Review, Selection and Installation of a Rapid Prototype Machine

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Date:
October 19, 2008

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I. Objective

The objective of this paper is to impress upon the reader the benefits and advantages of investing in rapid prototyping (additive manufacturing) technology thru the procurement of one or two new rapid prototyping machines and the creation of a new Prototype and Model Lab at the Kennedy Space Center (KSC). This new resource will be available to all of United Space Alliance, LLC (USA), enabling engineers from around the company to pursue a more effective means of communication and design with our co-workers, and our customer, the National Aeronautics and Space Administration (NASA).

II. Background

The Rapid Protoyping/3D printing industry mirrors the transition the CAD industry made several years ago, when companies were trying to justify the expenditure of converting to a 3D based system from a 2D based system. The advantages of using a 3D system seemed to be outweighed by the cost it would take to convert not only legacy 2D drawings into 3D models but the training of personnel to use the 3D CAD software. But the reality was that when a 3D CAD system is employed, it gives engineers a much greater ability to conceive new designs and the ability to engineer new tools and products much more effectively.

Rapid Prototyping (RP) is the name given to a host of related technologies that are used to fabricate physical objects directly from Computer Aided Design (CAD) data sources. These methods are generally similar to each other in that they add and bond materials in a layer wise-fashion to form objects, instead of machining away material. The machines used in Rapid Prototyping are also sometimes referred to as Rapid Manufacturing machines due to the fact that some of the parts fabricated in a RP machine can be used as the finished product. The name "Rapid Prototyping" is really a misnomer. It is much more than prototypes and it is not always rapid. Rapid Prototyping is also known as:

- Direct Digital Manufacturing (DDM)
- Rapid Manufacturing (RM)
- Desktop Manufacturing (DTM)
- Solid Freeform Fabrication (SFF)
- Freeform Fabrication (FFF)
- Layered Manufacturing
- Additive Fabrication

For the remainder of this paper, the technology of rapid prototyping and additive layer manufacturing shall be referred to as RP.

A. Terms and Concepts

There are a few major concepts and terms that need to be defined prior to evaluating the various technologies.

- **Anisotropic**: Refers to the fact that parts may have different physical properties depending on which direction measurements are made, and such differences can also arise if the exact same part is made in a different way. This can happen if the building orientation of the part in the machine is changed, and also from the sequence in which the part's elements are fabricated. [1]
- **Build layer**: All systems apply or deposit material in an XY plane, also referred to as the build layer or build section.[2]

- **Build Thickness**: This is the thickness of the material deposited, and has a direct impact on the model's surface finish and accuracy. Typically a table drops along the Z-axis the build layer thickness.[2]
- **Support method**: Part geometries which overhang need to be supported during the build process until the point that the model material is cured, or otherwise hardened, such that it can support its own weight. This is usually accomplished by building a support structure along with the model itself, or by supporting the overhang in build powder.[2]
- **Support Removal**: Most RP systems require that the support material be removed. This includes the removal of build powder, or removal of build supports (most are water soluble).[2]
- **Cure method**: The way in which the deposited materials bond together to produce a finished product. This also may include some post-build processing to ensure that the object has the desired strength. Some need to be cured in a light box; others require the part to be coated to increase part strength.
- **Digital Manufacturing:** The phrase used, in a variety of RP systems, to denote that a machine can not only fabricate prototypes, but fully also functional daily use parts.
- **STL file**: the Stereo-lithography tessellation file refers to the representation of 3D forms as boundary representation solid models constructed entirely of triangular facets. This is the industry standard file format, which most RP equipment can read. The RP equipment reads the data, adds support geometry if required, and then converts the information into machine-specific commands.[2]

B. Types of Rapid Prototyping Systems

The method by which layers are bonded together to produce a finished product varies from machine to machine. The most popular methods are listed below:

SLA – Stereo Lithography Apparatus

Stereolithography (SLA) was first developed by 3D Systems Corporation in 1986 and was the pioneer of Rapid Prototyping technologies. SLA is the most popular rapid prototyping method, and sometimes the word stereolithography is used as a synonym for rapid prototyping. It is an additive fabrication process in which a vat of ultraviolet-curable liquid sits underneath a UV laser that traces cross-section patterns onto the liquid one layer at a time. When the laser comes in contact with the liquid it solidifies. A support platform then lowers the cured layer and the laser traces the next layer on top. SLA machines usually produce acrylic blend parts that can simulate ABS, Polycarbonate, Nylon and Polypropylene. SLA is regarded as the most precise method of rapid prototyping, but the process of handling the liquid can be messy, and parts made from this process are susceptible to UV radiation and may degrade and become brittle over time.

SLS – Selective Laser Sintering

Selective Laser Sintering (SLS) uses a high powered laser to fuse together fine particles of plastic powder one layer at a time. SLS parts are made by laying down a thin layer of nylon powder, then a laser "draws" a cross section onto the nylon, fusing the particles of nylon together in the area of the laser beam. A roller system then distributes another layer of nylon powder over the last. Because of the possible volatility of the plastic powder, the whole operation is done inside a chamber that is purged with nitrogen. There is no need for a support material or system because the un-sintered powder particles act as the support material. When the machine has finished the last layer, the parts are allowed to cool slowly. The powder "cake" is then removed from the build chamber and the un-sintered powder is saved to be mixed in with virgin powder for another build. Most SLS parts are nylon based materials that be interspersed (or filled) with glass, carbon or ceramic particles, increasing the strength and properties of the final product.

FDM – Fused Deposition Modeling

Fused Deposition Modeling (FDM) extrudes a thin thread of plastic (somewhat like a weed-whacker string) thru a hot metal tip that temporarily melts the plastic as it traces cross-section patterns layer by layer. As the plastic cools, it hardens into a durable part. In order to support overhanging sections of a part, FDM uses a separate support material that is extruded in the same manner as the build material. The support material then has to be removed by either breaking it from the part or by dissolving it in a water soluble bath. FDM machines can produce parts made of ABS, Polycarbonate, an ABS/Polycarbonate blend and Polyphenylsulfone (PPS). The main deterrent of this technology is that the finished parts are highly anisotropic and tend to break between the build layers.

3DP – Three Dimensional Printing

Three-Dimensional Printing uses ink-jet printer technology to "print" onto a thin layer of powder with color and a binder (glue). This is the only technology that can fabricate parts in full color. Several other machines can print in color, but only one color at a time. 3DP machines can produce parts made of plaster like materials that can be infiltrated or coated with epoxy to help harden the material. Parts can also be strengthened by varying the type of powder and the binding glue.

MJM – Multi-Jet Modeling

Multi-Jet Modeling is a group of machines that build parts by squirting a photopolymeric build material in a liquid or melted state which cools or otherwise hardens to form a solid on impact, or by using UV light to cure the particles together. MJM machines can produce parts made out of acrylic blends.

FTI – Film Transfer Imaging

In film transfer imaging, a thin layer of material is dispensed onto a reciprocating film cartridge. The cartridge, which looks like an oversized camera film cassette, reciprocates in a motion similar to that of film in a camera. At each reciprocating movement, the cartridge brings a fresh layer of material onto the build surface, which is then imaged with UV flash photography one layer at a time.[3]

DMLS – Direct Metal Laser Sintering

Direct Metal Laser Sintering is based upon the same technology as Selective Laser Sintering, in which a bed of fine metal powder is heated and fused together using a high powered laser. This technology can be used to produce parts made of Titanium, Stainless Steel, Cobalt Chrome, 17-4 Steel, Inconel, Hasteloy and in the future will be able to produce Aluminum parts.

C. USA's Current Capabilities and Resources

USA currently owns four rapid prototyping machines, all of which are limited in their capability.

- ***Integrated Logistics***

  The Logistics and Materials directorate owns a Stratasys Prodigy Plus machine which is an FDM machine limited by a small build size. It is utilized by the NASA Shuttle Logistics Depot (NSLD) Machine shop.

- ***SRB Element***

  Launch and Recovery directorate owns two Z-Corporation Spectrum Z510 machines which are a 3DP machine that is limited by part strength. It is utilized by the Solid Rocket Booster (SRB) Mechanical Design Engineering group.

- ***Flight Operations Engineering***

  Flight Operations directorate owns a 3D Systems InVision XT that was purchased thru a capital account. The InVision XT is a MJM machine that is limited by size and strength. It is utilized by the Offsite Repair Lab & Fabrication Facility.

  With the exception of the brand new InVision XT (purchased in March 2008) owned by Flight Operations, the machines that USA currently owns are several years old and the technologies of newer machines have far surpassed their capabilities. Even the InVision XT is no longer being fabricated as it has been superseded by a faster machine that produces stronger parts.

- ***KSC's NASA Prototype Lab***

  There are several groups within USA that have worked with NASA owned Prototype Shops. NASA's KSC Engineering Directorate has a Prototype Lab facility adjacent to the Launch Equipment Test Facility (LETF) behind the Operations and Checkout Building (O&C). NASA's Marshall Space Flight Center (MSFC) Engineering Directorate and the John Glenn Research Center (GRC) have prototype shops as well. The difficulty with working with the KSC Prototype Lab has been that a USA individual needs a NASA "sponsor" to submit the work to the Lab. This often involves searching for a viable NASA charge number that has proved difficult to obtain. The KSC facility is incredibly busy and it is hard to find the proper justification to get your job moved to the front of the line. Sending jobs to other NASA centers have proved to be next to impossible because of the enormous amount of paperwork it takes to transfer funds to another center.

- ***Service Bureaus***

  Another option that is available is the use of service bureaus, which are companies that own several rapid prototyping machines and will fabricate parts from a supplied STL file for a fee. Unfortunately, procurement of their services proves to be a slow and lengthy process. There is also a security concern over transmission of design information to outside vendors, because many service bureaus are brokers and send the work out to other firms. But the major disadvantage of using service bureaus is that problems in the design are not caught until the parts come back, and the iterative process must begin again with procurement.

III. Comparison of Conventional Methods to the Rapid Prototyping Process

The real advantage to purchasing a rapid prototyping machine is that engineers can have access to the ability to create physical models and prototypes in real time without the time consuming method of requesting the services of the machine shop. RP machines can run on their own without constant watching. The RP machines can be started on Friday afternoon and can run unattended over the night and weekend and on Monday morning the part(s) are complete. Machine Shop workers cannot leave their machines unattended. Recently, the fabrication of a shop aid special tool made at the Launch Equipment Shop (LES) was compared to what it would take to fabricate the same shop aid on a Stratasys 400mc FDM machine.

- LES Machine Shop time = 81 hours
  - Includes tool path programming, jig fabrication and set-up, material set-up and tool fabrication
- Stratasys 400mc machine run time = 63.5 hours
  - Includes 62 hours and 47 minutes machine run time
  - 45 minutes of machine set-up and part finishing.

In essence, the above time for the FDM machine is only 45 minutes of labor due to the fact that the machine can run unattended, whereas the labor for the LES is the full 81 hours. This ends up being a savings of over $3000 for this particular shop aid.

Conventional methods of design do not allow for much lee-way. A flaw in the design may not become known until after the part has been made. At that point, often times, the part is scrapped and a new one is made out of expensive metal and using twice the amount of labor. Figure 1 summarizes the design iteration process using conventional means.

