STUDY OF CUSTOM TOOL CONTROL IN AVIATION AND AEROSPACE AND
SELECTION OF MATERIALS AND MANUFACTURING PROCESS

A Thesis
Presented to
the Faculty of the College of Business and Technology
Morehead State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
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April 27, 2017
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Tool control in aviation and aerospace is vital to safety and quality production and service. With various methods of tool control on the market, even the simplest, tool kitting is expensive. Tool kits are trays with cutouts custom made for tools, made from high density plastic foams. Typical manufacturing methods include CNC router or water jet cutter. A variety of foam are available for tool kitting applications. Materials testing revealed that 6-lb polyethylene foam is best suited for use in industry based on tensile strength, hardness, impact toughness, and chemical resistance. Water jet cutting is the most precise and efficient method for manufacturing tool kits, as it provides a clean, quality cut every time. Cost analysis showed that using these materials and methods to produce tool kits in house is astonishingly less expensive than outsourcing for medium to large sized companies.
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Mr. Sam Mason
Acknowledgements:

Mom - She has supported me through everything that I have ever done. She is always there to guide me and advise me whenever I was in need. She always put my interest first. She taught me that regardless of what I do or where I go, that I just need to be happy. I could not ask for a better mother. He always tells me what I need to hear, even if it’s not what I want to hear.

Dad - He leads by example. He taught me the one thing that nothing can replace, and that is strong work ethic. It is what has gotten me this far and will carry me through the rest of my life. He could not have raised me to be a better man if he tried.

Mr. Sam Mason – He has been a mentor for me since my early undergraduate rules. He taught be so much inside and outside of class. Your guidance has helped me tremendously in my time at the university. He so much time and effort in me as a professional. He has advised me academically and personally.

Dr. Hans Chapman – He advised me academically in my undergraduate studies and have been a great professor for various courses. He always put me up in front of people to hone my presentations skills to what they are today. He guided my thesis work and always kept me on the correct educational path.

Dr. Ahmad Zargari – As the head of our department you have always guided me. You have always pushed me to do better in my work and strive for greatness.

Dr. Nilesh Joshi – He has taught me so much over my years at the university. He showed me how to look at engineering from an economic standpoint, which has been a great asset.

All of you have impacted my life and education and for that I am forever thankful. The guidance I have received has made me the professional that I am today.
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1.1 Tools and Tool Control

The Smithsonian estimates that the first development and use of tools was at least 2.6 million years ago, these tools were as crude as possibly imaginable and made from the common stones of the region. (Smithsonian National Museum of Natural History, 2017) The tools were crude because construction and creation of items was crude. There has been a massive change from this time. Today, the world is on such the cutting edge of technology. Particularly in the aviation and aerospace industries, tools are vital. This industry uses a multitude of tools for building and maintaining their products and machines. Tools can include anything used to produce a product or perform maintenance. Tool control is a crucial part of being an effective operation. Tool control is essentially a procedure or system that keeps tools organized, free of debris, and protected. When tools are missing, it is apparent, and ideally there is a method of telling who has last used to missing tool. Aviation and Aerospace requires their products be protected from foreign debris, so it is important that tools are stored and organized in a manner that they are not able to be damaged or vulnerable to contamination or foreign debris. Tool control can be a very simple procedure or process once implemented.

1.2 Problem Statement

Tool control is becoming more and more of a problem for many companies with the constant advancement of technology and equipment. There is a greater need for many tools to be used by a company. Tools can be very expensive, so naturally it is important to take care of your
investment. Proper tool control can extend the life of your tools and lessen expenditures to replace lost or stolen tools.

Many industries require great precision and cleanliness in their field of work. Tools can be a leading cause of contamination. In the aviation and aerospace industry contamination can lead to failed inspection, rework, and malfunction of equipment. Foreign object debris leads to foreign object damage. Proper tool control prevents unwanted and unnecessary contamination of tools and whatever the tools are used to work on or build.

There is a market of tool kits available that claim to aid in tool control and cleanliness, but they require the customers to do all the work to customize them and are less than precise. There is a need for a process for creating custom tool control equipment and systems at in a cost-effective manner. This should be done at a reasonable price, because when tool control becomes more expensive that replacing the tools being controlled, the original purpose is defeated.

1.3 Significance of the Study

The significance of this study is to analyze the materials and manufacturing process used of tool control equipment in the aviation and aerospace industry. The need for tool control in this industry is apparent, but currently cost considerable financial allocation to obtain. Thus, researching materials used and manufacturing processes for these materials aims to highlight the best material and manufacturing process to yield tool control equipment that is cost effective and performs to the needs of industry.

1.4 Objectives

The overall goal of this study is to find the best material and manufacturing method for producing tool control equipment. This is broken down into three objectives. The first is to select
the best material for tool control equipment based on its physical properties. The second objective is to find the most precise and efficient method for manufacturing. Lastly a cost analysis will be performed on the material and manufacturing processes to determine if manufacturing tool control equipment in house is more cost effective that purchasing it from an external supplier.

1.5 Assumptions and Limitations

Many companies use a variety of tools for their processes, but some industries do not require the tool control that others do. Industries such as aerospace and aviation require a foreign object debris free environment and the array of tools must be protected and organizes. This study assumes that tool control is a vital part of manufacturing and maintenance and that companies are allotted a certain budget for tools and tool control each fiscal year. The application of any results of this study are intended for medium to large size aviation and aerospace maintenance and manufacturing organizations.

This study is limited by the financial abilities of the author and Morehead State University. The goal of this study is to create a process for building custom tool control equipment for industry. There may be aspects of the study in which the author is unable to reach the full potential of the study due to a limitation of funds for equipment and testing.

