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# The Design And Development Of An Additive Fabrication Process And Material Selection Tool

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# THE DESIGN AND DEVELOPMENT OF AN ADDITIVE FABRICATION PROCESS AND MATERIAL SELECTION TOOL

by

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# ABSTRACT

In the Manufacturing Industry there is a subset of technologies referred to as Rapid Technologies which are those technologies that create the ability to compress the time to market for new products under development [5]. Of this subset, Additive Fabrication (AF), or more commonly known as Rapid Prototyping (RP), acquires much attention due to its unique and futuristic approach to the production of physical parts directly from 3D CAD data, CT or MRI scans, or data from laser scanning systems [26] by utilizing various techniques to consecutively generate cross-sectional layers of a given thickness upon the previous layer to form 3D objects. While Rapid Prototyping is the most common name for the production technology it is also referred to as Additive Manufacturing, Layer Based Manufacturing, Direct Digital Manufacturing, Free-Form Fabrication, and 3-Dimensional Printing.

With over 35 manufacturers of Additive Fabrication equipment in 2006 [26], the selection of an AF process and material for a specific application can become a significant task, especially for those with little or no technical experience with the technology and to add to this challenge, many of the various processes have multiple material options to select from [26].

This research was carried out in order to design and construct a system that would allow a person, regardless of their level of technical knowledge, to quickly and easily filter through the large number of Additive Fabrication processes and their associated materials in order to find the most appropriate processes and material options to create physical reproductions of any part.

The selection methodology used in this paper is a collection of assumptions and rules taken from the author’s viewpoint of how, in real world terms, the selection process generally takes place between a consumer and a service provider.  The methodology uses those assumptions in conjunction with a set of expert based rules to direct the user to a best set of qualifying processes and materials suited for their application based on as many or as few input fields the user may be able to complete.

I would to dedicate this research to my family, who supported me through all my years of education.

# ACKNOWLEDGMENTS

I would like to thank Mydea Technologies of Orlando, Florida for supporting this research by providing its facilities, equipment, and knowledge based, especially, Michael F. Siemer, who has passed on a wealth of knowledge to me as my mentor.

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# LIST OF ACCRONYMS/ABREVIATIONS

| | |
|---|---|
| 3D | 3-Dimensional |
| 3DP | 3-Dimensional Printing |
| AF | Additive Fabrication |
| AM | Additive Manufacturing |
| CAD | Computer Aided Design |
| CAT | Computed Axial Tomography (CAT Scan) |
| DDM | Direct Digital Manufacturing |
| DLP | Digital Light Processing |
| DMD | Direct Metal Deposition |
| DMLS | Direct Metal Laser Sintering |
| FDM | Fused Deposition Modeling |
| FFF | Free Form Fabrication |
| LENS | Laser Engineered Net Shaping |
| LOM | Layered Object Manufacturing |
| MJM | Multi-Jet Modeling |
| MRI | Magnetic Resonance Imaging |
| OEM | Original Equipment Manufacturer |
| RP | Rapid Prototyping |
| RT | Rapid Technologies |
| RT | Rapid Tooling |
| SLA | Stereolithography |

| | |
|---|---|
| SLS | Selective Laser Sintering |
| STL | Stereolithography |

# CHAPTER 1: INTRODUCTION

## 1.1 Definition of Rapid Technologies

In the Manufacturing Industry there is a subset of technologies referred to as Rapid Technologies (RT). Rapid Technologies are those technologies that create the ability to compress the time to market for new products under development [5].

Of this subset, Additive Fabrication (AF), or more commonly known as Rapid Prototyping (RP), acquires much attention due to its unique and revolutionary approach to the production of physical parts. Parts are produced directly from 3D CAD (computer-aided design) data, MRI or CAT scans, or data from 3D scanning systems [26] by utilizing various techniques to consecutively generate cross-sectional layers of a given thickness upon the previous layer to form a three dimensional object.

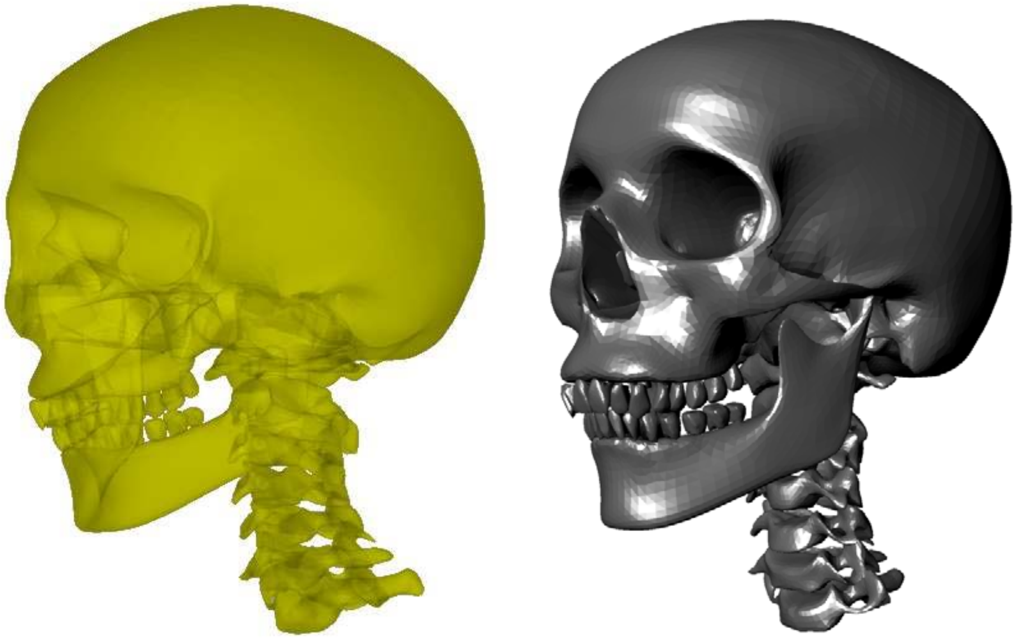


Figure 1. 3D MRI scan image and resulting CAD model used for production via Additive Fabrication.

While Rapid Prototyping is the most common name for this production technology it is also referred to as Layer Based Manufacturing, Additive Manufacturing (AM), Direct Digital Manufacturing (DDM), Free-Form Fabrication (FFF), and 3-Dimensional Printing (3DP). Currently the industry leaders are moving away from Rapid Prototyping as the all encompassing term since its name suggests a limitation in the use of its parts. Instead, as the technology is maturing, as it has in recent years, industry leaders are moving toward the use of Additive Fabrication (AF) as this name implies a method for the production of parts involving those technologies that use additive techniques without the suggested limitation on the use of those parts [15].

## 1.2 General Description of the Additive Fabrication Process

The first step in producing a physical part using any Additive Fabrication process is the creation of 3D data in the form of a 3D CAD model. This can be accomplished through the use of any one of the many 3D CAD modeling software packages available. There are two main types of 3D CAD models, surface and solid models.

Solid models are comprised of sets simple 3D primitives (boxes, cones, spheres, etc) that can be used to create more complex objects by Boolean operations (combining, subtracting, or unions) [5].

Figure 2. A solid model comprised of several solid geometric shapes merged through a Boolean operation.

Surfaces models are created in a similar fashion except they are made up of multiple trimmed surfaces joined together at the edges to form a complete "water-tight" skin that represents the part's geometry.

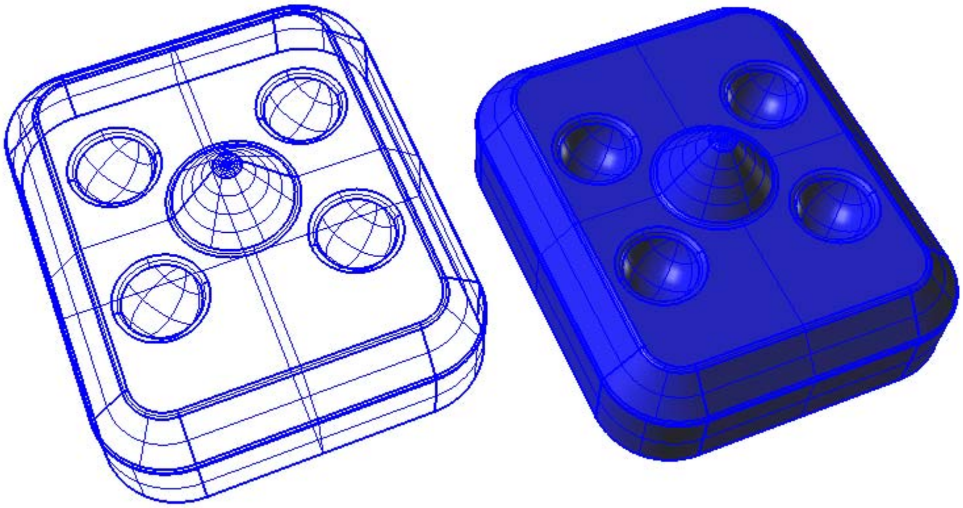


Figure 3. A surface model comprised of several zero-thickness skins trimmed to fit together and merged through edge-joining operations.

Once a 3D CAD model has been created the 3D data must be converted to a special file type, .STL, which has been universally recognized as the standard file type for the Additive Fabrication industry [5]. The .STL file type is an acronym for STereoLithography which was the first Additive Fabrication process made commercially available [26]. Other file types, .PLY, .WRL, and .VRML, can be utilized by a few AF systems to make use of the part's surface color information to produce parts in full three dimensional color [29]. A .STL file is generated by converting the CAD model's geometry into a complex representation of the part consisting of a mesh of triangular facets. The resolution or accuracy, referred to as the tessellation, of the .STL file in relation to the original CAD model can be defined by the user in order to output a file size that is manageable while keeping satisfactory resolution in the final part.

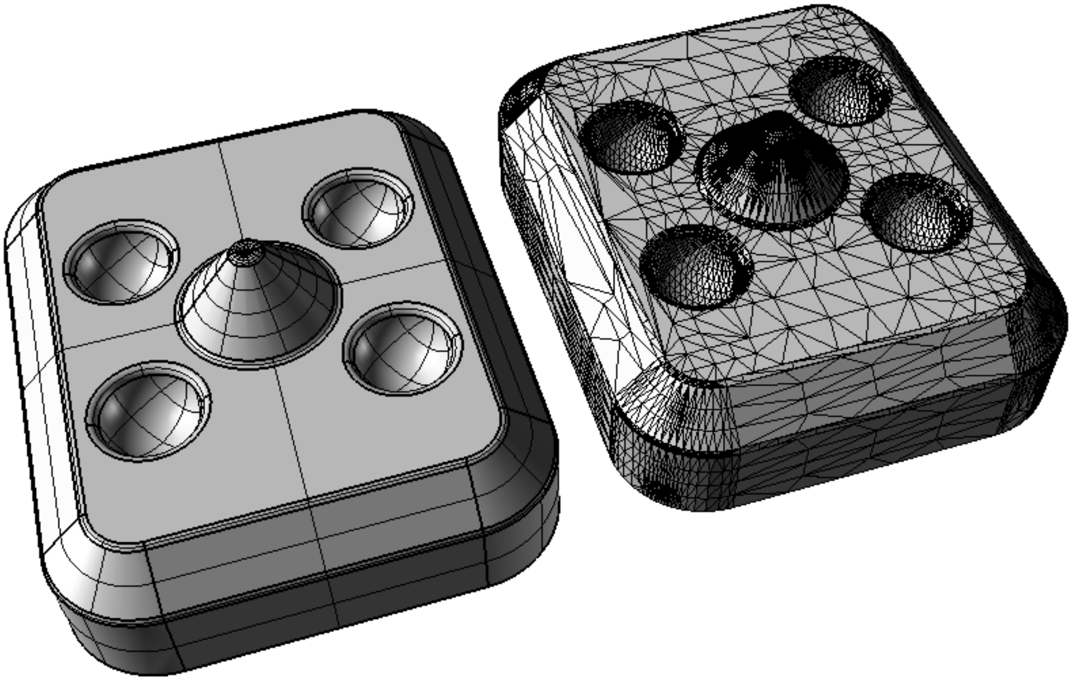


Figure 4. A .STL file along side its original CAD surface model.

Finally the .STL file is passed to the pre-processing software of the AF machine. Inside the preprocessing software the part file is digitally placed on a build platform where may be rotated, scaled, copied, or grouped/packaged with other parts for more efficient builds depending on the software and machine process. Following the setup of the parts to be built, the .STL files are then digitally sliced into hundreds to thousands of cross-sectional layers depending on the part's vertical height after orientation and the layer thickness build parameter of the machine. Some AF systems require an additional step of generating support structure to create a work surface for areas of the part that overhang beyond the extents of the previous layer while other systems make use of the adjacent unused build material for the work surface [5]. The slices and support data are then saved as a build file that includes all the information the AF machine will require to build the parts.

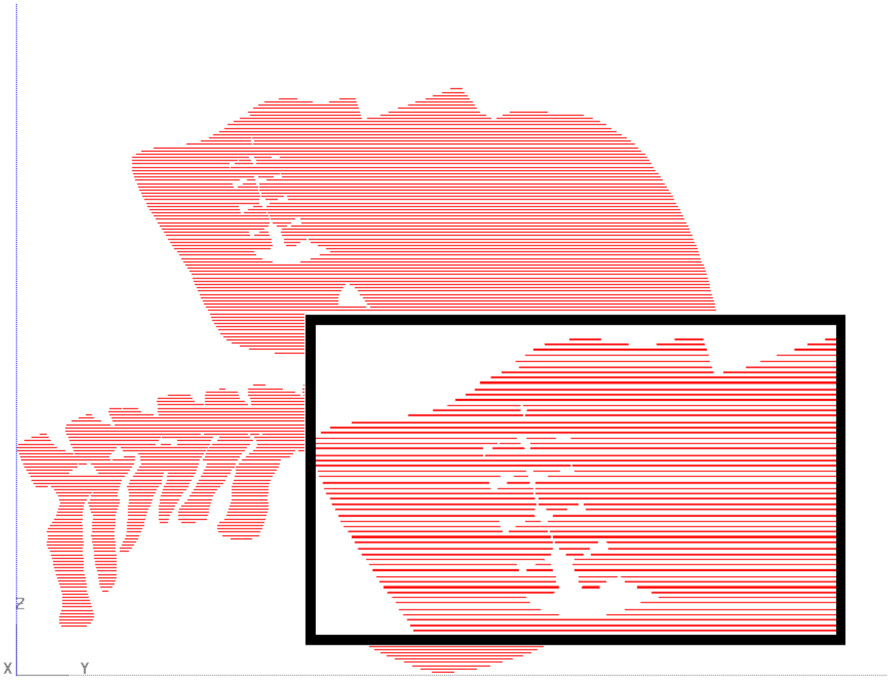


Figure 5. A sliced .STL file in pre-processing software.

Now the actual build process may begin. For those AF systems most widely used and available through most service bureaus, a short description of how each build process is performed will be explained in the upcoming sections.

Once the build is complete various post-processing steps specific to the build process must be completed before the part is ready for use. Generally this involves processes such as support structure removal, baking, infiltration with a second reinforcing material, or machining.

Most all AF parts can be further finished beyond their raw state directly from the machine to improve surface smoothness and texture. This can include sanding, tumbling, chemical polishes, painting, coatings, etc. The additional finishing steps often are not always functionally necessary but generally serve to improve the aesthetical qualities of the part.

## 1.3 Definitions of Additive Fabrication Processes

### 1.3.1 SLA

Stereolithography (SLA) is a process that solidifies ultraviolet light (UV) sensitive liquid resin with an UV point laser. This process is also commonly abbreviated as SLA as the first system was known as a Stereolithography Apparatus. A platform submerged to a depth of one layer’s thickness in a vat of UV sensitive resin provides support and a bonding surface for the current layer while computer controlled pivoting mirrors are used to “draw” the current layer’s cross-section with the point UV laser on the surface of the resin curing the liquid to a solid state as the laser makes contact with the resin.  The build platform (and previous layers) will then lower one layer after each cross-section is completed to begin the process again [1], [26].

### 1.3.2 LOM

Layered Object Manufacturing (LOM) is a process that uses a laser or knife to cut the cross-sectional shapes out of sheets of paper or plastic materials.  The material is unrolled across the build area and a heat activated adhesive is used to bond the current layer to the previous layer.  Since the excess areas surrounding part's cross-sectional geometry are used as support for the following layer, the knife or laser must also be used to hatch the excess areas to facilitate the removal of the part from the surrounding stack of material once the build is completed.  After each cross-section is cut out and surrounding area is hatched the remaining material is wound around waste roll in turn advancing a fresh section over the build area for the process to repeat [5], [3].

### 1.3.3 FDM

Fused Deposition Modeling (FDM) is a process that extrudes plastic wire through a heated nozzle that is direct by a mechanical x-y axis to "draw" the part's cross-sectional geometry at a given layer.  The plastic wire is extruded through the heated nozzle reaching the material's melting point making fusion with the previous layer possible. After the cross-section is complete the build platform lowers one layer to repeat the process.  FDM utilizes a rigid raster system of support structure extruded in the same manner as the build material to allow for over hanging part geometry.  This support structure is available in a manual break-away type as well as a soluble type that aids in the removal of the support structure from more complex geometries where manual support removal may be difficult or practically impossible.

### 1.3.4 SLS/DMLS

Selective Laser Sintering (SLS) is a process that uses a high energy laser to sinter or melt fine powder material together. The process uses a vertical feed piston which elevates to supply powder to a roller which transfers the powder to a build platform, covering the platform with one layer thickness. The laser then “draws” the cross-section of the part on the current layer fusing the powder material together. The build platform lowers one layer and the process then repeats. This process makes use of the unused loose material surrounding the part as a support structure.

### 1.3.5 3DP

3 Dimensional Printing (3DP) is a process that uses standard inkjet print heads to deliver binder to a bed of fine powder material. The process operates in the same way as SLS in that it uses a two piston and roller system to set up each layer. The print head moves along a single x-axis creating a stripe of binder specifically inside of the part’s cross-sectional boundaries and then advances along a second y-axis to create additional stripes until the layer is complete. The process is similar to a conventional inkjet and toner printing processes except the ink is instead a binder and the material is stationary as the print head advances along the length of the material in addition to the normal passes across it. This process also makes use of the surrounding unused loose material as a support structure [29].

### 1.3.6 LENS

Laser Engineered Net Shaping (LENS) is a process that jets a stream of metal powder through nozzles into a molten pool created by a high energy point laser.  As the metal powder enters the molten pool of metal material is built up creating a physical part. The process produces near net shapes that are fully dense that need no further heat treatments but do require some additional finishing and/or machining.

### 1.3.7 Polyjet

The Polyjet process creates high resolution functional parts by solidifying a photopolymer with UV lamps as it is deposited by a set of print heads.  The process uses a second material for support structure that is deposited simultaneously with the model material that can be easily removed leaving a different surface texture where support material is in contact with the part [16], [5].

### 1.3.8 MJM

Multi-Jet Modeling (MJM) is a process that uses materials jetted through nozzles in a phase change printing process.  Essentially thermoplastic or wax materials are heated to a melting point then deposited onto the previous layer in order to generate a physical part.  When wax is used as the model material the support structure will generally leave all down facing surfaces heavily marked with blemishes, however, when the model material is a thermoplastic and the support structure is a wax there are no surface marks remaining after post processing [1], [5], [24], [26].

### 1.3.9 DMD

Direct Metal Deposition operates much like the LENS technology with the addition of a patented closed loop feedback system of optical CCD cameras that monitor the current molten pool size verses the desired pool size which also for the build parameters to be dynamically adjusted in an effort to improve dimensional stability among other factors [27], [5].

### 1.3.10 DLP

This process uses Texas Instruments' Digital Light Processing (DLP) chip in order to project an image of a complete cross-sectional layer onto a photosensitive material solidifying the material a whole layer at a time in a single action. "This is a major increase in process speed over other photopolymer based technologies that either deposit and/or solidify only sections or points of a cross-sectional layer at a time" [6].

## 1.4 Brief State of the Industry

### 1.4.1 History of the Beginning

"Automated Rapid Prototyping technology has its roots in the early attempts to solidify liquid photopolymer with a pair of intersecting lasers that occurred between the late 1960's to the early 1970's" [26]. These attempts at producing physical 3-dimensional objects were finally made commercially available by Formigraphic Engine Co. in 1974 with a demonstration of the technology. The technique that utilized a single laser beam to cure photosensitive resin that later grew into Stereolithography was first introduced by Hideo Kodama in Japan in 1980. Six years later, Charles Hull was granted a US patent for a Stereolithography machine which led the way for the formation of 3D

Systems Inc. 3D Systems Inc. introduced the first commercially available machines in 1988 after beta testing a year earlier [26]. This new company opened the doors for an entirely new industry in manufacturing, Rapid Prototyping (now referred to as Additive Fabrication).