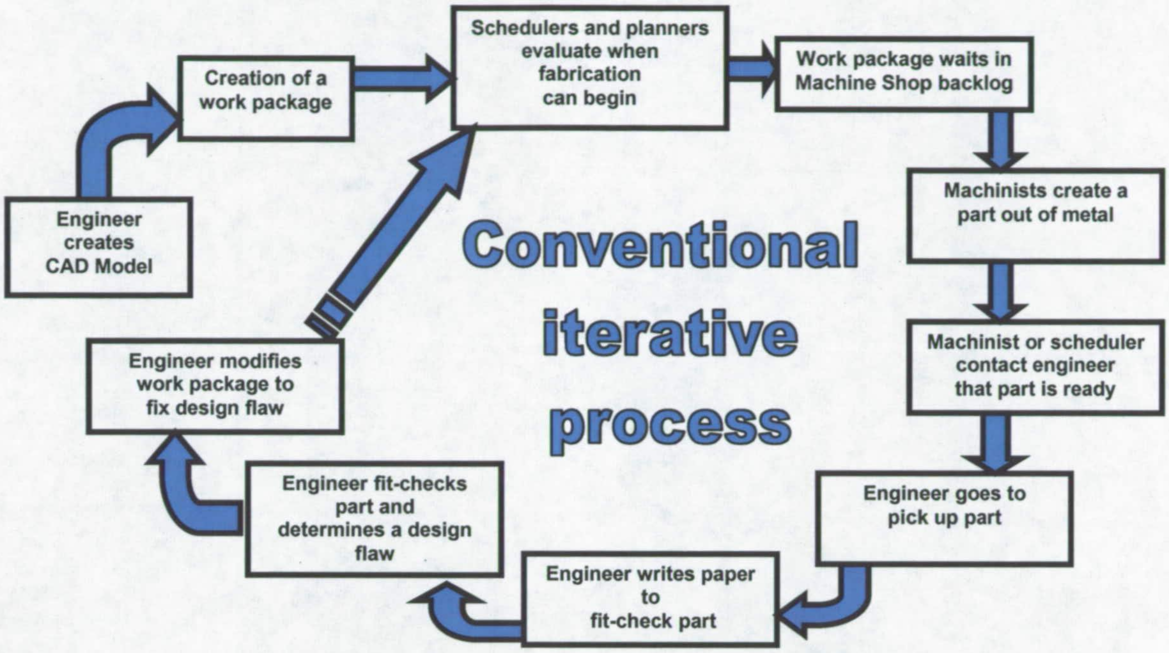

Figure 1 - *Conventional Design Iterative Process*

It takes an enormous amount of time to go thru the proper paperwork channels to get a part fabricated by the machine shop. Not only do you have to wait for the machinist to mill the part out, you have to wait for scheduling and transportation. Much time is wasted in this process.

The following is the account of a design process involving shop aid SA-2K7-005, which was fabricated at the LES. This shop aid was to be a work stand tool tray that would give the Shuttle tile technicians someplace to rest tools while up on the smaller portable work stands. The attachment method of the new tool tray included a clamping foot that would clamp around one of the lower handrail bars or the kick plate.

- The tool tray was designed in CATIA and sent off to the LES.
- Once all the tool trays were complete and delivered, it was discovered that the clamping foot did not work as planned.
- A change in the drawing was made and a new work order was written to modify one clamping foot, allow for a fit-check and then modify the other twenty clamping feet.
- The first modification did not go well, and the work package was re-written (and all necessary signatures were obtained) to include a new step to further modify the first clamping foot.
- The second modification worked better, but did not completely work. The work order was again re-written (and all necessary signatures were obtained) to include another step to modify the clamping foot further and then modify the other twenty clamping feet.

This entire process (post initial design) took over three months. This could have been avoided and would have taken a lot less time if a rapid prototyping machine had been used.

If additive layer manufacturing capabilities were available at the time of the design, then the clamping foot could have also been designed differently using the advantage of the ability to create assemblies all in one build and fully integrate and capture fasteners. Allowing for less time in assembling parts together and for less parts to come apart and create FOD (Foreign Objects and Debris).

IV. Design Involving Rapid Prototyping

The real advantage to owning a rapid prototyping machine is that engineers can have access to the ability to create physical models and prototypes in real time without the time consuming method of requesting the services of the machine shop. With the ability to create their own prototypes and models, engineers can reduce time taken in the iterative process of designing, fit-checking, then modifying, and fit-checking again. With some machines, it takes only slightly longer to create two models as it does to create one model. This allows engineers to create several versions of a model at the same time, reducing the iterative process even further. For example, a design engineer can go into a design review meeting with models of five alternative designs for a component. The models enable everyone involved in the selection process to quickly grasp the details of each alternative and discuss the relative advantages and disadvantages of each, quickly coming to a conclusion about the best design.[4] Rapid prototyping gives engineers the opportunity to detect any design flaws or come up with improvements prior to any metal cutting.

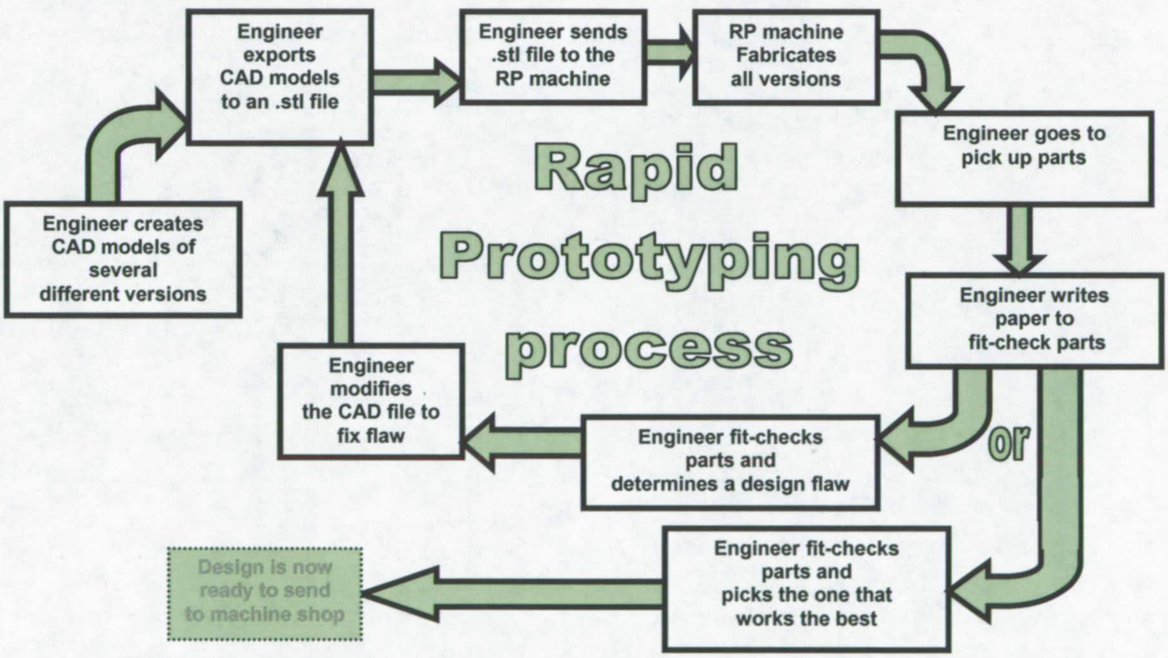

Figure 2 - *Rapid Prototyping Design Process*

Avoiding the need to create machine shop work packages and waiting for a permitting schedule is a huge advantage of the Rapid Prototyping machines. Small details that can be overlooked during design and drafting can be caught prior to sending it to the machine shop. During the conventional process, errors found during fabrication usually mean that materials and labor are scrapped. It becomes a waste of time and money when a part needs to be fabricated more than once during first stages of design. There is also the additional waste of time due to re-scheduling, new signature loop and documentation. There is also the hassle of juggling schedules on backlogged milling machines and lathes, which are much slower processes.

Another huge advantage to Rapid Prototyping is the ability to create design review models for use in discussion with customers. There is no substitute for being able to hold an exact scale model of a concept, especially where no hardware exists yet to compare it to. The prototypes can be used to convey design information much more quickly and efficiently than 2D drawings, isometric drawings, or 3D software screen shots.

> "Most non-technical people have a great deal of difficulty visualizing a part from looking at the drawing. Even engineers and toolmakers that look at drawings every day may require several minutes of studying an engineering drawing before they can create that geometry in their mind and really understand it. A model part, however, instantly and unambiguously communicates the design to everyone regardless of their ability to read drawings."[4]

The parts can also be used to evaluate designs via form, fit, and functional testing and as a design tool used to identify design errors not obvious when viewing 3D CAD files on the screen or 2D paper printed drawings.

Failure to properly communicate is often the root cause of problems in new product development. Rapid Prototyping offers a quick, clear, and concise description of a new design that improves comprehension and communication between interested parties. Better communication leads to the development of better products, along with possible reductions in time and cost.

This type of technology can be used, not just for prototypes, but for visual aids, presentation models, fit-check and assembly, training aids, ergonomic studies, fixtures and manufacturing aids. Some of the machines can produce parts that are so robust and strong that they can be used as end-use parts and assemblies that can be used on flight hardware, instead of a metal part machined at the machine shop. This process is called digital manufacturing; wherein parts normally fabricated in mass quantities, are fabricated from an STL file. They can be used to create fully functional end-use parts because of the strength of materials that are utilized in some machines.

The additive layer process also allows the creation of parts that would be impossible with conventional methods, such as fully integrated, captured fasteners. Assemblies can be built all in one shot. Parts do not have to be fabricated separately and then joined with fasteners or welding.

V. Potential Uses Identified within United Space Alliance, LLC

- Ground Operations
  - Shop Aids and Shop Aid prototypes
  - Thermoform molds for flight hardware protective covers
  - Ergonomic study models for Safety and Human Factors Engineering
  - Machine Shop evaluation models
  - Training aids for servicing of flight hardware
  - Optical targets for field metrology
- Program Integration
  - Quick fabrication of models of payloads for storage to be used to fit-check packaging requirements.
- Constellation
  - Scale models of ARES hardware for visualization and training purposes
- Flight Operations
  - Scale models of payloads and new flight hardware for training and visualization purposes
  - Prototypes of discontinued vendor parts for reverse-engineering processes
- Integrated Logistics
  - Pre-machining models to determine tool paths and best fabrication methods
  - Protective fixtures for use when repairing flight hardware

- SRB Element
    - o Evaluate designs via form, fit, and functional testing and as a design tool used to identify design errors
    - o Communication of stress / strain information with a physical model whose colors correlate to a stress plot
- Flight Software
    - o Rapid connector fabrication and assembly to help in meeting and beating schedules
- FCE/EVA Processing
    - o Early in the design cycle for anything requiring on-station maintenance [both IVA and EVA], a volumetrically accurate prototype should be available for time and motion studies of the crew performing maintenance. This approach should allow better, faster, and cheaper prototypes to be available for use.

VI. Benefits of Owning a Rapid Prototyping System

The advantages of using rapid prototyping technology are numerous, and are limited only by the ingenuity and innovativeness of its users. The key advantages as explained above include:

- Less time waiting for the machine shop
- Saving resources at the machine shop
- Saving labor and expensive materials
- Saving engineering design hours and reducing design errors
- Saving scheduling time due to faster product development

Non-realizable savings include:

- The ability to communicate more effectively with customers
- Improvements in product design thru higher capabilities
- More effective design evaluation
- The ability to show customers results throughout the design process and not just at the end.

A. Cost Benefits

Most companies have difficulty in justifying the cost benefits of a rapid prototyping facility. It is difficult to quantify the benefits, because many arise from what is avoided rather than what is eliminated or improved. Unlike the purchase of a new machine tool, which is justified in faster throughput and decreased cost per piece, rapid prototyping often offers the benefit of avoiding mistakes, improving quality and decreasing time to product implementation.[5] To determine the cost benefits of purchasing an RP machine, it was necessary to give estimated numbers, due to the fact that the use of RP within USA has been very limited and its benefits are not yet widely known.

Using RP to manufacture plastic parts (instead of machining)

A recent comparison was made of three separate machining jobs performed at the Launch Equipment Shop (LES) at KSC against the time it would take to fabricate with a rapid prototype machine. The time savings using a Stratasys 400mc FDM machine was 86%, and the time savings using a 3D Systems HiQ SLS machine was 59%. But these figures include labor and machine run time. LES Machine Shop workers cannot leave their machines unattended, where-as RP machines are designed to run unattended. So the labor savings of the above jobs is much more; probably somewhere closer to 95%. If the LES averages 24 man-hours per part and fabricates 200 [potential RP] parts per year, then labor savings alone would equal $192,000. But that figure does not include the time spent in planning and scheduling and backlog wait time.