1.6 Definition of Terms

**CAD/CAM** – Computer Aided Design/Computer Aided Manufacturing – The use of computer software to create objects and map to manufacturing tool paths and process, i.e. MasterCAM, SolidWorks
**Contamination** – the action or state of making or being made impure by polluting or poisoning

**CNC** – Computer Numeric Control – the control of machinery using numeric codes

**Foreign Object Damage** – The unintentional or unwanted alteration of a part, product or tool due to the presence of foreign object debris

**FOD** – Foreign Object Debris – The contamination of a part, product, or tool by material, dirt, chemicals, or other pollutants not natural to the specific item

**FOE** – Foreign Object Elimination – the act of removing and preventing contamination of parts, products, or tools by foreign object debris

**Tool Control** – the use of equipment and procedures to prevent tool loss, contamination, and damage

**Tool Control Equipment** – the array of foam tool box inserts, tool shadow boards, automated tool storage systems, and tool tracking programs

**Tool Inventory** – the collections of used or unused tools possessed by a company that are required to perform any tasks related to providing their specific product or service
Chapter 2: Literature Review

2.1 Tool Control Summary

The concept of tool control is often misunderstood as tool storage. Tool boxes do not keep track of tools, they simply hold them. Just because tools are stored in a box does not that they are controlled. Tools can be thrown into a box after each use with no regards to if the tools are clean or accounted for. The International Journal for Production Research explains tool control as follows:

“A method of loading a set of tools to the different machining centers of a shop is presented, where each part visits only one of the machining centers for its entire processing. Any tools which are required but unavailable for the processing of a part are borrowed from other machining centers. As a real-time control, the tool-returning policies for those borrowed tools and the job-dispatching rules at the machining centers are evaluated to maximize the throughput performance of the shop. Some experimental results are provided.” (Hogg, 2011)

Tool control can be use in any industry but specifically in vital to maintenance departments or companies who perform maintenance services.

2.2 Tool Control Benefits and Consequences of Its Absence

The benefits of tool control are like that of 5S and other lean initiatives. When all tools are accounted for, clean, and in proper working order, it leads to enhanced production and job efficiency. Lean initiatives focus on the elimination of waste. 5S stands for Sort, Set to Order, Shine, Standardize, and Sustain. The benefits of 5S include improved safety, decreases down time, higher employee morale, identify problems more quickly, developing control through visibility, establishes convenient work practice, increases product and process quality,
strengthens employees’ pride in their work, promotes stronger communication among staff, and empower employees to sustain their work area. (Intrieri, 2013) Tool control is essentially 5S to an extreme degree. Tool control carries the same benefits as well as a decrease in tool loss, tool damage, and contamination of work.

The consequences of not having proper tool control are like the same consequences that come with poor 5S methods, only to a more severe degree. Missing tools lead to increases in downtime when a tool is needed and cannot be found. Also, if a tool is left in a machine or aircraft a safety concern is created. Damage to tools can go unnoticed without a proper tool control procedure. Damaged tools lead to mistakes and deficiencies in workmanship. (Aviation Maintenance Technology, 2005). FOD or Foreign Object Debris is any substance or particle that contaminates a tool, part, or machine, that is not original to the work. FOD leads to foreign object damage, causing quality control and workmanship issues. Tool control can prevent this.

2.3 Available Tool Control - Storage

Tool kitting is one of the most popular methods of tool control and uses foam tool trays to organize tools. There is a wide array of companies who create tool kitting foam inserts and tracking systems. Most companies who provide this product, produce universal tool kitting foam that the customer can cut to fit their needs. Other companies will cut the foam for their customers if the customers provide the specifications for how they should be cut. Tool trays are typically created from two-part foam boards. A darker colored foam is layered over top of a lighter colored foam. The darker colored foam is cut so that when it is layered with the lighter foam that a void is left where the tool is placed. The foam is typically a high-density polyethylene foam to hold up to friction and sharp edges of tools during use. (Tool Keepers, 2016) Tools can also be organized on tool walls by using a method called shadow boarding. Shadow boarding refers to a
wall on which you can hang tools and the shape of the tool is outlined or shadowed on said board. (Intieri, 2013) Companies such as CribMaster and Tool Keeper build custom tool control storage solutions for its customers. CribMaster is one of the leaders in this industry. They provide everything for tool control including boxes for the tool trays and portable tool boxes that adhere to standard tool control methods. (Stanley Industrial and Automotive LLC., 2015) This is done with the specification provided by the customer. This can result in less companies using tool kitting control solutions due to the time that it takes to organize the specification of all its tools.

![Figure 1: Foam Tool Kits from PlaSteel AZ](image-url)
2.4 Tool Kitting Materials

Tool kits are typically constructed of two pieces of a plastic foam, one flat sheet, and another with the cut silhouettes of the tools. There are a large variety of plastic foams available on the market, but only a select few have the appropriate material properties for foam tool kitting. It is important to consider the forces that the product will incur when selecting a material for use. Open-cell polyethylene foams, cross-linked polyethylene foams, and closed-cell polyethylene foams are they most popular materials used for tool kitting currently. They each have their own benefits, but overall meet the needs of a material for this application.

Cellular plastic foams are made by chemically or mechanically expanding resins made from a plastic. These foams have a strength to weight ratio that can be up to five times greater than traditional metals. Plastic foams can be flexible or rigid, dense or open. Open-cell foams can be created by a means of adding gases either chemically or mechanically to the plastic resin. As the resin cools the plastic is foamed, being the gas bubble remain trapped forming the open cell plastic foam. (Schrader, Foams, 2000) Open-cell foams have the appearance of having air bubbles or gaps in their structure. Closed-cell foams are manufactured in a similar manner, but the air pockets are microscopic. Closed-cell foams contain uniform microcellular voids. This is produced by pre-saturating the material to be processed with a uniform concentration of a gas while controlling temperature and pressure to avoid cell nucleation. When pressure is released the nucleation of the gases occur at a specific temperature, following the material is cooled quickly to preserve the microcellular void structure. (Massachusetts Institute of Technology, United State of America Patent No. US4473665 A, 1984) Cross-linked polymers are the byproduct of introducing a cross linking agent to another polymer. A chemical reaction occurs, linking their polymer chains together. This is often used to make materials much stronger. (Royal
Polyethylene can be cross-linked with various other polymers and chemicals to create a polymer resin used to manufacture foam.

All the foams currently used for tool control have one thing in common. They all are made from some form of polyethylene. Polyethylene is \((C_2H_4)_n\), where \(n\) can range from about 100 to 1000. It is known as the most common commercial polymer. Polyethylene thermoplastics are typically subdivided into three groups; low-density polyethylene (LDPE), high-density polyethylene (HDPE), and ultra-high molecular-weight polyethylene (UHMWPE). LDPE has a more chain branching than HDPE, while HDPE is linear. UHMWPE has very long linear chain. The higher the linearity of a chain and longer length of chain typically attribute to a higher melting point and improved mechanical and physical properties. (Shackleford, Introduction to Materials Science for Engineers 8th Edition, 2015) Typically for tool kitting, the foam used is made of some variety of HDPE. This may be a closed-cell polyethylene or a cross-linked polyethylene.