### 1.4.2 Industries Served

Most everything we use today in our modern technological society is a product of some sort. While not everything is mechanical in nature, a large sum of our tangible world is comprised of parts and pieces making up assemblies of more complex devices all of which require design validation, testing, and feedback. The leading industry utilizing Additive Fabrication for the past three years has been Consumer Products/Electronics (23.7%) according to a survey conducted and reported by the 2007 Wohlers Report [26]. This is followed by Motor Vehicles (19.1%), Medical/Dental applications (13.6%), and then Industrial/ Business Machines (9.8%). The remaining 33.8% is comprised of Academic Institutions (8.6%), Aerospace (7.7%), Government/Military (6.9%), Architectural and GIS (4.6%), and Other (6.0%) [26].

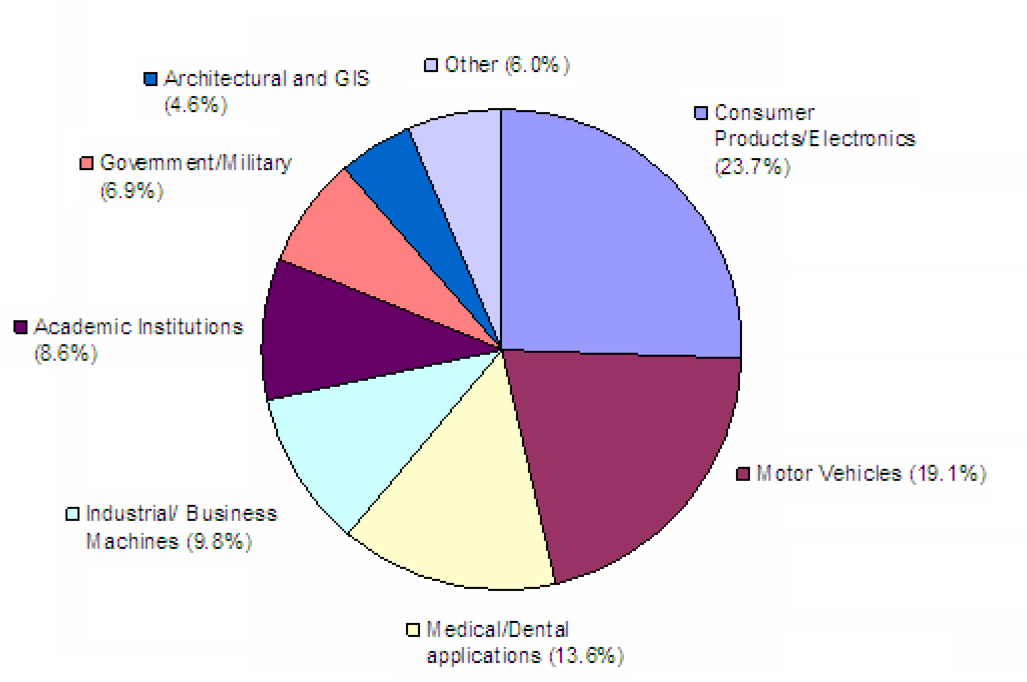


Figure 6. Percent distribution of Additive Fabrication in various industries [26].

### 1.4.3 Common Uses of Additive Fabrication

Various industries use Additive Fabrication in a variety of ways. The 2007 Wohlers Report also conducted a survey on how customers of system manufacturers and service providers use their parts. The list of common uses is shown below along with their percentages reported as by The Wohlers Report:

- 15.3% - Visual aids (for engineers, designers, architects, and medical professionals)
- 17.4% - Functional models
- 12.1% - Fit and Assembly
- 11.7% - Rapid manufacturing (custom and short-run production)
- 9.9% - Patterns for prototype tooling (including silicone molds)
- 9.9% - Patterns for metal castings

- 8.9% - Presentation models (including A/E/C and GIS models)
- 4.7% - Tooling components (created directly on an additive system)
- 2.7% - Ergonomic Studies
- 2.4% - Visual aids (for toolmakers)
- 1.7% - Fixtures and manufacturing aids
- 3.2% - Other

For the purposes of the selection methodology explained in this paper, these categories where grouped into 3 classes: *Mechanical Components*, *Architectural & Visual Display Models,* and *Pattern & Mold Production*. Each of these classes and the reasoning behind the division will be explained in detail in the Methodology section of this paper.

## 1.5 Future Directions of the Technology

As the Additive Fabrication industry continues to grow as leading experts predict there are a number of changes that are very likely to occur. These changes will occur because of market forces and expanding potential for the use of the technology.

The most obvious trend will be the dramatic lowering of the cost of the machines. This will cause more companies to internalize their prototyping processes and drive many of the current smaller service providers out of business. More and more industries will find uses for the technology as what is currently cost prohibitive and technically challenging will soon become inexpensive and easily obtainable.

As it is now there will continue to be a large push for more material options and production grade materials as engineers demand materials that simulate the final production materials for their testing as well as for their use as final end-use parts. The use of Additive Fabrication technologies to produce final end-use parts may be one of the most significant uses of this technology in the future. As material qualities improve and the machines' production speeds increase, more systems will be specialized solely for Rapid Manufacturing of small quantity production runs of final end-use parts [26]. Typical design limitations due to today's manufacturing constraints will be lifted and extremely complex single component parts will take the place of multi-part assemblies.

This will have a dramatic effect on the future of today's typical manufacturing companies as many low part quantity applications move from the traditional manufacturing techniques to the coming advanced Rapid Manufacturing technologies.

More non-technical people will find the technology assessable as 3D CAD modeling becomes a common skill taught at a young age and 3D content is made more available for download from the internet. The result, a new digital creative outlet is born for the next generation of youth. Today, there exists a 3D modeling program for children K-12 that allows the user to stretch and pull at shapes to create complex characters [4]. As system manufacturers produce more user friendly machines, normal consumer households will be able to have small desktop 3D printers for the everyday hobbyist and up and coming inventor. Soon thereafter, it will be common place for every household to have a desktop 3D printer for quick-fix parts, production of toys or other products downloaded from the internet, and printing of 3D scenes created from 3D image capture cameras.

Mass customization of parts will generate a market for base model products that are expandable to whatever the consumer wishes. This trend is already slowly beginning to surface with automobile companies offering more and more options to customize their vehicles and cell phone manufactures designing for customizable cell phone covers. As the everyday individual has easy access to Additive Manufacturing technology a large explosion of new products will be introduced into the market by a wave of new inventors [15].

In the medical field new additive techniques and advancements in bio-materials will allow for the 3-dimensional printing of organs [2]. This will extend the average lifespan of people across the globe and make donor waiting lists a thing of the past. Advanced 3D modeling techniques will allow for the engineering and design of perfect organs and muscle tissues for the alteration of the average man into near supermen.

Additive Manufacturing at the nano and atomic level will change everything. Conventional macro-scale manufacturing process will be of little use in the production of nano-robots and as a result new additive technologies will responsible for the production of the first nano-machines. The machines will be able to replicate and potentially give us everything we want or possibly fault into an unstoppable everything-eating virus-like machine dissolving the world into a “grey goo” [13].

All of the above predictions are very likely to take place within our lifetimes. However, for the very near future the main trends in Additive Fabrication will be that of machine costs lowering and growth in the number of material options. As this occurs more users of the technology will exist and ever increasing options for materials and processes will be present for those users to choose from.

## 1.6 Purpose Statement

This research was carried out in order to design and construct a system that would allow a person, regardless of their level of technical knowledge, to quickly and easily filter through the large number of Additive Fabrication processes and their associated materials in order to find the most appropriate processes and material options to create a physical reproduction of any part. The primary purpose and innovation of this research is the creation of a process and material selection methodology that utilizes a division of the selection criteria based on end use of the part for a customized user interface at the onset of the selection process while providing the ability for the user to pick and chose which selection criteria should be applied and in what order which allows the user to search as quickly or as extensively as desired.

## 1.7 Benefits of an Alternative to Human Experts

The implementation of a computer program for the selection of an Additive Fabrication process and material offers many advantages. Computers are known for their high speeds, high efficiencies and unmatchable repeatability when compared to humans. Even the most knowledgeable human expert in Additive Fabrication technologies often times must pause to take time to refer to a database of information to find the correct answer where computer programs excel at the task of filtering through large volumes of information quickly and accurately. In addition to the shear out-performance the computer program can provide, the coded expert knowledge and information can easily be added to, reproduced, and distributed to anyone where a single human resource has obvious throughput limitations.

## 1.8 General Conceptual Design Description

The process selection methodology initializes by asking the user to choose from 3 options for the intended end use of the part: *Mechanical Components*, *Architectural & Visual Display Models*, and *Pattern & Mold Production*. By initially dividing the selection criteria by the end use of the part, the user interface is much more specific to the needs of that specific part and therefore more helpful and familiar to the user of the selection system. An additional purpose for the design and construction of the process selection system was to create a system that was capable of guiding the user toward a set of best fit *options* for the Additive Fabrication process and material of their part rather than outputting a single, absolute best choice process and material. The concept of having options as the result rather than a single solution stems from the real world consideration that computer programs or mathematical decision based algorithms cannot take in all factors considered. To create the materials and processes results, several expert rule-based methods and various common selection criteria were utilized for filtering by specific quantitative and qualitative requirements to eliminate non-qualifiers.

## 1.9 Unique Features

Overall the selection methodology is designed to mimic the dialog between a customer and a technically trained customer service agent at a service bureau during an initial discussion on process and material selection for Additive Fabrication. To date, based on the research conducted, there has yet to be an Additive Fabrication/Rapid Prototyping process selection system designed with the initial step of dividing the selection criteria by end use of the part in a manner to customize the system's content to the user's application. This fact alone makes the system extremely unique and highly user-friendly as it presents users with examples and information from their fields and immediately eliminates confusion with terminology that the user may not be familiar with.

Additionally, the selection methodology only requires information from the user that is relatively specific to his or her general purposes and as a result only the information that her or she would be expected to know and have available are necessary to complete the selection process. Also the user is not required to input values into every field. The selection tool will recalculate the results after each input change is saved by the user. This will allow the user to see how each change in input modifies the results or offers new solutions and suggestions.

Lastly, the selection methodology is designed to present a set of options to the user as the result rather than a finite singular answer. It is unlikely that a program would be capable of taking in every factor for any given application and thusly, it cannot be assumed to have the perfect answer. The main function of this selection tool is to filter through the many processes and material options by the use of the user's entries into queries based on common requirements and criteria and then presenting those processes and material options that meet those requirements and criteria as well as offer suggestions to relax certain entries to make additional results available. This methodology does not require the use of a final ranking formula because the user can chose the order in which they complete the selection criteria fields. Once any of the selection criteria the user wishes to enter has been processed, a set of resulting AF process and material options is presented along with advice and additional information for the user to make the final call since there will almost always be additional criteria that the system hasn't considered.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Why is a Selection Tool Needed?  Issues in Current Selection Methodology

### 2.1.1 Large Number of Processes and Materials to Choose From

With over 35 manufacturers of Additive Fabrication equipment in 2006 [26], the selection of an RP process and material for a specific application can become a significant task, especially for those with little or no technical experience with the technology.  To add to this challenge, many of the various processes have multiple material options to select from and each year the number of material choices increases [26].  With so many choices of processes and materials even a person with a moderate level of familiarity of Additive Fabrication can not be sure they have exhausted their search and have selected the most appropriate process and material.

### 2.1.2 Requirement of an Expert for Proper Selection

Most users of the technology without a suitable in-house knowledgebase and capability will seek out the expert knowledge of a service bureau in order to facilitate their selection.  The use of an expert will generally save the Additive Fabrication user significant amounts of time and money by providing several appropriate processes and materials as well as potentially exposing the user to new or possibly less expensive processes that meet the application requirements that on their own, the user may have never seen.

### 2.1.3 Typical Process for the Selection of an RP Process and Material

#### 2.1.3.1 From the Consumer’s Viewpoint

In order to begin the selection process the Additive Fabrication user generally begins with a search of the internet or several trade magazines for a quality, reputable service provider and then making the initial contact. Many times this involves the execution of a non-disclosure agreement and in some cases the vendor must be approved by the corporation’s purchasing departments.

Once these steps have been completed, a discussion of the specific details of the actual application can take place. This process may take multiple phone calls or face-to-face meetings because even the best human expert may need time to research their material database. Even then it is rare that a service provider will have experience with every process which potentially may lead a customer towards a material and process which may not be the best possible option due to a lack of information or possibly by being driven by a service provider’s desire to use their in-house capabilities over others. Although the use of an expert generally will expedite and facilitate the selection process when compared to an individual that is unfamiliar with the technology, there is still often a significant time frame involved in the discussion due to many real world business issues.

#### 2.1.3.2 From the Service Provider’s Viewpoint

In addition to the possible initial hurdles of using a human expert there are other drawbacks to this method of selection from the service provider’s viewpoint. One or more human resources must be trained and made available to assist a potential customer with their application.  As with most technologies, reaching an expert level is difficult since this knowledge is highly based on personal experience which requires the employer to invest in a number of years of training an individual toward that expert role. Thereafter, continuous training must then be provided as the technology changes and grows each year.  Additionally, the common necessity for the execution of Non-Disclosure Agreements exposes service providers to additional liabilities as well as sometimes creating an inability to provide assistance for projects where an agreement cannot be reached.

## 2.2 Existing or Experimental Selection Tools and Their Selection Criteria

### 2.2.1 Selection Tools for the Purchase of AF Technology

Masood and Soo, *A Rule Based Expert System for Rapid Prototyping System Selection*, and Masood and Al-Alawi, *The IRIS Rapid Prototyping System Selector for Educational and Manufacturing Users*, conducted a great deal of research paper for their papers in an effort to create a process selection system to "help [the] potential purchaser in industry to select an RP system from a wide range of choices of commercially available RP systems."  Along with specific machine characteristics such as price, country of origin, OEM, machine size (desktop, office friendly, or commercial), build technology (laser or non-laser), the authors consider accuracy, layer thickness, build envelope, range of materials, build time, surface finish, and end application.  A set of surveys (RP vendor's questionnaire and RP user's questionnaire) was utilized to obtain the values for the various selection criteria.

The program’s flow is that of a question and answer session that begins with the user choosing between 4 types of searches: quick selection, detailed selection, build technology, and machine style. Each type of search process varies which selection criteria will be included during the question and answer session. The quick and detailed search types offer common selection criteria with the detailed selection type offering additional criteria. The build technology search type allows for process selection by whether the process is laser based or non-laser based as well as few other common criteria. The machine style search type allows for process selection by the machine size and usage environment (desktop, office friendly, or commercial).

Once the search type has been determined the program continues to ask questions until the completion of the program. The authors state that “the program then recommends the RP system,” or systems, “along with its full specifications and other valuable information such as sales record, market share, warranty period, training availability, and vendor details for that system.”

Although this system was targeted for users who are intending on purchasing an AF machine, it does provide insights into one approach for the selection process. The system offers the initial step of choosing between the 4 types of searches which eliminates several criteria from each of the search types reducing the user’s ability to make use of all of the various criteria. The system does not consider general material costs or provide any indication of typical build speeds for any of the process which are generally should be included as results to a selection process.

An outline for an Additive Fabrication selection methodology was described in Sriramon, DeLeon, and Winek's paper *Selecting the Appropriate Rapid Prototyping System for an Engineering Technology Program*. The paper considers a few common AF processes and their associated build materials, build envelopes, accuracy, maintenance, safety, and cost. This paper was written from the standpoint of a university looking to purchase a piece of AF equipment to add to their educational curriculum, however, several of the authors' selection criteria can still be considered valid for a person looking to select a process and material for the production of their single part. Primarily, the first point the authors discuss in the methodology of AF selection—the need to decide what is going to be done with the part. They describe this point in terms of the curriculum of the educational program by saying, "The curriculum needs of a program should be the single most important factor when considering the purchase of a RP [Rapid Prototyping/Additive Fabrication] machine…" and going on to say, "It is particularly important to consider the purpose of the RP model, which depends upon the curriculum." The other selection criteria are discussed in general terms, mainly as an introduction to the minimum necessary considerations of introducing an AF technology into an educational curriculum.

### 2.2.2 Selection Tools Using Mathematical Decision Theories

A neural network was used by Vosniakos, Maroulis, and Pantelis in their paper, *A Method for Optimizing Process Parameters in Layer-based Rapid Prototyping*, to calculate an optimal build orientation for a given part by viewing minimum build time and volumetric deviation from the original CAD model as optimization parameters. The basic methodology was to allow the user to select rotation intervals and specify the machine’s layer thickness in order to have a genetic algorithm run iterations of rotation about the x, y, and z-axis on a part to calculate an optimal orientation for the quickest build time with minimal deviation from the intended model shape by comparing volumes of the original CAD model and the pre-processed (sliced) model. Each of these two optimization criteria could be given a weight factor by the user.

The deviation of the volume was viewed in four terms: total volumetric error, mean absolute local volumetric error, the standard deviation of the local volumetric error, and the maximum absolute local volumetric error. The total volumetric error is the sum of the mean absolute local volumetric error which is the difference between the volume of one slice of the CAD model at the determined layer thickness for the AF machine and the extruded projection of the cross-section representing the slice that will be produced by the AF machine during the build. The total volumetric error was designed to serve as a metric or predictor for dimensional quality of a part, however, “it does not consider at all the way in which these deviations are distributed” and as a result the mean and standard deviations are utilized to allow the user to understand if the deviations are, in general, localized or spread evenly about the part’s surfaces.

While this system can potentially produce results that optimize the two build parameters discussed, volumetric deviation and build speed, it does not consider the real life issues of orienting a part based on its feature’s fragility, the need to remove support structure easily for complex geometries, or the basic desire to reduce support structure usage to reduce build costs. Also it does not take into consideration build efficiencies in certain process when multiple parts are required.

A modified technique of order preference by a similarity to ideal solution method (a modified TOPSIS method) was discussed in Byun and Lee's paper, *A Decision Support System for the Selection of a Rapid Prototyping Process using the Modified TOPSIS Method*. The authors made use of a survey sent out to several AF industry users and service providers. The results of the survey provided a list of attributes, or selection criteria, to consider in the modified TOPSIS approach. The authors also used this survey to gather data for the design of a benchmark test part that would be analyzed through physical measurements and serve to complete the values for the quantitative criteria for each process considered. Fuzzy logic was utilized for any criteria requiring a qualitative value. The result of this mathematical approach would be a ranked order of AF processes created from the modified TOPSIS method and a weighted pair-wise comparison matrix. This methodology requires the user to fully complete a large table (N x N) of criteria relationships, where N is the number of selection criteria. This element of the methodology alone would be very time consuming and doesn't allow for any missing data which may be unavailable or unknown to a novice user.

The criteria utilized in the authors' methodology were dimensional accuracy, surface roughness, part cost, build time, tensile strength, and percent elongation which the authors viewed could "provided sufficient information for the selection of an appropriate RP process." This would provide an extremely simplified case of the true complexity of the multifaceted nature involved with the various uses of Additive Fabrication.

The part cost and build time values were entered into the formula as fuzzy numbers. Generally, part cost and build time should be considered as highly variable outputs of a selection process as some AF processes can make use of build efficiencies. The survey's results suggested that only tensile strength and percent elongation should be used as material property considerations. This will severely limit an engineer's ability to specify material properties in the selection process despite additional material property information being available for most every AF material.

Additionally, dimensional accuracy and surface finish were treated as known quantitative values gathered from the authors' benchmark part. The authors overlook a significant consideration in that accuracy and surface finish are almost always feature based with layered based manufacturing processes such as Additive Fabrication, and as such, a value for those criteria will differ with various geometries.

A mathematical methodology to the selection of an AF process was utilized by Rao and Padmanabhan in their paper *Rapid Prototyping Process Selection using Graph Theory and Matrix Approach*. This methodology is similar to that used in a Quality Function Diagram (QFD). The process involved creating a list of attributes, or selection criteria, for the particular application or part in question and assigning values, either quantitative or qualitative, to each of the criteria. Qualitative values were turned into quantitative values through fuzzy logic. Then the relationship between each of the selection criteria was assigned a weight by the user based on fuzzy logic with a range of 11 values (the option for a smaller range was discussed if it were required). This would entail describing N x N relationships (where N is the number of selection criteria) in terms of a linguistic scale.  An example of this would be criteria A is “less important”, “equally important”, or “more important” than criteria B.  Additional linguistic terms such as “exceptionally less/more”, “extremely less/more”, “very less/more”, and “slightly less/more” were used to describe the relationships between criteria.  Finally a formula calculates an index for each of the given AF process based on the relationships entered by the user.  The AF process index with the highest value should be considered the most appropriate option for the application and criteria considered.

