – Electron Beam

EDM – Electrical Discharge Machining

FAA – Federal Aviation Administration

FDM – Fused Deposition Modeling

FEA – Finite Element Analysis

FEM – Finite Element Model

HIP – Hot Isostatic Press

IGB – Intermediate Gearbox

IRAD – Internal Research and Development

LS – Laser Sintering

MMPDS – Metallic Materials Properties Development and Standardization

M&P – Materials and Processes

NAVAIR – Navy Air Systems Command

NDI – Non-Destructive Inspection

NDT – Non-Destructive Testing

NIST – National Institute of Standards and Technology

OEM – Original Equipment Manufacturer

PBF – Powder Bed Fusion

RP – Rapid Prototyping

SLA – Stereolithography Additive

SLS – Selective Laser Sintering

STL – Stereolithography

TOPOP – Topology Optimization

VTOL – Vertical Takeoff and Landing

Appendix B

Figures

Cost Reduction:

$$Cost\ Score = \frac{[Original\ Unit\ Cost - Additive\ Unit\ Cost]}{Original\ Unit\ Cost} = Cost\ Savings$$

Cost Score is equivalent to an estimated cost savings. As the industry develops, cost estimates for additive manufacturing will become more accurate.

Speed/Lead Time Reduction:

$$Speed\ Score = \frac{[Original\ Lead\ Time - Additive\ Lead\ Time]}{Original\ Lead\ Time} = Time\ Savings$$

The Speed Score is an estimate of time saved by utilizing additive manufacturing. Lead time estimates will improve as the industry develops.

Supply Chain:

$$Transport\ Savings = \frac{[Orig. Transport\ Costs - AM\ Transport\ Costs]}{Orig. Transport\ Costs} = T_s$$

$$Inventory\ Savings = \frac{[Orig. Inventory\ Costs - AM\ Inventory\ Costs]}{Orig. Inventory\ Costs} = I_s$$

$$Procurement\ Savings = \frac{[Orig. Procurement\ Costs - AM\ Procurement\ Costs]}{Orig. Procurement\ Costs} = PO_s$$

$$Production\ Savings = \frac{[Orig. Production\ Costs - AM\ Production\ Costs]}{Orig. Production\ Costs} = PD_s$$

$$Supply\ Chain\ Score = \frac{[T_s + I_s + PO_s + PD_s]}{4\ x\ 100\%} = Total\ Supply\ Chain\ Savings$$

The Supply Chain Score is the total weighted average savings from transport, inventory, procurement, and production savings by shifting a part's supply chain to support additive manufacturing.

Figure B-1: Calculation of Additive Manufacturing Evaluation Score (AMES)

Design for Additive Manufacturing (DFAM)

The DFAM Score is the aggregate weighted scores of the additive material, savings from waste and weight, and the post processing needed after the print.

$$DFAM\ Score = \frac{[M_s + W_s + WT_s + P_s]}{4\ x\ 100\%}$$

Material Maturity:

Material Score (M_s), depends on the maturity level of the proposed material for additive manufacturing.

- Certified and Identified Suppliers = 100%
- In-house Development Testing = 50%
- Speculative Benefits and Suppliers = 25%
- None or No Identified Suppliers = 0%

Waste Reduction:

$$Waste\ Score\ (W_s) = \frac{Original\ Buy\ Weight\ [g] - Additive\ Buy\ Weight\ [g]}{Original\ Buy\ Weight\ [g]}$$

The Waste Score is the amount of material savings for manufacturing of the part.

Weight Reduction:

$$Weight\ Score\ (WT_s) = \frac{Original\ Flight\ Weight\ [g] - Additive\ Flight\ Weight\ [g]}{Original\ Flight\ Weight\ [g]}$$

The Weight Score is the flight weight of the part that contributes to the final vehicle weight.

Post Process:

The Post Process Score (P_s), depends on the level of post processing needed for the part after the print has been completed.

- No Post Processing = 100%
- Minimal Machining = 75%
- Any Machining and Heat Treating = 50%
- Machining, Heat Treating, HIP = 25%
- Machining, Heat Treating, HIP, Plating = 0%

Figure B-2: Calculation of Additive Manufacturing Evaluation Score (AMES)

Performance Score:

The performance score weighs two design factors together to assess additive manufacturing performance improvements.

$$Performance\ Score = \frac{TO_s\ +\ PC_s}{2\ x\ 100\%}$$

Topology Optimization:

The Topology Optimization Score (TO_s),is based on the available characteristics for optimizing; the more available, the better the score. The four characteristics are Internal Features, Thermal Management, Thick Walls, and Load Paths.