<table>
<thead>
<tr>
<th></th>
<th>LDPE (sheet grade)</th>
<th>HDPE (sheet grade)</th>
<th>HDPE (cross-linkable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>1813 psi</td>
<td>3800 psi</td>
<td>3089 psi</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>1624 psi</td>
<td>3756 psi</td>
<td>2915 psi</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>533%</td>
<td>654%</td>
<td>449%</td>
</tr>
<tr>
<td>Density</td>
<td>0.0334 lb/in^3</td>
<td>0.0383 lb/in^3</td>
<td>0.0347 lb/in^3</td>
</tr>
</tbody>
</table>

Looking at the table above, it can be seen the benefits of the HDPE over the LDPE. While LDPE has a greater elongation at break than cross-linkable HDPE, these properties are not derived from actual foam sample and the cross-linkable HDPE has yet to be crosslinked, which
will ultimately alter its material properties, making it superior to the LDPE. (MatWeb LLC., 2017)

2.5 Cutting Methods

The manufacturing of foam tool kits is not a highly-complicated process. Essentially one needs to be able to remove the silhouette of various tools from a solid foam sheet. This can be accomplished through various ways. High density foams can be cut using CNC routers, waterjets, hot wire cutters, CNC razor knifes, and air cutters. Each has their own advantages and disadvantages.

CNC routing is traditional used for woodworking purposes. The most common is a 3-axis machine which move on a XYZ plane. These machines are specifically used for cutting flat parts. Machining is performed through the movement along the arises of the machine. Cutting tools are mounted into a rotating spindle head. Servo motors drive the head along each of its axis. CNC routers today have RPM speeds ranging from 3,600 to 30,000 RPM. Feed rates typically can reach 1,500 inches per minute. Varying feed rates and RPM allow for adjustments to optimize cutting speed and quality. (Gisip, 2015)
CNC routing foam is a good choice because it is accurate and efficient. This method does create foam dust which is hazardous if inhaled. Many plastic foams, such as polyethylene, that are used for tool kits are listed as suspected carcinogens, therefore it is important to ensure that it is not inhaled or ingested. (Sax, 1975) Proper dust collection systems should be in place if this process is used. Also, stiffer foam will cut better that softer foams as they are more like the materials that CNC routers traditionally machine. When machining plastic foam it is important to consider a few factors: 1) They do not readily conduct heat but are easily affected by it; 2) Some contain abrasive fillers; 3) They are soft and yielding compared to metals and woods; 4) Some are quite brittle yet soft. Tools used for routing foams should have a keen cutting edge and smooth polished faces, producing a cooler cut. They should also have a relatively obtuse cutting angle to keep the tool form digging in and ripping the plastic foams. It is common practice to set up for cutting a plastic foam as if machining copper, brass, or other soft metal, if specific information regarding the plastic foam in not available. (Schrader, Machining Plastics, 2000)
Another method popular in foam cutting methods in waterjet cutting. Waterjet cutting uses high pressure water and an abrasive additive to cut through materials. The waterjet is the result of water and abrasive flow through a nozzle at high pressure, up to 55,000 psi. (Birtu, 2012) Waterjet uses abrasives made from garnet, aluminum oxide, silicon oxide, silica sand, olivine, and silicon carbide. Different abrasives are used for different applications. The abrasive is added to the water to aid in the cutting of materials by the impact of high pressure water and fine pieces of abrasive material on parts. (Khan, 2007)

First used for cutting cardboard, printed circuit boards, and pressed paper food containers, this method of cutting is now used for a wide array of nonmetallic materials including acrylcs, felts, foams, Mylar, plastic, polyethylene, polyimide, and rubber. Waterjet cutting for foam tool kits ideal because it is very precise and efficient. The operating costs of waterjet cutting are relatively low compared to many traditional machining processes. Foams cut with waterjet must be resistant to water absorption and mildew. Also, to use a waterjet cutter a
continuous flow of water is needed, this should be considered before selecting as a manufacturing method. Unlike many thermal cutting processes used on foam, waterjet cutting does not subject parts to additional thermal deformation or mechanical stress. Additionally, the process is dust free and odorless. Waterjet cutting is still a very dirty process, because of the water, abrasive, and material remove, so parts made on them will likely need to be cleaned before they reach the customer. (Schrader, Waterjet Machining, 2000)

Hotwire cutting foam is another option for cutting foam. Hotwire cutting uses a thin heated wire to cut through materials, without removing much material. Most hotwire machines use a robotic two axis system to feed material into the wire. The wire can move up and down, and in and out of the material. (Gallina, 2005)
Hotwire cutting is an effective method for cutting foam, but does not fit the bill for tool kitting. Foam tool kits need to have holes shaped like the tools. Hotwire cutters enter the material from and edge and exit from an edge, leaving two pieces in the end. This is not ideal for tool kitting foam applications.

Plasma arc cutting is not applicable to foam, but some of its concepts may be. PAC works using an electric arc and a high temperature, high pressure, ionized gas passed through a restrictive nozzle. The arc can reach approximately 50,000 degrees Fahrenheit, and exits the nozzle at a near sonic velocity to melt and blow away the material of the workpiece. (Elshennawy, 2000) While using PAC to cut foam would destroy it, the concept may be able to be applied to a new foam cutting method. The use of a highly-compressed air passed through a restricted nozzle could plausibly can blow away and cut through foam. Such and apparatus could be used as an alternative to manually cutting foam tool kits with a razor knife.
Chapter 3: Methodology

3.1 Data Collection – Objective One: Material Selection

To select the best material for use in tool control trays, it is important to analyze the physical properties of the materials and compare them to the properties desired for use in this application. Initial foam samples will be ordered from various distributors/manufacturers of tool foam. These samples will be reviewed based on their feel and overall resilience. Once foam samples have been reviewed, three final varieties of tool foam will be selected for use in analysis and testing. The exact material used for this research will be documented. Sheets of each of the foams will be ordered for use in this step of the methodology and for the following step.

Tool control foam will likely be submitted to four major adversities; impact, tensile stress, compression, and petroleum exposure. Testing will be performed on the three varieties of foam to determine how they will perform when exposed to these four conditions. This testing will yield results determining which material is best suited for use in the tool control application. The material which performs the best will be used in the next step of the methodology to determine the best method for manufacturing the foam trays out of it.