This methodology requires the user to fully complete a large table (N x N) of criteria which generally would be very time consuming and doesn’t allow for any missing or unknown data.  A user unfamiliar to AF would not know where to begin with creating the list of selection criteria and likely would not have all the corresponding data to fill in the values for the AF process for those selection criteria they might know of.

This methodology would potentially be viable with the use database of common selection criteria while providing values for the AF processes to be considered. However, much like other mathematical methodologies the authors overlook the fact that accuracy and surface finish are feature based with layered based manufacturing processes.  As stated before, a suggested value for any feature based criteria will differ with various geometries.

Six AF processes are used in a process selection tool in Lan, Ding, and Hong’s paper, *Decision Support System for Rapid Prototyping Process Selection Through Integration of Fuzzy Synthetic Evaluation and an Expert System*.  The authors describe a mathematical decision model for AF process selection “by using [an] expert system and fuzzy synthetic evaluation." The tool is comprised of 4 sections: a user interface for data entry, a database which stores data for each of the six AF processes considered, an expert knowledge-based selection system to compute a result set, and a process for the application of the fuzzy synthetic evaluation used to rank the result set by calculating the effects of user provided weight factors for various criteria.

The expert knowledge-based logic is the result of two surveys (user questionnaire and service provider questionnaire). The responses to the survey were processed into a hierarchical form with two selection criteria based levels. The first level considers technology, geometry, performance, economy, and productivity. The second level considers several sub-criteria under each of the first level criteria. Under technology there is dimensional accuracy and surface roughness. Under geometry there is maximum dimension and part complexity. Under performance there is mechanical strength and resistance to heat. Under economy there is running cost, post-processing cost, material cost, and equipment cost. Lastly, under productivity there is scan speed, overhead time, and post-processing time. From these options all or several of the six AF process are left to then rank by the fuzzy synthetic evaluation.

Several of the selection criteria used by the authors in the selection tool are expressed as qualitative when they are truly quantitative (and vice versa). Surface finish is expressed as a range for the user to select values when it is truly a variable value based on a particular feature, build orientation, and layer thickness. Heat resistance and mechanical behavior of the material is offered as a qualitative measure when it could easily be expressed with specific quantitative data from material property data sheets.

Other criteria offered are of little value such as running cost, post-processing cost, and equipment cost.  As qualitative measures, most users would select to obviously minimize those options.  Further still the user is expected to submit qualitative measures for the scan speed, overhead time, and post-processing time which are all complex machine specific issues that are not likely to be understood by a novice user as the authors provide no information as to the effect of those criteria.

Additionally, the weights that are given to the AF processes criteria profiles do not take into consideration that processes capabilities and other factors vary by machine and with a change in layer thicknesses for a given AF process.

### 2.2.3 Selection Tools with Minimal Factors Considered

Lou, Lan, Tzoul, and, Chen describe an online quoting system for Additive Fabrication that includes some information to their approach towards process and material selection in their paper, *The Development of Web Based E-commerce Platform for Rapid Prototyping System*.  The authors explain the various elements of their quoting system which includes the ability for the user to select from various materials options and the ability of the system to provide estimates for part cost and build time as outputs.  The authors also mention the ability of the system to aid the user in selecting the most appropriate options.  However, no explanation of the material and process selection methodology is presented.  The authors go on to thoroughly explain their estimation of build time with a lengthy set of dynamics equations describing each movement in the mechanics of the FDM process.  The authors compute part cost as a function of the estimated build time, material cost, per hour machine use cost, and labor costs.

If this methodology were to be implemented for each AF process, a complete study of each AF machine would be required to provide the ability to estimate the build time and resulting part cost in order for the user to obtain an online quote.

The effects of part orientation on cost for the building of parts in SLA, SLS, FDM, and LOM processes was discussed by Xu, Loh, and Wong in *Considerations and Selection of Optimal Orientation for Different Rapid Prototyping Systems*. The paper's theory states, "The ability to evaluate part building orientation among different RP processes is an essential step towards the identification of the most suitable RP process among those available for the fabrication of a part, given desired functional requirements of the part and objectives to be achieved." This logic stems from the considerations of how a part's orientation during a build can drastically affect the part's overall build time and the resulting build cost due to longer builds or increase use of support structure. Additionally, a part's orientation during a build can significantly affect a particular feature's surface finish and dimensional accuracy. With those factors considered, the authors use an algorithm which "chooses one criterion as the primary optimization objective and the rest as secondary objectives." For their paper, the authors used the build cost as the primary consideration for optimization. This left build time, accuracy, and surface finish as secondary considerations.

In general, for most AF processes, this case of build cost optimization simply means orienting a part in such a way that a minimal amount of support structure is used (for those processes that utilize support) while orientating the part for the quickest build time. Whether build time or support structure cost has a greater effect on the total cost of the part will vary by process, however, the authors chose to view material cost, in this case, specifically the cost associated with the additional support/wasted material, as the most significant factor in build cost determination.  The quickest build time is generally accomplished by orienting the part such that its minimum dimension is inline with the z-axis.  Both of these (minimization of build time and waste material usage) can generally be accomplished in tandem very quickly by a simple visual inspection of the part by any minimally trained individual.  This methodology could be very useful in the future if variations in the prioritizing of criteria were possible and accurate part analysis software for the build time and support material usage for every build process were made available.

In *Part Orientation and Build Cost Determination in Layered Manufacturing* Alexander, Allen, and Dutta expand upon their earlier paper, *Determination and Evaluation of Support Structures in Layered Manufacturing*, by adding considerations for part accuracy, hollow parts, processes that do not use support structures, and a detailed method for calculating the total build cost based on the parts orientation in the build platform.  The authors discuss using a cost-based optimization of orientation method as the criteria for the selection of an AF process.

The authors' theory suggests that the primary concern for users of AF technologies is to minimize build costs and then, as a secondary issue, reduce the level of surface roughness by way of minimizing the stair-stepping effect either over the entire part or a specific user selected area.  The methodology describes defining the resulting characteristics of various orientations of a given part and a generic profile model of the characteristics of most AF processes.

Orientation characteristics include the height of the part, the quality of the surfaces based on the stair-stepping effect, and additionally for processes with support structure, surface area in contact with support structure and the volume of support structure used.  These characteristics were used to rank various orientations by trials and select the best orientation for the part in a given process.

AF processes characteristics are defined by creating a model, or formula, which includes factors for whether support structure is used or not, the maximum angle of overhang for features without requiring support, and surface accuracy defined by a factor for surface area in contact with support structures (additional support would require additional post processing time/cost to remove support structures and additional finishing effort to correct any increase in surface roughness due to the support structure's contact with a surface).  These characteristics were used with the output of the optimized orientation to determine a build cost.

The authors also discussed using the functions for orientation optimization and process cost profiles together to calculate the optimum build orientation in all processes that would output the lowest cost production route.

The authors' methodology is an extremely simplified case of process selection where build time/cost is considered to be the highest concern for users of AF technologies which often is not the case as many other factors of greater importance will generally contribute to the selection decision.  Surface finish is considered to be a secondary concern to total cost, which often times the complete opposite may be true.

The authors make assumptions in order to generalize the characteristics functions which are incorrect for various instances of many part geometries.  The authors assume that “the best orientation will be contained within the set of orientations with the largest footprint” meaning that minimizing the part’s height during a build will minimize the build time.  Many part geometries defy this assumption, such as a thin walled tube in the FDM process.  For this process the authors would suggest building the tube on its side however this would produce a longer build with unnecessary support producing a part with a low level of surface quality than if the part were built standing upright. Additionally, the weight factors utilized to create the profiles for the AF processes “can only be determined by a database of experimental information” making the ratings given for the process factors considered by the authors are highly subjective.

Campbell and Bernie designed the beginnings of a highly feature-based selection program in their work entitled, *Creating a Database of Rapid Prototyping System Capabilities*.  The authors discuss the efforts of others to analyze the use of various AF processes through use of benchmark parts and how this has potential for misinformation as these benchmark parts with specific geometries may, in some situations, be better suited for certain AF processes than others.

As an alternative to this methodology the authors purpose the hypothesis that “any component can be considered as a collection of form features… e.g. holes, slots, bosses” and “that once the capability of an RP machine has been determined for individual features, its capabilities for any component containing these features can be predicted.” This methodology required a large database of tolerances for every type of feature considered in every machine considered which was derived through calculations based on OEM provided spec sheets for machine accuracy and tolerances. The program then applies a predetermined set of searches to the database for “which RP systems can meet a combination of build envelope, material properties, or multiple feature tolerances.” The author’s methodology includes the option for relaxation of search ranges when no output is returned to the user. The authors also discuss providing the output of cost and build time estimates but provide no discussions of how those are accomplished.

The drawback of this methodology is that it is, as the author states, “a major task…to determine the values for every feature built using every RP system.” Additionally the user is asked to complete the potentially tedious task of entering “the model dimensions and required tolerances for each feature in the part” making the system unusable for extremely complex geometries with organic shapes. A discussion of the authors’ intentions for future work would include a feature recognition algorithm for CAD models which would simplify the process from the standpoint of requiring less user provided input however the output of such a system would still in most cases be extremely complex and difficult to review quickly even by experience designers or engineers.

In Xu, Wong, and Loh’s paper, *Toward Generic Models for Comparative Evaluation and Process Selection in Rapid Prototyping and Manufacturing*, four Additive Fabrication processes using four selection criteria were modeled by either an experimental study or by the creation of quantitative formulas with several complex considerations in each. The paper discusses the formulas created for the various selection criteria models; for dimensional accuracy, surface roughness/finish, build time, and build cost.  Four AF processes were examined; SLA, FDM, SLS, and LOM.

The experimental study for dimensional accuracy analyzed a purpose built benchmark part which focused solely on features in the x-y plane while acknowledging that features in the z-direction are highly feature based.  This study provides a good quantitative representation of 2D extrusion-based features but omits any analysis of complex 3D geometry due to the multifaceted nature associated with such geometry.

The model created for a process' surface finish considers vertical, horizontal, and incline planar surfaces to make a table of measurements using a surface roughness measuring tool.  The paper describes surface roughness as a combination of factors: the individual process, the accuracy of the specific machine, build orientation, layer thickness, and the material used.  It further specifically notes the factors of an inclined planar surface to be based on the stair-stepping effect, the cross-sectional layer's build pattern, and distortion between/in layers.  The paper goes on to create a formula for calculating an estimate of surface roughness for inclined planar surfaces based on angle of incline and the process layer thickness.  While this provides an excellent estimate of a processes' surface roughness, it is not capable of computing surface roughness for more complex geometries since a 3D geometry's surface roughness may be variable with each feature.

The model created for build time utilizes a calculated estimate based on the pre and post-processing times, and machine build time—the former being highly unpredictable and feature based.  The actual machine build time is calculated using a formula considering the sum of the time for the formation of part including support structure (when applicable) and the delay before the initiation of the following layer. This model may provide a rough estimate for the actual machine build time for a few processes but is not valid for several others. Additionally, the machine build time formula is not simple enough to be done quickly and effectively by a novice user and efficiencies in build techniques for multiple part builds were not considered.

The model created for build cost considers four factors: the cost of running the machine, material cost, and the costs in pre and post processing. Excluding material cost, the factors considered in the model's formulas are highly variable (feature based and business operations related) and the data necessary to complete the model is not likely to be available to most users of AF technologies.

### 2.2.4 Higher End Selection Tools

A web-based selection program entitled *RP Selector, A Tool for the Choice of Process Chains Based on RP/FFF for Prototypes and Small Series Production* (authors' names unknown) funded by the IVF Industrial Research and Development Corporation through a grant from NUTEK (Swedish Business Development Agency) currently exists as a non-profit project created and published to the internet for demonstration. The methodology was designed to provide the user with a set of suggested processes based on user inputs. The set of suggested processes encompass several Rapid Technologies that allow for suggestions for processes that can handle single unit quantities to small batch production runs. Several Swedish service providers and companies that are users of Rapid Technologies were involved with the creation and verification of the methodology.

The selection tool begins with the user choosing between four categories: Design Model, Visualization Model, Plastic, and Metal.  The user then enters different information about the part in question based on the initial category selected.

The processes covered by this selection tool are divided into 3 categories: general AF technologies (SLA, SLS, FDM, LOM, inkjet, and 3DP), Tool Inserts for Plastic Shaping (Epoxy Tool, Metal Spray Tool, 3D Keltool, Cast Kirksite, SLS, Metal Copy, and Silicone Molding), and Tools for Metal Casting (investment casting, plaster casting, sand casting, SLS and sand form from AF method).

Several outputs are displayed in a table based on the selection criteria utilized in the selection process.  The selection criteria consist of questions posed to the user about the size of the part, quantity, minimum wall thickness, and material.  The output table consists of strictly qualitative estimates and information for factors such as surface finish, color, cost, possibility to process large parts, precision of the process, process capability for complex parts, delivery time (weeks), number of process steps, surface finish, and process capability for thin walls.  The output table generally only consists of a few of the factors based on which initial option was selected.

This approach considers many Rapid Technology based processes including Additive Fabrication but lacks in user entered selection criteria.  Most of the selection criteria are left remaining in the output table still for the user to filter through.  With the program accepting only minimal information about the part and application, the output (assuming the unseen logic is correct) can only be considered as very rough suggestions as to a starting point for additional research.

One of the apparent main criteria is part quantity. As part quantity goes up the system drives the user toward more conventional manufacturing processes while eliminating several AF technologies altogether without any consideration towards the part's size or complexity. Most conventional manufacturing technologies have strict process specific limitations that a designer likely would not have considered in the design. In this situation the advice would require a redesign of the part where an Additive Fabrication technology could have been successful.

Additionally, the output table, other than time given in weeks, does not provide any quantitative results. The results are given as either an index value to refer to a rough information guide about the output table headings or as "good", "fair", "average", or similar subjective terms which leaves the user without any real guidance.

Bibb, Taha, Brown, and Wright describe their theories of operation as well as some specific selection methodology to their Additive Fabrication process selection tool in their paper, *Development of a Rapid Prototyping Design Advice System*. The authors discuss several of their operational theories and assumptions used in the creation of their methodology such as assuming the user is not familiar with AF technologies and giving meaningful advice and informative content, suggesting several results that a user could use to pursue a quote in market, and the assumptions that cost and lead time will vary by service provider (as well as several others that coincide and agree with this authors work which can be found in this paper's section entitled Assumptions and Logic for the Additive Fabrication Selection Methodology).

The system created by the authors uses a rule based computer program to follow a set of routines designed to eliminate process options as each criteria is selectively entered through a pre-determined script. This approach requires the user to, at a minimum, attempt to complete the script regardless of the number of inputs actually entered rather than allow the user to isolate the inputs they are particularly concerned with. Also, this approach predetermines selection criteria's priority order which then eliminates the user's ability to determine which criteria are of greatest concern.

The authors utilize CAD model analysis to obtaining inputs for some of the part's precise data (volume, part extents, etc) as well infer some estimated data regarding the part's features. The authors justify this approach of obtaining feature based data from the CAD file by discussing the benefit over the "alternative method of manually defining the object as an assembly of primitive shapes…as this would take an unreasonably long time." This can work well for precise information however may require a long processing time for models with complex geometries and large file sizes.

A major drawback of the methodology of Bibb, Taha, Brown, and Wright is that they have put a "limit on the number of parts [each process] can reliably produce." This assumption can unnecessarily eliminate processes when, generally, any number of additional service providers can be employed to produce a large quantity of parts.

# CHAPTER 3: METHODOLOGY OF PROCESS AND MATERIAL SELECTION

## 3.1 Introduction to the Methodology

The Additive Fabrication selection methodology used in this paper is a collection of assumptions and rules gathered from several years of daily work assisting engineers, inventors, architects, doctors, and designers select a process and material for the production of their prototypes, end use parts, or low volume production runs. It takes into account various assumptions taken from the author's viewpoint of how, in real world terms, the selection process generally takes place between a consumer and a service provider. The methodology uses those assumptions in conjunction with a set of expert based rules to give guidance to the user as to the best qualifying process and materials suited for their application based on as many or as few inputs to the selection criteria the user may have available.

## 3.2 Assumptions and Logic for the Additive Fabrication Selection Methodology

The following sections are comprised of some of the significant basic assumptions and logic used to create the selection methodology. The sections are divided by assumptions and logic about the user, the program's functionality, and the selection criteria that was used.

### 3.2.1 Assumptions and Logic for the User

The selection methodology assumes that the user is, at least initially, intending on using an AF technologies for the application. This assumption is the basis for the elimination of other conventional manufacturing technologies from the selector. Off-the-shelf solutions, other rapid technologies, or conventional manufacturing processes may be mentioned in the results as suggestions to be considered when applicable.

The selection methodology assumes that the user can utilize service bureaus to obtain the part(s) required.  Therefore the user then has numerous AF technologies available to them.

The selection methodology assumes the user has all of the most common AF technologies and materials available to them at the initiation of the program.  Future work will include an option to eliminate or “grey out” certain processes or materials to allow for a capabilities profile to be created and saved for vendors or in-house resources.  This reflects some common real world situations where companies require the use of certain vendors who may not have every AF technology available.

The selection methodology assumes the user has no prior experience with AF technologies.  Guidance for each selection criteria section during each step of the process will be given in a special help and information section set aside from the main content area.  This ensures that experienced users are not overwhelmed with information crowded into the main area but it is available if needed.

### 3.2.2 Assumptions and Logic for the Selection Methodology

The selection methodology only offers selection advice on AF technologies although some other technologies may be presented in the results as other suggested alternatives to be further explored by the user.

The selection methodology presents advice and guidance rather than finite results dictating the optimal process selection.  The results section includes multiple process/material options or at least alternatives if certain criteria are relaxed by the user.

This logic is based on the fact that there are additional unknown variables to be considered in real world applications beyond what any computer logic may consider.

The selection methodology operates and presents results quickly and efficiently. The user will be able to select from various sections of selection criteria that are of importance to the user’s application and ignore those that are of no importance or unavailable at the time. The user will be able to calculate the results at any point in the selection process.

The selection methodology does not have a single predetermined course or script of action. As each set of selection criteria is entered, a new updated set of suggested results with explanations is presented. This allows the user to stop the selection process at any time once he or she is satisfied with the results. This will prevent the user from being required to enter unnecessary or unknown information before seeing the results suggested.

The selection methodology displays the suggested results with additional information to facilitate a discussion with a service bureau regarding the results and how those resulting selections where made.

### 3.2.3 Assumptions and Logic for the Selection Criteria

The selection methodology divides selection criteria into 3 major classes: *Mechanical Components*, *Architectural & Visual Display Models*, and *Pattern & Mold Production*. A more detailed discussion for this logic will be presented later in this chapter.

The selection methodology is not heavily based on geometric 3D primitives to make selection decisions as the nature of the various AF technologies is unlimited in geometric and organic complexity. A selection system based on geometric shapes would not allow for the more organic shapes created in CT and MRI scans, character models, or art pieces and thusly, severely limit the possible applications of the program.

The selection methodology considers surface finish/texture to be a feature based variable since Additive Fabrication is a layered based manufacturing technique with a stair-stepping effect that can range in severity for angled or curved surfaces as well as the variation in resolutions in the x, y, and z-axis. This can produce a part with a variable surface finish/texture depending on that degree of angle or curvature in the parts geometry and how it is oriented on the build platform. In Additive Fabrication, typically only vertical and horizontal walls generally have a relatively constant surface finish regardless of the part being built but this is still not always the case. Without this assumption an extremely complex feature based analysis of the part file would need to be performed for each of the many available processes and the output would likely provide little help to the user as even a simple radius would output a varying surface finish value.

The selection methodology only considers CAD file information entered by the user for use as selection criteria. This may include part volume, extents dimensions, minimum feature size, wall thickness, etc. This also will prevent the need for a complex feature based analysis of the part and allows the user to manually enter values for those features they are concerned with rather than a computer qualifying every feature and surface in the model.

The selection methodology does not consider build time as an input in selecting the results. Until a service bureau is obtained by the user, lead times are generally unknown. Additionally, post processing times, often varying by a vendor’s processes, are unknown due to varying feature complexity as well as options for additional part finishing and the times required for those optional secondary processes.  Build times are presented (qualitatively) in the results for general consideration by the user and for cases when part quantity is high in relation to the part size.

