The Design for Manufacturing and Assembly Analysis and Redesign of an Aircraft Refueling Door Hinge Utilizing Additive Manufacturing

Kurt A. Schwarz

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THE DESIGN FOR MANUFACTURING AND ASSEMBLY ANALYSIS AND REDESIGN OF AN AIRCRAFT REFUELING DOOR HINGE UTILIZING ADDITIVE MANUFACTURING

by

Kurt A. Schwarz

A Thesis Submitted to the College of Engineering and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University

Daytona Beach, Florida

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II
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Last but not least I would like to thank my family. Without their guidance, encouragement, forward thinking and unconditional love I would not be here today. They have worked tirelessly to give me the best possible chance to succeed in whatever I chose to pursue and for that I am forever grateful.
In this thesis, an aircraft door hinge assembly provided by Gulfstream Aerospace was analyzed following an established process called DFMA. The hinge was then redesigned to be additively manufactured, which is uncommon currently in industry for load bearing components. It was shown that the Design for Manufacturing (DFM) guidelines were inadequate when applied to the new technology of additive manufacturing (AM). This was primarily due to AM’s unique and unprecedented manufacturing capabilities.

A conservative redesign approach was followed due to a limitation in current AM material properties and time available for analysis. Despite this, a significant improvement in weight reduction and part count was still achieved. The total weight of the hinge assembly was reduced approximately 22% and the number of parts reduced from six to two. This weight reduction is estimated to save $56,000 in fuel over the course of 6000 flight hours per hinge redesigned, totaling $112,000 per G650 aircraft. All design work and weight estimations were performed in CATIA V5.
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DEFINITIONS & NOMENCLATURE

AM        Additive Manufacturing
BOM       Bill of Materials
CAD       Computer Aided Design
DFAM      Design for Additive Manufacturing
DFMA      Design for Manufacture and Assembly
DLP       Digital Light Processing
DMLS      Direct Metal Laser Sintering
DMP       Direct Metal Printing
EBF\(^3\)  Electron Beam Freeform Fabrication
EBM       Electron Beam Melting
ECM       Electrochemical Machining
EDM       Electric Discharge Machining
FDM       Fused Deposition Modeling
LOM       Laminated Object Manufacturing
SFF       Solid Freeform Fabrication
SGC       Solid Ground Curing
SHS       Selective Heat Sintering
SL        Stereolithography
SLS       Selective Laser Sintering
SLM       Selective Laser Melting
Chapter 1: Background

1.1 Introduction

The two methodologies that frame the work of Design for Manufacture and Assembly (DFMA) focus on design for ease of manufacturing and ease of assembly (Boothroyd & Dewhurst, 2011). The overall goal is to reduce manufacturing and assembly costs while also quantifying the improvements. Components are reduced to their simplest form to optimize machining and assembly while also reducing the total number of parts by combining their functions.

However, now that additive manufacturing (AM) technology has matured to produce quality end-use parts, the possibilities of manufacturing have significantly increased (Boothroyd & Dewhurst, 2011). Currently the DFMA process does not take advantage of the new design freedoms AM offers. Components can be combined and optimized into new innovative designs previously thought too complex for machining. By not considering this new disruptive technology (Wohlers, 2012) in the design and manufacturing process, potential savings are being missed.

1.2 Overview of Additive Manufacturing

The concept of manufacturing a product by building up layer by layer of material was first published in the 1890’s when J. Blanther patented a method for creating topographical maps using layers of wax plates (Bourell et al, 2009). Topographical contour lines were drawn on the wax plates which were then stacked, cut and smoothed to create either a positive or negative of the desired terrain. It would be 60 years until a technique similar to modern day AM processes appeared. In 1951 Munz created a system for selectively exposing transparent photo emulsion material layers to generate 3D objects within a clear cylinder (Bourell et al, 2009). After each layer of material was cured, a piston would be lowered and additional layers were added. The
finished object could either be manually carved or photochemically etched out. This system has features found in modern stereolithography (SL) including the platform, piston and resin basin. A current SL configuration is illustrated in Figure 1.

![Photopolymer layering system](https://en.wikipedia.org/wiki/Stereolithography)

Figure 1: Photopolymer layering system (Wikipedia.org).

The concept of Solid Freeform Fabrication (SFF) was further expanded in 1968 with Swainson’s Photosculpture process. He created a system that utilized two intersecting lasers to crosslink or degrade a polymer (Bourell et al, 2009). The overall concept of Photosculpture is presented in Figure 2.
During the 1950’s, an alternate SFF process that utilized powder rather than photographic emulsion sheets was developed by Ciraud (Bourell et al, 2009). An advantage of this method was any material that can at least be partially melted could be used. His system has all the features of a modern day direct deposition AM process shown in Figure 3. The direct deposition process uses particles applied to a matrix by gravity, magnetostatics, electrostatics or nozzle placement. These particles are then heated by a laser beam(s) to locally melt them causing adhesion to each other and forming a continuous layer.

Figure 2: The process of Photosculpture using intersecting laser beams (Swainson, 1977).
In 1974 DiMatteo recognized that by stacking the layers of selectively cured photopolymer resin he could create cast molds for parts that would be very difficult or impossible to create using traditional subtractive manufacturing methods such as CNC machining (Bourell et al, 2009). Figure 4 is a simple sketch of one of his layered casting molds, complex parts such as airfoils and die punches can also be created using this method.
In 1979 Housholder proposed a new concept called powder laser sintering or more commonly known today as Selective Laser Sintering (SLS) (Bourell et al, 2009). Unlike the direct deposit method, SLS does not spray particles out of a nozzle. Instead a reservoir deposits a small amount of powder onto the build platform and is then spread out evenly using a blade or roller as shown in Figure 5A. Once the laser has sintered the desired cross section the build platform moves down one layer thickness and a new layer of powder is distributed. Figure 5B details the sintering process (Excell & Nathan, 2010).

![Figure 5A: Powder laser sintering process.](image)

![Figure 5B: Sintering process.](image)

Figure 5: The powder selective laser sintering process (Wikipedia.org).

During the 1980’s there was a rapid increase in SFF technology when in 1986 Charles W. Hull patented and commercialized a process, stereolithography (SL), through his company 3D Systems (3DS) (Bourell et al, 2009). This process consisted of a concentrated beam of ultraviolet light focused on the surface of a vat filled with liquid photopolymer. Under the control of a
computer the beam traced out the cross section of the part. Once completed, the build platform is lowered one layer thickness and the next cross section is cured on top of the previous. The first commercially available AM system was called the SLA-1 where SLA stood for Stereolithography Apparatus (Bourell et al, 2009).

With the rise of SL technology and the creation of companies such as 3DS in the U.S., NTT Data CMET in Japan and Electro Optical Systems (EOS) in Germany, AM technology began expanding quickly (Wohlers, 2014). This interest worldwide led to the development of additional AM technologies such as fused deposition modeling (FDM) by Stratasys, solid ground curing (SGC) by Cubital and laminated object manufacturing (LOM) by Helisys.