Impact testing of materials will be performed using a Izod pendulum testing machine. This machine uses a pendulum to swing and strike a sample, breaking off a portion of the material. The machine reads the amount of energy absorbed by the material during a fracture. The data recorded is interpreted to determine the materials toughness against impact. Resulting data is displayed in units of lb/ft-in. (Shackleford, Mechanical Behavior, 2009)

To determine how the various materials will withstand tearing their individual modulus of elasticity will be tested. Resulting data from testing will include, Young’s modulus, yield
strength, ultimate tensile strength, and breaking point. The Young’s modulus, or modulus of elasticity is a ratio of the stress applied to a material to the strain along an axis, or deformation over the initial length. The yield strength is the point at which a material plastically deforms and will no longer return to its original form. The ultimate tensile strength of a material is the highest amount of strain that a material can endure before it begins to perform. This test will be performed of a uniaxial tensile testing machine. A sample of material is inserted in the machine and stretched vertically until it breaks. Throughout the duration of the test, data is being collected by a computer on how the material is reacting. The resulting data is displayed in a stress-strain curve, providing material properties such as young’s modulus, yield strength, ultimate tensile strength, and breaking point. (Shackleford, Mechanical Behavior, 2009)

A compressive test will also be performed on the materials to determine how well they will endure the compressive weight of the tools. This will be tested using a Rockwell Hardness tester. This hardness tester presses a specialized tip against a material to determine its hardness, or compressive strength. The results are determined on the Rockwell scale based on the indenter tip used and the read-out given. This hardness can be compared to other materials that have been previously tested. (University at Buffalo, 2017) For testing softer materials, the Rockwell Hardness Scale HRL will be used along with a 1/4” ball indenter. (Phase II Plus, 2014)

Tool control trays will likely be exposed to 12 chemicals, so testing of the effects of this chemical on the foam being considered is important. This test is performed by applying chemicals that the foams are likely to come into contact to samples of the foam in sealed containers. They sit for an agreed upon period and then are examined for changes in properties. (Intertek Group PLC., 2017). Below the chemical to be tested with the foam are listed and described. (MSDS Online, 2017)
Table 2: Chemical Descriptions from MSDS Online

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled Water (control)</td>
<td>Distilled Water</td>
</tr>
<tr>
<td>Acetone</td>
<td>(CH3)2CO - Odorless, volatile, highly flammable - used for cleaning and</td>
</tr>
<tr>
<td></td>
<td>removing paints and petroleum products</td>
</tr>
<tr>
<td>Mineral Spirits</td>
<td>Petroleum Distillate - volatile, highly flammable - used for cleaning and</td>
</tr>
<tr>
<td></td>
<td>removing paints and petroleum products</td>
</tr>
<tr>
<td>Highway Diesel Fuel</td>
<td>Naphthalene - contains sulfur, highly flammable - used to fuel diesel</td>
</tr>
<tr>
<td></td>
<td>combustion engines</td>
</tr>
<tr>
<td>87 Octane Gasoline</td>
<td>Petroleum derived - volatile, highly flammable - used to fuel gasoline</td>
</tr>
<tr>
<td></td>
<td>internal combustion engines</td>
</tr>
<tr>
<td>Elky Pro Multi-Purpose Cleaner*</td>
<td>All-purpose aerosol foam cleaning agent, no CFCS</td>
</tr>
<tr>
<td>WD-40</td>
<td>Aliphatic Hydrocarbon and Petroleum Base Oil, volatile and flammable -</td>
</tr>
<tr>
<td></td>
<td>used for corrosion resistance and moisture displacement</td>
</tr>
<tr>
<td>Purple Power Degreaser*</td>
<td>Degreasing compound</td>
</tr>
<tr>
<td>Pennzoil 10W-30 Motor Oil</td>
<td>Petroleum motor oil - used for lubrication in internal combustion engines</td>
</tr>
<tr>
<td>Way Lube</td>
<td>Distillates from Hydrotreated Heavy Paraffinic, Solvent Refined Heavy</td>
</tr>
<tr>
<td></td>
<td>Napthenic Distillate - Flammable - used to lubricate machinery</td>
</tr>
<tr>
<td>DTE 24 Hydraulic Fluid</td>
<td>Mineral oil base - Flammable - used in hydraulic driven applications</td>
</tr>
<tr>
<td>Valvoline Multi-Purpose Grease</td>
<td>lithium based extreme pressure grease - flammable - used for lubrication</td>
</tr>
<tr>
<td></td>
<td>of moving parts</td>
</tr>
</tbody>
</table>

* - indicates product ingredients unavailable due to patent information.

3.2 Data Collection - Objective Two: Manufacturing Testing

Once a material has been selected as the superior choice for the tool control tray application, the next step is to determine the most precise and effective way to cut the foam sheets to fit the various tools. Testing will be performed using a CNC router with two different bits, a waterjet cutter, and an air cutter. These methods have been selected as the best possible methods for the manufacturing of foam tool trays based on the literature review. This will satisfy the second objective of this study.

The first method to be tested will be the use of a CNC router. The CNC router will be outfitted with two different foam cutting bits to determine which bit produces the cleanest and
most efficient cut. One bit will be a straight single flute ¼” router bit. The second will be a two-fluted spiral ¼” router bit. A simple hammer outline will be followed by the router. This will show how the material reacts to being cut using a CNC router following straight lines, curves, and sharp changes of direction.

Although waterjet cutting foam is a very common practice in industry, a waterjet cutting machine is unavailable for testing. Because of this, waterjet cutting will not be tested, but instead researched. An interview will be set up with a company that currently cuts foam using waterjet machining. This interview will be used to gather information regarding materials, abrasives, pressures, feed rates, and cutting times for this method of manufacturing. This information will be used to replace the actual testing of waterjet cutting.

These cutting methods will be analyzed on two different criteria. The first criterion will be the efficiency of the process. This will be measured by a time study of the manufacturing process to determine which method requires the least amount of time to manufacture a tool tray. The second criterion will be precision. This will be measured by examining the quality of the cut (cleanliness of lines, tearing, chunk out, etc.) and the dimensions of the cut out compared to the programmed or originally traced dimensions.

3.3 Cost Analysis

This final step of the methodology will satisfy the third and final object of determining the cost of the methods and manufacturing processes. A cost analysis will be performed on the foam and manufacturing method. This cost analysis will look at the cost of the foam sheeting and the cost of the equipment needed to manufacture tool trays from the foam. The operating and maintenance cost for the manufacturing equipment will also be considered. This information will
determine the cost for a company to produce one tool tray on their own. This information will be able to be later used by companies to determine if building their own tool control kits is worth the investment. Below you can see the formulas used for the cost analysis.