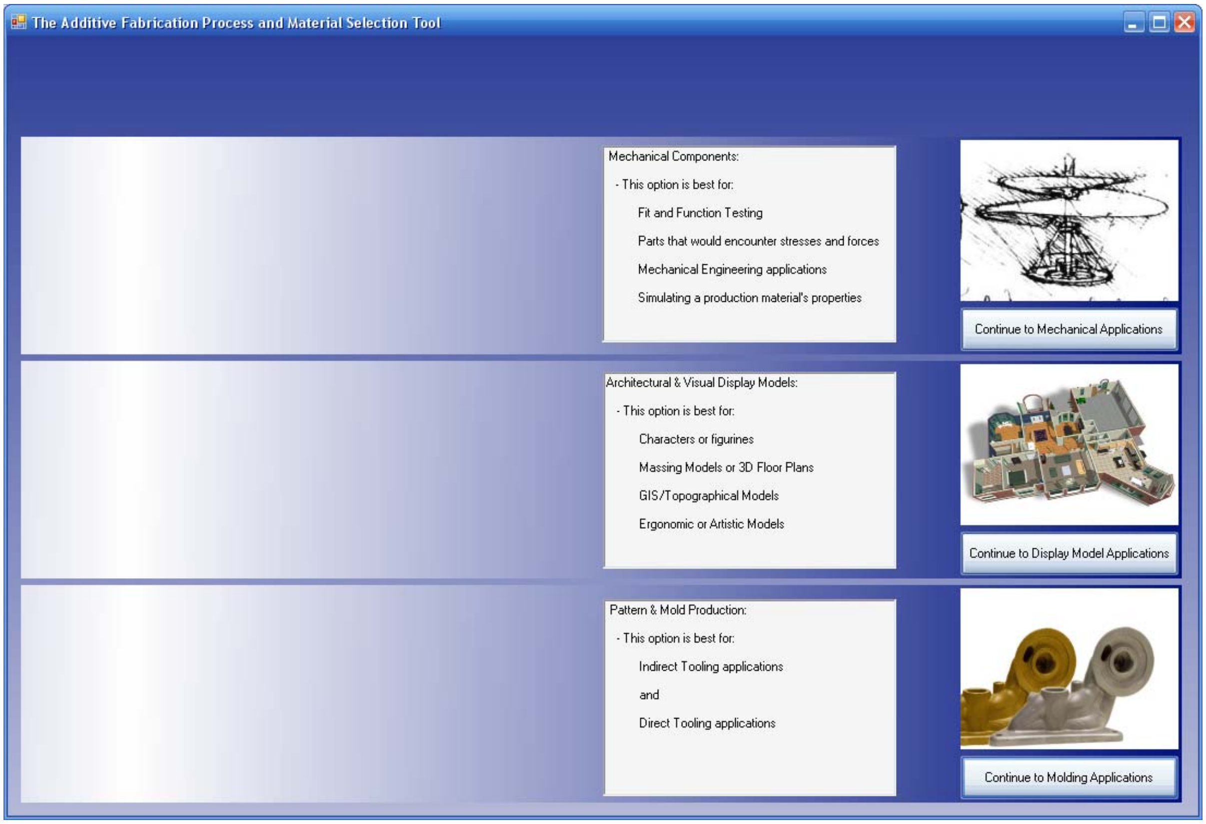
The selection methodology does not eliminate processes because of part quantity. Additional machine resources may be employed to obtain virtually any quantity of parts in any process.  However, the system still may present the suggestion to explore higher volume production processes as needed.

The selection methodology generally does not consider specific machines as selection criteria.  The results section will display a list of the machines capable of producing the parts in the resulting processes solely for reference.  An option for the creation of a vendor/in-house capabilities profile will, in future works, allow for the elimination of certain machines and as a result those materials and processes will not be shown in the results.

The selection methodology treats build cost as a qualitative measure rather than a quantitative one.  Many variables affect the actual final build cost; minimum build costs vary by vendor, process efficiencies in different RP technologies affect build costs in multiple part orders, vendor price negotiations, etc.  Build cost as a qualitative measure is discussed further during an explanation of the selection criteria later in this chapter.

## 3.3 Selection Criteria and the Expert Rule Based Logic

The selection methodology begins with the user being presented with a choice between three part type classes: *Mechanical Components*, *Architectural & Visual Display Models*, and *Pattern & Mold Production*.



Mechanical Components:
- This option is best for:
  Fit and Function Testing
  Parts that would encounter stresses and forces
  Mechanical Engineering applications
  Simulating a production material's properties

Architectural & Visual Display Models:
- This option is best for:
  Characters or figurines
  Massing Models or 3D Floor Plans
  GIS/Topographical Models
  Ergonomic or Artistic Models

Pattern & Mold Production:
- This option is best for:
  Indirect Tooling applications
  and
  Direct Tooling applications

Figure 7. The selection options for the part application classes.

The distinction was introduced into the Additive Fabrication selection methodology because of the first question typically asked to the customer by a service provider agent, “How do plan on using the part?” The answer to this question immediately routes the service agent to a pre-determined set of questions for that type of application as well as changes the terminology, examples, and even units of measurement used in the discussion. While all of the same selection criteria is made available and may still be utilized for each of the 3 above mentioned classes, how the questions are presented, suggestions, and examples given to the user vary by the user’s part’s application. This provides the user with a more customized and familiar experience with terminology, pictures, and figures common to their field and part application. Each of the initial classes are discussed thoroughly below.

### 3.3.1 Mechanical Components

The Mechanical Components class of the Additive Fabrication Process and Material Selection Tool is intended for those parts requiring fit and functional testing. Creating a prototype for fit testing generally requires the production of parts that will most closely match the CAD file's geometry so that one can be assured the part will interact properly, as intended, with other components in the design's assembly. Functional testing may include loading a part with forces or stresses and require specific mechanical related material properties. Some examples of these types of models would be functional components, electronic housings, medical devices, and applications requiring specific material properties and performance.

Figure 8. Examples of typical mechanical components.

When the user selects the Mechanical Components class, the user interface is customized for those types of applications.  This includes using pictures of parts that are of a more mechanical nature in the selection criteria pages to help describe a particular selection criterion’s inputs, discussing examples in the help section in terms of mechanical type applications, and the use of terminology geared more towards that used in mechanical engineering.

### 3.3.2 Architectural & Visual Display Models

The Architectural & Visual Display Models class of the Additive Fabrication Process and Material Selection Tool is intended for those parts created for the purpose of visual or tangible communication tools.  These parts involve the creation of form, shape, texture, and feel, or ideas, concepts, expressions, and art.  Parts that fall under the Architectural & Visual Display Models section generally are not mechanically intensive and concerns of machine accuracy and mechanical material properties are less important whereas concerns of feature detail, surface finish, and post processing techniques might be much more important.  Some examples of these types of models would be scaled buildings models, characters, ergonomic forms, 3D logos, surgical planning models from MRI or CT scans, and works of art.

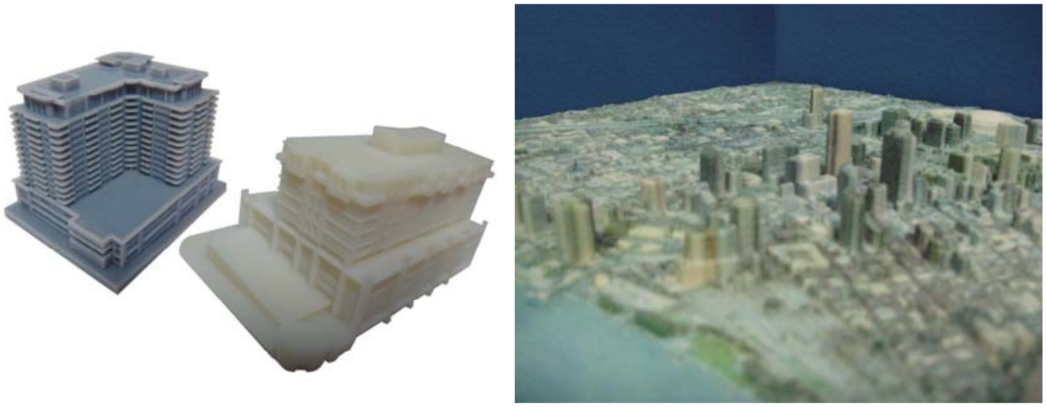


Figure 9.  Examples of typical Architectural models.

Figure 10. Examples of Visual Display models.

When the user selects the Architectural & Visual Display Models class, the user interface is customized for those types of applications.  This includes using pictures of parts that are of a more artistic nature in the selection criteria pages to help describe a particular selection criterion’s inputs, discussing examples in the help section in terms of visual type applications, and presenting additional explanations for engineering intensive terminology.

### 3.3.3 Pattern & Mold Production

The Pattern and Mold Production class of the Additive Fabrication Process/Material Selection Tool is intended for those parts created for the purpose of direct or indirect tooling. These parts are used for copying parts through a molding process in one of two methods, direct or indirect tooling. Indirect tooling uses the AF part as a pattern to create a mold, or negative, of the part which can then be used to cast other materials in the part's shape. Direct tooling uses AF processes to produce the mold itself, directly from the AF machine, using AF materials which can then be used in the same manner as the mold created from the pattern in indirect tooling. Parts that fall under the Pattern and Mold Production class are often times a mix of some mechanical requirements, and surface finish and feature detail requirements. Patterns and molds generally require above average feature detail and surface finish and should be easily post processed for surface finish improvements. Any part application that may need to be reproduced in low volume or another material other than those available in AF would qualify as an example.

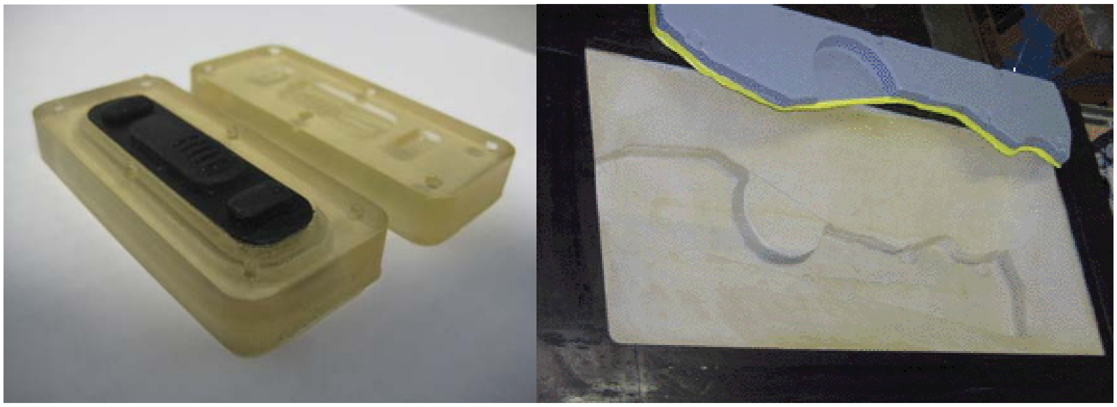
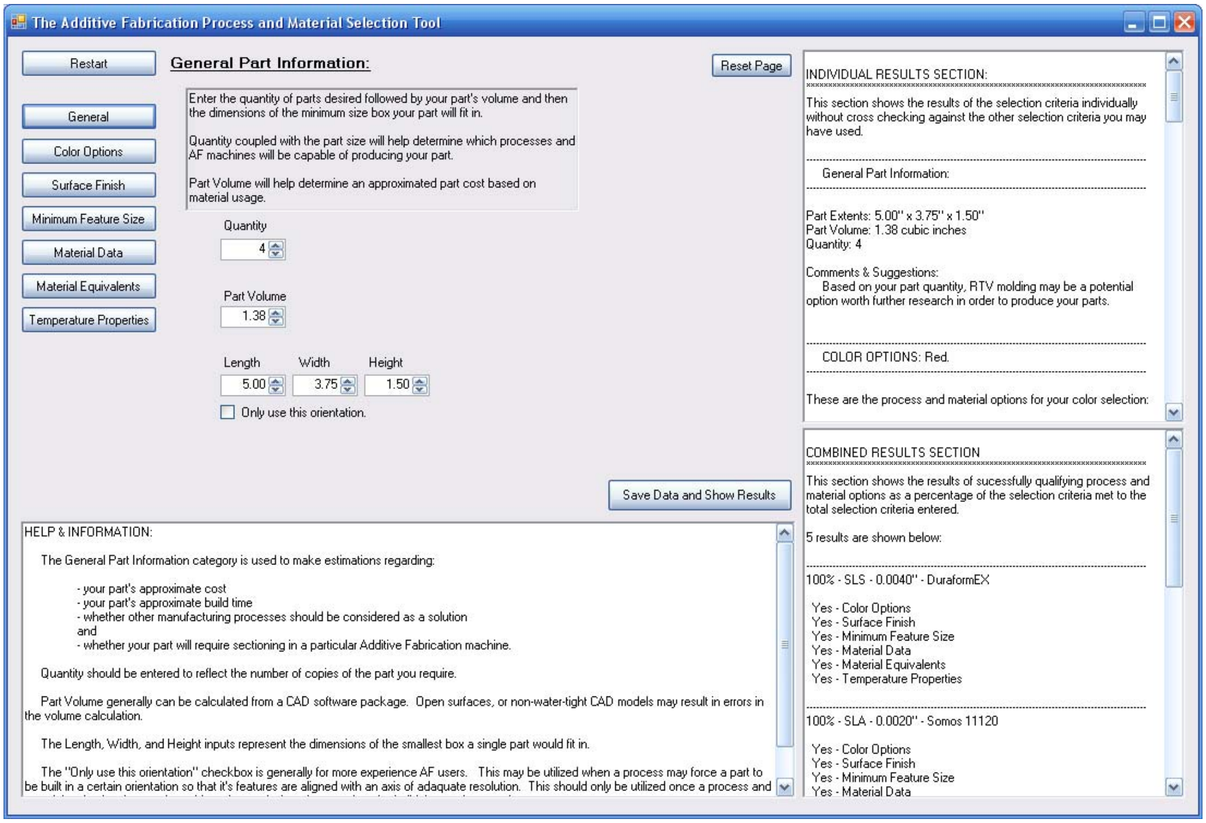


Figure 11. Examples of direct (left) and indirect tooling (right).

### 3.3.4 Explanation of the Selection Criteria

After entering into one of the three part classes the user then has the option of completing any one, multiple, or all of the offered selection criteria categories he or she would like to utilize in the consideration of the application and in what order to precede. The technique used in the selection methodology, of a non-scripted order to, and selective usage of, the selection criteria lets the user decide which criteria are considered more important by completing those first, returning results, and then applying additional selection criteria if desired. This also allows the user to see exactly how each modification to the selection process affects the results making the selection tool also an educational tool as the user becomes more experienced with how changes to the selection criteria fields affect the results.

The process begins with the user entering data into the fields of a given selection criteria category. The user interface for the selection tool can be seen below:



**General Part Information:**

Enter the quantity of parts desired followed by your part's volume and then the dimensions of the minimum size box your part will fit in.

Quantity coupled with the part size will help determine which processes and AF machines will be capable of producing your part.

Part Volume will help determine an approximated part cost based on material usage.

Quantity: 4

Part Volume: 1.38

Length: 5.00 Width: 3.75 Height: 1.50

☐ Only use this orientation.

HELP & INFORMATION:

The General Part Information category is used to make estimations regarding:

- your part's approximate cost
- your part's approximate build time
- whether other manufacturing processes should be considered as a solution
and
- whether your part will require sectioning in a particular Additive Fabrication machine.

Quantity should be entered to reflect the number of copies of the part you require.

Part Volume generally can be calculated from a CAD software package. Open surfaces, or non-water-tight CAD models may result in errors in the volume calculation.

The Length, Width, and Height inputs represent the dimensions of the smallest box a single part would fit in.

The "Only use this orientation" checkbox is generally for more experience AF users. This may be utilized when a process may force a part to be built in a certain orientation so that it's features are aligned with an axis of adaquate resolution. This should only be utilized once a process and

```
INDIVIDUAL RESULTS SECTION:
****************************************************************
This section shows the results of the selection criteria individually
without cross checking against the other selection criteria you may
have used.

----------------------------------------------------------------
    General Part Information:
----------------------------------------------------------------

Part Extents: 5.00" x 3.75" x 1.50"
Part Volume: 1.38 cubic inches
Quantity: 4

Comments & Suggestions:
    Based on your part quantity, RTV molding may be a potential
option worth further research in order to produce your parts.


----------------------------------------------------------------
    COLOR OPTIONS: Red.
----------------------------------------------------------------

These are the process and material options for your color selection:
```

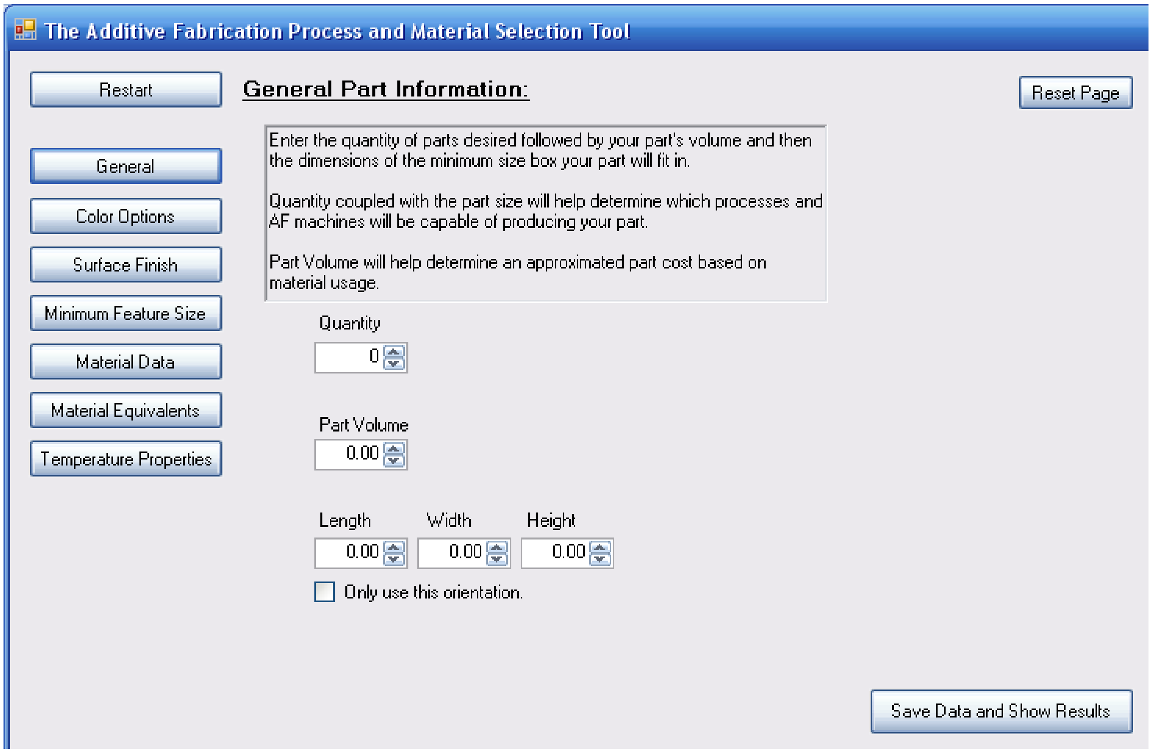
```
COMBINED RESULTS SECTION
****************************************************************
This section shows the results of sucessfully qualifying process and
material options as a percentage of the selection criteria met to the
total selection criteria entered.

5 results are shown below:

----------------------------------------------------------------
100% - SLS - 0.0040" - DuraformEX

 Yes - Color Options
 Yes - Surface Finish
 Yes - Minimum Feature Size
 Yes - Material Data
 Yes - Material Equivalents
 Yes - Temperature Properties

----------------------------------------------------------------
100% - SLA - 0.0020" - Somos 11120

 Yes - Color Options
 Yes - Surface Finish
 Yes - Minimum Feature Size
 Yes - Material Data
```

Figure 12. Main user interface (the General Part Information category selected).

This data is then used individually as well as in conjunction with other inputs in the execution of an expert based set of rules guided by the previously discussed assumptions that make up the selection methodology. Each of the selection criteria categories are explained in detail in the following sections.

### 3.3.4.1 General Part Information

The General Part Information page is consistent for all three of the part type categories and considers four inputs: part size, part volume, part quantity, and an optional forced orientation checkbox.



General Part Information:

Enter the quantity of parts desired followed by your part's volume and then the dimensions of the minimum size box your part will fit in.

Quantity coupled with the part size will help determine which processes and AF machines will be capable of producing your part.

Part Volume will help determine an approximated part cost based on material usage.

Quantity: 0

Part Volume: 0.00

Length: 0.00 Width: 0.00 Height: 0.00

☐ Only use this orientation.

Figure 13. Isolated view of the General Part Information page.

The part's size is input as the minimum length, width, and height dimensions of the smallest box the part would fit into. A part with its extents dimensioned can be seen below as it would be entered.