- Four Characteristics = 100%
- Three Characteristics = 75%
- Two Characteristics = 50%
- One Characteristic = 25%
- No Characteristics = 0%

Part Consolidation:

Part Consolidation Score (PC_s), is determined from the number of parts that can be aggregated or consolidated; the more parts that can be consolidated, the better.

- More Than Five Parts = 100%
- Four Parts = 75%
- Three Parts = 50%
- Two Parts = 25%
- No Consolidation = 0%

Figure B-3: Calculation of Additive Manufacturing Evaluation Score (AMES)

Total Additive Manufacturing Evaluation Score (AMES) Calculation

The Total Score aggregates the five major factors of cost, speed, supply chain, design, and performance.

$$AMES\ Total\ Score = \frac{Cost + Speed + Supply\ Chain + DFAM + Performance}{5\ x\ 100\%}$$

The AMES method assumes equal weight of the five factors. However, if one of the factors had priority of another, a weight factor can be applied.

$$Total\ Score = Cost * W_1 + Speed * W_2 + Supply\ Chain * W_3 + DFAM * W_4 + Performance * W_5$$

Where

$$W_1 + W_2 + W_3 + W_4 + W_5 = 1$$

Figure B-4: Calculation of Additive Manufacturing Evaluation Score (AMES)

Appendix C

Tables

Table C.1: AMES - Part 1

Part 1	Score	Notes
Category		Production - Drives - Cases
Manufacturing Method		Casting
Materials		Mag to Aluminum
Part Size		Medium
Cost Score	**30%**	$3,100
Lead Time Score	**50%**	112 days
Supply Chain Score	**75%**	
DFAM Score	**45%**	
Material Maturity Score	50%	
Waste Score	80%	80% Savings
Weight Score	0%	Magnesium is lighter
Post Process Score	50%	
Performance Score	**75%**	
Topology Optimization Score	75%	
Part Consolidation Score	75%	
Total Score	**55%**	

Table C.2: AMES - Part 2

Part 2	Score	Notes
Category		Production - Drives - Cases
Manufacturing Method		Casting
Materials		Mag to Aluminum
Part Size		Large
Cost Score	**30%**	$4,228
Lead Time Score	**48%**	192 days
Supply Chain Score	**55%**	
DFAM Score	**30%**	
Material Maturity Score	50%	
Waste Score	20%	
Weight Score	0%	
Post Process Score	50%	
Performance Score	**63%**	
Topology Optimization Score	75%	
Part Consolidation Score	50%	
Total Score	**45%**	

Table C.3: AMES - Part 3

Part 3	Score	Notes
Category		Production - Rotors
Manufacturing Method		Casting
Materials		Titanium
Part Size		Small
Cost Score	**15%**	$1,775
Lead Time Score	**80%**	655 days
Supply Chain Score	**55%**	
DFAM Score	**55%**	
Material Maturity Score	100%	
Waste Score	80%	
Weight Score	15%	
Post Process Score	25%	
Performance Score	**38%**	
Topology Optimization Score	50%	
Part Consolidation Score	25%	
Total Score	**49%**	

Table C.4: AMES - Part 4

Part 4	Score	Notes
Category		Production - Rotors
Manufacturing Method		Casting
Materials		Titanium
Part Size		Small
Cost Score	**20%**	3520
Lead Time Score	**45%**	182 days
Supply Chain Score	**55%**	
DFAM Score	**55%**	
Material Maturity Score	100%	
Waste Score	80%	
Weight Score	15%	
Post Process Score	25%	
Performance Score	**75%**	
Topology Optimization Score	75%	
Part Consolidation Score	75%	
Total Score	**50%**	

Table C.5: AMES - Part 5

Part 5	Score	Notes
Category		Production - Rotors - Others
Manufacturing Method		Casting
Materials		Titanium
Part Size		Small
Cost Score	**20%**	$3,520
Lead Time Score	**29%**	49 days
Supply Chain Score	**55%**	
DFAM Score	**48%**	
Material Maturity Score	50%	
Waste Score	75%	75% waste savings
Weight Score	15%	
Post Process Score	50%	
Performance Score	**63%**	
Topology Optimization Score	75%	
Part Consolidation Score	50%	
Total Score	**43%**	

Table C.6: AMES - Part 6

Part 6	Score	Notes
Category		Production - Structures - Airframe
Manufacturing Method		Casting
Materials		Aluminum
Part Size		Med
Cost Score	**10%**	$535
Lead Time Score	**45%**	182 days
Supply Chain Score	**55%**	
DFAM Score	**39%**	
Material Maturity Score	50%	
Waste Score	20%	
Weight Score	10%	
Post Process Score	75%	
Performance Score	**50%**	
Topology Optimization Score	75%	
Part Consolidation Score	25%	
Total Score	**40%**	