Extrusion based systems commonly referred to as Fused Deposition Modeling (FDM) are the most recognized method of AM today (Palermo, 2013). Unlike SL or SLS, FDM does not use a reservoir of material to create the part. Instead FDM uses a filament of material that is fed through a nozzle, melted and layered on a build platform very similar to a conventional ink jet printer. This setup is illustrated in Figure 6. As each cross section is completed the platform moves down one layer thickness and the next layer of material is extruded on top of the previous layer. While plastics are commonly used, anything that can be extruded can be layered. For example, hydrogels are used to create support structure for soft tissue growth in the medical industry (Gibson, Rosen, 2010). Key aerospace organizations, such as NASA, Piper, and Bell helicopters have shown great interest towards the continuously developing technology of FDM. (Stratasys, 2014).
The process of solid ground curing (SGC) is very different from FDM. Each cross-section of the part is generated by curing a thin liquid photopolymer layer using UV light and optical masks to create voids (Gebhardt, 2003). After each layer is completed, a wiper cleans away residual liquid and fills voids with melted wax for support. A milling disk then trims the layer to the desired thickness and prepares for the next layer. The wax is melted away once the part is completed (Lee, 1999).

Laminated object manufacturing (LOM) differs from both FDM and SGC in its method of building up each layer. A roll of laminate passes over the build area and is adhered to the substrate with a heated roller. The cross-section is then cut out using either a knife or laser. Once completed, the build platform is lowered to allow a new sheet of laminate to scroll over. The resulting models have wood-like characteristics and can be finished accordingly. Larger models can be made using this method due to the lack of chemical reactions (Palermo, 2013).
The commercialization of AM technologies in the 1980’s and 1990’s brought about many companies seeking to take advantage of this emerging market. Gartner reports that in 2015, more than 217,000 3D printers will have been shipped worldwide since their commercialization. This is more than double the total sold up until 2014 which was 108,151 (Rivera, 2014). 3DSystems and Stratasys Ltd are leaders of the FDM market. Their FDM systems range in price between $1000 to well over $500,000 and can be as small as a desktop printer or as large as a small car. Other AM technology branches are more exclusive due to the increased complexity and cost of the machines such as Direct Metal Printing (DMP) and Electron Beam Melting (EBM).

Advancing the manufacturing technology itself is only half the job. If AM is to be successful and have a significant impact, designers and engineers must understand and incorporate it into their products.

1.3 Overview of Design for Manufacture and Assembly (DFMA)

The proactive design process known as “design for ease of manufacture” or “manufacturability” has been around in one form or another since before the Second World War (Boothroyd et al, 2011). However, it was not until the 1970’s that a quantitative measure of the manufacturability of a product became available without relying upon supplier estimates. At the forefront of this research was Dr. Geoffrey Boothroyd, through his research at Salford University in England and the University of Massachusetts (UMass) along with research from his graduate students he published the first DFA handbook in the early 1970’s that cataloged feeding and orientation techniques for small parts (Boothroyd et al, 2011).

This DFMA handbook utilized a coding system in order to catalog the various solutions to feeding and orienting parts. This code identified and categorized which parts should be easy to feed and orient automatically along with those that would be difficult or impossible to automate.
This code along with data obtained from research were combined to create a systematic method that provided designers with a technique to quantify a product’s ease of automatic assembly.

After receiving funding for a 3-year research program to study Design for Manufacturing (DFM) at UMass and while pursuing his interest in Design for Assembly (DFA), Dr. Boothroyd reached out to his colleagues Alan Redford and Ken Swift in England who also received grants to study Product Design for Automation at Salford University (Boothroyd et al, 2011). Additional contributions were made by Bill Wilson from UMass in the area of initial selection of materials and processes, along with Winston Knight from Oxford University who focused on design for forging. DFA and DFM joined to become DFMA (Boothroyd et al, 2011).

During the process of developing an analytical method for designing products for the ease of both assembly and manufacturing, conflicts arose (Boothroyd et al, 2011). Ease of manufacturing dictates that components be divided into simple shapes whereas ease of assembly has shown that reducing the number of parts in an assembly not only reduces the cost of assembly, but the overall cost as well. This led to the creation of the simple criteria that determine whether a component part should be considered for elimination. These criteria are the key to product simplification and cost reduction and are as follows (Boothroyd et al, 2011, P.10-11);

1. “During operation of the product, does the part move relative to all other parts already assembled? Only gross motion should be considered – small motions that can be accommodated by integral elastic elements, for example, are not sufficient for a positive answer.”
2. “Must the part be of a different material or be isolated from all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.”

3. “Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible?”

Using this knowledge, the DFA Handbook for both automatic and manual assembly was published at UMass. Studies were performed at major companies who had implemented the DFA methodology and it has been shown that hundreds of millions of dollars annually were saved (Boothroyd et al, 2011).

The goal of DFMA was to produce a tool that designers could use at a high level to locate possible problems later on in the design process. In 1980, Peter Dewhurst joined Dr. Boothroyd at UMass and together they developed a computer version of the DFA handbook. Due to U.S. companies preferring to use computers rather than hand calculations, the DFA analysis was offered in a software package that contributed significantly to the growth and success in the U.S. industry (Boothroyd et al, 2011). An example of the software’s user interface is shown in Figure 7.
This work led to the creation of Boothroyd Dewhurst Inc. (BDI) in 1981 and trademarked the term “DFMA”. One of the biggest breakthroughs for DFA occurred in 1988 when the Ford Motor Company reported that the DFA software had saved them billions of dollars on their Taurus line of automobiles (Boothroyd et al, 2011). DFM research continued at University of Rhode Island (URI) until 1996. All the commercial software was developed through research supported by industry. The results of this research have been made freely available in the form of 22 research reports from UMass and over 100 reports from URI.
1.4 Motivation for this Research

In no other industry is there such a focus on reducing weight and utilizing advanced designs more than aerospace. The advancements in additive manufacturing (AM) technology over the last 20 years provide new possibilities in engineering, allowing engineers to rethink how components are designed and manufactured. AM now creates end-use components, opening up a wide range of new possibilities. Additively manufactured parts are already being used in aerospace applications with companies such as Boeing, Lockheed Martin and Airbus, and will continue to become more common.

With the increasing application of AM, new guidelines need to be created based around the idea of Design for Additive Manufacturing (DFAM). Currently the Design for Manufacture and Assembly (DFMA) process does not incorporate AM or consider the new possibilities brought about by its ability to manufacture complex parts with no added difficulties to the user. Engineers can now design and optimize for function rather than for ease of manufacturing and/or assembly.

1.5 Objective

The main objective of this thesis research is to demonstrate the improvements that can be made to an existing aerospace assembly by utilizing the design freedom available through additive manufacturing (AM). A comparison will be made between the current design and the additively manufactured assembly following the DFMA process.
Chapter 2: Additive Manufacturing & DFMA Expanded

2.1 The Additive Manufacturing Process

Despite how different each AM method and process is from each other, they all fundamentally follow the same procedure to create a part. Computer Aided Design (CAD) software is first used to create the part, that is then converted to a STL file for transferring to an AM machine. Each machine has a user interface for manipulating the model and modifying parameters prior to printing. Once completed, post processing might be required depending on the parts use. The generic procedure for creating an AM part is broken down into eight steps (Gibson & Rosen 2010), they are as follows:

**Step 1: CAD**

For a part to be additively manufactured it must first be created in 3D modeling software. Without CAD and the ability to represent solids in a computer AM would not exist. Any brand of software that outputs a 3D solid or surface representations may be used. Reverse engineering equipment such as laser scanners can also be used to create these models.

**Step 2: Conversion to STL**

The file format STL has become the standard format for transferring AM files and is accepted by nearly every machine produced today (Chua & Leong, 2003). An STL file contains no construction data, modeling history, etc. and approximates the surfaces of the model with a series of triangles. The user usually defines the size of these triangles in the CAD software allowing for a finer or rougher approximation of the model. The general rule of thumb is to make the triangle offset smaller than the resolution of the AM machine. Additional software can be used to analyze the STL file to search for inconsistencies or errors in the approximation.
Step 3: Transfer File

Often additional actions are required before the part can be built. Most AM systems have built in software that allows the user to view and manipulate the part as shown in Figure 8. The location, orientation and scaling can be altered to improve the print quality, print time or to print multiple parts at once.