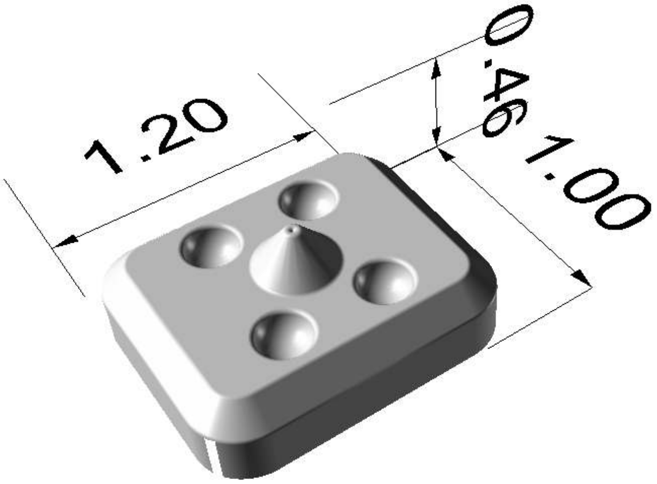


Figure 14. A part with the measurements of its extents shown.

This input gives the extents of the part which can be used to determine if the part will fit in a particular machine or need to be sectioned as well as help in determining the part's estimated build cost for each of the results provided.

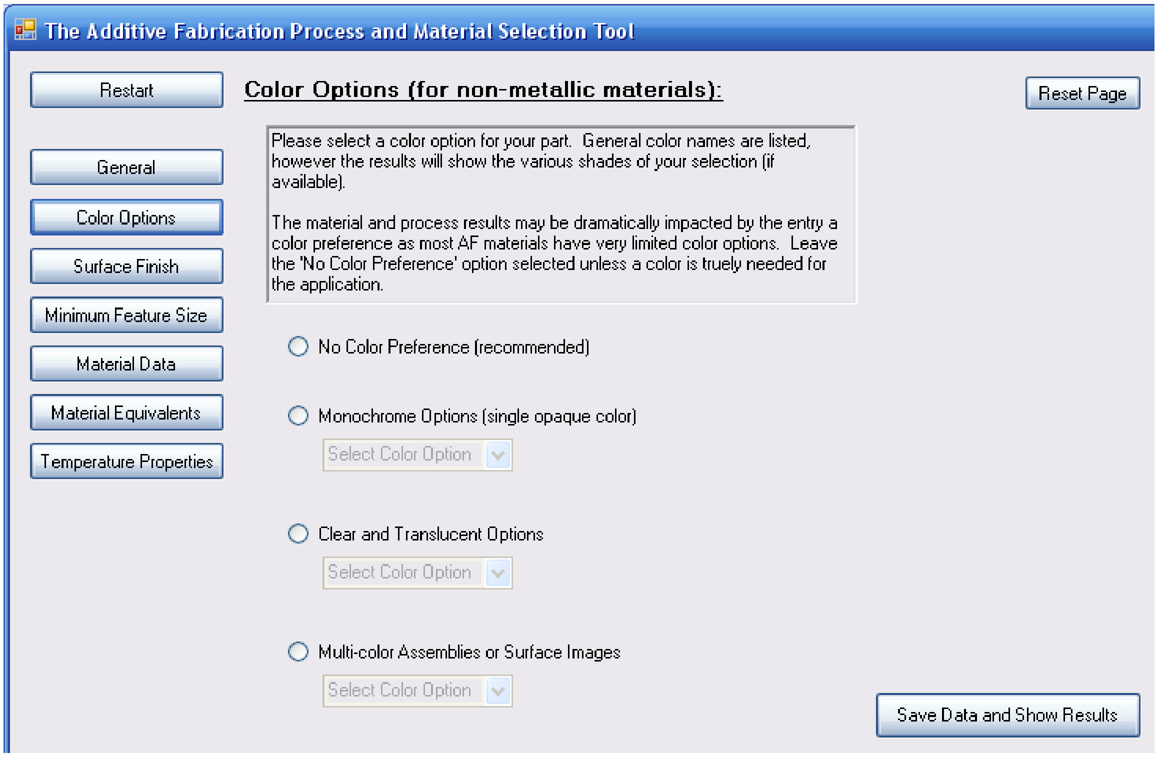
The part's volume is simply used in conjunction with the outputted material results in estimating the part's cost.

Part quantity is used in conjunction with several other factors to provide specific outputs to the results. Quantity is also used to determine if other conventional manufacturing options should be considered especially when combined with the material equivalents options and part size inputs. Quantity is also combined with the size input to determine how many parts may fit per build which allows the system to estimate build times and production costs in various Additive Fabrication processes.

The 'Only use this orientation' checkbox is generally for more experienced AF users. In most AF processes part orientation affects the build time by changing the vertical height of the build resulting in longer or shorter builds and therefore the cost will change as a result. This optional feature of the selection tool may be utilized when a process may force a part to be built in a certain orientation so that its features are aligned with an axis of adequate resolution. This should only be utilized once a process and material option has been selected from the results in order to update the build time and cost estimates.

#### 3.3.4.2 Color Options

The Color Options page is also consistent for all three of the part type classes and offers 4 radio button style selections to choose from: No Color Preference, Monochrome, Clear/Translucent, and Multicolored/Surface Images.



Please select a color option for your part. General color names are listed, however the results will show the various shades of your selection (if available).

The material and process results may be dramatically impacted by the entry a color preference as most AF materials have very limited color options. Leave the 'No Color Preference' option selected unless a color is truely needed for the application.

Figure 15. Isolated view of the Color Options page.

The ‘No Color Preference’ option has no effect on the results when checked and is recommended to the user due to the limitations in color options for most all Additive Fabrication materials. A color choice can dramatically reduce the results to only a few processes and materials due to the fact that currently only a few processes offer any variety in colors for a particular material.

The ‘Monochrome’ option activates a list of the several opaque colors currently available. A monochrome selection will generally produce only a few material/process results.

Similarly, the ‘Clear/Translucent’ option activates a list of the several clear or translucent colors currently available. A clear or translucent selection will generally produce only a few material/process results.

For models requiring multi-color surface information, such as stress flow analysis, logos, or graphics, the ‘Multicolored/Surface Images’ option is available.

Figure 16.  Examples of parts produced complete with color information.

This option limits the user to only three options, Z Corporation’s 3DP process with a plaster based material, Objet Geometries Polyjet process used on the Connex machine which has several options for materials, and the SLA processes which can produce parts with generally up to two different colors by over-curing select areas of a model during the build process.  These are the only technologies currently capable of producing parts with multi-color information directly from digital data.

### 3.3.4.3 Surface Finish

The Surface Finish page utilizes three options for the ranking of processes by their quality of surface finish. The system divides the possible geometric surface configurations into the following categories: vertical surfaces, horizontal surfaces, and non-orthogonal surfaces (each considered relative to the orientation of the part to the build platform's coordinate system). Typically only vertical and horizontal walls can be considered relatively constant regardless of the part being built and therefore the selection tool isolates each of those two cases, individually, and ranks the various processes by an expert based qualitative measure. Quantitative measures are generally not available for vertical or horizontal surfaces and would require a substantial study in itself as those surfaces can, in some processes, vary by the angle the part is rotated about the z-axis in the build platform. For the third option, non-orthogonal surfaces, where surface finish is extremely feature based, the processes are ranked by layer thicknesses. As a general rule, a thinner layer thickness will produce parts with a better surface finish for surfaces that slope or curve with the machine's z-axis.

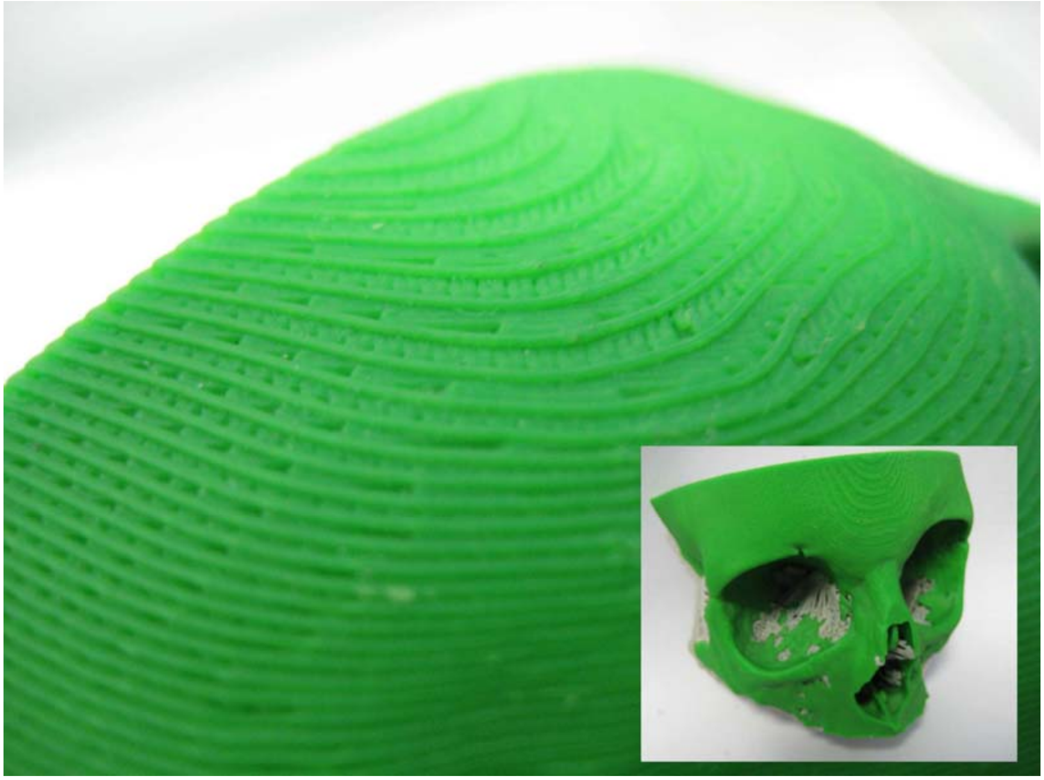
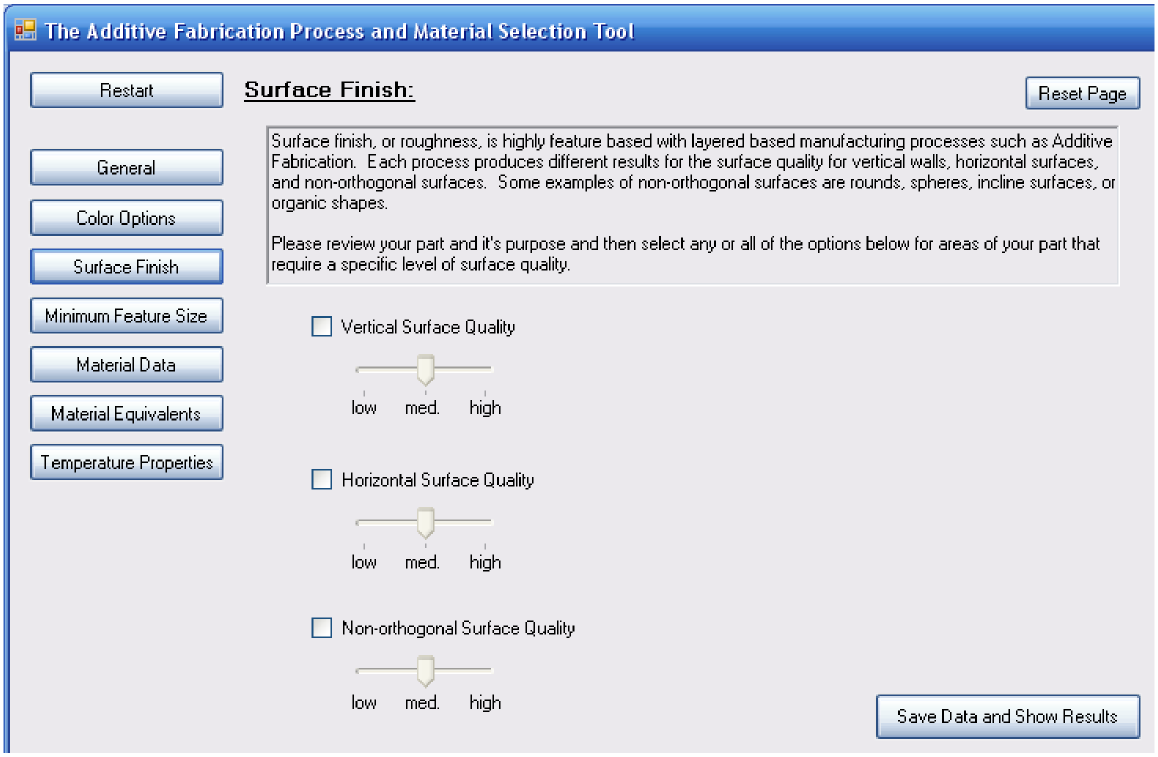


Figure 17. Close up of a non-orthogonal surface on an organic model. Demonstration of surface finish varying with features in layered based manufacturing.

The user is asked to consider his or her part and select from one or more of the three options presented by activating the desired checkboxes and to then use the corresponding slider bars for each to make a qualitative decision regarding the quality of surface finish they need for that surface geometry. This allows the user to have the option of examining how the output of the resulting processes are affected by considering various levels of surface finish quality for each of the options individually or in combinations.



Surface finish, or roughness, is highly feature based with layered based manufacturing processes such as Additive Fabrication. Each process produces different results for the surface quality for vertical walls, horizontal surfaces, and non-orthogonal surfaces. Some examples of non-orthogonal surfaces are rounds, spheres, incline surfaces, or organic shapes.

Please review your part and it's purpose and then select any or all of the options below for areas of your part that require a specific level of surface quality.

☐ Vertical Surface Quality

☐ Horizontal Surface Quality

☐ Non-orthogonal Surface Quality

Figure 18. Isolated view of the Surface Finish page.

For each of the three surface quality measures, the AF processes and materials used in the selection tool were grouped into categories of various levels of surface quality based on expert knowledge and experience. The groups were then tied to a qualitative measure index on the slider bar so that when a given index on the bar was selected the group associated with that index is presented in the results.

### 3.3.4.4 Minimum Feature Size

The Minimum Feature Size page uses numeric inputs for the dimension of the minimum feature size of concern and the minimum wall thickness of the part in order to provide the user with the processes that are capable of producing a part with features of that size.

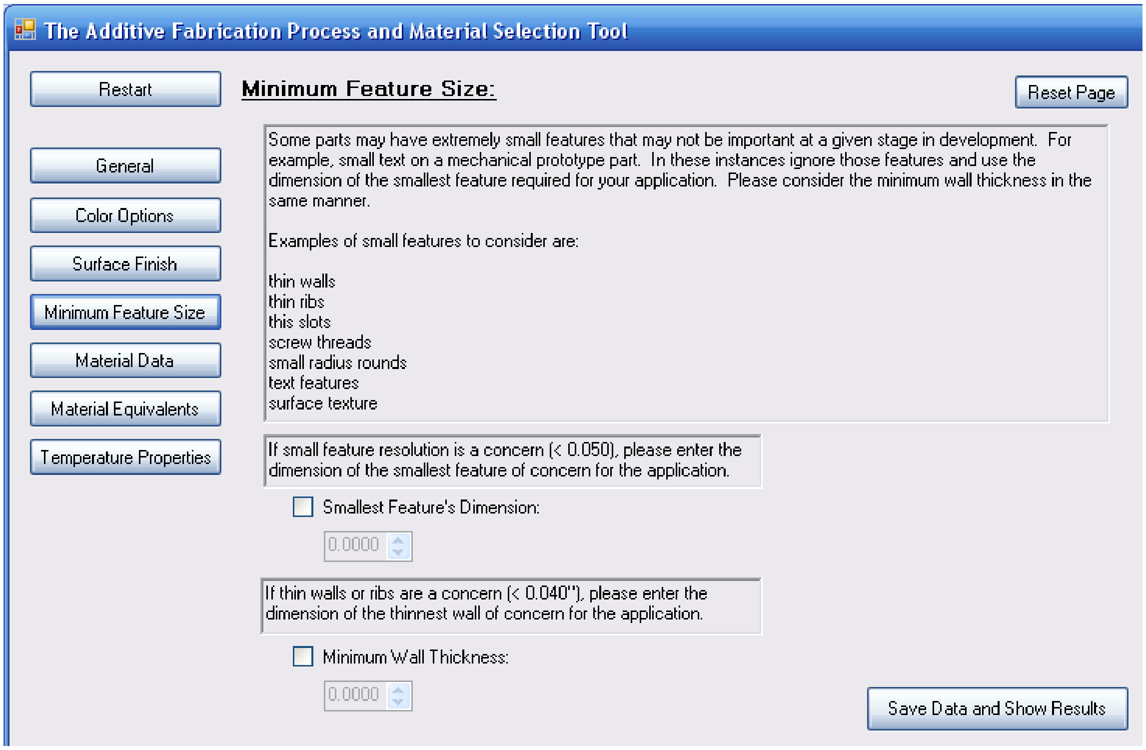
The user is instructed to enter the dimension of the smallest feature of *concern* rather than just the smallest feature size since there are instances in prototyping where something like a text embossment may not be of concern whereas a slightly larger screw thread might be the true critical feature. By allowing the user to choose the smallest feature of concern it eliminates the need for a complex feature based analysis of every feature of the part and does not eliminate results unnecessarily by considering non crucial features. If an AF process can successfully produce the minimum feature size of concern it should then be capable of producing all other larger features of concern. Some examples of common small features on parts are thin walls or ribs, thin slots, shallow cuts, text (raised or cut in), small diameter holes, surface texturing, or small radius rounds.

Figure 19. Examples of parts with features that may be considered 'small' for common AF technologies.

The Minimum Feature Size page also accepts a numerical input for the minimum wall thickness of concern. This function considers the limitations on wall thicknesses in AF processes as a special case due to the fact that some AF processes may only be capable of producing a certain minimum wall thickness reliably, but at the same time, still may be capable of producing small details embossed on those walls. Generally this is a result of the fragility of the material and the common requirement of post processing steps.

The user's input is used to filter through a database of processes for values of the minimum feature size and minimum wall thickness in order to eliminate non-qualifiers. Generally, as the value for the smallest feature size and wall thickness decrease, an increasing number of processes are disqualified from the results.

In the instance that no results are returned for the user's given feature dimension, a few of the highest resolution processes will be presented as results with the numerical difference from the inputted value along with the note that the minimum feature is below all current available processes.



Some parts may have extremely small features that may not be important at a given stage in development. For example, small text on a mechanical prototype part. In these instances ignore those features and use the dimension of the smallest feature required for your application. Please consider the minimum wall thickness in the same manner.

Examples of small features to consider are:

thin walls
thin ribs
this slots
screw threads
small radius rounds
text features
surface texture

If small feature resolution is a concern (< 0.050), please enter the dimension of the smallest feature of concern for the application.

☐ Smallest Feature's Dimension:

0.0000

If thin walls or ribs are a concern (< 0.040"), please enter the dimension of the thinnest wall of concern for the application.

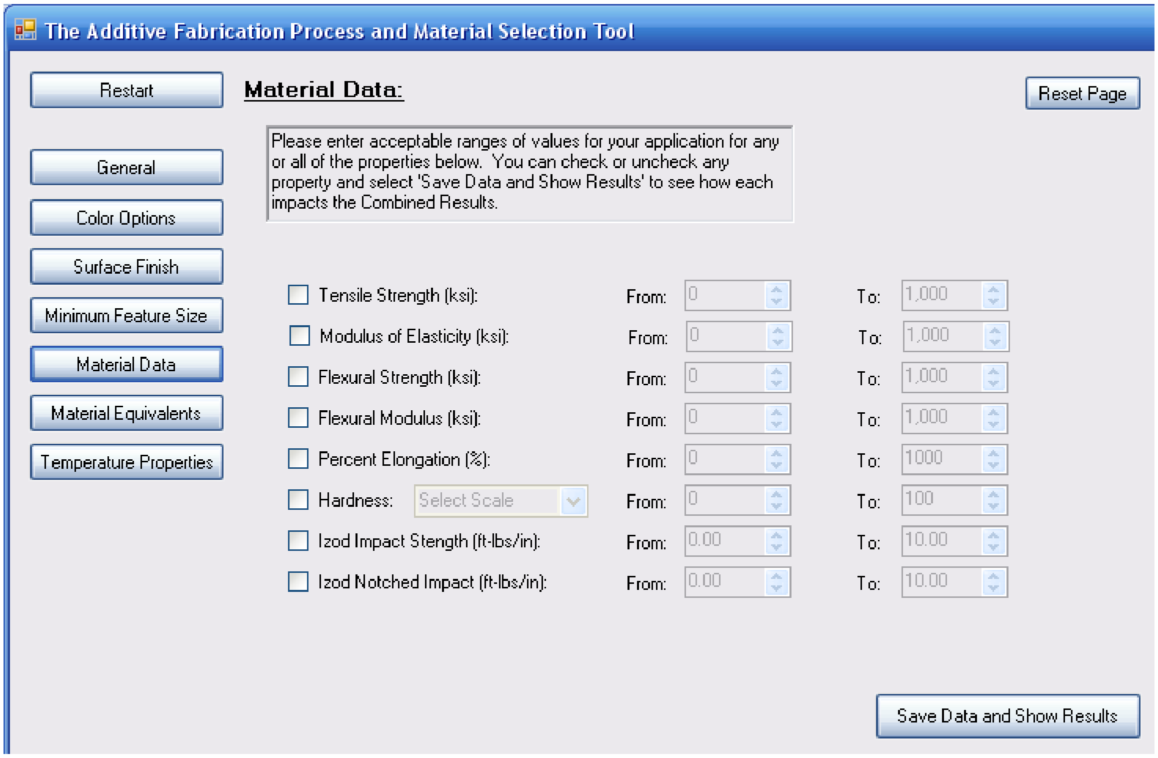
☐ Minimum Wall Thickness:

0.0000

Figure 20. Isolated view of the Minimum Feature Size page.