Table C.7: AMES - Part 7

Part 7	Score	Notes
Category		Production - Structures - Airframe
Manufacturing Method		Sheetform
Materials		Aluminum
Part Size		Med
Cost Score	**10%**	$555
Lead Time Score	**45%**	112 days
Supply Chain Score	**55%**	
DFAM Score	**34%**	
Material Maturity Score	50%	
Waste Score	20%	
Weight Score	15%	
Post Process Score	50%	
Performance Score	**50%**	
Topology Optimization Score	75%	
Part Consolidation Score	25%	
Total Score	**39%**	

Table C.8: AMES - Part 8

Part 8	Score	Notes
Category		Production - Structures - Airframe
Manufacturing Method		Casting
Materials		Aluminum
Part Size		Med
Cost Score	**10%**	$1,015
Lead Time Score	**45%**	154 days
Supply Chain Score	**55%**	
DFAM Score	**34%**	
Material Maturity Score	50%	
Waste Score	20%	75% waste savings
Weight Score	15%	
Post Process Score	50%	
Performance Score	**38%**	
Topology Optimization Score	50%	
Part Consolidation Score	25%	
Total Score	**36%**	

Bibliography

[1] Sheet Lamination | Additive Manufacturing Research Group | Loughborough University.

[2] Alkaios Bournias Varotsis. 3D Printing vs. CNC machining. Library Catalog: www.3dhubs.com.

[3] Davide Sher. The global additive manufacturing market 2018 is worth $9.3 billion, December 2018. Library Catalog: www.3dprintingmedia.network.

[4] The Additive Manufacturing Industry Landscape 2019: 171 Companies Driving the Industry Forward [Updated], February 2019. Library Catalog: amfg.ai Section: Blog.

[5] Terry Wohlers. *Wohlers Report 2020*. Wohlers Associates, Fort Collins, Colorado, 25 edition, 2020.

[6] Dr. Vivek Saxena. Additive Manufacturing in Aerospace and Defense 2015. Library Catalog: SlideShare.

[7] Kunal Ahuja and Sonal Singh. Additive Manufacturing with Metal Powders Market to surpass 4.5 kilo Tons Consumption By 2024 | ManufacturingTomorrow. Library Catalog: www.manufacturingtomorrow.com.

[8] 3D model Flying Taxi Bell Nexus | CGTrader.

[9] Bell's Self-Flying APT 70 Cargo Drone Hauls a Heavy Load. *Wired*.

[10] Paolo Priarone, Giuseppe Ingarao, Rosa Lorenzo, and Luca Settineri. Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions. *Journal of Industrial Ecology*, January 2017.

[11] AS332 Super Puma Intermediate Gearbox.

[12] SKF Aerospace.

[13] S. K. Bhaumik, M. Sujata, M. Suresh Kumar, M. A. Venkataswamy, and M. A. Parameswara. Failure of an intermediate gearbox of a helicopter. *Engineering Failure Analysis*, 14(1):85–100, January 2007.

[14] 3D Printing, Additive & Lattice Software | Netfabb Features | Autodesk. Library Catalog: www.autodesk.co.uk.

[15] David L. Bourell and Christopher E. Roberts. Photonics Applied: 3D Laser Printing: Selecting and using materials for additive manufacturing processes, December 2017. Library Catalog: www.laserfocusworld.com.

[16] Megan Rose Dickey. Hope You Trust 3D Printers — Boeing Uses Them To 'Print' Parts For Its Planes. Library Catalog: www.businessinsider.com.

[17] John Power. 3D Printing takes off in the Aviation Industry. How Additive Manufacturing is shaping Airbus' Supply Chain. – Technology and Operations Management.

[18] ISO/ASTM 52900(en), Additive manufacturing — General principles — Terminology.

[19] The 3D opportunity primer: The basics of additive manufacturing | Deloitte Insights.

[20] Dorothy Neufeld. 10 Top 3D Printing Companies, November 2019. Library Catalog: investingnews.com Section: Emerging Tech Investing.

[21] Michael Goldstein. Bell Nexus VTOL Air Taxi Makes A Splash At 2019 Consumer Electronics Show. Library Catalog: www.forbes.com Section: Lifestyle.

[22] Fatigue, Fail-Safe, and Damage Tolerance Evaluation of Metallic Structure for Normal, Utility, Acrobatic, and Commuter Category Airplanes.

[23] Damage-Tolerance and Fatigue Evaluation of Structure.

[24] What is Design for Additive Manufacturing?, June 2016. Library Catalog: www.engineersrule.com Section: 3D Printing.

[25] Introduction to Nondestructive Testing.

[26] Ben Sampson. Introduction to non-destructive testing, October 2018. Library Catalog: www.aerospacetestinginternational.com Section: Features.