Figure 8: MakerWare user interface from a MakerBot. (Makerbot.com)

Step 4: Setup Machine

Every AM system has parameters that allow the user to fine tune the printing process to achieve the desired build quality. Depending on the complexity of the system, parameters such as layer thickness, fill percentage, build speed, nozzle and build plate temperature, and material types may be modified.
**Step 5: Build**

Depending on the AM system, the amount of preparation required varies. Most require some form of layer control / zeroing of the build platform using height adjustments, setting up of the material and cleaning of the build platform from previous builds. Once the setup is completed, the automated process can begin to build the part.

**Step 6: Removal and Cleanup**

Once a build is completed the user should be able to remove the part from the AM machine and use it. However, this is not commonly the case. Typically once a build is completed the additional material needs to be removed from around the part. Either residual material left behind or secondary support material used to create overhangs or holes. A great deal of manual skill can be required because mishandling at this stage can reduce product quality. This process can also be viewed as the beginning of the post-process stage.

**Step 7: Post-Process**

The amount of post processing required is application specific. Simple models used for visualization might not need the detailed surface finishing required by end use AM parts. Surface finishing such as polishing, smoothing or coatings all depend on the parts intended application. In some cases a heat treatment is necessary to relieve internal stresses built up during the printing process.

**Step 8: Application**

While AM is capable of producing parts similar or identical to conventionally manufactured parts it is very important to note that the material properties may be anisotropic and different
from conventionally created materials. It is very possible that during the AM process bubbles or small voids form within parts that can compromise strength. Improper material bonding is another concern but as AM technology matures, these problems become less and less of an issue and material properties will become more consistent and reliable (Gibson & Rosen 2010).

2.2 Additive Manufacturing Material Possibilities

Theoretically any material capable of melting can be used for AM in one form or another. The temperature at which melting occurs dictates which process is the most ideal. Metals are best left to laser systems such as Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS). Systems such as Electron Beam Melting (EBM) are better suited for reactive or high melting temperature metals due to the vacuum environment and high energy laser beam (Arcam, 2015).

Materials capable of being extruded such as thermoplastics, rubbers, gels or ceramics are viable for systems such as FDM. It is also common to use thermoplastics in laser systems, the only difference is the form of the material before melting. Material for extrusion systems are typically in the form of filaments which can be fed into the nozzle from spools. Laser systems require the material to be in a fine powder form to allow for smooth spreading of the layers and quality parts. Table 1 overviews the different materials used in AM systems.
Table 1: Different types of materials available for each AM technology (Gibson & Rosen 2010).

<table>
<thead>
<tr>
<th>Type</th>
<th>Technology</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion</td>
<td>Fused Deposition Modeling (FDM)</td>
<td>Thermoplastics, rubber, clay &amp; gels</td>
</tr>
<tr>
<td>Wire</td>
<td>Electron Beam Freeform Fabrication (EBF³)</td>
<td>Almost any metal alloy</td>
</tr>
<tr>
<td>Granular</td>
<td>Direct Metal Laser Sintering (DMLS)</td>
<td>Almost any metal alloy</td>
</tr>
<tr>
<td></td>
<td>Electron Beam Melting (EBM)</td>
<td>Almost any metal alloy</td>
</tr>
<tr>
<td></td>
<td>Selective Laser Melting (SLM)</td>
<td>Titanium alloys, Cobalt Chrome alloys, Stainless Steel and Aluminum</td>
</tr>
<tr>
<td></td>
<td>Selective Heat Sintering (SHS)</td>
<td>Thermoplastic Powder</td>
</tr>
<tr>
<td></td>
<td>Selective Laser Sintering (SLS)</td>
<td>Thermoplastics, metal powders and ceramic powders</td>
</tr>
<tr>
<td>Laminated</td>
<td>Laminated Object Manufacturing (LOM)</td>
<td>Paper, metal foil and plastic film</td>
</tr>
<tr>
<td>Light Polymerized</td>
<td>Stereolithography (SLA)</td>
<td>Photopolymer</td>
</tr>
<tr>
<td></td>
<td>Digital Light Processing (DLP)</td>
<td>Photopolymer</td>
</tr>
</tbody>
</table>

2.3 Advantages & Disadvantages of AM

Advances in AM technology have demonstrated its seemingly endless design possibilities (Maxey, 2014). However, it is critical to understand the limitations and disadvantages of AM. As this technology continues to develop, engineers and designs must understand the boundaries of this technology if they are to optimize utilization.

The primary advantages of AM as compared to conventional methods are its ability to produce low volume parts, quickly, with minimal to no waste or needed supply chains (Gibson & Rosen 2010). A common factor considered in the aerospace industry is the Buy-to-Fly ratio which is defined as the ratio between raw material used and the weight of the component itself (Arcam, 2015). Current ratios can be as high as 15 but AM opens up the possibility of achieving extremely low ratios close to 1. Beyond the machine itself the additive building process does not require any additional tooling and parts can be built on site, eliminating the need for shipping and inventory. Parts can be redesigned and manufactured at speeds not achievable through
subtractive manufacturing. Very complex and custom design parts can be produced as they are needed, greatly reducing turnaround time and machining costs (Gibson & Rosen 2010).

Each AM process has its own unique limitations depending on the equipment such as the power of the laser or grain size of the powder. However, there is one issue that affects all of AM, material properties (Royal Academy of Engineering, 2013). Material properties of AM components are currently the focus of much research. Due to the nature of the AM process, it is very difficult to achieve isotropic material properties and equal strength compared to conventionally formed materials. However, metal alloys with densities of 99% and higher have been achieved, resulting in ultimate strength values equal to or higher than conventionally forged metals, at the cost of reduced ductility (Murr, 2009, Wraith, 2014).

Another advantage of AM is its speed in low volume production. In a high volume production environment, AM machines fall behind conventional machining. It will take a new generation of AM machines to compete with injection molding and casting methods (Royal Academy of Engineering, 2013). One issue facing additive manufacturing’s integration into a production setting is reliability. Graham Bennett, technical director of layer manufacturing at CRDM, said it best “For companies looking for a rejection rate of just a few parts per million, there is no way our technology can come close to that” (Royal Academy of Engineering, 2013, p. 18).

The last main disadvantage of AM is cost. Whether it’s a school integrating AM into its curriculum or a company interested in exploring its possibilities, initial costs are high. This technology is relatively new and only distributed by a limited number of companies. Only in recent years has AM technology become available to the general population with units priced under $1000, but this is limited to low quality plastic extrusions machines. When properly
utilized the cost savings offered by AM can increase quickly and secure its place in the manufacturing industry.

2.4 Variables in the Additive Manufacturing Process

Compared to traditional subtractive manufacturing methods, AM has additional variables and parameters. Subtractive methods have the advantage of starting with a solid piece of material with consistent properties. When the proper steps are taken during machining, the end use product will have predictable and consistent mechanical properties. The science behind the creation of these raw materials for subtractive machining is well established and understood.

Currently one of the largest obstacles for AM is the ability to produce end-use parts with consistent, reliable material properties. In order for an AM process to be successful in a production setting it must be proven that it is capable of consistently producing quality parts. Each AM process has its own set of variables that contribute to inconsistent material properties.