**Equation 1: Total Cost**

\[ TC = FC + VC \]

- **TC** = Total Cost
- **FC** = Fixed Cost (Equipment and Maintenance)
- **VC** = Variable Costs

**Equation 2: Variable Cost**

\[ VC = M + L + O \]

- **M** = Materials Cost
- **L** = Labor Cost
- **O** = Overhead

**Equation 3: Overhead Cost**

\[ O = 10\% \times (M + L) \]

**Equation 4: Cost Per Unit**

\[ \frac{TC}{n} = \text{Cost Per Unit} \]

- **n** = number of units produced

This cost analysis information will be able to be compared to the cost of outsourcing a tool kits. Once comparing the cost, it will be clear if manufacturing tool kits in house is financially beneficial over outsourcing their production to another company.
Chapter 4: Data Analysis and Results

4.1.1 Materials Testing: Tensile Strength

There were three varieties of foam that were put to the test for the research project: 4-lb Cross-Linked Polyethylene, 4-lb Cross-Linked Polyethylene Fire-Retardant, and 6-lb Polyethylene. Each foam’s tensile strength, hardness, and chemical resistance was tested using various methods. Impact strength in this case is related to the hardness of the material.

The first test was the tensile test. Each foam was cut into a sample for the tensile testing machine. The samples had a gauge length of 3.375 inches and measured 0.5 inches wide and 0.25 inches thick. The cross-sectional area was .125 cubic inches. Samples are mounted in the testing apparatus as show below. The sample is pulled apart at a rate of 0.25 inches per minute. A computer recorded the data for force being applied by stretching the sample, and the displacement of said sample.
Figure 5: Shimadzu Tensile Tester with foam sample
Figure 6: 4-lb XPE sample post break
Figure 7: 4-lb XPE Fire Retardant sample post break
Figure 8: 6-lb PE sample post break
Data was collected by the computer every five hundredths of a second. This massive data pool was condensed into a recorded point every ten seconds. Stress and strain were calculated using the following formulas to gain the proper data for the stress-strain curve.

**Equation 5: Stress**

\[
\text{Stress} = \frac{\text{Load}}{\text{Cross-sectional Area}}
\]

**Equation 6: Percent Strain**

\[
\% \text{ Strain} = \left(\frac{\text{Displacement Length}}{\text{Guage Length}}\right) \times 100
\]

The results of the tensile test are displayed in the following tables and graphs.

**Table 3: 4-lb XPE Tensile Data**

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<td>230</td>
<td>19.837</td>
<td>0.958</td>
<td>28.39</td>
<td>158.696</td>
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<td>240</td>
<td>19.837</td>
<td>1</td>
<td>29.625</td>
<td>158.696</td>
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<td>1.041</td>
<td>30.859</td>
<td>162.016</td>
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<td>280</td>
<td>21.778</td>
<td>1.166</td>
<td>34.563</td>
<td>174.224</td>
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</tbody>
</table>
The results from this show us multiple things regarding the materials. The 4-lb XPE has the greatest elastic properties reaching almost 80% strain, displacing a total of 2.583 inches before breaking, and having an ultimate tensile strength of 157 lb feet per square inch. The 4-lb XPE Fire Retardant under-performed its counter-part at 50% strain, 1.708 inches of displacement, and an ultimate tensile strength of 146 lb feet per square inch. While the 6-lb PE only reached 39.5% strain and 1.333 inches of displacement, it had the highest ultimate tensile strength at 174.2 lb feet per square inch. 6-lb PE also has the highest yield strength by far at 106 lb feet per square inch.
4.1.2 Materials Testing: Hardness

Hardness testing for the tool control foam was performed using a Phase 2 Digital Hardness Tester. The measurement scale used was HRL with a ¼” steel ball penetrator. This is standard for this scale. HRL scale differs from the typical HRC scale as it is not used for hard materials such as steel, and is reserved for softer materials. Table 5 below presents the results from the test on the 3 varieties of tool foam.

<table>
<thead>
<tr>
<th>Material</th>
<th>4-lb Cross-linked Polyethylene</th>
<th>4-lb Cross-linked Polyethylene FR</th>
<th>6-lb Polyethylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Test</td>
<td>65.6</td>
<td>67</td>
<td>70.8</td>
</tr>
<tr>
<td>2nd Test</td>
<td>63.4</td>
<td>63.7</td>
<td>65.6</td>
</tr>
<tr>
<td>3rd Test</td>
<td>66.7</td>
<td>65.8</td>
<td>65.3</td>
</tr>
<tr>
<td>Average</td>
<td><strong>65.23</strong></td>
<td><strong>65.50</strong></td>
<td><strong>67.23</strong></td>
</tr>
</tbody>
</table>

Table 6: HRL Hardness Testing Results

Of the three varieties of tool foam the 6-lb Polyethylene measured the highest average hardness. This likely due to it being the highest density of all the foam options. However, that maybe, it is not outstandingly harder that the other options. All three options possess relatively the same hardness. This data is however inconclusive all together. When measuring the hardness of a foam, it is standard to use a Shore Hardness Tester in the D or OO scale. (MatWeb, 2017) This testing apparatus was not available to the author for use. HRL is reserved for soft materials but not materials this soft. In order to register a hardness reading one ½” thick sample of foam was stacked on top of one ¼” thick sample of the same variety. A piece of ABS Plastic was tested using the same method and scale and received a reading of 91.6. Foam should be outstandingly softer that solid ABS plastic. The foam sample also received damage to them from
the test outside of the predicted indentation from the penetrator (Figure 9) It is the opinion of the author that Morehead State University should purchase a Shore Hardness tester with various scales for materials testing of softer materials. In future research on this topic, a Shore Hardness Tester in the D or OO scale would be required.