Using RP to evaluate designs prior to manufacturing

As explained above, during the manufacturing of the adjustable work-stand tool trays (SA-2K7-005), the delivery and implementation of the new shop aid was delayed due to a design error not caught during the design process. The result was three additional months of adjustment and modification to the design and the delivered part. These three months could have been avoided if an RP machine was available to create a prototype or prototypes for evaluation prior to manufacturing.

B. Non-Realized Benefits

Non-realized benefits include how engineers design new products. Before the advent of additive layer manufacturing, engineers had to account for tool paths and manufacturing methods when designing new products. Additive layer manufacturing opens up a new method of fabrication, one in which tool paths are obsolete. This creates the ability to design more complex and functional parts. Recently, USA Ground Operations Tool Design was given the task of creating a protective shield for the External Tank insulative foam up at the forward attach fitting to the solid rocket boosters. In the design of this protective shield, a clamping fixture was designed to hold together an upright support beam and a horizontal beam. The easiest method of design, fabrication and assembly of this clamping fixture was clearly that of additive layer manufacturing (figure 3a). When faced with limited time and difficulty of sending the fabrication of these parts out to a service bureau, a re-design was completed so that the fixture could be fabricated at the on-site machine shop. The result was an assembly consisting of eighteen parts, and one weld; creating a more complicated and heavier part (figure 3b).

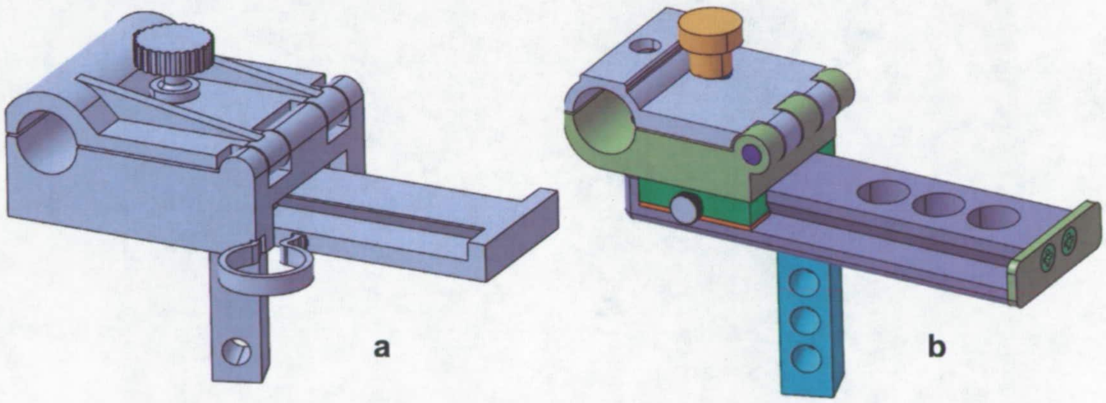

Figure 3 - *Differences in Design of Clamping Fixture*

VII. How Other Companies Utilize Rapid Prototyping

- Architectural firms produce scale models of buildings and landscapes[5]
- Formula 1 racing teams fabricate scale models of vehicles for wind tunnel testing.[5]
- The European-built Vega launcher will include FDM polycarbonate parts in each of the engines in all three stages of the rocket.[5]
- SAAB Avitronics is using additive fabrication to produce electronic surveillance devices. The company uses laser sintering to manufacture antenna RF boxes for unmanned aircraft.[5]

- AdvaTech Manufacturing uses laser sintering to fabricate an airplane windshield defroster out of one piece instead of three parts and six rivets.[5]
- Boeing subsidiary, On-Demand Manufacturing, fabricates hard to manufacture ECS ducts for F-18 military jets.[5]
- EOIR technologies produced a battle-ready ABS camera mount for the M1 Abrams tank.[5]
- Caterpillar used laser sintering to manufacture hundreds of complex wire harness covers.[5]
- Stratasys is using direct digital manufacturing to manufacture 32 components for its new large format production machine. [3]
- Burn masks with better fit that improve recovery [5]
- Full-size automobile instrument panels made in one piece [5]
- Recreation of a murder victim's likeness [5]
- On-demand creation of components for a self-designed droid [5]
- Components for exploration submersibles [5]
- Skulls of accident victims to prepare for reconstructive surgery [5]
- Color models, revealing areas of stress for finite element analysis [5]
- Wind-tunnel models for testing complex aerospace and motor-sports designs [5]
- Jigs, fixtures and assembly aids for product manufacturing [5]
- Custom and personalized awards, trophies and other giveaway products [5]

The following chart, compiled by Wohlers Associates shows how organizations are using additive processes for a range of applications.[5]

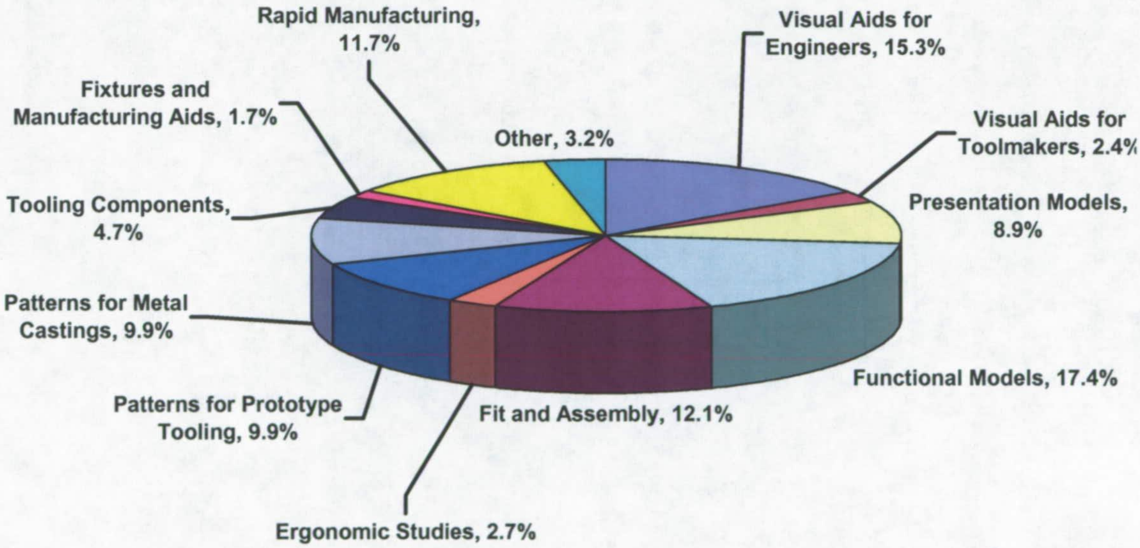

Figure 4 - *How Companies Are Applying Additive Processes*[5]

VIII. Evaluation of Selected Machines

USA Ground Operations Tool Design Engineering researched and compiled a list of fourteen different rapid prototyping machines, comparing them to one another. These fourteen machines come from six different manufacturers and range in price from $38,000 to $406,000. There were three SLS machines, four MJM machines, two 3DP machines and five FDM machines.

- Selective Laser Sintering Machines
  - 3D Systems SinterStation HiQ
  - EOS P390
  - EOS Formiga P100
- Multi-Jet Modeling Machines
  - 3D Systems InVision XT
  - 3D Systems ProJet HD 3000
  - Objet Eden 500V
  - Objet Connex 500
- Three Dimensional Printing Machines
  - Z-Corp Z450
  - Z-Corp Z510
- Fused Deposition Modeling Machines
  - Dimension SST 1200
  - Dimension Elite
  - Stratasys Vantage SE
  - Stratasys 400mc (large tray)
  - Stratasys 900mc

No SLA machines were evaluated based upon the complexity of handling the liquid build material as well as the fragility of the acrylic based parts it produces. DMLS machines were not evaluated either because of the high cost of the systems.

A. Benchmarking

Each company was sent an STL file of a shop aid inspection mirror holder created in CATIA (see figure 5). Benchmark samples were acquired from ten of the machines (figure 6) and the fabrication and material costs were compared to each other. Figure 7 shows the various fabrication times for each machine. The times were broken up into set-up time, machine run time, and post processing time. Figure 8 shows the comparison of the cost of build and support materials between each machine. Some machines show no cost for support material due to the fact that the uncured build material is the support material.