The main variables involved with extrusion based AM systems are layer thickness, nozzle temperature, nozzle size, feed rate and chamber temperature (Gibson & Rosen 2010). Due to the nature of the tool path, an extruded AM part will experience stronger bonding in the X-Y plane as compared to the Z direction (Gibson & Rosen 2010). As shown in Figure 9, the material is continuously extruded along the tool path in the X-Y plane, however when the platform is lowered one layer, the resulting new layer bonds to cooler, harder material. This causes the material properties to vary greatly in the Z direction as compared to the X-Y. Improper bonding can also occur if the nozzle fails to adequately melt the material or burns it. The build chamber must keep the part at an elevated temperature to prevent premature cooling and shrinking (Gibson & Rosen 2010). The feed rate determines how thick the resulting tool path is. A high feed rate can result in excess material being laid down causing overflow. A slow feed rate can
produce weak walls or support material that will cause the build to fail. Ultimately the resolution of the extrusion machine is determined by the nozzle size and layer thickness. Additionally, nozzles are round in shape so it is technically impossible to produce perfectly square corners.

![Figure 9: Simplified extrusion system illustrating the axis locations (Wikipedia.org).](image)

Granular systems that utilize lasers to melt materials have different variables that affect each build. Parameters such as the laser, scan, powder and temperature are often inter-related and vary between each material and build. The main parameters for the laser are power, spot size, pulse duration and pulse frequency (Gibson & Rosen 2010). The motion of the laser has several parameters that need to be controlled as well such as the scan speed, spacing and pattern. These ultimately determine how evenly the material will be heated and the strength of the bonding. Compared to the extrusion AM systems, the granular systems are more sensitive to the properties of the raw material and require higher standards to produce quality parts. The powder particle shape, size and distribution, bed density and layer thickness all factor into a successful build (Gibson & Rosen 2010). The last main parameter is the temperature. Granular systems have to control the temperature of the powder bed and powder feeder while maintaining uniform heating.
across the build environment. Uneven heating can lead to shrinking, warping and degraded mechanical properties (Gibson & Rosen 2010).

2.5 Applications of AM Technology in the Aerospace Industry

According to the 2014 Wohlers Report that surveyed 111 companies worldwide, 29% of them were utilizing additive manufacturing to produce functional parts. Additionally about 40% were using it for fit/assembly, prototyping and patterns (Wohlers, 2014). Over the last 25 years additive manufacturing has proven itself capable of producing quality end-use components. A technology once thought only able to create prototypes has developed into what some are calling the new age of direct digital manufacturing (Wohlers, 2014). Major aerospace companies are taking advantage of additive manufacturing, rapidly integrating it into their product development structure.

One of the most successful applications of AM into the aerospace industry was with GE Aviation. In 2013 they announced that a major part of their new LEAP engine would be additively manufactured. Starting in 2015 they will begin producing more than 30,000 fuel nozzles annually. The design and manufacturing freedom of AM allow engineers to reduce the number of parts from 20 down to a single piece as shown in Figure 10. The new nozzle is also 25% lighter and 5 times more durable (Rockstroh et al, 2013, LaMonica, 2013, Wohlers, 2014).

Figure 10: Additively manufactured fuel nozzle by GE Aviation (Rockstroh et al, 2013).
Lockheed Martin is another major aerospace manufacturing company utilizing AM. The Juno space probe is en route to Jupiter with a dozen EBM manufactured brackets. According to Lockheed, it takes 28 days to manufacture one aluminum bracket. By switching to AM, they can produce 300 over the same time span (Maxey, 2014). The F-35 Joint Strike Fighter program is also exploring the possibility of incorporating titanium AM parts in the wing and tail structure (Tadjdeh, 2014). Rick Ambrose, the executive vice president of Lockheed’s space systems division said “The real end goal isn’t just to do 3-D printing, it’s about delivering a capability at a much lower cost across the board.” (Jayakumar, 2014, p. 1).

The Boeing Company has also been incorporating AM into its aerospace products. For example, when it comes to satellites every ounce of weight and cubic inch is critical, and is why 3D printed brackets have been integrated into their satellites (Tadjdeh, 2014). AM allows engineers to create complex brackets ideal for the small spaces found on satellites. Boeing has also utilized additively manufactured polymer-based air ducts into their F/A-18 Super Hornet aircraft. A new field for AM is UAVs, their smaller size and production volume makes them great platforms (Tadjdeh, 2014).

A joint study by EADS Innovation Works (IW) and EOS GmbH has demonstrated the savings potential of additively manufactured aerospace parts (EOS, 2014). An Airbus A320 nacelle hinge bracket initially manufactured through steel casting was redesigned to be direct metal laser sintered out of titanium. The design flexibility allowed engineers to reduce the overall energy cost of the part by 40% while using 25% less material (EOS, 2014). It was estimated this new design reduced the weight of each plane by approximately 10 kg. Examples of designs optimized for weight reduction through AM are shown in Figure 11.
These are just a few examples of how AM is making a significant impact on the aerospace industry. With industry leaders such as Boeing, Lockheed Martin and GE taking the lead by integrating AM into their products the benefits are clear and will encourage further development of this technology for aerospace applications.

2.6 DFMA Methodology

While the concept of DFMA might be simple, creating a quantitative method and implementing it into different companies is very complex and each case has its own unique challenges. However each situation has the same goal, to minimize the number of components and manufacturing steps. The reduction of the number of parts reduces design work, documents to be updated, inventory, bill of materials (BOM) and chance of assembly error. Decreasing the number of manufacturing steps leads to lower machining costs and reduced chance for machining errors. The combination of these two steps can lead to higher profit margins and quicker product delivery.

In order to properly implement the DFMA process, the “over-the-wall” ideology illustrated in Figure 12 has to be eliminated. Also referred to as an “information silo” (Ensor, 1988), this requires designers and engineers to work closely with manufacturing rather than
acting as two independent groups. By coordinating with manufacturing, designers and engineers can gain a better understanding of their capabilities to create components that are more producible. Decisions made during the design phase have a large influence over the lifespan of the product despite what the cost break down indicates as illustrated in Figure 13.

Figure 12: Illustration of the "Over-the-wall" design method (Munro & Associates, 1989).

Figure 13: Cost vs. Influence diagram “Who casts the biggest shadow?” (Munro & Associates, 1989).
DFMA analysis can be used in three main ways: 1) As the basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure, reduce manufacturing/assembly costs, and to quantify the improvements; 2) As a benchmarking tool to study competitors’ products and quantify manufacturing and assembly difficulties; and 3) As a should-cost tool to help control costs and to help negotiate suppliers contracts (Boothroyd & Dewhurst, 2011). The DFMA analysis performed for this research falls under the first category.

The first part of design for manufacturing is material and process selection. According to Boothroyd and Dewhurst, engineers and designers commonly choose to work only with familiar materials. This can lead to uneconomical decisions and eliminating the opportunity for major improvements early in the design process. The chart shown in Figure 14 is a guide for choosing which combination of material and manufacturing method is the most common. In the aerospace industry aluminum alloys are commonly used for airframes and skins while the more exotic alloys such as nickel and titanium are used in key high temperature areas such as engine turbine blades (Mraz, 2014). Additionally thermoplastics are commonly used for ducting to achieve complex shapes while remaining light weight.
Figure 14: Chart showing the compatibility between different materials and manufacturing methods (Boothroyd & Dewhurst, 2011).

The method of manufacturing determines which guidelines should be followed.