### 3.3.4.5 Mechanical Material Properties

The Mechanical Material Properties page presents several mechanical properties for the user to enter acceptable ranges of values for any single property or all that are listed. The properties made available to the user by the Additive Fabrication Process and Material Selection Tool are those that are commonly made available in most OEM material data sheets. They are Tensile Strength, Modulus of Elasticity, Flexural Strength, Flexural Modulus, Percent Elongation, Izod Un-notched Impact Strength, Izod Notched Impact Strength, and Hardness.



**Material Data:**

Please enter acceptable ranges of values for your application for any or all of the properties below. You can check or uncheck any property and select 'Save Data and Show Results' to see how each impacts the Combined Results.

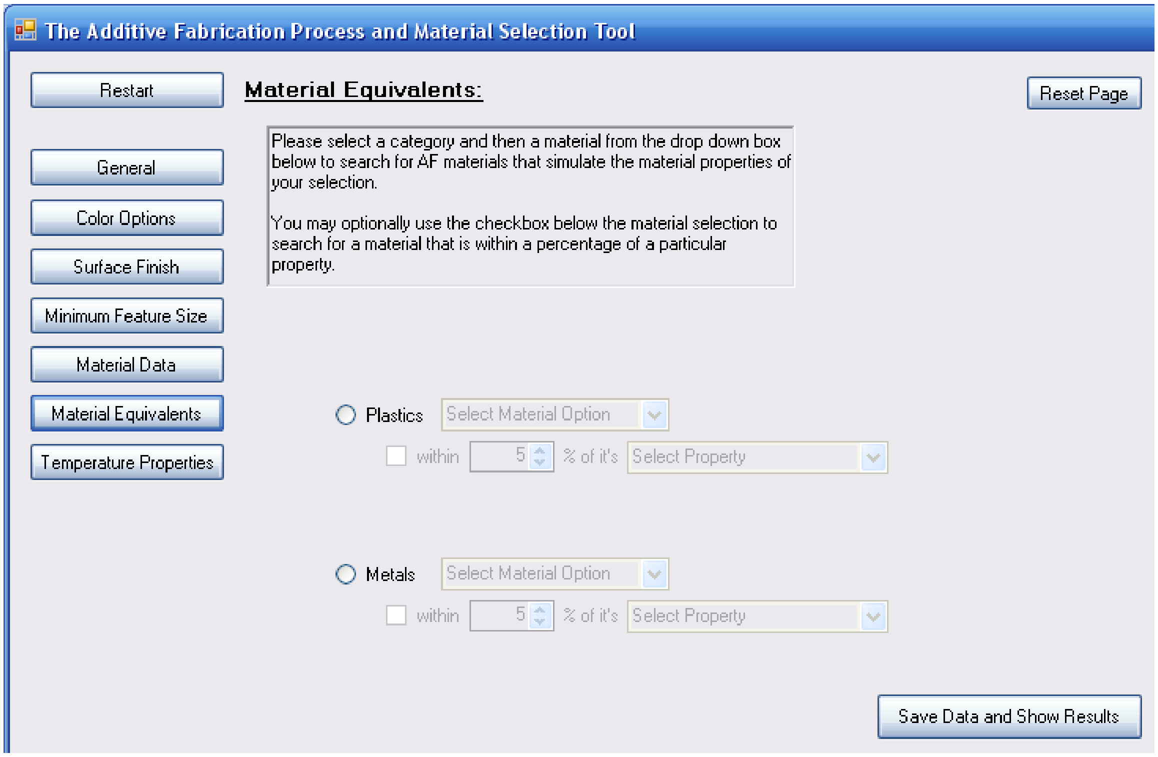
☐ Tensile Strength (ksi): From: 0 To: 1,000
☐ Modulus of Elasticity (ksi): From: 0 To: 1,000
☐ Flexural Strength (ksi): From: 0 To: 1,000
☐ Flexural Modulus (ksi): From: 0 To: 1,000
☐ Percent Elongation (%): From: 0 To: 1000
☐ Hardness: Select Scale From: 0 To: 100
☐ Izod Impact Stength (ft-lbs/in): From: 0.00 To: 10.00
☐ Izod Notched Impact (ft-lbs/in): From: 0.00 To: 10.00

Figure 21. Isolated view of the Mechanical Material Properties page.

These properties are simply used to filter through a database of values and eliminate non-qualifiers. In the instance that no results are returned within the user's given range, the nearest available results, both higher and lower than the entered range, will be presented along with the difference away from the boundary values as a percentage and a suggestion to relax the constraints on the range. The user also has the option to include or exclude any one of the properties during a search to see how the permutations of adding or removing various constraints on the properties affect the results. In cases where the data for a particular material's mechanical property is not available from the OEM datasheet the material will not be eliminated from the results however a note will be added to those results to that effect.

#### 3.3.4.6 Material Equivalents

The Material Equivalents page allows the user the option of selecting a desired material from the provided lists that he or she was intending on using or simulating. Once a desired material is selected the user can then utilize an optional search tool. The user may enter a percent range of a particular mechanical property. This is similar to the Mechanical Material Properties page but requires the user only know the name of the material her or she is attempting to simulate.



Please select a category and then a material from the drop down box below to search for AF materials that simulate the material properties of your selection.

You may optionally use the checkbox below the material selection to search for a material that is within a percentage of a particular property.

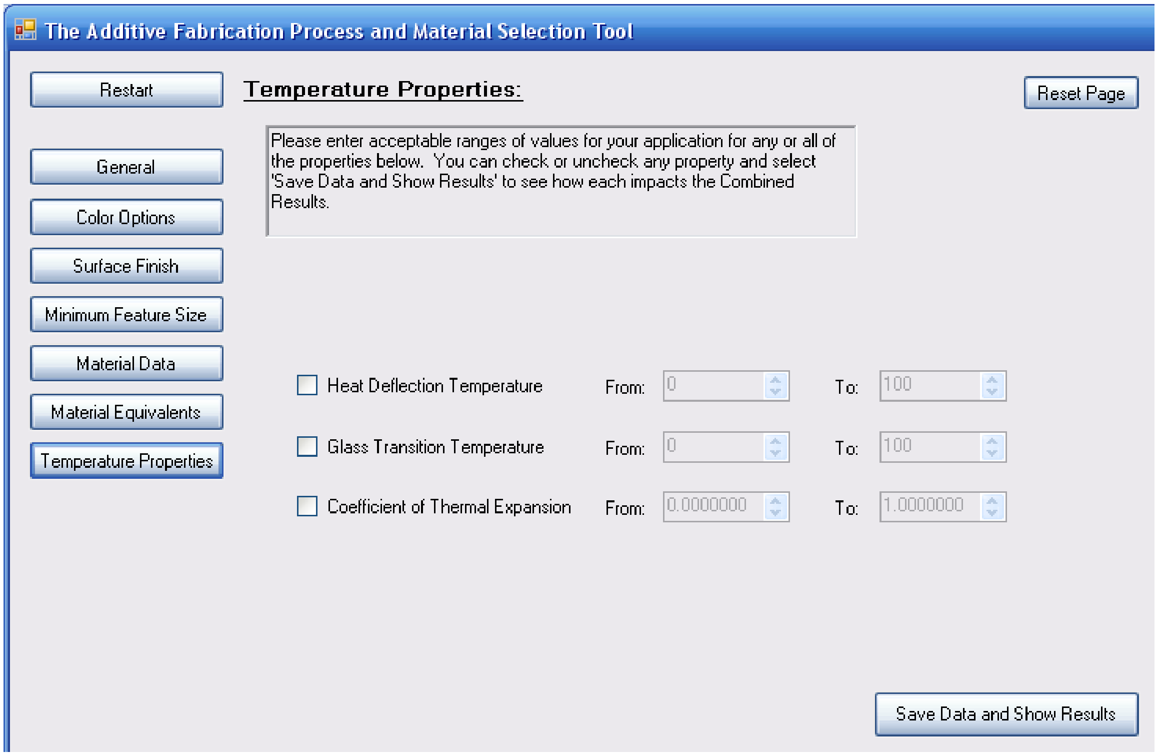
Figure 22. Isolated view of the Material Equivalents page.

There are two lists provided to the user, metals and plastics, which allows for a faster search by the user. The two lists are comprised of several unique Additive Fabrication materials, a few common production materials that are available for use in Additive Fabrication technologies, and several Additive Fabrication materials where the mechanical properties of that material are close to that of a common production material. It is not uncommon for an Additive Fabrication material to be advertised as “X-like” such as Polypropylene-like or ABS-like because their mechanical properties are very similar and provide a reasonable equivalent for cost effective testing purposes.

The ranges of values entered by the user are simply utilized to filter through a database of materials and eliminate non-qualifiers.

### 3.3.4.7 Temperature Properties

The Temperature Properties page offers several temperature properties for the user to enter acceptable ranges of values for any single property or all that are available. The properties made available to the user by the Additive Fabrication Process/Material Selection Tool are those that are commonly made available in most OEM material data sheets. They are Heat Deflection, Glass Transition Temperature, and the Coefficient of Thermal Expansion.



Please enter acceptable ranges of values for your application for any or all of the properties below. You can check or uncheck any property and select 'Save Data and Show Results' to see how each impacts the Combined Results.

☐ Heat Deflection Temperature From: 0 To: 100
☐ Glass Transition Temperature From: 0 To: 100
☐ Coefficient of Thermal Expansion From: 0.0000000 To: 1.0000000

Figure 23. Isolated view of the Temperature Properties page

These properties are simply used to filter through a database of values and eliminate non-qualifiers. In the instance that no results are returned within the user's given range, the nearest available results, both higher and lower, will be presented along with the difference away from the boundary value as a percentage along with a suggestion to relax the constraints on the range. The user also has the option to include or exclude any one of the properties during a search to see how the various permutations of adding or removing various constraints on the properties affect the results. In cases where the data for a particular material's temperature property is not available from the OEM datasheet the material will not be eliminated from the results however a note will be added to those results to that effect.

### 3.3.5 Explanation of the Results' Qualitative Measures and Suggestions

Once the user has completed any selection criteria and selected to show results, the results window fills with information based on the user's inputs. Some of the information presented to the user in the results window is of a qualitative nature based on the assumptions made in this paper. Other information is generated to provide suggestions to obtain more process and material results from the selection tool by the relaxation of certain ranges of values for specific selection criteria. Lastly, additional information is generated to provide suggestions for the potential consideration of other manufacturing processes to produce the part(s). These cases are discussed in further detail below.

#### 3.3.5.1 Cost as a Qualitative Measure in the Results

As it has been mentioned in the assumptions for the selection methodology, cost is computed for each process and material as a qualitative value. This is due to primarily to the assumption that the user has multiple service providers available to them which can vary prices greatly from process to process and material to material. Some providers may charge based on material usage while others by machine build time and others may use a combination of both factors.  There are a number of factors beyond even those most basic ones that may go into the end cost of a particular process and material from any given service provider and therefore the selection methodology only considers the known base cost of the material, general part information provided by the user, and some assumptions about the individual process to estimate a part cost as a qualitative measure.  Some of the factors that affect part cost that are considered for an individual Additive Fabrication process and material are discussed below:

The part's volume is simply used as a multiplier for the material cost to provide a baseline cost-of-goods estimate.

The part's minimum height (after orientation) is used as a multiplier for the individual process speeds to provide a portion of the build time cost factor.

The ability of certain processes to make use of efficiencies in the build process for multiple parts can affect how other processes compare in terms of cost.  Processes with these types of efficiencies can reduce the affect of the build time cost factor when multiple parts are being considered.

The part's volume to extents ratio (part volume/LWH of part extents) may be considered useful as it can provide an estimated amount of process time per layer which can then be added to the build time cost factor.

The part's size in relation to the individual process' build chamber size can create the need for sectioning of the part and post joining at additional estimated costs.

These factors are considered individually and then summed to produce a comparative value for cost for each of the individual processes and materials displayed in the results.

### 3.3.5.2 Production Speed as a Qualitative Measure in the Results

Production speed (or build time) is presented in the results section as a qualitative measure due to the assumptions that production speeds, in a real world, vary greatly by service provider and change from day to day. Production speed is presented primarily for consideration when larger quantities are desired which typically only then are build times more of a relevant factor in use of a service provider. The production speed result does not make use of part information but is rather a general qualitative rating for the specific process presented. If in the case that larger quantities are desired, additional grouping or pre-packing of parts can be performed manually which can lower build times and overall project durations beyond what can be currently managed by automated packing systems.

### 3.3.5.3 Suggestions for Other Manufacturing Processes in the Results

While Additive Fabrication has its advantages over conventional manufacturing techniques, it also has its drawbacks. Additive Fabrication technologies are typically best for applications that require small complex parts in low quantities—however, there are exceptions. The selection methodology assumes the user is intending on utilizing an Additive Fabrication technology but this may not always be the best option. The user should generally always ensure that a suitable off-the-shelf component cannot be sourced before considering designing and building a custom part. Additionally, some custom parts in low quantities may be machined in the actual production material for a cost comparable to that of an Additive Fabrication process that can only simulate the production material. In some instances, especially those of higher part quantities or metal materials, other manufacturing techniques such as plastic injection molding or machining or castings may be suggested in the results as a more economical route to the production of the part. The suggestions made in the results section will only serve as a note for consideration by the user and will not affect the actual resulting set of processes presented.

#### 3.3.5.4 Criteria Relaxation in the Results

With the current limitations for material and process options in Additive Fabrication, it is very likely that new users will enter inputs that will eliminate all or nearly all of the material and process options. This can easily occur, for example, when too tight of a range is entered into a mechanical property’s filter, resulting in only one result being returned. In instances like this the user may initially think they have found the only material that will meet their need when in actuality a broader range might have provided several results that could have worked just as well for the application or possibly better when combined with another category of the selection criteria.

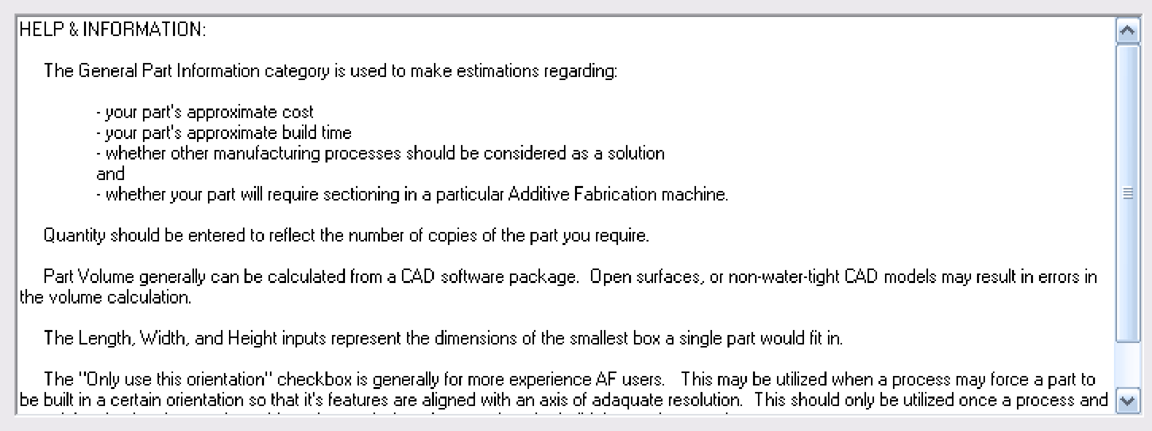
For these types of situations the selection tool’s results will give feedback to the user suggesting that a broader range is entered to provide additional results. The selection tool will also present a few other processes and materials that are the next closest to the boundary values provided along with a percent difference displayed. With this information the user will know that there are additional materials within a certain percent of what they initially hoped for and whether or not it is worth relaxing the filter range to allow for those results to be utilized in the final Combined Results section.

### 3.3.6 Explanation of the Help Window

The Help Window is shown under the selection criteria categories and its content type changes for each of the three selection classes to make use of examples and terminology used in those types of applications. The content itself will change when each of the selection criteria categories are selected for use to provide additional explanations and examples of the selection criteria.

The Help Window is designed to provide additional information to the user that is specific to the selection criteria category currently in use. This provides the user with additional guidance if necessary while keeping that information set aside so as to not overload the main areas with too much content.

An example of the Help Window can be seen in the following figure:



HELP & INFORMATION:

The General Part Information category is used to make estimations regarding:

- your part's approximate cost
- your part's approximate build time
- whether other manufacturing processes should be considered as a solution

and

- whether your part will require sectioning in a particular Additive Fabrication machine.

Quantity should be entered to reflect the number of copies of the part you require.

Part Volume generally can be calculated from a CAD software package. Open surfaces, or non-water-tight CAD models may result in errors in the volume calculation.

The Length, Width, and Height inputs represent the dimensions of the smallest box a single part would fit in.

The "Only use this orientation" checkbox is generally for more experience AF users. This may be utilized when a process may force a part to be built in a certain orientation so that it's features are aligned with an axis of adaquate resolution. This should only be utilized once a process and

Figure 24. The Help & Information window (help for the General Part Information category is currently displayed).

# CHAPTER 4: RESULTS

## 4.1 How the Results Are Presented

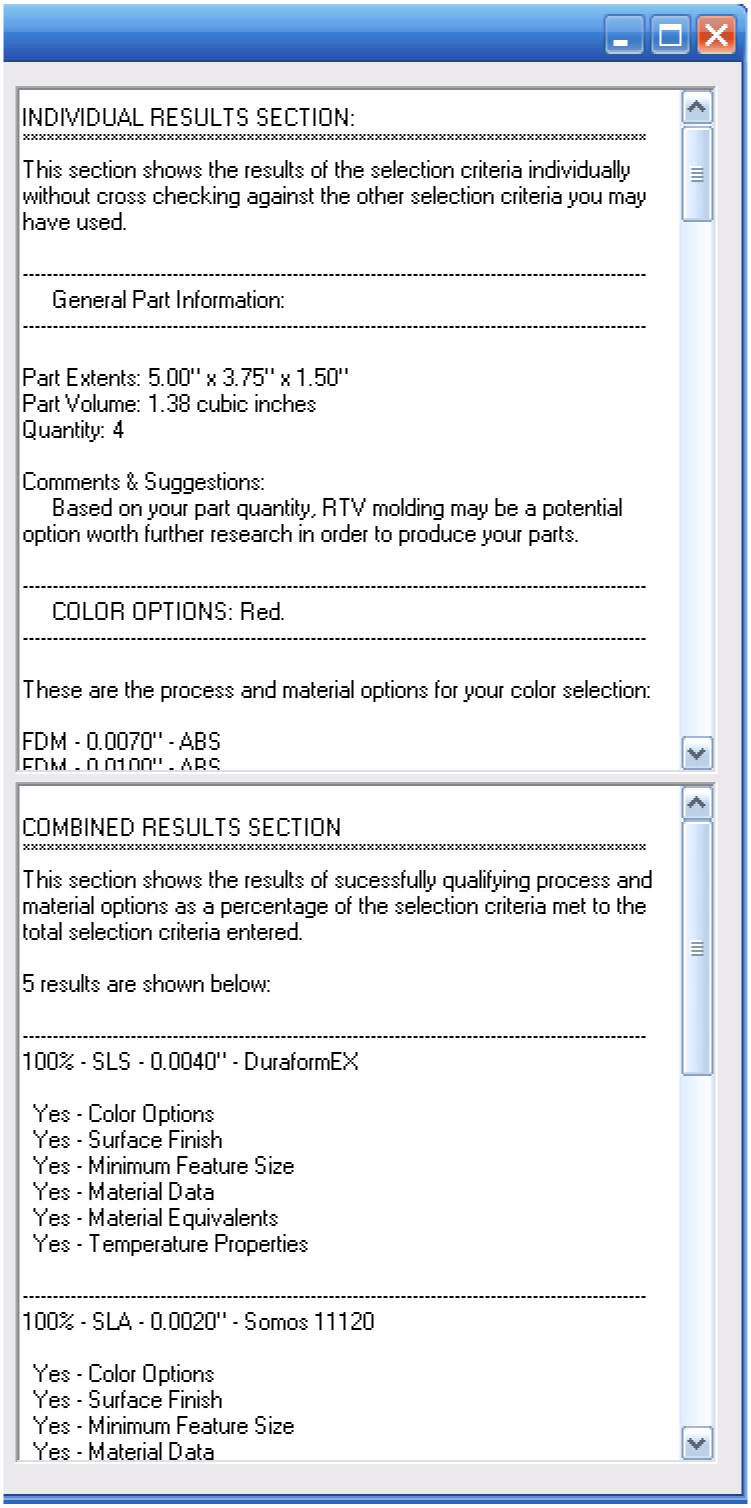
### 4.1.1 Visual Layout

Once the user has saved any entries in the selection criteria, the selection tool displays the results in a window to the right of the main selection criteria window. The results window is horizontally divided into two sections: the Individual Selection Criteria Results section and the Combined Results section. The top section displays the results for each of the selection criteria pages individually, without cross-checking against the other selection criteria pages' inputs. The bottom section displays a list of results from the combined viewpoints of all the selection criteria. All results, in both the top and bottom sections, are displayed as headers in the following format. The header format is shown below:

"PROCESS - LAYER THICKNESS - MATERIAL NAME"

An example of the format is shown below using the Stereolithography process with its layer thickness value set to 0.0020 of an inch while using the DSM Somos 11120 material:

Example: SLA – 0.0020" – 11120



INDIVIDUAL RESULTS SECTION:

This section shows the results of the selection criteria individually without cross checking against the other selection criteria you may have used.