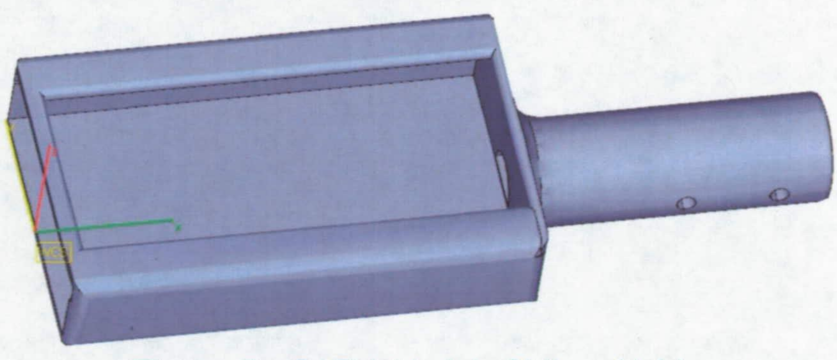

Figure 5 - *CATIA Model of Mirror Holder*

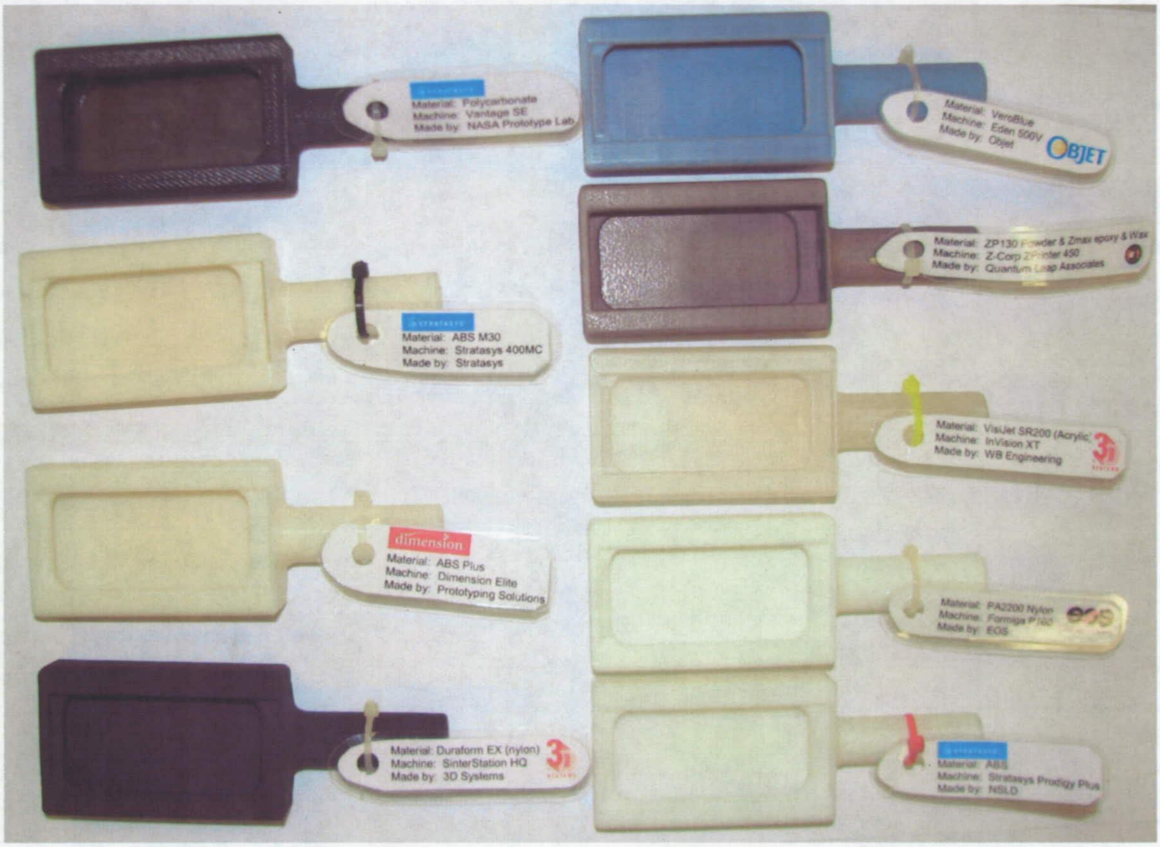

Figure 6 - *Benchmark Samples from Selected Vendors*

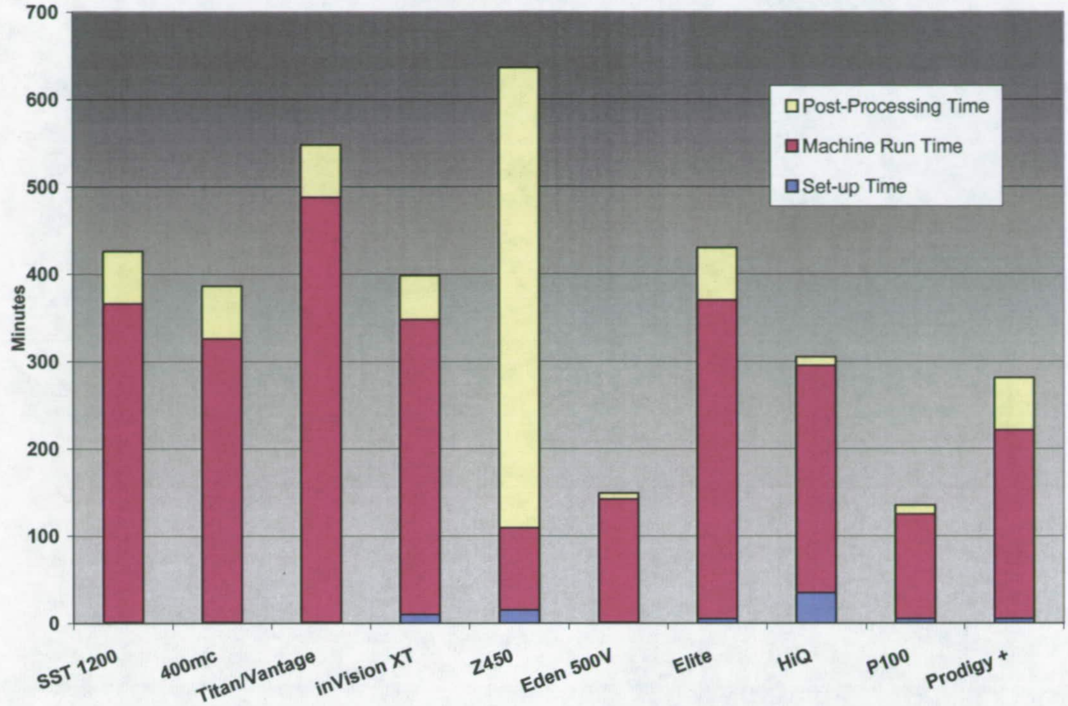

Figure 7 - *Comparison of Fabrication Time of Benchmarked Samples*

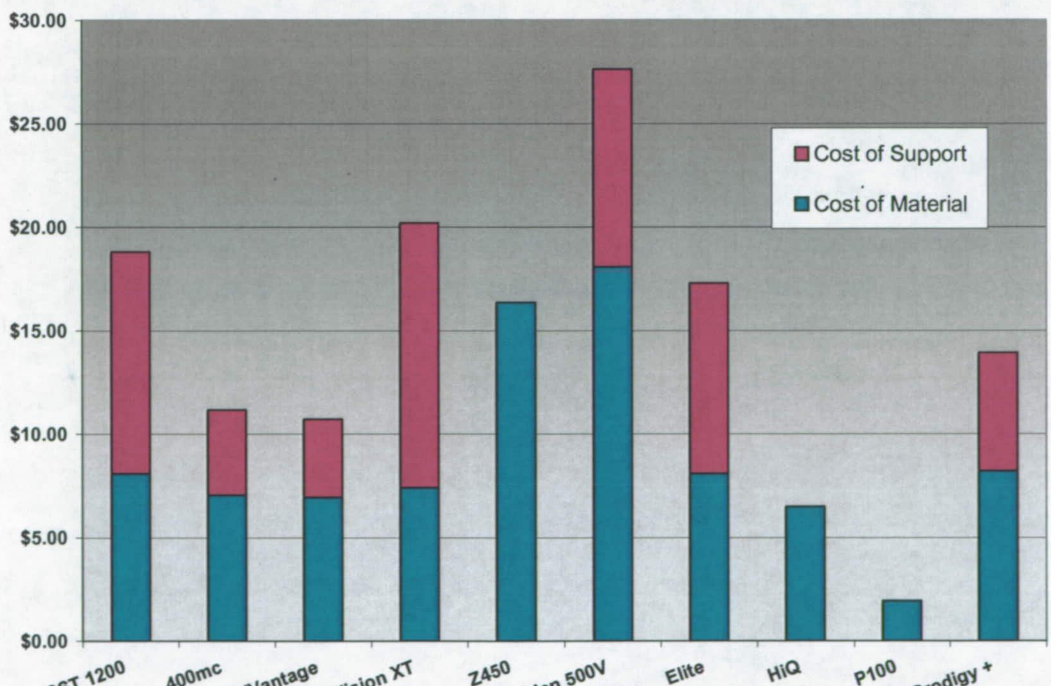

Figure 8 - *Comparison of Material Cost of Benchmarked Samples*

Each mirror holder was measured in sixteen different locations and compared to the computer model to determine the accuracy of the machine. Each manufacturer has an advertised accuracy rate, which is shown next to the actual [measured] accuracy in Table 1 below. The actual accuracy was computed by taking the average of the sixteen measurement deviations from the computer model.

	Advertised Accuracy (inches)	Actual Accuracy (inches	Difference (inches)
Formiga P100	0.004	0.003	-0.001
400MC	0.005	0.003	-0.002
Eden 500V	0.004	0.004	0.000
Dimension Elite	0.003	0.004	0.001
SinterStation HiQ	0.002	0.008	0.006
Vantage SE	0.005	0.013	0.008
Z-Printer 450	0.005	0.015	0.010
InVision XT	0.002	0.016	0.014
Prodigy Plus	unknown	0.019	-

Table 1 - *Comparison of Accuracy*

B. Decision Making Process

The information obtained by the benchmark samples was added to a large list of other information on each of the machines. This information was then fed into a decision making procedure based upon the Kepner-Tregoe Decision Analysis Procedure, where each machine was given a score for a category and that category was given a weight based upon the objective.

- Kepner-Tregoe based decision making procedure[6]
  - Step 1: State decision
  - Step 2: Develop objectives
  - Step 3: Classify objectives into MUSTS and WANTS
  - Step 4: Weigh the WANTS
  - Step 5: Generate alternatives
  - Step 6: Compare alternatives against the WANTS
    - Establish a rating scale for each criterion
  - Step 7: Multiply each alternative's rating by the weight
  - Step 8: Add up all the points for each alternative
- The option with the highest score will not necessarily be the one to choose, but the relative scores can generate meaningful discussion and lead the team toward consensus.

Step 1: State Decision

The decision/purpose was defined to be to choose a rapid prototyping machine, or combination of machines, to purchase for the use within United Space Alliance, LLC for the Space Shuttle Contract engineers and management while also considering Constellation development.

- The rapid prototyping system is intended to be utilized for visualization, functional testing and manufacturing of tools, ground support equipment, and training aides
- Ability to create detailed show and tell/visualization models
- Ability to create full-scale parts for fit-checks and functional testing

Step 2: Develop Objectives

To help develop a representative list of objectives, invitations to a brainstorming session were sent out to engineers, technicians, and management from all different parts of the company. The meeting, held on December 10th, 2007, was attended by sixteen people from KSC and nine people from Johnson Space Center (JSC).

From the brainstorming session, the ensuing discussions, and e-mails, a list of objectives were compiled and refined over the next few weeks. Fourteen objective categories were developed, in which nine of those categories were broken down into further elements. Table 2 below shows the main objectives along with the weights assigned to them in step 4.

Step 3: Classify Objectives into MUSTS and WANTS

The purchase of a rapid prototype machine is more of a desire to improve existing capabilities. The added benefit of its procurement and implementation is not a necessity, and therefore all of the objectives were determined to be WANTS.

Step 4: Weigh the WANTS

To help determine the decision weights, a short questionnaire was put together and sent to all the participants of the brainstorming session as well as a few others who did not attend. The questionnaire asked each person to rate some of the attributes of a Rapid Prototyping System that they felt was most important to United Space Alliance, LLC (Appendix A). Due to the lack of response, the results from the questionnaires (Appendix B) were used only as a guide to determining the weights used in the final decision analysis.

Objective	Weight	
Easy to maintain and operate	10	Further breakdown
Good maintenance service plan	9	Further breakdown
Durable Materials	9	Further breakdown
High Tolerance	8	
Variety of Materials	8	Further breakdown
Large Build Envelope	7	
Minimal Facility Requirements	7	Further breakdown
Material Compatible with Flight Hardware	7	Further breakdown
Minimal Initial Cost	6	
Minimal Consumables Cost	5	
Minimal operator time	5	Further breakdown
Minimal maintenance cost	4	
Powerful Software	4	Further breakdown
Fast Build Speed	3	
Company Profile	3	Further breakdown

Table 2 - *Objectives and Weights Used in Decision Analysis*

Step 5: Generate alternatives

The alternatives were chosen from a large field of machines. Internet research resulted in over 60 machines available on the market. From this list, 14 machines were chosen from six different manufacturers, based upon availability and functionality.

Machine	Manufacturer	Type
InVision XT	3D Systems Corporation	MJM
SinterStation HiQ	3D Systems Corporation	SLS
ProJet HD 3000	3D Systems Corporation	MJM
Elite	Dimension (a business unit of Stratasys Inc.)	FDM
SST 1200	Dimension (a business unit of Stratasys Inc.)	FDM
EOSINT P 390	Electro Optical Systems (EOS) GmbH	SLS
Formiga P 100	Electro Optical Systems (EOS) GmbH	SLS
Connex 500	Objet Geometries Ltd.	MJM
Eden 500V	Objet Geometries Ltd.	MJM
400mc (large tray)	Stratasys Inc.	FDM
900mc	Stratasys Inc.	FDM
Vantage SE	Stratasys Inc.	FDM
Z450	Z Corporation	3DP
Z510	Z Corporation	3DP

Table 3 - *Machine Alternatives*

Step 6: Compare alternatives against the WANTS

The weighted objectives, developed in step 2 were then put into a decision matrix where the scoring is based on a 1 to 10 scale. The alternative which best fulfills that objective receives a 10, the rest are given scores based on how well they compare to the best alternative. Yes or no questions are assigned 8 and 2 respectively.

For those objectives which were further broken down, each sub-objective was given a percentage of the major objective's weight. For example, the objective, "Durable Materials," was broken down into Tensile Strength, Flexural Strength, Impact Strength, and Heat Deflection Temperature (Table 4). The major objective weight was 9, and the sub-objective weights were 30%, 20%, 30% and 20% respectively. The sub-objectives were assigned a number based on a 1 to 10 scale.