Boothroyd & Dewhurst distinguish 12 different manufacturing methods for analysis. They are as follows; Product Design for Manual Assembly, Electrical Connections and Wire Harness Assembly, High-Speed Automatic and Robot Assembly, Printed Circuit Board Design for Manufacture and Assembly, Machining, Injection Molding, Sheet Metalworking, Die Casting, Design for Powder Metal Processing, Sand Casting, Investment Casting, and Hot Forging.

For the purpose of this research, only the Product Design for Manual Assembly will be described in detail, as the aerospace door hinge in question falls under this category.
2.7 Application of Product Design for Manual Assembly

The process of manual assembly can be separated into two categories, handling and insertion/fastening. Following the DFMA process, there are five design guidelines for handling and seven for insertion/fastening which are summarized below (Boothroyd et al, 2011). Figures 15, 16 and 17 show examples of these guidelines.

**Design Guidelines for Part Handling**
1. Create parts as symmetric as possible.
2. If part is not symmetric, make obviously asymmetric.
3. Provide features that prevent jamming while stacked or stored in bulk.
4. Avoid features that allow tangling.
5. Avoid parts that are sticky, slippery, delicate, flexible, very small/large or hazardous.

**Design Guidelines for Insertion and Fastening**
1. Design parts so there is little or no resistance to assemble and provide generous tolerances when possible.
2. Standardize by using common parts, processes and methods across all models and product lines.
3. Use pyramid assembly, provide progressive assembly about one axis. Best to assemble from above.
4. Avoid the need to hold down parts for assembly, provide self-aligning features.
5. Design parts that locate themselves before being released.
6. When possible use the most cost effective mechanical fasteners. Snap fittings instead of riveting or screws for example.
7. Avoid the need to reposition the partially completed assembly.

As mentioned in the handling guideline, part symmetry is a factor in quick and efficient handling. In order to classify different shapes based on their symmetry, an alpha and beta system was created. The alpha angle represents the amount a part must rotate about the axis perpendicular to the axis of insertion to repeat its orientation. Beta is the angle through which a part must rotate about the axis of insertion to repeat its orientation (Boothroyd et al, 2011). Shown in Figure 15 are the alpha and beta values for some simple shapes.
Figure 15: The alpha and beta rotational symmetry values (Boothroyd et al, 2011).

<table>
<thead>
<tr>
<th>α</th>
<th>0</th>
<th>180</th>
<th>180</th>
<th>90</th>
<th>360</th>
<th>360</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>0</td>
<td>0</td>
<td>90</td>
<td>180</td>
<td>0</td>
<td>360</td>
</tr>
</tbody>
</table>

Figure 16: Geometric (left) and other (right) features that affect part handling (Boothroyd et al, 2011).

Figure 17: Example of improving ease of assembly (Boothroyd et al, 2011).
The assembly efficiency of a part is measured using the DFA index that is defined as the theoretical minimum number of parts ($N_{min}$) multiplied by the basic assembly time of one part ($t_a$) divided by the estimated time to complete the assembly ($t_{ma}$). Represented as $E_{ma} = \frac{N_{min} \cdot t_a}{t_{ma}}$ (Boothroyd et al, 2011). The theoretical minimum number of parts represents an ideal situation when all separate parts are combined into a single piece. This is where the complex design possibilities of additive manufacturing can have a major impact.

Figures 18 and 19 show the original classification systems for manual handling and insertion time with the possible values for the spring shown in Figure 17 highlighted. By taking into consideration the alpha and beta values along with the size, shape and weight of a part, an estimated handling time can be obtained. The spring has the same shape as the cylinder in Figure 15 so therefore it has the same alpha and beta values. The classification process consists of a two digit number identified by the rows and columns. Their intersection represents the time in seconds. This produces an insertion score of 00 and a handling score of 01 that results in an approximated insertion time of 1.5 seconds and a handling time of 1.43 seconds. A similar system is used for the insertion and fastening classification. Additional factors that affect handling time such as part thickness, chamfer design, obstructed access and restricted vision are also addressed (Boothroyd et al, 2011).
**Figure 18:** The original classification system for part features affecting insertion time (Boothroyd Dewhurst, Inc. 1999).
Figure 19: The original classification system for part features affecting manual handling time (Boothroyd Dewhurst, Inc. 1999).

### MANUAL HANDLING-ESTIMATED TIMES (s)

<table>
<thead>
<tr>
<th>Key:</th>
<th>Parts are easy to grasp and manipulate</th>
<th>Parts present handling difficulties (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One hand</td>
<td>Thickness &gt;2 mm</td>
<td>Thickness ≤2 mm</td>
</tr>
<tr>
<td></td>
<td>Size &gt;15 mm</td>
<td>Size ≤6 mm</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.13</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>3.95</td>
<td>2.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parts need tweezers for grasping and manipulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts can be manipulated without optical magnification</td>
</tr>
<tr>
<td>Parts are easy to grasp and manipulate</td>
</tr>
<tr>
<td>Thickness &gt;0.25 mm</td>
</tr>
<tr>
<td>0 ≤ β ≤ 180°</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Two hands for manipulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts present no additional handling difficulties (e.g., sticky, delicate, slippery, etc.) (1)</td>
</tr>
<tr>
<td>α ≤ 180°</td>
</tr>
<tr>
<td>Size &gt;15 mm</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parts can be handled by one person without mechanical assistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts do not severely nest or tangle and are not flexible</td>
</tr>
<tr>
<td>Part weight &lt;10 lb</td>
</tr>
<tr>
<td>Parts are easy to grasp and manipulate</td>
</tr>
<tr>
<td>α ≤ 180°</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>
An example of the Product Design for Manual Assembly methodology and the savings that the process produces is detailed in the following example with an analysis for a controller assembly. Shown in Figure 20 is the complete controller assembly with all the components labeled. Following that is Table 2 which details the analysis performed on the original design. Note that the part count is 25 and requires 227 seconds to assemble one unit.

Figure 20: Original controller assembly (Boothroyd et al, 2011).
Table 2: The worksheet analysis for the original controller assembly (Boothroyd et al, 2011).