The samples of foam used were supplied by Cascade Tool and Foam Supply. All of their products pass the compressive strength test ASTM D3575 SUFIX D AT 25%. This is a compressive deflection test to determine how a flexible closed cell material reacts when compressed. (American Society of Testing and Materials, 2017) A measurement is taken when the material is compressed 25% of the gauge height. Passing this test is interpreted as meeting or exceeding the standard for a materials performance on this test.
4.1.3 Materials Testing: Impact Resistance

Impact resistance was unable to be tested for due to a lack of the proper equipment. The test would have been performed using a Izod Pendulum Impact Tester. (American Society of Testing and Materials, 2017) However, the hardness of a material has a direct correlation to its impact resistance or toughness. Very hard materials have a tendency to be very brittle while softer materials are less brittle. This is not to say that foam is tougher that steel because steel is harder. The tool foam would likely perform well during impact testing, but only with a blunt edge. Any sharp edge would compromise the integrity of the foam allowing it to tear and not cleanly break. Based on the dropping of various tools or various shapes and weights from a height of 1.5 feet, the tool foam was undamaged or physically changed by the impact. In this application, tool foam will not undergo major impacts and would perform well under impact endured from standard applications.

4.1.4 Materials Testing Results: Chemical Resistance

Testing of chemical resistance was performed on all three of the varieties of foam by application of 12 different chemicals that would be common in the industry of use. Below the arrangement of chemicals and samples can be seen. One ½” square sample of each foam was placed into a circular zone of a dividing plate to separate it from the rest of the samples. The dividing plate and samples were placed on top of an absorbent pad to prevent contamination of samples by other chemicals used near. The testing was performed in the drawer of a tool box to simulate real industry application of the foam. Chemical samples were applied once per day for one month, excluding weekends. This was to replicate the use of tool foam kits based on a standard 40-hour work week.
<table>
<thead>
<tr>
<th>Applied Chemical</th>
<th>4-lb Density Cross Linked Polyethylene</th>
<th>ValuePlas Fire-Retardant</th>
<th>6-lb Density Polyethylene</th>
<th>4-lb Density Cross Linked Polyethylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled Water (control)</td>
<td>1</td>
<td>13</td>
<td>25</td>
<td></td>
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<tr>
<td>Acetone</td>
<td>2</td>
<td>14</td>
<td>26</td>
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<tr>
<td>Mineral Spirits</td>
<td>3</td>
<td>15</td>
<td>27</td>
<td></td>
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<tr>
<td>Highway Diesel Fuel</td>
<td>4</td>
<td>16</td>
<td>28</td>
<td></td>
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<tr>
<td>87 Octane Gasoline</td>
<td>5</td>
<td>17</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Elky Pro Multi-purpose Cleaner</td>
<td>6</td>
<td>18</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>WD-40</td>
<td>7</td>
<td>19</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Purple Power Degreaser</td>
<td>8</td>
<td>20</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Penzoil 10W-30 Motor Oil</td>
<td>9</td>
<td>21</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Way Lube</td>
<td>10</td>
<td>22</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>DTE 24 Hydraulic Fluid</td>
<td>11</td>
<td>23</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Valvoline Multi-purpose Grease</td>
<td>12</td>
<td>24</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

Procedure: 2-3 drops of each chemical will be applied to the designated sample every 24 hours for 5 days, followed by 2 days of zero application. This process will be repeated for a total of four weeks. This simulates approximately one month of exposure to each chemical based on a standard 40 hour work week.
This first day of application shed light on what was to come from the performance of the 3 varieties of tool foam. Thinner viscosity chemical was more easily absorbed or displaced from the sample, while high viscosity chemical would sit on top of the foam samples. Acetone and Mineral Spirits applied to the first variety of foam has almost all evaporated by the time the rest of the samples received their application.
Figure 10: Day 1 Chemical Resistance Test - Pre-Application
Figure 11: Day 1 Chemical Resistance Testing - Post Application
After the 30th day of testing the samples were all examined to determine if the chemical applications have cause any adverse effects. All three samples were completely unaffected by water. Acetone and mineral spirits both had little effect on the samples. These chemical quickly evaporate, not allowing for damage. Highway diesel fuel was absorbed into all the samples, but cause no other changes, as did 87 octane gasoline. Elky Pro Multi-Purpose Cleaner was not absorbed by the samples, but left a residue on the top of the foam that was easily wiped away. This is likely because it is applied as a foam spray. WD-40, 10W-30 motor oil, way lube, and DTE 24 Hydraulic fluid were absorbed into both the 4-lb cross-linked polyethylene and the 4-lb cross-linked polyethylene fire retardant. This resulted in extremely saturated foam after 30 days of testing. While the 6-lb polyethylene absorbed some of these chemical, most the chemical remained on top of the foam or rolled off onto the absorbent pad. The 6-lb polyethylene possesses a stronger and less porous skin on the top and bottom of the foam, only allowing for absorption from the cut sides of the sample. The other two samples have a more porous skin allowing for absorption from all sides of the sample. Purple power degreaser had an interesting effect on all the samples. Purple power degreaser had a low enough viscosity that is allowed for easy absorption, but some of the chemical evaporate leaving a white/purple residue on top of and inside the foam. The top layer could be cleaned off, but the cellular structure of the foam still contains some residue. The residue did not affect the make-up or physical qualities of the foam. The Valvoline multi-purpose grease was spread a top each sample and along one side. The grease was not absorbed by any of the samples and only somewhat penetrated when applied along a cut side. The grease was easily cleaned of the sample with a rag.
4.2.1 Manufacturing: CNC Router