General Part Information:

Part Extents: 5.00'' x 3.75'' x 1.50''
Part Volume: 1.38 cubic inches
Quantity: 4

Comments & Suggestions:
Based on your part quantity, RTV molding may be a potential option worth further research in order to produce your parts.

COLOR OPTIONS: Red.

These are the process and material options for your color selection:

FDM - 0.0070'' - ABS
FDM - 0.0100'' - ABS

COMBINED RESULTS SECTION

This section shows the results of sucessfully qualifying process and material options as a percentage of the selection criteria met to the total selection criteria entered.

5 results are shown below:

100% - SLS - 0.0040'' - DuraformEX

Yes - Color Options
Yes - Surface Finish
Yes - Minimum Feature Size
Yes - Material Data
Yes - Material Equivalents
Yes - Temperature Properties

100% - SLA - 0.0020'' - Somos 11120

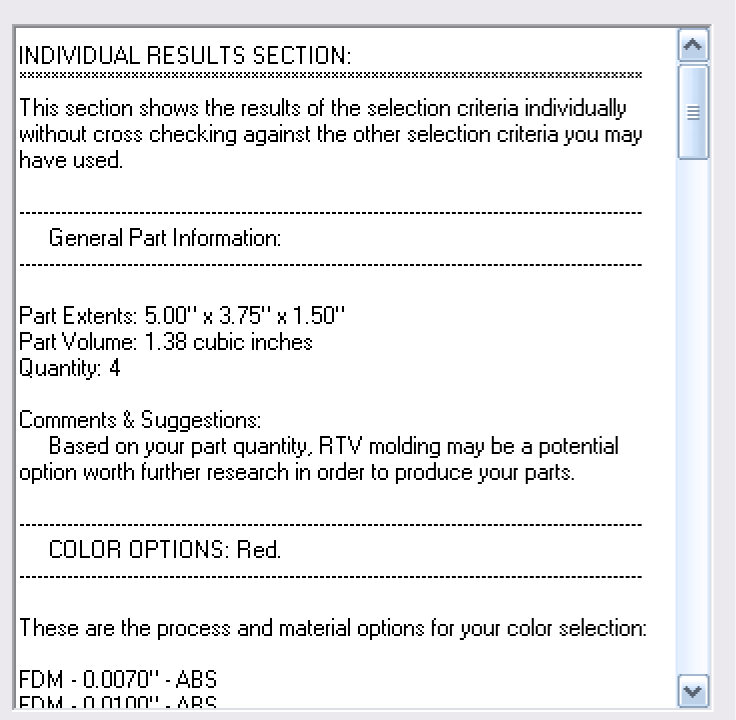
Yes - Color Options
Yes - Surface Finish
Yes - Minimum Feature Size
Yes - Material Data

Figure 25. Isolated view of the results window.

### 4.1.2 Detailed Description of the Results Window

#### 4.1.2.1 Individual Selection Criteria Results Section

The Individual Selection Criteria Results section of the Results window displays results for each selection criteria category (ex: Color Options page, Surface Finish page, etc) as if each were the only one in the selection tool utilized by the user. This means that each of the individual selection criteria categories operate independently of the entries made into the other selection criteria categories when calculating its results. The effect is that the user is able to see the results for each selection criteria page individually before they are affected by the other selection criteria pages. This is particularly useful when a user is especially focused on a critical selection criterion as it allows for the user to keep the processes that satisfy just that criteria visible, without loosing that information when other criteria is entered into the selection tool. Additionally, the user is able to diagnose why a specific process or material result that is showing up in their critical selection criteria's section is being excluded from the Combined Results section by seeing which of the other individual selection criteria results is lacking that particular result and therefore responsible for the exclusion of the process or material from the Combined Results section. The user has the option of then going back to experiment with relaxing the criteria responsible for excluding the specific process or material to see if it may then still be able to meet the application's requirements.



```
INDIVIDUAL RESULTS SECTION:
********************************************************************************
This section shows the results of the selection criteria individually
without cross checking against the other selection criteria you may
have used.

-----------------------------------------------------------------------------------------------------
    General Part Information:
-----------------------------------------------------------------------------------------------------

Part Extents: 5.00'' x 3.75'' x 1.50''
Part Volume: 1.38 cubic inches
Quantity: 4

Comments & Suggestions:
    Based on your part quantity, RTV molding may be a potential
option worth further research in order to produce your parts.

-----------------------------------------------------------------------------------------------------
    COLOR OPTIONS: Red.
-----------------------------------------------------------------------------------------------------

These are the process and material options for your color selection:

FDM - 0.0070'' - ABS
FDM - 0.0100'' - ABS
```

Figure 26. Isolated view of the Individual Results section.

In all instances where no results are returned, a suggestion to revisit the selection criteria and relax the requirements is displayed in a message box immediately after the inputs are saved by the user.

Each of the outputs for the Individual Selection Criteria Results section are discussed below.

The General Part Information page is summarized in the Individual Selection Criteria Results section under the General Comments header. The General Comments header displays the inputted values for the part's bounding box dimensions, volume, and the quantity required as well as makes suggestions based on part quantity as to whether other manufacturing processes should be explored in addition to AF technologies.

The Color Options header in the Individual Selection Criteria Results section simply lists all the materials and their associated processes that can produce the desired part color requirements.

The Surface Finish header in the Individual Selection Criteria Results section lists those groups of processes and materials that meet or exceed the qualitative measure entered by the user for each of the three surface quality cases. The Surface Finish header displays up to four lists: one for each of the three surface quality cases activated (vertical, horizontal, and non-orthogonal) and one list which considers any combination of the surface quality measures depending on which sliders were activated by the user.

The Minimum Feature Size header in the Individual Selection Criteria Results section lists all the processes and materials capable of producing parts that meet or exceed the minimum feature size and wall thickness requirements. The Minimum Feature Size header displays up to 3 lists: one list for the results of the minimum feature size, one list for the minimum wall thickness, and one which considers the combination of feature size requirements.

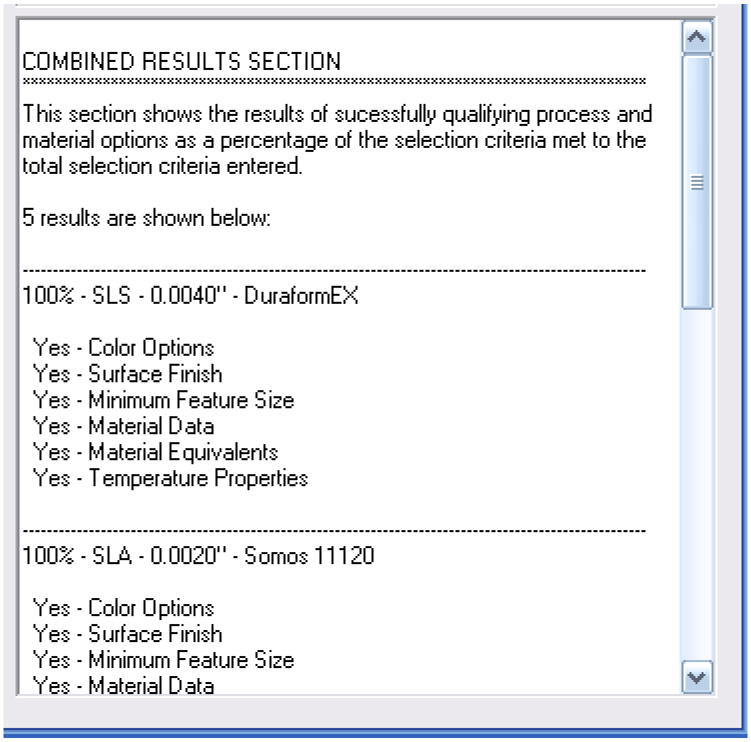
The Material Properties header in the Individual Selection Criteria Results section displays the materials and their associated processes that satisfy the desired mechanical material requirements in lists for each of the material properties activated by the user. The Material Properties header displays up to 9 lists: one for each of the mechanical material properties and one list which considers any combination of the mechanical material properties depending on which were activated by the user.

The Material Equivalents header in the Individual Selection Criteria Results section displays the materials and their associated processes that are capable of producing parts with or by simulating the user specified material. If the user has selected to use the optional method of searching for a material equivalent by a percent range of a particular mechanical material property, then the additional results for that query will be displayed in a second list.

The Temperature Properties header in the Individual Selection Criteria Results section displays the materials and their associated processes that satisfy the desired temperature property requirements in a list for each of the temperature properties activated by the user. The Temperature Properties header displays up to 4 lists: one for each of the temperature properties and one list which considers any combination of the temperature properties depending on which were activated by the user.

#### 4.1.2.2 Combined Results Section

The Combined Results section of the Results window begins with a header presenting the number of process and material results. The Combined Results section then displays a list of the qualifying processes and materials based on all of the combined selection criteria entered by the user. This list of process and material headers is accompanied by additional information listed below each header.



```
COMBINED RESULTS SECTION
*****************************************************************************************
This section shows the results of sucessfully qualifying process and
material options as a percentage of the selection criteria met to the
total selection criteria entered.

5 results are shown below:

-------------------------------------------------------------------------------------------------
100% - SLS - 0.0040" - DuraformEX

  Yes - Color Options
  Yes - Surface Finish
  Yes - Minimum Feature Size
  Yes - Material Data
  Yes - Material Equivalents
  Yes - Temperature Properties

-------------------------------------------------------------------------------------------------
100% - SLA - 0.0020" - Somos 11120

  Yes - Color Options
  Yes - Surface Finish
  Yes - Minimum Feature Size
  Yes - Material Data
```

Figure 27.  Isolated view of the Combined Results Section.

Below the process and material headers are each of the main selection criteria categories listed with indicators as to whether that process and material satisfied at least some of the selection criteria within that category.  For those categories with multiple selection criteria contained within (ex. Mechanical Material Properties), the category name is followed by a pair of parentheses containing the number of satisfied criteria out of the number of criteria entered by the user.  The general estimates can be found by clicking on the result's header.  The general estimates display estimates for the number of parts that can fit per build (or if there is a need for sectioning of the part), the relative per part cost, and the relative build speed for several AF machines for that process and material.

The process and material results are displayed as headers in the format that was discussed earlier and are preceded by their percentage of satisfied selection criteria.  The processes are ranked according to a percentage calculated by dividing the number of the selection criteria that were successfully met by the number of selection criteria that were entered by the user. Some of the main selection criteria categories are actually a collection of several individual selection criteria, as it is in the case of the Mechanical Material Properties page where each of the mechanical material properties are actually an individual selection criterion. For these cases, each of the individual selection criteria are counted in the summation of the successfully met selection criteria. This presents the user with an order for the process and material options such that those that have met the most selection criteria are displayed first. If the user is not satisfied with the results, the selection tool allows the user to dynamically edit any of the selection criteria and update the results with new process and material options at any given time.

## 4.2 Case Study for the Mechanical Components Selection Class

This case study will review the application of the Additive Fabrication Process and Material Selection Tool in the assistance of selecting an appropriate process and material for an application of Direct Digital Manufacturing using AF technologies which required the form, fit, and function of an electrical component housing for a small quantity production run.

### 4.2.1 Description of the Part and Application

This application of the selection tool considers the electrical component housing seen below.

Figure 28.  The electrical component housing used in the case study.

This part serves as a the front cover of an enclosure for several printed circuit boards (PCB) that combine to operate as a key-code access security panel for an entryway locking system in a industrial factory floor setting.  The appearance of the front cover of the housing required customization for a customer's specific requirements to such a degree that modification of the existing injection molded units was not possible. Additionally, once built, the customized housing component will require some finishing work to the external surfaces which includes painting the parts to a gloss finish as specified by the customer's requirements.  A total of four end use parts with a quick turn around time were required for the application, justifying the exploration of AF technologies as a solution.

As seen in the above figure, the exterior of the housing has a curved face with a series of holes of various sizes and shapes for an LCD display, numeric keypad, and LED lights.  The customer's company logo can be seen embossed in cut-in text on the front surface of the part.  When looking at the interior of the front cover, several mechanical type features can be seen.  This includes several snap features for assembly to an existing injection molded mounting plate, stand-offs for the several PCB components, and thin supporting ribs for several of the stand-offs.

### 4.2.2 Initiation of the Selection Process and the Selection Criteria Entries

The user begins by selecting one of the three part classes that best describes the application. The three classes presented to the user are *Mechanical Components*, *Architectural & Visual Display Models,* and *Pattern & Mold Production*. Since this part needs to meet several mechanical material requirements as well as serve as a final end use part that requires fit and functionality, the Mechanical Components class is selected.

With the selection of the Mechanical Components class the user interface adjusts its presentation for mechanical type applications.

The selection criteria window is now displayed in the upper left corner of the screen which, on its left, includes a column of buttons for each selection criteria category and, on its right, the selection criteria content and input fields. Below the selection criteria window is the Mechanical Components Help and Suggestions window which displays additional information regarding the particular selection criteria in use. This window is set aside from the selection criteria's content in order to reduce the volume of information displayed in one area and provide a quicker run-through of the selection process for the more experienced AF users. Adjacent to and to the right of both the selection criteria window and the Mechanical Components Help and Suggestions window is the Results window which at this point displays a description of each of the results sections of the Results window and how the user should consider using each during the selection process.

The General Part Information page defaults as the initial starting point. It accepts the approximate size of the part, volume, and required quantity. The part's extents and volume are measured in the designer's CAD program to be 5.00" x 3.75" x 1.50" and 2.14 cubic inches, respectively. As stated before, the application requires a total of four parts be produced so the part quantity value is increased to four.

The Color Options page is selected next as it is next in the column of buttons. The page suggests that the user select the "No Color Preference" option as it limits the number of results returned. Since the part will be finished and painted as an end use part the "No Color Preference" option is selected.

This application only required the use one of the three options listed in the Surface Finish page. The part's exterior surface consists almost entirely of curved, non-orthogonal surfaces which required a medium to high level of surface finish to minimize the finishing time required. The interior's surface is a shell of the exterior surface with the addition of the several vertical and horizontal mechanical features. The surface finish for these hidden interior features was not considered important and therefore no entries were made regarding the part's vertical or horizontal walls.

For the Minimum Feature Size page, the designers CAD package was again used to calculate the inputs. From a quick visual inspection of the part, the smallest feature of concern was found to be the company's embossed logo's cut depth with a dimension of 0.015". The minimum wall thickness on the part was found to be the thin support ribs for the stand-offs which measured 0.035" in width.

One of the main concerns for the application was the part's mechanical material properties when produced. It was decided by the designer that the main requirements used in the Mechanical Material Properties page would be the Flexural Modulus and the Izod Notched Impact Strength. All other mechanical material properties selection criteria were left inactive. The Flexural Modulus was utilized because of the need to ensure the snap fits would work as designed. Therefore the designer chose a range for the Flexural Modulus using values of commonly used production materials. The lower end of the range started at a value similar to molded Polypropylene of 200,000 psi and on the high end of the range maxed out at a value similar to molded ABS plastic of 400,000 psi. For the Izod Notched Impact Strength range, a range of 0.50 to 2.5 was entered.

The next selection criteria category in the column of selection criteria buttons is the Material Equivalents button. Plastics were selected to keep costs low and to stay consistent with the design intent for the use of snap features for assembly. From the plastics drop-down box several materials were thought to be possibly suitable by the designer but through trials and examination of the results Polypropylene plastic was selected. The optional usage of the mechanical material requirements was not necessary for this application because the designer had specific values available to him which were used in the Mechanical Material Properties page.

The application only required the use of one of the selection criteria in the Temperature Properties page. The part would generally not experience any extreme environments however it was possible for the factory environment to have a slightly elevated room temperature. The Heat Deflection Temperature was given a range of 100 to 200 degrees Celsius to meet this requirement.

### 4.2.3 The Individual Selection Criteria Results

As the user has saved into the system the inputs or changes to each page, the Results window updates its information. The individual results for each of the selection criteria categories are discussed below in the order they appear to the user. All lists of process and material results displayed in the Individual Selection Criteria Results section conform to the format discussed earlier.

The first result displayed in the Individual Selection Criteria Results section is the summary of the inputs to the General Part Information page. The part's bounding box dimensions, volume, and quantity are displayed for reference. Below those items is a paragraph that is inserted based on the quantity which describes the potential consideration for the use of RTV molds and urethane castings as a possible solution for the application. This is suggested because a quantity of four units may justify the additional set-up cost of a poured rubber mold, for example, in order to gain better material properties if the results failed to return any processes based on the ranges entered.

The Color Options page presents, in this case, just a single line of text that indicates the user selected “No Color Preference” which will have no effect on the Combined Results.

For this application only non-orthogonal surface finishes were considered therefore the individual results for the Surface Finish section of the results displays a single line of text indicating to the user that the processes and materials shown meet the medium level non-orthogonal surface finish requirement. The list of qualifying processes and materials is then shown below.

The Minimum Feature Size returns a line of text indicating that the list shown of processes and materials satisfy the requirements for a 0.015” minimum feature size and a 0.035” minimum wall thickness.

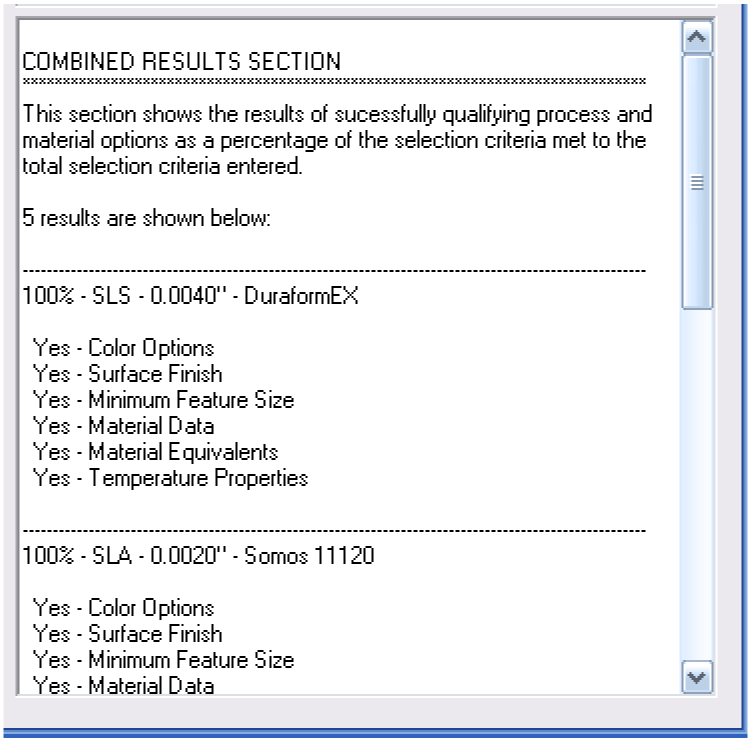
The Mechanical Material Properties individual results section begins with a short paragraph informing the user that the Mechanical Material Properties results may require iterations of adjustments to the values entered into the ranges to provide a reasonable number of options for the user to choose from.  The results then show a separate list of results for each of the mechanical material property selection criteria activated with the nominal values for the property considered by the user shown next to the material and associated process name.  In this application a list of results is presented for the Flexural Modulus and for the Izod Notched Impact Strength based on the user’s entered ranges. The Mechanical Material Properties individual results section then shows a list of processes and materials that meet the combination of mechanical material properties, again, with each result showing the nominal values for the material properties considered by the user.