<table>
<thead>
<tr>
<th>Item name</th>
<th>Number of items</th>
<th>Manual handling code</th>
<th>Handling time per item, s</th>
<th>Manual insertion code</th>
<th>Insertion time per item, s</th>
<th>Total operation time, s</th>
<th>Figures for min. parts</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pressure regulator</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>00</td>
<td>1.50</td>
<td>3.45</td>
<td>1</td>
<td>Place In fixture</td>
</tr>
<tr>
<td>2. Metal frame</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>06</td>
<td>5.50</td>
<td>7.45</td>
<td>1</td>
<td>Add</td>
</tr>
<tr>
<td>3. Nut</td>
<td>1</td>
<td>00</td>
<td>1.13</td>
<td>36</td>
<td>8.00</td>
<td>9.13</td>
<td>0</td>
<td>Reorient and adjust</td>
</tr>
<tr>
<td>4. Reorientation</td>
<td>1</td>
<td>98</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>18.00</td>
<td>0</td>
<td>Add</td>
</tr>
<tr>
<td>5. Sensor</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>08</td>
<td>6.50</td>
<td>8.45</td>
<td>1</td>
<td>Add and hold down</td>
</tr>
<tr>
<td>6. Strap</td>
<td>1</td>
<td>20</td>
<td>1.80</td>
<td>08</td>
<td>6.50</td>
<td>8.30</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>7. Screw</td>
<td>2</td>
<td>11</td>
<td>1.80</td>
<td>39</td>
<td>8.00</td>
<td>19.60</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>8. Apply tape</td>
<td>1</td>
<td>99</td>
<td>12.00</td>
<td>12.00</td>
<td>12.00</td>
<td>24.00</td>
<td>0</td>
<td>Operation</td>
</tr>
<tr>
<td>9. Adapter nut</td>
<td>1</td>
<td>10</td>
<td>1.50</td>
<td>49</td>
<td>10.50</td>
<td>12.00</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>10. Tube assembly</td>
<td>1</td>
<td>91</td>
<td>3.00</td>
<td>10</td>
<td>4.00</td>
<td>7.00</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>11. Screw fastening</td>
<td>1</td>
<td>92</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>10.00</td>
<td>0</td>
<td>Operation</td>
</tr>
<tr>
<td>12. PCB assembly</td>
<td>1</td>
<td>83</td>
<td>5.60</td>
<td>08</td>
<td>6.50</td>
<td>12.10</td>
<td>1</td>
<td>Add and hold down</td>
</tr>
<tr>
<td>13. Screw</td>
<td>2</td>
<td>11</td>
<td>1.80</td>
<td>39</td>
<td>8.00</td>
<td>19.60</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>14. Connector</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>31</td>
<td>5.00</td>
<td>6.95</td>
<td>0</td>
<td>Add and snap fit</td>
</tr>
<tr>
<td>15. Earth lead</td>
<td>1</td>
<td>83</td>
<td>5.60</td>
<td>31</td>
<td>5.00</td>
<td>10.60</td>
<td>0</td>
<td>Add and snap fit</td>
</tr>
<tr>
<td>16. Reorientation</td>
<td>1</td>
<td>98</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>18.00</td>
<td>0</td>
<td>Reorient and adjust</td>
</tr>
<tr>
<td>17. Knob assembly</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>08</td>
<td>6.50</td>
<td>8.45</td>
<td>1</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>18. Screw fastening</td>
<td>1</td>
<td>92</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>10.00</td>
<td>0</td>
<td>Operation</td>
</tr>
<tr>
<td>19. Plastic cover</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>08</td>
<td>6.50</td>
<td>8.45</td>
<td>0</td>
<td>Add and hold down</td>
</tr>
<tr>
<td>20. Reorientation</td>
<td>1</td>
<td>98</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>18.00</td>
<td>0</td>
<td>Reorient and adjust</td>
</tr>
<tr>
<td>21. Screw</td>
<td>3</td>
<td>11</td>
<td>1.80</td>
<td>49</td>
<td>10.50</td>
<td>36.90</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>25</strong></td>
<td></td>
<td><strong>227.43</strong></td>
<td></td>
<td></td>
<td><strong>5</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After analyzing each component of the controller assembly, Table 3 explains the design changes and their respective assembly time savings. The redesigned controller is compared to the original in Figure 21 and after analyzing the new assembly the savings are evident. Shown in Table 4, the assembly was reduced from 25 parts to 10 with the assembly time reduced from 227 to 84 seconds. A significant improvement over the original assembly.

Table 3: The design changes and associated savings (Boothroyd et al, 2011).
Figure 21: Controller assembly before (left) and after (right) the analysis (Boothroyd et al, 2011).

Table 4: Analysis of the redesigned controller (Boothroyd et al, 2011).

<table>
<thead>
<tr>
<th>Item name</th>
<th>Number of items</th>
<th>Manual handling code</th>
<th>Handling time per item, s</th>
<th>Manual insertion code</th>
<th>Insertion time per item, s</th>
<th>Total operation time, s</th>
<th>Figures for min. parts</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pressure regulator</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>00</td>
<td>1.50</td>
<td>3.45</td>
<td>1</td>
<td>Place in fixture</td>
</tr>
<tr>
<td>2. Plastic cover</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>06</td>
<td>5.50</td>
<td>7.45</td>
<td>1</td>
<td>Add and hold down</td>
</tr>
<tr>
<td>3. Nut</td>
<td>1</td>
<td>00</td>
<td>1.13</td>
<td>39</td>
<td>8.00</td>
<td>9.13</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>4. Knob assembly</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>08</td>
<td>6.50</td>
<td>8.45</td>
<td>1</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>5. Screw fastening</td>
<td>1</td>
<td>92</td>
<td>5.00</td>
<td>5.00</td>
<td>10.00</td>
<td>12.00</td>
<td>0</td>
<td>Operation</td>
</tr>
<tr>
<td>6. Reorientation</td>
<td>1</td>
<td>98</td>
<td>9.00</td>
<td>9.00</td>
<td>18.00</td>
<td>21.00</td>
<td>1</td>
<td>Reorient</td>
</tr>
<tr>
<td>7. Apply tape</td>
<td>1</td>
<td>99</td>
<td>12.00</td>
<td>12.00</td>
<td>24.00</td>
<td>24.00</td>
<td>0</td>
<td>Operation</td>
</tr>
<tr>
<td>8. Adaptor nut</td>
<td>1</td>
<td>30</td>
<td>1.50</td>
<td>49</td>
<td>10.50</td>
<td>12.00</td>
<td>0</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>9. Sensor sub.</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>39</td>
<td>8.00</td>
<td>9.90</td>
<td>1</td>
<td>Add and screw fasten</td>
</tr>
<tr>
<td>10. PCB assembly</td>
<td>1</td>
<td>83</td>
<td>5.60</td>
<td>30</td>
<td>2.00</td>
<td>5.60</td>
<td>1</td>
<td>Add and snap fit</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>83.98</strong></td>
<td><strong>5</strong></td>
<td></td>
</tr>
</tbody>
</table>

The savings produced by the DFMA process are well documented and the advancement of additive manufacturing increases the possibilities for the redesign process. The simplification and optimization can be taken farther due to the increased manufacturing flexibility of AM.

Established designs created for conventional manufacturing methods should be revisited and analyzed.
Chapter 3: Methods

3.1 Current Door Hinge

The assembly chosen for this research is a goose neck hinge used on access and service doors on Gulfstream aircraft. While this assembly is not ideally suited for a DFMA analysis, the process will be used as an additional method of quantifying the improvement. The current hinge assembly is composed of six unique main pieces and is machined out of three different materials, two different aluminum alloys and a stainless steel, as shown in Figure 22. The single point refueling door installation consists of two hinges and is subject to handling loads equal to 100 pounds ultimate in any direction (Gulfstream GVI-GER-1039). The hinges are installed as shown in Figure 23 and the loads are assumed to be equally divided between the two of them.

Figure 22: Components of the current door hinge.

The aircraft fuselage mounting area and the door panel are a composite material and could not be altered during this redesign. For that reason the mounting holes locations and
overall footprint were not altered from the original design. The fuselage (blue) and door (green) areas are visible in Figure 22.

![Figure 22: Illustration of fuselage and door areas.](image)

The six components that make up the hinge assembly and their roles are as follows:

**Hinge Fitting:** Attaches to the composite wing fairing of the aircraft using blind rivets and composi-lok. Houses the axle that the hinge rotates about.

**Ball Plunger Housings:** Attaches to the hinge fitting and provides the mounting location for the spring loaded ball stoppers. The ball stoppers interact with the hinge stoppers to hold open the door as shown in Figure 24.

**Goose Neck:** Connects the composite door to the hinge fitting. Unique shape allows for easy access to bay area while clearing curved surfaces.

**Hinge Stoppers:** Attaches to both sides of the goose neck and interfaces with the ball stoppers. Their shape allows the spring loaded balls to smoothly transition up and over the locking mechanism. A close up view shown in Figure 24.