Objective	Weight	Sub Weight
Durable materials	9	
Tensile Strength		0.30
Flexural Strength		0.20
Impact Strength		0.30
Heat Deflection Temperature (at .45MPa)		0.20

Table 4 - *Breakdown of the Objective "Durable Materials"*

The scale was determined by examining the machines with the highest and lowest scores, and then creating a scale accordingly. For example, the sub-objectives, "Tensile Strength" and "Heat Deflection Temperature" were given the following scales:

Score	Tensile Strength Value	Heat Deflection Temperature Value
0	<1000 psi	<=100 °F
1	1000 to 1999 psi	101 to 131 °F
2	2000 to 2999 psi	132 to 162 °F
3	3000 to 3999 psi	163 to 193 °F
4	4000 to 4999 psi	194 to 224 °F
5	5000 to 5999 psi	225 to 255 °F
6	6000 to 6999 psi	256 to 286 °F
7	7000 to 7999 psi	287 to 317 °F
8	8000 to 8999 psi	318 to 348 °F
9	9000 to 9999 psi	349 to 379 °F
10	=>10000 psi	>=380 °F

Table 5 - *Example Breakdown of Sub-Objective Scale*

Step 7: Multiply each alternative's rating by the weight

Each machine then was given a score from 1 to 10 based upon the determined scale. That score was then multiplied by the percentage of the sub-weight and then all the sub-weights were summed together and then multiplied by the objective weight to get a score for the objective. As an example, consider the EOS P390 machine's score for Durable Materials (Table 6).

Objective	Weight	Sub Weight	EOS P390		
Durable materials	9			7.6	**68.4**
Tensile Strength		0.30	6962	6	1.8
Flexural Strength		0.20	10733	5	1
Impact Strength		0.30	4.12	10	3
Heat Deflection Temperature (at .45MPa)		0.20	350	9	1.8

Table 6 - *Example of Sub-Weight Calculation*

The EOS P390 uses a material called PrimePart DC that has a tensile strength of 6962 psi. According to the tensile strength scale, it receives a score of 6. That score of 6 is then multiplied by 30% to give us 1.8. When the 1.8 is added up with the other sub-weighted scores, we get a total score of 7.6 for all the sub-objectives. This number is then multiplied by the weight of the objective, in this case 9, to give us a total score of 68.4.

Step 8: Add up all the points for each alternative

Each machine and its corresponding attribute scores were entered into an Excel spreadsheet to reveal the final weighted score. Figure 9 shows a snap-shot of part of the decision matrix, which is attached as Appendix C.

Objective	Weight	Sub Weight	SinterStation HiQ			InVision XT			ProJet HD 3000		
					542			578			6[illegible]
Easy to maintain and operate	10			3.5	35		5.8	58		6	6[illegible]
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1.[illegible]
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1[illegible]
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0[illegible]
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0[illegible]
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0[illegible]
L[illegible] Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0[illegible]
Ti[illegible] jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0[illegible]
Ti[illegible] jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0[illegible]
O[illegible]		0.07	low	2	0.1	low	2	0.1	low	2	0[illegible]
G[illegible]			not available	0	0	not available	0	0	not avail	0	
C[illegible] network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0[illegible]
Good m[illegible]	9			7.8	70		9	81		9	8[illegible]
Li[illegible] warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	
Durable materials	9			6.8	61		1.8	16		1.8	1[illegible]
Tensile Strength		0.30	6961	6	1.8	4900	4	1.2	4900	4	1[illegible]
Flexural Strength		0.20	19000	10	2	7500	2	0.4	7500	2	0[illegible]
Impact Strength		0.30	1.4	4	1.2	not avail		0	not avail		
Heat Deflection Temperature (at .45MPa)		0.20	370	9	1.8	114.8	1	0.2	114.8	1	0[illegible]
High tolerance	8		0.002	8	64	0.002	8	64	0.001	10	8[illegible]
Variety of materials	8			4	32		1.5	12		2.1	1[illegible]
Color Variety		0.10	2	2	0.2	1	1	0.1	3	3	0[illegible]
Quantity of different types of materials		0.40	7	7	2.8	1	1	0.4	2	2	0[illegible]
Ability to print in different colors without changing cartridges			no			no			no		

<1 minute = 10
1 to 5 min = 9
6 to 10 min = 8
11 to 15 min = 7
16 to 20 min = 6
21 to 25 min = 5
26 to 30 min = 4
31 to 60 min = 3
>60 min = 2

Figure 9 - *Snap-Shot of Decision Matrix*

After an over-all best comparison was made between the machines, the weights of the objectives were manipulated to produce other scenarios. Four different scenarios were created:

- Need for a machine to produce parts that will be used on flight hardware or will be used for end use parts
- Need for a machine to produce only visual and presentation aids
- Need for a machine that cost the least, saves man hours and has minimal facility modifications to get it functional
- Need for a machine that can produce large thermoform molds

Table 7 shows how the weights varied according to the scenario.

Objective	Best Overall	Flt Hdwr & End Use	Visual	Cost & Time	Thermoform Molds
Easy to maintain and operate	10	7	7	8	7
Good maintenance service plan	9	6	6	8	6
Durable Materials	9	10	4	4	10[2]
High Tolerance	8	9	7	5	5
Variety of Materials	8	10	10[1]	4	5
Large Build Envelope	7	7	7	7	10
Minimal Facility Requirements	7	5	4	6	6
Material Compatible with Flight Hardware	7	10	2	2	2
Minimal Initial Cost	6	6	6	8	4
Minimal Consumables Cost	5	5	7	10	8
Minimal operator time	5	5	10	9	5
Minimal maintenance cost	4	4	4	10	4
Powerful Software	4	4	5	5	10[3]
Fast Build Speed	3	3	9	7	5
Company Profile	3	3	3	6	3

1) Color variety was bumped up to 50% of the variety of materials weight
2) Heat deflection temperature was bumped up to 70% of the durable materials weight
3) Ability to sparse fill parts was bumped up to 50% of the powerful software weight

Table 7 - *Scenario Scales*

C. Results

The weights of each scenario were fed into the decision matrix and each machine was evaluated according to the objective. For a full breakdown of the objectives and their weights, refer to the attached Appendix C. Table 8 shows the results of the scoring and the ranking for each machine according to the various scenarios.

	Overall Good Machine		Flight Hardware Compatibility & End Use Parts		Presentation and Visual Aid		Cost & Time & Facility Mods		Thermoform Molds & Large Volume	
Machine	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
HiQ	541.9	6	544.7	4	495.6	13	536.7	13	529.1	5
InVision XT	538.2	8	501.4	9	517.7	7	625.5	2	467.1	11
ProJet HD	564.9	3	530.8	6	549.2	1	644.6	1	489.6	7
Eden 500V	488.9	12	481.9	11	503.0	11	548.3	11	437.4	14
Connex 500	486.1	13	483.9	10	496.0	12	523.9	14	433.4	15
Z450	485.9	14	446.7	15	548.2	2	616.0	3	480.1	9
Z510	483.9	15	449.6	14	545.8	3	606.8	4	481.4	8
SST 1200	514.8	10	478.9	12	506.0	10	572.3	9	464.9	12
Elite	541.8	7	507.9	8	488.0	14	587.1	6	473.9	10
Prodigy +	502.2	11	474.6	13	520.5	5	586.2	7	463.8	13
Vantage SE	565.5	2	551.5	2	520.5	5	571.2	10	529.6	4
400mc	595.3	1	586.0	1	535.5	4	603.0	5	575.7	1
900mc	535.1	9	525.0	7	447.5	15	482.4	15	524.7	6
EOS P390	543.7	5	543.4	5	509.5	9	541.3	12	570.3	2
EOS P100	546.5	4	544.8	3	516.9	8	585.2	8	544.6	3

Table 8 - *Ranking Results for Selected Machines by Scenario*

The machine that comes out on top for three of the five scenarios is the Stratasys 400mc (Figure 10), which is Fused Deposition Modeling machine with a 16" x 14" x 16" build size. The 400mc is the replacement for the Vantage SE (scored number two in two scenarios), which can now only be bought used. The Vantage SE is used in KSC NASA Prototype Lab, and it was included in this evaluation as a comparison to known results. The 400mc can fabricate parts out of ABS, Polycarbonate, ABS/Polycarbonate blend, and Polyphenylsulfone. The machine and its accessories cost $184,645, which includes a 1 year warranty. The yearly service warranty costs $18,130. Material costs around $4.13 per cubic inch for both the plastic and the support material, which is water soluble. The fact that this machine can fabricate parts from a variety of material is one of its main strengths. Unfortunately, the FDM process creates parts that are anisotropic, which may become a problem for some parts.

Figure 10 - *Stratasys 400MC*

The 3D Systems ProJet HD (Figure 11) is a fairly new model, and has captured a top spot in two out of the five scenarios. It is very similar to its predecessor, the InVision XT, which received a number two ranking under the low cost scenario. The ProJet is a multi-jet modeler in that it squirts out an acrylic based material out of tens of tiny little nozzles onto a platform, which is then hardened by UV lamps. The ProJet is one of the lowest costing machines with the highest accuracy. Its advertised accuracy is plus or minus .001 inches. When we compared the benchmarking samples, we saw that the InVision XT, which is the predecessor to the ProJet had an average measured accuracy of plus or minus .016 of an inch, which is nowhere near the advertised accuracy. The ProJet has a maximum build size of 11.75" x 7.3" x 8", which is about average. The machine and accessories, including a one year warranty is $74,900 with an annual service warranty of $9,600. The cost of material is less than that of the 400mc, but it also has a lower strength. The company that fabricates the ProJet, 3D Systems, has been going thru a lot of changes recently that have not been for the better. There are several people within the industry that do not see an investment in a 3D Systems machine to be a good deal.

Figure 11 - *3D Systems ProJet HD3000*

Two machines that did fairly well in the evaluation were the EOS P100 and the P390. The P100 is the smaller cousin to the P390. They are both Selective Laser Sintering machines, and the P390 costs more than the 400mc, but it may be worth the cost. The P390 has a build envelope of 13.4" x 13.4" x 24.4", which is a decent size. All the materials are nylon based, but can be aluminum filled, glass-filled or carbon filled. There are nine materials that are available thru the manufacturer, but EOS is one of the only a handful of companies that allow its customers to use other vendor's materials without voiding the service warranty. The parts are fairly accurate, with an advertised accuracy of ± 0.004 inch. We evaluated a benchmark sample from the P100, and it had the highest accuracy of the nine benchmark samples we received at ± 0.0031 inch. The machine and accessories costs $380,000 and has a yearly service contract of $35,000. But the material costs less than one dollar per cubic inch.

Figure 12 - *EOS INT P390*

The deciding factor of the choice in a rapid prototyping machine is not cost. Instead, the choice will depend on the goals for the models to be produced.[3] If the machine needs to produce models that are simply visual aids, then an inexpensive 3D Printer, such as the 3D Systems Projet or the Z-Corporation Z450, will probably suffice. But if the machine needs to be able to stand up to fit-check tests, something with a little stronger material will be called for, such as the Stratasys 400mc. If a variety of materials will be necessary in order to meet demands of digital manufacturing, then a more versatile machine, such as the EOS INT P390, will be better suited for the job.

IX. Proposal for a New Facility

In order to effectively use the new rapid prototyping resources that USA will procure, a new facility, called the Prototype and Model Lab (PML) should be created. This new facility will be a resource to all of USA, enabling engineers from around the company to pursue a more effective means of communication and design. The PML will house a majority of USA's assets in rapid prototyping technology and knowledge, and will be employed by one or more dedicated technicians or engineers. The PML staff would process orders for models and prototypes for those who are unable to run the software and machine. But the main function of the PML is to serve as a facility that [properly trained] engineers could run themselves, freeing up the need for a large staff.

The new Prototype and Model Lab will need to be located in a building that is accessible by most USA engineers, meaning, a building that is not in a restricted access area. If area access were not a factor, then the preferred location would be within the Vehicle Assembly Building (VAB); to ensure access to everyone, a building such as the Processing Control Center (PCC) across the street from the VAB and the Operations Support Building (OSB) is better suited to house the PML.

Depending on the machines purchased for, or transferred to the PML, different facility requirements exist. Regardless of location and machine, the following requirements are necessary.