The Material Equivalents individual results section displays a line of text indicating that the list shown of processes and materials are capable of simulating or using Polypropylene plastic.  When the material is only a simulator of the required material, the list provides an additional descriptor in parenthesis for the material name indicating that it is a simulator of desired material.

The Temperature Properties individual results section begins with a short paragraph informing the user that the Temperature Properties results may require iterations of adjustments to the values entered into the ranges to provide a reasonable number of options for the user to choose from. The results then show a separate list of results for each of the temperature property selection criteria activated with the nominal values for the property considered by the user shown next to the material and associated process name. In this application a list of results is presented for the Heat Deflection Temperature based on the user's entered ranges. If additional temperature properties were entered, the Temperature Properties individual results section would then show a list of processes and materials that met the combination of temperature properties with each result showing the nominal values for the temperature properties considered by the user.

### 4.2.4 The Combined Results

In the Combined Results section of the Results window, a header is displayed indicating that 5 processes and materials met all the qualifications. The process and material results are ranked according a percentage of the number of the selection criteria that were successfully met. The top 2 combined results can be seen in the figure below.



```
COMBINED RESULTS SECTION
********************************************************************************
This section shows the results of sucessfully qualifying process and
material options as a percentage of the selection criteria met to the
total selection criteria entered.

5 results are shown below:

--------------------------------------------------------------------------------
100% - SLS - 0.0040'' - DuraformEX

  Yes - Color Options
  Yes - Surface Finish
  Yes - Minimum Feature Size
  Yes - Material Data
  Yes - Material Equivalents
  Yes - Temperature Properties


--------------------------------------------------------------------------------
100% - SLA - 0.0020'' - Somos 11120

  Yes - Color Options
  Yes - Surface Finish
  Yes - Minimum Feature Size
  Yes - Material Data
```

Figure 29. The Combined Results section.

The top three results shown tied for first place which were then ranked by alphabetical order.

The first result shown was SLS – DuraformEX – 0.004” meeting 100% of the combined selection criteria. This material fully satisfied the requirements for the surface finish, minimum feature size, flexural modulus, Izod notched impact strength, material equivalents, and heat deflection temperature.

The second result shown was SLA – 11120 – 0.002” meeting 100% of the combined selection criteria. This material fully satisfied the requirements for the surface finish, minimum feature size, flexural modulus, Izod notched impact strength, material equivalents, and temperature properties.

The third result shown was SLA – 11120 – 0.004” meeting 100% of the combined selection criteria. This material fully satisfied the requirements for the surface finish, minimum feature size, flexural modulus, Izod notched impact strength, material equivalents, and temperature properties.

The fourth result show was Polyjet – DurusWhite – 0.0006” meeting 60% of the combined selection criteria. This material fully satisfied the requirements for the surface finish, minimum feature size, Izod notched impact strength, and material equivalents. DurusWhite fell below the flexural modulus range and below the heat deflection temperature range.

The fifth result shown was FDM – ABS – 0.007” meeting 40% of the combined selection criteria. This material fully satisfied the requirements for the minimum feature size and temperature properties. ABS plastic in the FDM process did not meet the medium surface finish requirement, was below the range for the flexural modulus, and did not match the Polypropylene requirement.

It can clearly be seen that a significant number of material and process selection options were found to be acceptable solutions for this application. From this point in the results the user can choose from the list of AF options presented or revisit some of the selection criteria and adjust various entries to narrow or expand the results as needed.

# CHAPTER 5: CONCLUSION

This paper discussed the design and implementation of an Additive Fabrication Process and Material Selection Tool.  Currently, the common practice in the industry is still to use a human expert and a database of available materials to assist users of AF in the selection of a material and process.  This selection tool was designed because as the industry continues to increase the number of material options and invent new processes, the growing number and variety of users of AF technologies will require some expert knowledge-based assistance in the selection of a process and material for their application.  This selection tool attempts to solve many of the common real world issues to the process of selecting appropriate AF processes and materials.

Several assumptions and logic have been gathered from industry experts and the author’s years of personal experience as a service provider which have been assembled into a set of rules and logic for a computer based application to assist users of AF in finding a set of best qualifying options to choose from for the production of their parts.

This tool serves to correct, improve upon, and update many of the concepts covered in the existing literature.  An increase in the number of materials and processes considered by the tool has been implemented.  An increase in the number and types of selection criteria has been implemented.  The system returns results without the need to enter large amounts of data.  The selection tool’s user can choose from any single or multiple selection criteria and still receive results.  The use of quantitative measures for criteria that is feature based has been more appropriately updated to be a qualitative measure.  The selection tool considers build time as an outputted result and considers efficiencies in those certain AF processes that benefit from multi-part builds in calculating that result. The system does not hard code a rank of importance for selection criteria and leaves the decision as to which criterion is more important for the application to the user. These are just some of the most important improvements to the existing literature that the system has implemented.

With theses improvements and corrections, a user, regardless of their level of technical knowledge, can quickly and easily filter through the increasingly large number of AF processes and materials in order to produce a physical reproduction of any part.

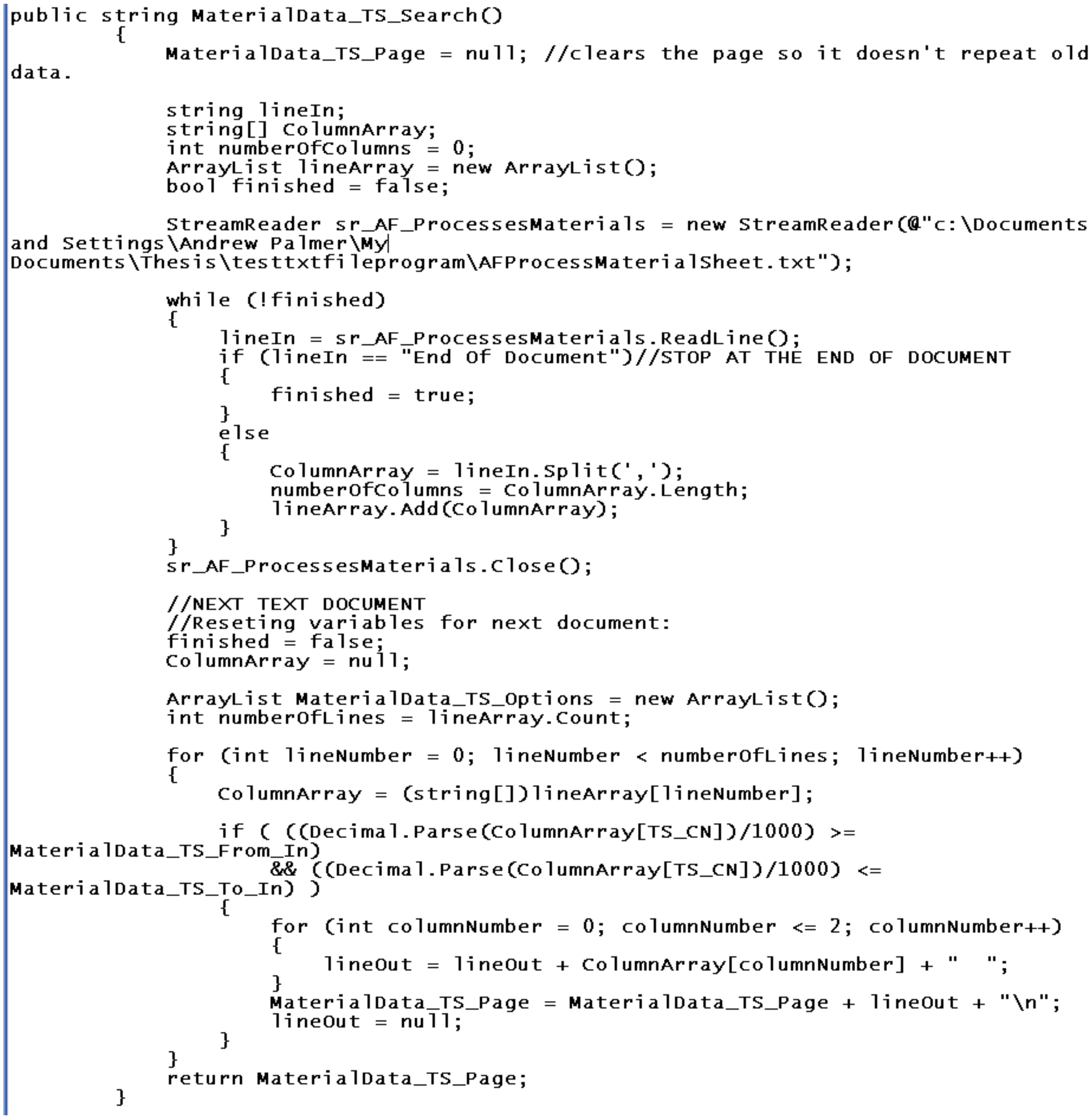
Lastly, a case study was presented to explain the use of the selection tool, demonstrate its functionality, and illustrate the outputted results.

# CHAPTER 6: FUTURE WORK

This work and research will continue in the form of several additions and improvements to the selection tool. The tool will be kept up to date with current materials and processes as they introduced or discontinued. As additional standardized data is made available, more information will be made available to the user to aid in the selection process as well as serve for educational purposes. The selection tool will be capable of creating and saving vendor or in-house capability profiles to allow searches that isolate only those processes that may be available to the user. The selection tool will include a Medical Applications selection class to assist doctors and surgeons in selecting processes and materials for their specialized uses of AF such as the production of surgical implants, scan data models, and certified materials. The user’s STL file will be displayed in a 3D environment which will allow the user to inspect and make manual measurements of the model such as part volume, extents, surface area, and specific feature sizes. Lastly the selection tool will include additional information on conventional manufacturing as well as include some processes in the results presented to the user.

# APPENDIX A: SAMPLE CODE

Sample of Computer Code, The Tensile Strength Property Search:



```
public string MaterialData_TS_Search()
        {
            MaterialData_TS_Page = null; //clears the page so it doesn't repeat old
data.

            string lineIn;
            string[] ColumnArray;
            int numberOfColumns = 0;
            ArrayList lineArray = new ArrayList();
            bool finished = false;

            StreamReader sr_AF_ProcessesMaterials = new StreamReader(@"c:\Documents
and Settings\Andrew Palmer\My
Documents\Thesis\testtxtfileprogram\AFProcessMaterialSheet.txt");

            while (!finished)
            {
                lineIn = sr_AF_ProcessesMaterials.ReadLine();
                if (lineIn == "End Of Document")//STOP AT THE END OF DOCUMENT
                {
                    finished = true;
                }
                else
                {
                    ColumnArray = lineIn.Split(',');
                    numberOfColumns = ColumnArray.Length;
                    lineArray.Add(ColumnArray);
                }
            }
            sr_AF_ProcessesMaterials.Close();

            //NEXT TEXT DOCUMENT
            //Reseting variables for next document:
            finished = false;
            ColumnArray = null;

            ArrayList MaterialData_TS_Options = new ArrayList();
            int numberOfLines = lineArray.Count;

            for (int lineNumber = 0; lineNumber < numberOfLines; lineNumber++)
            {
                ColumnArray = (string[])lineArray[lineNumber];

                if ( ((Decimal.Parse(ColumnArray[TS_CN])/1000) >=
MaterialData_TS_From_In)
                    && ((Decimal.Parse(ColumnArray[TS_CN])/1000) <=
MaterialData_TS_To_In) )
                {
                    for (int columnNumber = 0; columnNumber <= 2; columnNumber++)
                    {
                        lineOut = lineOut + ColumnArray[columnNumber] + "  ";
                    }
                    MaterialData_TS_Page = MaterialData_TS_Page + lineOut + "\n";
                    lineOut = null;
                }
            }
            return MaterialData_TS_Page;
        }
```

## Sample of Computer Code, The Vertical Surface Finish Search:

```
public string SurfaceFinishVerticalSearch()
        {
            SurfaceFinish_Page = null; //clears the page so it doesn't repeat old data.

            string lineIn;
            string[] ColumnArray;
            int numberOfColumns = 0;
            ArrayList lineArray = new ArrayList();
            bool finished = false;

            StreamReader sr_AF_ProcessesMaterials = new StreamReader(@"c:\Documents and
Settings\Andrew Palmer\My Documents\Thesis\testtxtfileprogram\AFProcessMaterialSheet.txt");

            while (!finished)
            {
                lineIn = sr_AF_ProcessesMaterials.ReadLine();
                if (lineIn == "End Of Document")//STOP AT THE END OF DOCUMENT
                {
                    finished = true;
                }
                else
                {
                    ColumnArray = lineIn.Split(',');
                    numberOfColumns = ColumnArray.Length;
                    lineArray.Add(ColumnArray);
                }
            }
            sr_AF_ProcessesMaterials.Close();

            //NEXT TEXT DOCUMENT
            //Reseting variables for next document:
            finished = false;
            ColumnArray = null;

            ArrayList SurfaceFinishOptions = new ArrayList();
            int numberOfLines = lineArray.Count;

            for (int lineNumber = 0; lineNumber < numberOfLines; lineNumber++)
            {
                ColumnArray = (string[])lineArray[lineNumber];

                if (VerticalSurfaceFinish_In <=
Int32.Parse(ColumnArray[VerticalSurfaceQuality_CN]))
                {
                    for (int columnNumber = 0; columnNumber <= 2; columnNumber++)
                    {
                        lineOut = lineOut + ColumnArray[columnNumber] + "  ";
                    }
                    SurfaceFinish_Page = SurfaceFinish_Page + lineOut + "\n";
                    lineOut = null;
                }
            }
            return SurfaceFinish_Page;
        }
```

# APPENDIX B:  SAMPLE TABLE OF PROCESSES AND MATERIALS

# Sample Table of AF Processes and Materials

| PROCESS | MATERIAL | LAYER THICKNESS | Approx. Material Cost, $/cu.in | Vertical Surface Quality (0-2) | Horizontal Surface Quality (0-2) | NonOrtho Surface Quality (0-2) | Minimum Feature Size | Minimum Wall Thickness | TS (psi) | E (psi) | FS (psi) | FM (psi) | %Elongation | Hardness | Hardness Scale | Izod Impact (ft-lb/in) | Izod Notched (ft-lb/in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4.00 | 5 | 6 | 7 | 8.0000 | 9.0000 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18.00 |
| FDM | ABS | 0.0070 | 5.00 | 1 | 1 | 1 | 0.0150 | 0.0150 | 3200 | 236000 | 6000 | 266000 | 6 | R105 | Rockwell | 4.0 | 2.00 |
| FDM | ABS | 0.0100 | 5.00 | 0 | 1 | 0 | 0.0200 | 0.0200 | 3200 | 236000 | 6000 | 266000 | 6 | R106 | Rockwell | 4.0 | 2.00 |
| FDM | ABS | 0.0130 | 5.00 | 0 | 0 | 0 | 0.0300 | 0.0300 | 3200 | 236000 | 6000 | 266000 | 6 | R107 | Rockwell | 4.0 | 2.00 |
| FDM | ABSi | 0.0050 | 7.00 | 1 | 1 | 1 | 0.0100 | 0.0100 | 5400 | 277700 | 8830 | 264000 | 3.1 | R108 | Rockwell | 4.1 | 1.90 |
| FDM | ABSi | 0.0070 | 7.00 | 1 | 1 | 1 | 0.0150 | 0.0150 | 5400 | 277700 | 8830 | 264000 | 3.1 | R109 | Rockwell | 4.1 | 1.90 |
| FDM | ABSi | 0.0100 | 7.00 | 0 | 1 | 0 | 0.0200 | 0.0200 | 5400 | 277700 | 8830 | 264000 | 3.1 | R110 | Rockwell | 4.1 | 1.90 |
| FDM | ABSi | 0.0130 | 7.00 | 0 | 0 | 0 | 0.0300 | 0.0300 | 5400 | 277700 | 8830 | 264000 | 3.1 | R111 | Rockwell | 4.1 | 1.90 |
| FDM | ABS-Plus | 0.0070 | 7.00 | 1 | 1 | 1 | 0.0150 | 0.0150 | 5295 | 329500 | 7604 | 319737 | 4 | 0 | 0 | 0.0 | 1.80 |
| FDM | ABS-Plus | 0.0100 | 7.00 | 0 | 1 | 0 | 0.0200 | 0.0200 | 5295 | 329500 | 7604 | 319737 | 4 | 0 | 0 | 0.0 | 1.80 |
| Polyjet | FullCure720 | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 6090 | 309000 | 10200 | 286800 | 20 | 0 | 0 | 0.0 | 0.55 |
| Polyjet | VeroWhite | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 7221 | 361775 | 10817 | 309865 | 20 | 83 | Shore D | 0.0 | 0.45 |
| Polyjet | VeroBlue | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 7990 | 397300 | 12122 | 287535 | 20 | 83 | Shore D | 0.0 | 0.44 |
| Polyjet | VeroBlack | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 7352 | 317840 | 11542 | 330020 | 18 | 83 | Shore D | 0.0 | 0.45 |
| Polyjet | TangoGrey | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 632 | 0 | 0 | 0 | 47 | 75 | Shore A | 0.0 | 0.00 |
| Polyjet | TangoBlack | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 290 | 0 | 0 | 0 | 47.7 | 61 | Shore A | 0.0 | 0.00 |
| Polyjet | TangoPlus | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 211 | 0 | 0 | 0 | 218 | 27 | Shore A | 0.0 | 0.00 |
| Polyjet | DurusWhite | 0.0006 | 12.00 | 2 | 2 | 2 | 0.0100 | 0.0200 | 3089 | 164691 | 4814 | 148785 | 44 | 76 | Scale D | 0.0 | 0.83 |
| SLA | Somos 11120 | 0.004 | 15.00 | 2 | 2 | 1 | 0.0200 | 0.0300 | 7200 | 400000 | 9900 | 320000 | 15 | 0 | 0 | 0.0 | 0.50 |
| SLA | Somos 11120 | 0.002 | 15.00 | 2 | 2 | 2 | 0.0200 | 0.0200 | 7200 | 400000 | 9900 | 320000 | 15 | 0 | 0 | 0.0 | 0.50 |

| HD (F) | GT (F) | TE (in/in/F) | Material Equivalent 1 | Material Equivalent 2 | Material Equivalent 3 | COLOR 1 | COLOR 2 | COLOR 3 | COLOR 4 | COLOR 5 | COLOR 6 | COLOR 7 | COLOR 8 | COLOR 9 | COLOR 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 |
| 195 | 219 | 5.60E-05 | ABS | 0 | 0 | White | Black | Blue | Red | Green | Yellow | Grey | 0 | 0 | 0 |
| 195 | 219 | 5.60E-05 | ABS | 0 | 0 | White | Black | Blue | Red | Green | Yellow | Grey | 0 | 0 | 0 |
| 195 | 219 | 5.60E-05 | ABS | 0 | 0 | White | Black | Blue | Red | Green | Yellow | Grey | 0 | 0 | 0 |
| 188 | 240 | 6.70E-06 | ABS | 0 | 0 | Translucent-Natural | Translucent-Red | Translucent-Amber | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 188 | 240 | 6.70E-06 | ABS | 0 | 0 | Translucent-Natural | Translucent-Red | Translucent-Amber | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 188 | 240 | 6.70E-06 | ABS | 0 | 0 | Translucent-Natural | Translucent-Red | Translucent-Amber | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 188 | 240 | 6.70E-06 | ABS | 0 | 0 | Translucent-Natural | Translucent-Red | Translucent-Amber | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 204 | 0 | 4.90E-05 | ABS | 0 | 0 | Natural | White | Black | Dark-Grey | Blue | Red | Orange | Fluorescent-Yellow | Olive-Green | 0 |
| 204 | 0 | 4.90E-05 | ABS | 0 | 0 | Natural | White | Black | Dark-Grey | Blue | Red | Orange | Fluorescent-Yellow | Olive-Green | 0 |
| 109 | 0 | 0 | 0 | 0 | 0 | Semi-Tranparent Amber | | | | | | | | | |
| 109 | 136 | 0 | 0 | 0 | 0 | White | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 120 | 120 | 0 | 0 | 0 | 0 | Light Blue | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 117 | 145 | 0 | 0 | 0 | 0 | Black | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 37 | 0 | 0 | 0 | 0 | Light Gray | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 13 | 0 | 0 | 0 | 0 | Black | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 15 | 0 | 0 | 0 | 0 | Semi-Tranparent Amber | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 98 | 97 | 0 | Polypropylene | 0 | 0 | Off White | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 120 | 105 | 0 | ABS | Polybutylene Terephthalate | 0 | Clear | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 120 | 105 | 0 | ABS | Polybutylene Terephthalate | 0 | Clear | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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