![Figure 23: CATIA model of two installed hinges and load analysis directions.](image)
The current hinge is machined out of three different materials. Aluminum 7050-T7451, Aluminum 7075-T7351 and Stainless Steel 440C. Due to the fact that the spring loaded ball stoppers are machined out of stainless steel, the hinge stoppers also need to be stainless steel to minimize wear from repeated use. Table 5 below shows the properties of each metal obtained from ASM Aerospace Specification Metals Inc. and MatWeb.com. For the purpose of this research, the density was the only material property required to determine weight savings.

Table 5: Properties of the materials used in the goose neck hinge.

<table>
<thead>
<tr>
<th></th>
<th>Al 7075-T7351</th>
<th>Al 7050-T7451</th>
<th>Stainless Steel 440C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/in³)</td>
<td>0.102</td>
<td>0.102</td>
<td>0.275</td>
</tr>
<tr>
<td>Yield Tensile (psi)</td>
<td>63,100</td>
<td>68,000</td>
<td>186,000</td>
</tr>
<tr>
<td>Ultimate Tensile (psi)</td>
<td>73,200</td>
<td>76,000</td>
<td>254,000</td>
</tr>
</tbody>
</table>

Using the 3D modeling software CATIA, the volume and weight of each part was approximated using their respective material density. Shown in Table 6 are the results of these measurements along with the total weight estimated for the hinge assembly. This weight does not take into account the spring loaded ball stoppers, fasteners, grounding cables or the axle. These components will be used on the redesigned hinge as well.
The design of each part can be compared to the guidelines for part handling and insertion/fastening described in section 2.7. Overall each part conforms well to the handling guidelines of obvious asymmetry and no delicate or flexible parts. The other guidelines do not apply. This assembly also follows the insertion and fastening guidelines that apply such as the self-aligning axis and requiring little to no resistance to assembly.

### 3.2 Door Hinge Redesigns

The geometric locations of all the main features remained unchanged from the original hinge to avoid the need to redesign other components. In order to redesign the entire hinge assembly to be additively manufactured and for the purpose of this research, several assumptions were made:

1. The entire hinge assembly is manufactured out of the same material, either aluminum 7050-T7451 or 7075-T7351.
2. The balls in the spring loaded ball stoppers are aluminum but their casings may remain stainless steel.
3. The material properties of the additively manufactured aluminum are equal to or greater than equivalent wrought aluminum.

The first two assumptions, from basic knowledge of additive manufacturing, can be easily made. However, the third assumption is more difficult to achieve. Until the technology progresses to a point where equivalent material properties are possible, engineers will have to
consider the reduced strength and ductility into designs. In many situations, the reduced ductility can easily be designed around or is not a factor such as in this case. The loads experienced by the hinge are during opening and closing while on the ground and reduced ductility may not affect its performance.

While making these assumptions and following the DFA guidelines of reducing the number of parts, it was possible to take the existing smaller parts and incorporate them into their respective parent part. The resulting hinge redesign is shown in Figure 25.

![Figure 25: Redesigned door hinge for additive manufacturing.](image)

Due to the geometric similarity between the two designs, the hinges are interchangeable. By integrating the parts together, it was possible to remove surplus material no longer required to support features. Similar to the original design, the parts are obviously asymmetric, not delicate and/or hazardous per the part handling guidelines. Additionally the assembly is still self-aligning about the axle and produces little to no resistance to assemble.
Chapter 4: Results

4.1 Assembly Comparison

The smaller components such as the hinge stoppers and ball plunger housings were integrated into their respective larger parent part as shown in Figures 26 and 27. The two hinge stoppers in addition to providing the locking mechanism also provide a mounting bracket for grounding cables. As is visible in Figure 26, by combining the two stoppers into the geometry of the goose neck a significant amount of material was eliminated. Reducing their total volume by 59% and weight by 85%. There was no longer a need for excess support structure for the two mounting holes and the grounding attachment point was integrated into the center of the neck. The forces experienced by the hinge stoppers are relatively small so the need for any additional structural support material is not needed. The integrated stoppers shown in Figure 26B can withstand over 500 pounds before shearing would occur.

Following the same measurement procedure discussed for the original hinge design, the new hinges volume and weight were determined and are shown in Table 7.

<table>
<thead>
<tr>
<th>Hinge Component</th>
<th>Volume (in³)</th>
<th>Weight (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Goose Neck Hinge</td>
<td>5.714</td>
<td>0.583</td>
</tr>
<tr>
<td>2 Hinge Fitting</td>
<td>4.308</td>
<td>0.439</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10.022</strong></td>
<td><strong>1.022</strong></td>
</tr>
</tbody>
</table>
The reduction in material is even more evident when comparing the ball plunger housings shown in Figure 27. By integrating the supports directly into the hinge fitting geometry, the need for additional mounting material was completely eliminated. The only forces the housings encounter are a small side loading due to the spring compressing when opened. The design flexibility of AM allowed the supports to be designed solely around countering this torque.
Under the assumption of equal material properties and following the original design, the decision to manufacture the entire hinge assembly from Al 7075-T7351 will not affect its performance. The changing of hinge stopper material from stainless steel and plunger housing material from Al 7050-T7451 is structurally insignificant. The stainless steel was used to reduce wear due to the spring loaded balls being stainless steel as well. The changing of these materials should not have any adverse effects and the loads experienced by these components is very minimal. With the integrated housing supports shown in Figure 27B, a tensile force in excess of 6,000 pounds would be required to deform the housing supports. The total volume and weight of the housings were reduced 53%.

4.2 DFMA Analysis

Before any analysis is performed it is important to note again that this goose neck hinge assembly is not an ideal candidate for the application of product design for manual assembly. While it falls into the manual assembly category, this assembly does not have a large number of small parts, does not require inserting of parts, is not manufactured in mass quantities, stored in bulk or uses multiples of the same part. Each part of the hinge assembly is unique, clearly asymmetric, non-stackable and easily handled. For this reason, a full DFMA analysis will not be the main method for quantifying the improvements but rather a supplementary analysis to a simplified design comparison.

When determining the alpha and beta values for each part, the initial orientation of insertion assumed can alter the resulting values. For the values shown in Tables 8 and 9, the initial part orientation was determined by each parts location when fully assembled and in the closed position. Figures 28 and 29 are CATIA renderings with shadows to represent the insertion slots.
Figure 28: Projected slots used for insertion calculations on the original hinge assembly.

Table 8: Alpha and beta values for original hinge.

<table>
<thead>
<tr>
<th>Part</th>
<th>Goose Neck</th>
<th>Hinge Fitting</th>
<th>Right Housing</th>
<th>Left Housing</th>
<th>Right Stopper</th>
<th>Left Stopper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>$\beta$</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
</tbody>
</table>

Figure 29: Projected slots used for insertion calculations on the redesigned hinge assembly.

Table 9: Alpha and beta values for redesigned hinge.

<table>
<thead>
<tr>
<th>Part</th>
<th>Goose Neck</th>
<th>Hinge Fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>$\beta$</td>
<td>360</td>
<td>360</td>
</tr>
</tbody>
</table>
With the alpha and beta values determined for each part, their respective insertion and handling times were determined using the manual insertion-estimated times chart along with manual handling-estimated times chart shown in Figures 18 and 19. Tables 10 and 11 are the worksheet analysis breakdowns for handling and insertion times for both hinge assembly designs. The alpha and beta values did not change due to the fact that the parts are still assembled the same way. The parts can only be assembled in one orientation, resulting in a score of 360 for each one. Even though this analysis does not translate well to this assembly, it should be noted that just reducing the part count from six to two reduced the total time to handle and assemble by 67% or 29.8 seconds.