- Three phase, 240 volt power (for the rapid prototype machine)
- Single phase, 240 volt power (for periphery equipment)
- Air conditioning\humidity controls
- Storage area
- Access to waste streams
- Access to basic shop tools and machinery
- Computer network access
- Adequate lighting
- Work bench\tables
- Double door\rollup door (required for installation)

As a result of the above machine evaluations, it is recommended to either purchase the Stratasys 400mc or the EOS P390. Also recommended is to move one of the SRB Element Z-Corporation Z510s into the new facility to combine the machines in one location for ease of accessibility.

Because of the nature of the Selective Laser Sintering process and powders, there are several requirements that will be necessary for a successful and safe operation.

- Clean, dry compressed air (for nitrogen gas generation) or a supply of bottled nitrogen
- Exhaust venting (for excess nitrogen)
- Explosion proof vacuum cleaner
- Oxygen monitoring sensor
- Anti-static floor mats

The main requirement of operating a Fused Deposition Modeling machine is the availability of a method to remove the support material thru a water and detergent bath. The Stratasys recommended cleaning station includes a sink and a circulating pump. The detergent bath along with the dissolved support material may be disposed of in a normal sewer system as long as it is diluted. Therefore it will be highly recommended to have the sink hooked up to a sewer drain.

X. Conclusion

In the same way that investing in 3D CAD modeling software outweighed the cost, the advantages of using a rapid prototyping system seems to be outweighed by the cost of investment and training, but in the long run, it gives engineers an incredible opportunity to 1) communicate more effectively with customers, 2) correct mistakes before production, and 3) fabricate new products and tools that are impossible using conventional means.

There are over 60 rapid prototype machines available on the market today. Deciphering which machine will work the best is a tough endeavor, but using a Kepner-Trego based decision analysis showed that the best machine for United Space Alliance, LLC is the Stratasys 400mc. The 400mc will allow its users to make parts and assemblies out of several different plastics, and has a fairly large build chamber. The greatest disadvantage of the 400mc is in the way it builds parts; it requires the use of a support material that must be removed after the build is complete and the completed parts have a tendency to break across the layers.

Other machines that rise to the top include the 3D Systems ProJet, which is smaller and cheaper than the 400mc, but produces less robust parts. The EOS P390 also has many advantages to offer USA, including a large variety of plastics including carbon filled and glass filled parts that are strong and durable, but the cost of machine and the facility requirements are a big concern.

Aside from helping the shuttle program develop new and better tools and equipment, a rapid prototyping machine (and the ability to use the rapid prototyping method to its full potential) will help USA as it transitions itself from the shuttle program to the constellation program, allowing this company to remain at the front of the technology curve.

XI. References

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[6] Kepner Trego Problem Solving & Decision Making. Skillman, New Jersey: Kepner-Trego Publishing Services Group. 1989.

XII. Appendices

Appendix A: Rapid Prototyping System Attribute Questionnaire.

Attribute
questionnaire.doc

Appendix B: Attribute Questionnaire Compiled Results

Questionnaire
Results.xls

Appendix C: Decision Matrix

Decision Matrix.xls

Appendix D: Companies Contacted or Interviewed

Companies
Contacted or Intervie

Appendix A:

Rapid Prototyping System Attribute Questionnaire

Rate the following attributes of a Rapid Prototyping System that you feel is most important to United Space Alliance.

	Extremely important	Very important	Somewhat important	Not very important	Not at all important	Don't Know
1. Ability to make scale models without having to manipulate the CAD file	☐	☐	☐	☐	☐	☐
2. Ability to cut or section large parts without having to manipulate the CAD file	☐	☐	☐	☐	☐	☐
3. Ability to honeycomb or sparse fill parts without manipulating the CAD file	☐	☐	☐	☐	☐	☐
4. Ability to use finished parts on flight hardware	☐	☐	☐	☐	☐	☐
5. Material selection variety	☐	☐	☐	☐	☐	☐
6. Ability to build parts in full color	☐	☐	☐	☐	☐	☐
7. Easy to maintain and operate	☐	☐	☐	☐	☐	☐
8. Fast build speed	☐	☐	☐	☐	☐	☐
9. Good maintenance service plan	☐	☐	☐	☐	☐	☐
10. High accuracy/tolerances	☐	☐	☐	☐	☐	☐
11. High material strength	☐	☐	☐	☐	☐	☐
12. Material flexibility (a foam or elastomer type material)	☐	☐	☐	☐	☐	☐
13. Large build envelope	☐	☐	☐	☐	☐	☐
14. Low consumables cost	☐	☐	☐	☐	☐	☐
15. Low initial cost	☐	☐	☐	☐	☐	☐
16. Low maintenance cost	☐	☐	☐	☐	☐	☐
17. Low or no post processing	☐	☐	☐	☐	☐	☐
18. Minimal facility requirements	☐	☐	☐	☐	☐	☐

Directorate: ☐ FCE/EVA Processing ☐ Flight Operations ☐ Flight Software ☐ Ground Operations ☐ Integrated Logistics ☐ Orbiter Element ☐ Program Integration ☐ SRB Element

Department: ____________________

Appendix B:

Attribute Questionnaire Compiled Results

Appendix B
Attribute Questionnaire Compiled Results

Attribute	AVERAGE SCORE	STANDARD DEVIATION	Respondent 1	Respondent 2	Respondent 3
7. Easy to maintain and operate	5.083	0.79	5	4	5
9. Good maintenance service plan	5.083	0.79	6	5	6
10. High accuracy/tolerances	5.000	0.74	4	4	6
13. Large build envelope	4.909	0.54	5	5	6
2. Ability to cut or section large parts without having to manipulate the CAD file	4.818	0.98	6	4	6
1. Ability to make scale models without having to manipulate the CAD file	4.727	0.79	5	4	5
5. Material selection variety	4.667	0.89	5	5	6
11. High material strength	4.667	0.49	5	5	4
3. Ability to honeycomb or sparse fill parts without manipulating the CAD file	4.600	0.97	4	5	6
18. Minimal facility requirements	4.500	0.67	4	4	6
4. Ability to use finished parts on flight hardware	4.417	1.16	6	6	4
17. Low or no post processing	4.417	0.51	4	4	5
12. Material flexibility (a foam or elastomer type material)	4.364	0.81	5	5	4
16. Low maintenance cost	4.333	0.89	5	4	4
8. Fast build speed	4.250	0.75	5	3	4
14. Low consumables cost	4.091	0.83	4	3	4
6. Ability to build parts in full color	3.833	0.83	4	3	3
15. Low initial cost	3.750	0.97	3	3	4
Directorate			Ground Operations	Ground Operations	Integrated Logistics

Appendix B
Attribute Questionnaire Compiled Results

Attribute	Respondent 4	Respondent 5	Respondent 6	Respondent 7	Respondent 8
7. Easy to maintain and operate	4	4	5	6	5
9. Good maintenance service plan	5	4	6	5	4
10. High accuracy/tolerances	5	4	5	5	5
13. Large build envelope	4	5	5		4
2. Ability to cut or section large parts without having to manipulate the CAD file		5	5	5	3
1. Ability to make scale models without having to manipulate the CAD file		5	5	5	3
5. Material selection variety	5	3	5	3	5
11. High material strength	5	5	5	4	5
3. Ability to honeycomb or sparse fill parts without manipulating the CAD file		4	5	4	3
18. Minimal facility requirements	4	5	5	4	4
4. Ability to use finished parts on flight hardware	4	3	5	3	3
17. Low or no post processing	4	4	5	5	4
12. Material flexibility (a foam or elastomer type material)	5	5	5	3	3
16. Low maintenance cost	4	4	5	4	3
8. Fast build speed	4	4	5	4	4
14. Low consumables cost	4	5	5	4	3
6. Ability to build parts in full color	3	5	5	3	4
15. Low initial cost	3	3	5	4	3
Directorate	Ground Operations	Constellation	Ground Operations		SRB Element

Appendix B
Attribute Questionnaire Compiled Results

Attribute	Respondent 9	Respondent 10	Respondent 11	Respondent 12
7. Easy to maintain and operate	6	5	6	6
9. Good maintenance service plan	5	4	5	6
10. High accuracy/tolerances	6	5	6	5
13. Large build envelope	5	5	5	5
2. Ability to cut or section large parts without having to manipulate the CAD file	5	4	6	4
1. Ability to make scale models without having to manipulate the CAD file	5	5	6	4
5. Material selection variety	5	4	5	5
11. High material strength	4	4	5	5
3. Ability to honeycomb or sparse fill parts without manipulating the CAD file	4		6	5
18. Minimal facility requirements	4	4	5	5
4. Ability to use finished parts on flight hardware	4	5	4	6
17. Low or no post processing	5	4	5	4
12. Material flexibility (a foam or elastomer type material)	4		5	4
16. Low maintenance cost	5	5	6	3
8. Fast build speed	5	5	5	3
14. Low consumables cost	5	5		3
6. Ability to build parts in full color	4	5	4	3
15. Low initial cost	4	4	6	3
Directorate	Ground Operations	Ground Operations		Ground Operations

Appendix C:

Decision Matrix

Appendix C
Decision Matrix
Weighted Decision - For Use on Flight Hardware as a Functional Protoype or End Use Product

Objective	Weight	Sub Weight	SinterStation HiQ			InVision XT			ProJet HD 3000		
These weights represent the use of a finished product on flight hardware as a functional prototype or end use part					545			501			531
Easy to maintain and operate	7			3.5	25		5.8	41		6	42
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1.8
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0.1
Time for set-up inbetween jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0.5
Time for set-up inbetween jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0.2
On-board diagnostics		0.07	low	2	0.1	low	2	0.1	low	2	0.1
Good up-time statistics			not available	0	0	not available	0	0	not avail	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	6			7.8	47		9	54		9	54
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	2
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	3
Durable materials	10			6.8	68		1.8	18		1.8	18
Tensile Strength		0.30	6961	6	1.8	4900	4	1.2	4900	4	1.2
Flexural Strength		0.20	19000	10	2	7500	2	0.4	7500	2	0.4
Impact Strength		0.30	1.4	4	1.2	not avail		0	not avail		0
Heat Deflection Temperature (at .45MPa)		0.20	370	9	1.8	114.8	1	0.2	114.8	1	0.2
High tolerance	9		0.002	8	72	0.002	8	72	0.001	10	90
Variety of materials	10			4	40		1.5	15		2.1	21
Color Variety		0.10	2	2	0.2	1	1	0.1	3	3	0.3
Quantity of different types of materials		0.40	7	7	2.8	1	1	0.4	2	2	0.8
Ability to print in different colors without changing cartridges			no			no			no		
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	7		3510	7	49	686	2	14	686.2	2	14
Minimal facility requirements	5			4.3	21		8	40		8	40
Runs on 110V		0.18	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6
Humidity can be above 75%		0.14	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	yes	8	1.6	yes	8	1.6
Material compatible with flight hardware	10			7.5	75		3.6	36		3.6	36
Low occurrence of FOD/Shatterability		0.50	excellent	10	5	poor	4	2	poor	4	2
Has a fire-resistant grade of material		0.30	HB	3	0.9	none	0	0	none	0	0
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	6		$365,930	1	6	$71,500	9	54	$74,900	9	54
Minimal consumables cost (most basic material & support cost/cu in)	5		$2.33	8	40	$3.79	6	30	$3.79	6	30
Minimal operator time	5			5.6	28		8	40		8	40
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	4		$28,100	1	4	$9,000	8	32	$9,600	8	32
Powerful Software	4			7	28		4.9	20		6	24
Ability to join smaller parts to make larger part without Magics		0.16	yes	8	1.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	no	2	0.3	no	2	0.3	no	2	0.3
Ability to stack parts		0.06	yes	8	0.5	no	2	0.1	yes	8	0.5
Ability to nest parts		0.12	yes	8	1	no	2	0.2	yes	8	1
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	3		260	6	18	338	4	12	est. 338	4	12
Company Profile	3			8	24		8	24		8	24
Years in business		0.50	20	10	5	20	10	5	20	10	5
Number of all models worldwide		0.50	3934	6	3	3934	6	3	3934	6	3