Using a CNC router to machine tool foam for tool kitting is a common industry practice. To cut the foam without ripping or tearing specialized router bits are required. For this research project two different foam cutting bits were used. The first was a ¼” two flute spiral bit and the
second was a ¼” singular flute straight bit (Figure 13 and 14). Each of the three varieties of foam were machined using both bits, for a total of 6 tests. An AXYZ router was used along with a custom vacuum box for holding the foam in place. Measurements were taken from a stubby slotted screw driver to design the cutting tool paths using MasterCAM X9 (Figure 15 and 16).
Figure 13: 1/4" 2 Flute Spiral Foam Router Bit
Figure 14: 1/4" Singular Flute Straight Router Bit
Figure 15: Stubby Slotted Screw Driver Design and Toolpath on MasterCAM X9
Figure 16: Backplot Verification of Toolpath on MasterCAM X9
To hold the foam in place on the router work bed a nontraditional method was used. Typical clamps and vises could not be used to hold the work piece because of the characteristics of foam compared to traditional wood. A vacuum box was built to hold the foam. It was composed of wood side with a pegboard top. The side included a plastic fitting for a wet/dry vacuum hose to connect. With a vacuum connected and running, the foam could be placed on top of the pegboard, where the suction from the vacuum would secure the foam to the box. 100% silicone was used to seal all joints of the apparatus to create the most suction possible from the vacuum. (Figure 17)
The first bit tested was the ¼” two flute spiral. The router was set to run at 20 inches per minute and 18000 RPM. The first foam sample to be tested was 4-lb Cross-linked Polyethylene. The 4-lb XPE cut easily, allowing the bit to precisely follow the program. There were some hairy pieces of foam still attached on the edges of the cut out, where the tools clearance angle and overall spiral shape did not always cut, but make small tears in the foam (Figure 18). This was easily cleaned up by hand. The final product was somewhat rough looking, but overall was
accurate and clean. 4-lb Cross-linked Polyethylene – Fire Retardant was the second sample tested. Very like the first sample, this foam allowed for précised movement of the cutting tool. The cleanliness of the cut left much to be desired. All the edges contained torn pieces of foam, that were too large to clean up without large amounts of time (Figure 19). The last sample to be tested with this cutting tool was the 6-lb Polyethylene. On the first test of this foam a problem occurred. The surface of the foam was slick enough that the custom-built vacuum box could not hold the foam in one place during sharp directional changes. The author increased the sizes and number of the holes in the vacuum box to allow for a greater suction hold on the foam (Figure 21). This fixed the issue. During the second test of this foam, the cutting tool could easily follow the program with little resistance of variation. Initially the cleanliness left much to be desired, but the hairy edges were very easily cleaned up to yield the best finish product from this cutting tool (Figure 20).
Figure 18: 4-lb XPE 2 Flute Spiral Bit Cut
Figure 19: 4-lb XPE-FR 2 Flute Spiral Bit Cut
Figure 20: 6-lb PE 2 Flute Spiral Bit Cut
The second cutting tool used was the ¼” singular flute straight bit. The same order of samples was used during the second round of testing, as well as the same spindle speed and feed rate. The 4-lb XPE cut precisely and cleanly, not leaving near the hairy edges as the previous bit (Figure 22). The 4-lb XPE-FR cut as precisely as the first cut. Cleanliness improved with this bit, but still left some to be desired (Figure 23). The final test on the 6-lb PE resulted in the best overall product. The cuts were precise and clean. There was little to no debris on the edges. (Figure 24).
Figure 22: 4-lb XPE Singular Flute Straight Bit Cut
Figure 23: 4-lb XPE-FR Singular Flute Straight Bit Cut
4.2.2 Manufacturing: Water Jet

The author did not have access to a water jet cutter to use for actual testing for this research thesis. Industry knowledge and practices were used to take place of physical testing. Cascade Tool and Foam (the supplier of foam sample used in testing) offers custom tool kits built to customer specification. Per Cascade they use water jet cutting for all their custom tool kits. (Cascade Tool and Foam, 2017) Cascade has stated that water jet cutting their foam yields the cleanest and most precise cut (Figure 25).
JetEdge is an industry leading water jet manufacturer who provide information for this research project regarding the cutting of tool foams using a CNC water jet cutter. The MasterCAM file used on the CNC router was submitted to Jeff Schibley at JetEdge to obtain the cutting details for the same shape and thickness of foam. Using a Boss Cutter from JetEdge at 55,000 psi with no abrasive the stubby screw driver can be cut in 9.3 seconds. This is an average feed rate of 70.9 because there is 11 inches of travel in cutting the screwdrivers outline. (Schibley, 2017) To produce the clean and precise shapes and corners the waterjet slows down its feed rate in shapes that require sharp and frequent directional changes. To calculate these, figure the specification for the JetEdge Boss Cutter were used. Referring to Figure 24, water jet allows for a precise and clean cut in an efficient manner.
### 4.3 Cost Analysis

An analysis of the cost was performed on both the CNC routing and waterjet manufacturing options of in house manufacturing. The material cost of the foam is quoted from the same supplier that provided the foam samples used in the materials testing. As 6-lb Polyethylene performed the best in the materials testing and manufacturing tests, pricing for it was used for the cost analysis. Below, in Table 7 and Table 8, the cost of the two manufacturing options using the same foam are presented.

**Table 8: CNC Router Cost**

<table>
<thead>
<tr>
<th>CNC Router</th>
<th>FIXED COST</th>
<th>VARIABLE COST</th>
<th>TOTAL COST</th>
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<tr>
<td></td>
<td>Laguana Swift 4x4 3HP</td>
<td>$11,995.00</td>
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<td>Tooling</td>
<td>$150.00</td>
<td>$150.00</td>
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<tr>
<td>Total FC</td>
<td>$12,145.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5000 units 1/2&quot; PE Tool Foam</td>
<td>$132,750.00</td>
<td>$132,750.00</td>
</tr>
<tr>
<td></td>
<td>5000 units 1/4&quot; PE Tool Foam</td>
<td>$55,828.96</td>
<td>$55,828.96</td>
</tr>
<tr>
<td>2,000 Hours</td>
<td>Labor = 1 @ $18.00/hr</td>
<td>$36,000.00</td>
<td>$36,000.00</td>
</tr>
<tr>
<td></td>
<td>Overhead 15%</td>
<td>$33,686.84</td>
<td>$33,686.84</td>
</tr>
<tr>
<td>Total VC</td>
<td>$258,265.80</td>
<td>$258,265.80</td>
<td></td>
</tr>
<tr>
<td>Total FC</td>
<td>$12,145.00</td>
<td>$12,145.00</td>
<td></td>
</tr>
<tr>
<td>Total VC</td>
<td>$258,265.80</td>
<td>$258,265.80</td>
<td></td>
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<tr>
<td>5000 units Total Cost</td>
<td>$270,410.80</td>
<td>$270,410.80</td>
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<tr>
<td>Total Cost Per Unit</td>
<td>$54.08</td>
<td>$54.08</td>
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The only major difference in the cost of these two manufacturing options is the fixed cost. A water jet cutter cost a considerable amount more than a CNC router. The different in fixed cost between the router and water jet is $47,755.00. Water jet cutter are more precise in there cutting than routers are, which adds reason to the added expense. Tool kits measuring 24” x 42” with 50 tool cut outs will cost $63.63 per unit using a water jet and $54.08 on a CNC router. Below in Table 9 the cost of outsourcing the manufacturing of custom tool kits.