Table 10: Worksheet analysis for the original hinge assembly.

<table>
<thead>
<tr>
<th>Item Name</th>
<th>Number of Items</th>
<th>Handling Code</th>
<th>Handling Time (s)</th>
<th>Insertion Code</th>
<th>Insertion Time (s)</th>
<th>Total Operation Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goose Neck</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>06</td>
<td>5.5</td>
<td>7.45</td>
</tr>
<tr>
<td>Hinge Fitting</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>06</td>
<td>5.5</td>
<td>7.45</td>
</tr>
<tr>
<td>Plunger Housings</td>
<td>2</td>
<td>30</td>
<td>1.95 x 2</td>
<td>06</td>
<td>5.5 x 2</td>
<td>14.9</td>
</tr>
<tr>
<td>Stoppers</td>
<td>2</td>
<td>30</td>
<td>1.95 x 2</td>
<td>06</td>
<td>5.5 x 2</td>
<td>14.9</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>44.7</strong></td>
</tr>
</tbody>
</table>

Table 11: Worksheet analysis for the redesigned hinge assembly.

<table>
<thead>
<tr>
<th>Item Name</th>
<th>Number of Items</th>
<th>Handling Code</th>
<th>Handling Time (s)</th>
<th>Insertion Code</th>
<th>Insertion Time (s)</th>
<th>Total Operation Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goose Neck</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>06</td>
<td>5.5</td>
<td>7.45</td>
</tr>
<tr>
<td>Hinge Fitting</td>
<td>1</td>
<td>30</td>
<td>1.95</td>
<td>06</td>
<td>5.5</td>
<td>7.45</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>14.9</strong></td>
</tr>
</tbody>
</table>

To elaborate more on the DFMA coding system shown above, an example will be made of the Handling Code value of 30 for the Goose Neck in Table 11. This code was determined from the chart shown in Figure 19 and the parts corresponding alpha and beta values of 360 along with its size. Added together the value of 720 falls into the fourth row in the “One hand” category resulting in the first digit “3”. This part is easily held with one hand and is larger than
15mm which determines the second digit of “0” from the first column. This same method is used to determine all the codes shown.

However, the real impact and savings brought on by incorporating additive manufacturing into this hinge design is not the assembly time, but rather the reduction in weight and part count. Time to assemble components is the main focus for many large scale, mass production facilities where products are being produced on the scale of hundreds or thousands per day. The aerospace industry however is more focused with reducing weight and produces aircraft at a much slower rate.

4.3 Improvements and Savings

The most important improvement of the redesigned hinge is its reduction in weight. The combination of using lighter materials, eliminating unneeded support structure and consolidating parts led to a total weight reduction of approximately 22%. Table 12 summarizes all the reductions achieved by redesigning the hinge utilizing manufacturing capabilities only feasible through additive manufacturing.

Table 12: Material and design improvements as a result of the redesign.

<table>
<thead>
<tr>
<th>Property</th>
<th>Original Design</th>
<th>AM Redesign</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lb.)</td>
<td>1.30</td>
<td>1.02</td>
<td>22%</td>
</tr>
<tr>
<td>Volume (in³)</td>
<td>11.54</td>
<td>10.02</td>
<td>13%</td>
</tr>
<tr>
<td>Part Count</td>
<td>6</td>
<td>2</td>
<td>67%</td>
</tr>
<tr>
<td>Fasteners</td>
<td>16</td>
<td>14</td>
<td>13%</td>
</tr>
</tbody>
</table>

To emphasize the importance of weight reduction on aircraft, in 1994 Gulfstream determined that for every additional pound of weight, their aircraft had to burn $50,000 more in fuel over the course of 6000 flight hours. Translated to 2013 that cost would be $200,000. Using
the 2013 estimate, the cost savings of reducing 0.28 pounds from just one door hinge would save approximately $56,000 per 6000 flight hours. Taking into account that each G650 aircraft has two of these hinges, the estimated savings per plane would be $112,000.

A great example of focusing on reducing fuel costs through weight reduction is the American Airlines employee-led effort called Fuel Smart. Their goal is to safely reduce fuel consumption by implementing techniques such as weight reduction, single-engine taxi, engine wash, winglets and more. They concluded that by reducing just one pound of weight from an aircraft they saved 114 pounds of jet fuel each year. Totaling approximately 2850 pounds of fuel over the service life of the aircraft (Lyons, 2011, American Airlines, 2012). When applied across their fleet of more than 600 aircraft this leads to significant savings.

The impact of even a slight weight reduction in an aircraft can result in noticeable savings in fuel burn over the lifetime of the plane. By taking full advantage of AM and applying redesigned parts all throughout an aircraft, unprecedented weight reductions can result in a new generation of super-efficient aircraft.
Chapter 5: Conclusion

The seemingly unrestricted design and manufacturing possibilities offered by the additive manufacturing (AM) process made it possible to redesign the aircraft door hinge with significant reductions in weight and part count. By consolidating the smaller components into their parent parts as features, the need for excess support and mounting material was eliminated. This resulted in a weight reduction of approximately 22% per hinge assembly and reduced the number of parts from six to two.

However, by integrating multiple parts into a single piece, the reparableility has decreased. If broken, entire pieces will have to be replaced rather than an individual component. While the reduction in part count is favorable to the assembly process and reduces the possibility of issues during service, the primary advantage is the weight reduction. Every ounce saved results in increased aircraft performance, reduced fuel burn, reduced carbon emissions and increased profits. This redesigned hinge is estimated to save $56,000 in fuel burned over the course of 6000 flight hours, per hinge on the aircraft. This totals approximately $112,000 per G650 aircraft.

The DFMA guidelines proved to be ill-suited for analyzing assemblies designed for additive manufacturing. The Design for Manufacturing (DFM) theory of simplifying each part down to its most basic shape to reduce machining does not apply to AM. By minimizing the amount of machining required, inevitably excess material will remain that adds unnecessary weight. In weight sensitive aerospace applications this is unacceptable.

The Design for Assembly (DFA) approach of reducing the number of individual parts however is well suited for AM applications. As was shown in this redesign, AM allows the
consolidation of parts together without worry about difficulty of manufacturing. AM allows the DFA process to be taken to a new extreme.

The new technology of AM provides design possibilities previously thought too impractical or impossible for subtractive machining. To fully utilize the benefits of AM, guidelines for Design for Additive Manufacturing (DFAM) need to be explored. It is clear that the aerospace industry can benefit from AM and as the technology continues to advance, opportunities for savings and improvements will follow.
**Future Considerations**

When dealing with new and exciting technology such as additive manufacturing there are many opportunities for further research. For the purpose of this research and due to limitations in information available the design changes were conservative to avoid deviating from the current design and requiring additional structural analysis. There is a considerable amount of structural redesign and optimization work that can be performed on this hinge. Through a detailed structural analysis, a greater reduction in material is possible. A trade study should be performed to determine if switching to titanium is beneficial, potentially increasing the weight savings substantially by taking full advantage of AM’s capabilities.

To better determine DFMA’s effectiveness when working with AM, additional analysis should be performed on assemblies that are better suited for a redesign, preferably ones that have a large number of smaller components that require handling, inserting and repositioning. This will provide a better understanding of how well DFMA can be adapted to accommodate AM and where it falls short.

Additionally, as was mentioned throughout this research, the material properties of AM parts are a major hurdle currently preventing wider implementation into industry. There is currently much effort being put towards developing standards and processes to produce consistent, reliable and sufficient material properties. With so many factors affecting each type of AM process, any research towards this is greatly sought after.
BIBLIOGRAPHY