Objective	Eden 500V			Connex 500			Z450		
These weights represent the use of a finished product on flight hardware as a functional prototype or end use part			482			484			447
Easy to maintain and operate		5.8	40		5.8	40		5.6	39
Time spent per month cleaning & servicing	150 minutes	6	1.1	150 minutes	6	1.1	110 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	no	2	0.2	no	2	0.2
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Time for set-up inbetween jobs	10 minutes	8	0.7	10 minutes	8	0.7	127 minutes	2	0.2
Time for set-up inbetween jobs with different material	15 minutes	7	0.6	15 minutes	7	0.6		2	0.2
On-board diagnostics	low	2	0.1	low	2	0.1	good	8	0.6
Good up-time statistics	95%	8	0	95%	8	0	not available	0	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		4.5	27		4.5	27		9	54
Little or no parts that the warranty doesn't cover	no	2	1	no	2	1	yes	8	4
Close service technician	Atlanta	7	1.4	Atlanta	7	1.4	Jupiter, FL	10	2
Difficulty in sending a service technician	medium	7	2.1	medium	7	2.1	easy	10	3
Durable materials		4.5	45		4.5	45		2.1	21
Tensile Strength	8744	8	2.4	8744	8	2.4	3480	3	0.9
Flexural Strength	10991	5	1	10991	5	1	6236	1	0.2
Impact Strength	0.79	3	0.9	0.79	3	0.9	not avail		0
Heat Deflection Temperature (at .45MPa)	120	1	0.2	120	1	0.2	239	5	1
High tolerance	0.004	4	36	0.004	4	36	0.005	2	18
Variety of materials		5.9	59		8.3	83		2.4	24
Color Variety	3	3	0.3	3	3	0.3	thousands	10	1
Quantity of different types of materials	7	7	2.8	28	10	4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			yes			yes		
Ability to mix materials	no	2	0.4	yes	8	1.6	no	2	0.4
Ability to change out materials mid way thru build	yes	8	2.4	yes	8	2.4	no	2	0.6
Large build envelope	2348	5	35	2443	5	35	640	1	7
Minimal facility requirements		3.7	18		3.7	18		6.1	30
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	no	2	0.4	no	2	0.4	yes	8	1.6
Humidity can be above 75%	no	2	0.3	no	2	0.3	no	2	0.3
Temperature can change up to 20 degrees	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require ventilation/dust collector	yes	8	0.8	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	no	2	0.4	no	2	0.4	yes	8	1.6
Material compatible with flight hardware		3.6	36		3.6	36		2.6	26
Low occurrence of FOD/Shatterability	poor	4	2	poor	4	2	worst	2	1
Has a fire-resistant grade of material	none	0	0	none	0	0	none	0	0
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$196,000	7	42	$261,000	4	24	$60,270	9	54
Minimal consumables cost (most basic material & support cost/cu in)	$6.74	3	15	$6.74	3	15	$1.94	8	40
Minimal operator time		8	40		8	40		5.6	28
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	yes	8	3.2	yes	8	3.2	no	2	0.8
Minimal maintenance cost	$9,900	7	28	$13,900	6	24	$5,500	9	36
Powerful Software		5.7	23		5.7	23		6	24
Ability to join smaller parts to make larger part without Magics	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts	no	2	0.3	no	2	0.3	no	2	0.3
Ability to stack parts	no	2	0.1	no	2	0.1	yes	8	0.5
Ability to nest parts	yes	8	1	yes	8	1	yes	8	1
Knows how much material you have onboard	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need	yes	8	1	yes	8	1	yes	8	1
Can inport STL files	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	141	9	27	141	9	27	94	10	30
Company Profile		3.5	11		3.5	11		5	15
Years in business	7	3	1.5	7	3	1.5	12	5	2.5
Number of all models worldwide	878	4	2	878	4	2	3003	5	2.5

Objective	Z510			SST 1200			Elite		
These weights represent the use of a finished product on flight hardware as a functional prototype or end use part	**SRB Element**		450	**Boeing Space Station**		479			508
Easy to maintain and operate		4.9	34		6.9	48		6.9	48
Time spent per month cleaning & servicing	330 minutes	4	0.7	110 minutes	8	1.4	110 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	25 minutes	4	0.3	25 minutes	4	0.3
Time for set-up inbetween jobs		2	0.2	30 seconds	10	0.9	30 seconds	10	0.9
Time for set-up inbetween jobs with different material		2	0.2	10 minutes	8	0.6	10 minutes	8	0.6
On-board diagnostics	good	8	0.6	medium	6	0.4	medium	6	0.4
Good up-time statistics	not available	0	0	3500 hours b	8	0	3500 hours b	8	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		9	54		9	54		9	54
Little or no parts that the warranty doesn't cover	yes	8	4	yes	8	4	yes	8	4
Close service technician	Jupiter, FL	10	2	Palm Coast,	10	2	Palm Coast,	10	2
Difficulty in sending a service technician	easy	10	3	easy	10	3	easy	10	3
Durable materials		2.1	21		3.7	37		4.2	42
Tensile Strength	3480	3	0.9	3200	3	0.9	5295	5	1.5
Flexural Strength	6236	1	0.2	6000	1	0.2	7604	2	0.4
Impact Strength	not avail		0	2	6	1.8	1.8	5	1.5
Heat Deflection Temperature (at .45MPa)	239	5	1	205	4	0.8	204	4	0.8
High tolerance	0.005	2	18	0.005	2	18	0.003	6	54
Variety of materials		3.2	32		2.3	23		1.5	15
Color Variety	thousands	10	1	7	9	0.9	1	1	0.1
Quantity of different types of materials	3	3	1.2	1	1	0.4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			no			no		
Ability to mix materials	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	1120	2	14	1200	3	21	768	2	14
Minimal facility requirements		5.5	27		5.6	28		5.6	28
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	yes	8	1.6	no	2	0.4	no	2	0.4
Humidity can be above 75%	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	yes	8	1.6	no	2	0.4	no	2	0.4
Material compatible with flight hardware		2.6	26		5.5	55		6	60
Low occurrence of FOD/Shatterability	worst	2	1	fair	6	3	fair	7	3.5
Has a fire-resistant grade of material	none	0	0	HB	3	0.9	HB	3	0.9
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$75,465	9	54	$39,700	10	60	$43,050	9	54
Minimal consumables cost (most basic material & support cost/cu in)	$1.86	8	40	$8.80	1	5	$8.80	1	5
Minimal operator time		5.6	28		8	40		8	40
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	$7,900	8	32	$3,600	9	36	$3,950	10	40
Powerful Software		6	24		6	24		6	24
Ability to join smaller parts to make larger part without Magics	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts	no	2	0.3	yes	8	1.4	yes	8	1.4
Ability to stack parts	yes	8	0.5	no	2	0.1	no	2	0.1
Ability to nest parts	yes	8	1	no	2	0.2	no	2	0.2
Knows how much material you have onboard	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need	yes	8	1	yes	8	1	yes	8	1
Can inport STL files	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	94	10	30	365	4	12	365	4	12
Company Profile		5	15		6	18		6	18
Years in business	12	5	2.5	6	2	1	6	2	1
Number of all models worldwide	3003	5	2.5	7013	10	5	7013	10	5

Appendix C

Decision Matrix

Weighted Decision - For Use on Flight Hardware as a Functional Protoype or End Use Product

Objective	Weight	Sub Weight	Prodigy Plus			Vantage SE			400mc			900mc			EOS P390			EOS Formiga P100		
These weights represent the use of a finished product on flight hardware as a functional prototype or end use part			NSLD		475	NASA Prototype Lab		551			586			525			543			545
Easy to maintain and operate	7			6	42		6	42		6.1	43		6.1	43		4.1	28		4.5	32
Time spent per month cleaning & servicing		0.18	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	660 minutes	2	0.4	660 minutes	2	0.4
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	2 hours	2	0.1	2 hours	2	0.1
Time for set-up inbetween jobs		0.09	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	45 minutes	3	0.3	45 minutes	3	0.3
Time for set-up inbetween jobs with different material		0.08	15 minutes	7	0.6	15 minutes	7	0.6	10 minutes	8	0.6	10 minutes	8	0.6	1 1/2 hours	2	0.2	1 1/2 hours	2	0.2
On-board diagnostics		0.07	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4
Good up-time statistics			unknown	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	6			8.4	50		8.4	50		8.4	50		8.4	50		7.8	47		7.8	47
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Novi, MI	4	0.8	Novi, MI	4	0.8
Difficulty in sending a service technician		0.30	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials	10			3.7	37		6.9	69		8	80		8	80		7.6	76		7.6	76
Tensile Strength		0.30	3200	3	0.9	7600	7	2.1	8000	8	2.4	8000	8	2.4	6962	6	1.8	6962	6	1.8
Flexural Strength		0.20	6000	1	0.2	14000	9	1.8	15900	10	2	15900	10	2	10733	5	1	10733	5	1
Impact Strength		0.30	2	6	1.8	2.3	6	1.8	2.6	6	1.8	2.6	6	1.8	4.12	10	3	4.12	10	3
Heat Deflection Temperature (at .45MPa)		0.20	195	4	0.8	280	6	1.2	372	9	1.8	372	9	1.8	350	9	1.8	350	9	1.8
High tolerance	9		0.005	2	18	0.005	2	18	0.005	2	18	0.005	2	18	0.004	4	36	0.004	4	36
Variety of materials	10			2.3	23		4.9	49		4.6	46		4.2	42		4.9	49		4.9	49
Color Variety		0.10	7	9	0.9	7	9	0.9	1 & custom	2	0.2	1 & custom	2	0.2	3	3	0.3	3	3	0.3
Quantity of different types of materials		0.40	1	1	0.4	3	3	1.2	4	4	1.6	3	3	1.2	9	9	3.6	9	9	3.6
Ability to print in different colors without changing cartridges			no			no			no			no			no	2		no	2	
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	no	2	0.6	yes	8	2.4	yes	8	2.4	yes	8	2.4	no	2	0.6	no	2	0.6
Large build envelope	7		640	1	7	3584	8	56	3584	8	56	31104	10	70	4381	9	63	1006	2	14
Minimal facility requirements	5			5.6	28		5.4	27		5.4	27		5.4	27		4.3	22		4.3	22
Runs on 110V		0.18	yes	8	1.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require drainage		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4
Humidity can be above 75%		0.14	yes	8	1.1	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	yes	8	0.8	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Material compatible with flight hardware	10			5.5	55		7.1	71		8.6	86		8.6	86		7.5	75		7.5	75
Low occurrence of FOD/Shatterability		0.50	fair	6	3	good	8	4	good	8	4	good	8	4	excellent	10	5	excellent	10	5
Has a fire-resistant grade of material		0.30	HB	3	0.9	V2	5	1.5	V0	10	3	V0	10	3	HB	3	0.9	HB	3	0.9
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	6		$40,000	10	60	$182,850	6	36	$184,645	6	36	$406,370	0	0	$380,000	1	6	$200,000	5	30
Minimal consumables cost (most basic material & support cost/cu in)	5		$8.92	1	5	$7.61	2	10	$7.61	2	10	$7.61	2	10	$1.09	9	45	$1.09	9	45
Minimal operator time	5			8	40		8	40		8	40		8	40		5.6	28		5.6	28
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	yes	8	3.2	yes	8	3.2	yes	8	3.2	yes	8	3.2	no	2	0.8	no	2	0.8
Minimal maintenance cost	4		$5,000	9	36	$14,500	6	24	$18,130	5	20	$35,000	0	0	$35,000	0	0	$17,500	5	20
Powerful Software	4			6.7	27		7.6	31		7.6	31		7.6	31		7	28		7	28
Ability to join smaller parts to make larger part without Magics		0.16	no	2	0.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Ability to stack parts		0.06	no	2	0.1	no	2	0.1	no	2	0.1	no	2	0.1	yes	8	0.5	yes	8	0.5
Ability to nest parts		0.12	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	3		216	7	21	487	1	3	325	6	18	487	1	3	180	8	24	120	9	27
Company Profile	3			8.5	26		8.5	26		8.5	26		8.5	26		5.5	17		5.5	17
Years in business		0.50	17	7	3.5	17	7	3.5	17	7	3.5	17	7	3.5	18	8	4	18	8	4
Number of all models worldwide		0.50	7013	10	5	7013	10	5	7013	10	5	7013	10	5	656	3	1.5	656	3	1.5