<table>
<thead>
<tr>
<th>Table 9: Water Jet Cutter Cost</th>
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<tr>
<td><strong>Water Jet Cutter</strong></td>
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<tr>
<td><strong>FIXED COST</strong></td>
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<td>JetEdge Boss Cutter $59,900</td>
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<td>Total FC $59,900</td>
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<td><strong>VARIABLE COST</strong></td>
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<td>5000 units 1/2” PE Tool Foam $132,750.00</td>
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<tr>
<td>5000 units 1/4” PE Tool Foam $55,828.96</td>
</tr>
<tr>
<td>2,000 Hours Labor = 1 @ $18.00/hr $36,000.00</td>
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<tr>
<td>Overhead 15% $33,686.84</td>
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<td><strong>Total VC</strong> $258,265.80</td>
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<td><strong>TOTAL COST</strong></td>
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<td>Total FC $59,900.00</td>
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<td>Total VC $258,265.80</td>
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<tr>
<td>5000 units Total Cost $318,165.80</td>
</tr>
<tr>
<td>Total Cost Per Unit $63.63</td>
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(Frey, 2017)
The manufacturing of tool kits in house has major financial benefits. Even compared to the most expensive option of water jet manufacturing, purchasing custom tool kits from another supplier is $336.37 more expensive per units. Airborne Aviation Maintenance in Wilmington, Ohio Employees right at 500 aviation technicians (Smith, 2017). Each technician has at least one tool box. If each technician averages 10 drawers of tools, it would require 5000 tool kits to control all their tools. If Airborne were to purchase a CNC router, enough materials for 5000 units, and pay one laborer to work for an entire year, it would cost $270,410.80 to produce tool kits for all their technicians. Upgrading to a water jet cutter will raise the price to $318,165.80. Purchasing the tool kits from Tool Keepers (an industry leading tool kit manufacturer), would cost $2,000,000.00. A breakeven chart is not needed to see that manufacturing tool kits in house is much more cost effective that purchasing them from a custom manufacturer. It is also important to consider that once a company such as Airborne has been outfitted, they will have the equipment to produce tool kits for future employees, or even consider manufacturing tool kits for other companies. To produce the tool kits in house it is 628% cheaper than purchasing them from another supplier. The in house production of tool kits would not be worth the investment for smaller companies, only medium to larger size companies would gain the full benefit of producing in house.
Chapter 5: Conclusion of Research

5.1 Conclusion

Based on the research of tool control in the aviation and aerospace industry, testing or materials, and research of manufacturing methods a conclusion was reached regarding the production of tool control kits in house versus purchasing custom built kits from an outside source. The evidence gathered throughout the entirety of this study was overall all conclusive and points to the most efficient and financially logical decision. The three main objectives of the study were met through execution of the methodology and yielded decisive results.

The materials testing portion of the study was designed and executed to satisfy objective one. This objective was to determine which of the tool foam options possessed the best material properties for tool kit applications. While all the contenders are currently used in industry for application, one variety stood above the rest. 6-lb Polyethylene foam yielded the best overall performance based on the testing. 6-lb PE did not reach the highest percent strain in the tensile test, but showed the highest yield strength, tensile strength and breaking point. For tool control application, it is not likely that a high percentage of strain will be reached or maintained for any extended period, thus the higher overall strength results in the 6-lb PE being the superior option. Also, the 6-lb PE performed the best overall in the chemical resistance test. It had a less porous skin on the top and bottom allowing for the least absorption of chemical. Only slight absorption occurred when chemicals gained access to a cut side of the foam, and even then, only resulted in slight absorption and no damage to the foam. While the hardness testing results were overall in conclusive because of inadequate equipment, all the foams possessed the same general hardness
and what testing was performed produced results that pointed to 6-lb PE as the hardest of all the foams. Impact testing could not be performed but based on research of the material property of impact toughness, it is assumed by the author that all the sample options would have performed similar with marginal difference between them. With 6-lb Polyethylene out performing in all materials test that yielded conclusive results, it is determined as the highest quality option for tool kitting and tool control.

Manufacturing testing analyzed the precision and efficiency of two cutting methods of foam. The first method of testing was using the CNC router. The CNC router was efficient, and overall precise. During the testing of two different bits in the router the 6-lb PE was the cleanest cutting foam. One tool could be cut quickly and precisely. Water jet cutting was researched do to a machine not being accessible for testing. Water jet produces an extremely clean and precise cut at a faster rate than the router. Water jets are overall more useful as a piece of equipment than a router as they can also be used for cutting metal and ceramics. The selection of a water jet cutter is the most highly advised option for creating custom tool kits.

Once a material had been selected a cost analysis was performed against both manufacturing options as well as the cost of purchasing custom tool kits from an outside retailer or provider. The most financially logical option is to build tool kits in house with the use of a water jet cutter and 6-lb Polyethylene foam. This option is over 600% less than outsourcing. The fixed cost of the waterjet is less than $50,000 more than a CNC router and has the benefit of being more efficient and more precise and over all versatile as a machine than a router would be. It should be taken into consideration that an individual producing tool kits would only have one year of work based upon this study. This should be taken into consideration when looking to produce one’s own tool kits. An already employed individual could be placed on this as a
project, as hiring an employee for one year of work is not practical and there may not be another place for them with the company.

It is the professional opinion of the author that any company looking to implement tool control and tool kitting into their facility build them in house. The overall cost of outsourcing the production of tool kits is outstandingly more expensive. Once the equipment and procedure for producing one’s own tool kits is purchased it is immediately paid off by the difference in price of purchasing form another provider. Also, the company would have the added benefit of being able to create kits for new hires and company expansions without having to deal with a supplier. The water jet cutter would also be a great addition to any engineering maintenance and facilities department as it is versatile for making custom parts as well as tool control.

5.2 Future Research Recommendations

There are a few recommendations the author would like to make if this research would be continued. To gain more data and greater results in is recommended that MSU or the author purchase or gain access to a Shore Durometer in the scale of D and an Izod impact testing machine. These apparatuses would shed more light on the material properties of tool control foam as well as be applicable for other university materials science testing/projects. Also, any continuation of this research should include hands on testing of foam on a water jet cutter. While research is good, physical testing provides data and more accurate results. The creation of .NC codes for tool cutouts should be more ineptly researched and tests. This would add more depth to the study overall and yield information regarding the design process of tool kits and tool control.
Finally, the use of 1/8” bits for cutting foam on the CNC router should be tested. The author believes that 1/8” bits will result in sharper lines and a better fit for tools over a ¼” bit.
## Appendix

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