Appendix C
Decision Matrix
Weighted Decision - Visual Aids and Presentations

Objective	Weight	Sub Weight	SinterStation HiQ			InVision XT			ProJet HD 3000			Eden 500V			Connex 500			Z450			Z510			SST 1200			Elite		
These weights represent the use of a finished product for Visual Aids and Presentations					496			518			549			503			496			548	SRB Element		546	Boeing Space Station		506			488
Easy to maintain and operate	7			3.5	25		5.8	41		6	42		5.8	40		5.8	40		5.6	39		4.9	34		6.9	48		6.9	48
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1.8	150 minutes	6	1.1	150 minutes	6	1.1	110 minutes	8	1.4	330 minutes	4	0.7	110 minutes	8	1.4	110 minutes	8	1.4
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0.6	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0.1	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	25 minutes	4	0.3	25 minutes	4	0.3
Time for set-up inbetween jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0.5	10 minutes	8	0.7	10 minutes	8	0.7	127 minutes	2	0.2		2	0.2	30 seconds	10	0.9	30 seconds	10	0.9
Time for set-up inbetween jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0.2	15 minutes	7	0.6	15 minutes	7	0.6		2	0.2		2	0.2	10 minutes	8	0.6	10 minutes	8	0.6
On-board diagnostics		0.07	low	2	0.1	low	2	0.1	low	2	0.1	low	2	0.1	low	2	0.1	good	8	0.6	good	8	0.6	medium	6	0.4	medium	6	0.4
Good up-time statistics			not available	0	0	not available		0	not avail	0	0	95%	8	0	95%	8	0	not available	0	0	not available	0	0	3500 hours t	8	0	3500 hours t	8	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	6			7.8	47		9	54		9	54		4.5	27		4.5	27		9	54		9	54		9	54		9	54
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	no	2	1	no	2	1	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	2	Atlanta	7	1.4	Atlanta	7	1.4	Jupiter, FL	10	2	Jupiter, FL	10	2	Palm Coast,	10	2	Palm Coast,	10	2
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	3	medium	7	2.1	medium	7	2.1	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials	4			6.8	27		1.8	7.2		1.8	7.2		4.5	18		4.5	18		2.1	8.4		2.1	8.4		3.7	15		4.2	17
Tensile Strength		0.30	6961	6	1.8	4900	4	1.2	4900	4	1.2	8744	8	2.4	8744	8	2.4	3480	3	0.9	3480	3	0.9	3200	3	0.9	5295	5	1.5
Flexural Strength		0.20	19000	10	2	7500	2	0.4	7500	2	0.4	10991	5	1	10991	5	1	6236	1	0.2	6236	1	0.2	6000	1	0.2	7604	2	0.4
Impact Strength		0.30	1.4	4	1.2	not avail		0	not avail		0	0.79	3	0.9	0.79	3	0.9	not avail		0	not avail		0	2	6	1.8	1.8	5	1.5
Heat Deflection Temperature (at .45MPa)		0.20	370	9	1.8	114.8	1	0.2	114.8	1	0.2	120	1	0.2	120	1	0.2	239	5	1	239	5	1	205	4	0.8	204	4	0.8
High tolerance	7		0.002	8	56	0.002	8	56	0.001	10	70	0.004	4	28	0.004	4	28	0.005	2	14	0.005	2	14	0.005	2	14	0.003	6	42
Variety of materials	10	1.00		2.5	25		1.4	14		2.5	25		4.2	42		5.7	57		5.9	59		6.1	61		5.4	54		1.4	14
Color Variety		0.50	2	2	1	1	1	0.5	3	3	1.5	3	3	1.5	3	3	1.5	thousands	10	5	thousands	10	5	7	9	4.5	1	1	0.5
Quantity of different types of materials		0.10	7	7	0.7	1	1	0.1	2	2	0.2	7	7	0.7	28	10	1	1	1	0.1	3	3	0.3	1	1	0.1	1	1	0.1
Ability to print in different colors without changing cartridges			no			no			no			yes			yes			yes			yes			no			no		
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.6	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.20	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Large build envelope	7		3510	7	49	686	2	14	686.2	2	14	2348	5	35	2443	5	35	640	1	7	1120	2	14	1200	3	21	768	2	14
Minimal facility requirements	4			4.3	17		8	32		8	32		3.7	15		3.7	15		6.1	24		5.5	22		5.6	22		5.6	22
Runs on 110V		0.18	no	2	0.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4
Humidity can be above 75%		0.14	no	2	0.3	yes	8	1.1	yes	8	1.1	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	no	2	0.2	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4
Material compatible with flight hardware	2			7.5	15		3.6	7.2		3.6	7.2		3.6	7.2		3.6	7.2		2.6	5.2		2.6	5.2		5.5	11		6	12
Low occurrence of FOD/Shatterability		0.50	excellent	10	5	poor	4	2	poor	4	2	poor	4	2	poor	4	2	worst	2	1	worst	2	1	fair	6	3	fair	7	3.5
Has a fire-resistant grade of material		0.30	HB	3	0.9	none	0	0	none	0	0	none	0	0	none	0	0	none	0	0	none	0	0	HB	3	0.9	HB	3	0.9
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	6		$365,930	1	6	$71,500	9	54	$74,900	9	54	$196,000	7	42	$261,000	4	24	$60,270	9	54	$75,465	9	54	$39,700	10	60	$43,050	9	54
Minimal consumables cost (most basic material & support cost/cu in)	7		$2.33	8	56	$3.79	6	42	$3.79	6	42	$6.74	3	21	$6.74	3	21	$1.94	8	56	$1.86	8	56	$8.80	1	7	$8.80	1	7
Minimal operator time	10			5.6	56		8	80		8	80		8	80		8	80		5.6	56		5.6	56		8	80		8	80
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	no	2	0.8	yes	8	3.2	yes	8	3.2	yes	8	3.2	yes	8	3.2	no	2	0.8	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	4		$28,100	1	4	$9,000	8	32	$9,600	8	32	$9,900	7	28	$13,900	6	24	$5,500	9	36	$7,900	8	32	$3,600	9	36	$3,950	10	40
Powerful Software	5			7	35		4.9	25		6	30		5.7	28		5.7	28		6	30		6	30		6	30		6	30
Ability to join smaller parts to make larger part without Magics		0.16	yes	8	1.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	yes	8	1.4	yes	8	1.4
Ability to stack parts		0.06	yes	8	0.5	no	2	0.1	yes	8	0.5	no	2	0.1	no	2	0.1	yes	8	0.5	yes	8	0.5	no	2	0.1	no	2	0.1
Ability to nest parts		0.12	yes	8	1	no	2	0.2	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	no	2	0.2	no	2	0.2
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	9		260	6	54	338	4	36	est. 338	4	36	141	9	81	141	9	81	94	10	90	94	10	90	365	4	36	365	4	36
Company Profile	3			8	24		8	24		8	24		3.5	11		3.5	11		5	15		5	15		6	18		6	18
Years in business		0.50	20	10	5	20	10	5	20	10	5	7	3	1.5	7	3	1.5	12	5	2.5	12	5	2.5	6	2	1	6	2	1
Number of all models worldwide		0.50	3934	6	3	3934	6	3	3934	6	3	878	4	2	878	4	2	3003	5	2.5	3003	5	2.5	7013	10	5	7013	10	5

Appendix C
Decision Matrix
Weighted Decision - Visual Aids and Presentations

Objective	Weight	Sub Weight	Prodigy Plus			Vantage SE			400mc			900mc			EOS P390			EOS Formiga P100		
These weights represent the use of a finished product for Visual Aids and Presentations			NSLD		521	NASA Prototype Lab		521			535			447			510			517
Easy to maintain and operate	7			6	42		6	42		6.1	43		6.1	43		4.1	28		4.5	32
Time spent per month cleaning & servicing		0.18	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	660 minutes	2	0.4	660 minutes	2	0.4
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	2 hours	2	0.1	2 hours	2	0.1
Time for set-up inbetween jobs		0.09	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	45 minutes	3	0.3	45 minutes	3	0.3
Time for set-up inbetween jobs with different material		0.08	15 minutes	7	0.6	15 minutes	7	0.6	10 minutes	8	0.6	10 minutes	8	0.6	1 1/2 hours	2	0.2	1 1/2 hours	2	0.2
On-board diagnostics		0.07	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4
Good up-time statistics			unknown	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	6			8.4	50		8.4	50		8.4	50		8.4	50		7.8	47		7.8	47
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Novi, MI	4	0.8	Novi, MI	4	0.8
Difficulty in sending a service technician		0.30	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials	4			3.7	15		6.9	28		8	32		8	32		7.6	30		7.6	30
Tensile Strength		0.30	3200	3	0.9	7600	7	2.1	8000	8	2.4	8000	8	2.4	6962	6	1.8	6962	6	1.8
Flexural Strength		0.20	6000	1	0.2	14000	9	1.8	15900	10	2	15900	10	2	10733	5	1	10733	5	1
Impact Strength		0.30	2	6	1.8	2.3	6	1.8	2.6	6	1.8	2.6	6	1.8	4.12	10	3	4.12	10	3
Heat Deflection Temperature (at .45MPa)		0.20	195	4	0.8	280	6	1.2	372	9	1.8	372	9	1.8	350	9	1.8	350	9	1.8
High tolerance	7		0.005	2	14	0.005	2	14	0.005	2	14	0.005	2	14	0.004	4	28	0.004	4	28
Variety of materials	10	1.00		5.4	54		6.8	68		3.4	34		3.3	33		3.2	32		3.2	32
Color Variety		0.50	7	9	4.5	7	9	4.5	1 & custom	2	1	1 & custom	2	1	3	3	1.5	3	3	1.5
Quantity of different types of materials		0.10	1	1	0.1	3	3	0.3	4	4	0.4	3	3	0.3	9	9	0.9	9	9	0.9
Ability to print in different colors without changing cartridges			no			no			no			no			no	2		no	2	
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.20	no	2	0.4	yes	8	1.6	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4
Large build envelope	7		640	1	7	3584	8	56	3584	8	56	31104	10	70	4381	9	63	1006	2	14
Minimal facility requirements	4			5.6	22		5.4	22		5.4	22		5.4	22		4.3	17		4.3	17
Runs on 110V		0.18	yes	8	1.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require drainage		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4
Humidity can be above 75%		0.14	yes	8	1.1	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	yes	8	0.8	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Material compatible with flight hardware	2			5.5	11		7.1	14		8.6	17		8.6	17		7.5	15		7.5	15
Low occurrence of FOD/Shatterability		0.50	fair	6	3	good	8	4	good	8	4	good	8	4	excellent	10	5	excellent	10	5
Has a fire-resistant grade of material		0.30	HB	3	0.9	V2	5	1.5	V0	10	3	V0	10	3	HB	3	0.9	HB	3	0.9
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	6		$40,000	10	60	$182,850	6	36	$184,645	6	36	$406,370	0	0	$380,000	1	6	$200,000	5	30
Minimal consumables cost (most basic material & support cost/cu in)	7		$8.92	1	7	$7.61	2	14	$7.61	2	14	$7.61	2	14	$1.09	9	63	$1.09	9	63
Minimal operator time	10			8	80		8	80		8	80		8	80		5.6	56		5.6	56
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	yes	8	3.2	yes	8	3.2	yes	8	3.2	yes	8	3.2	no	2	0.8	no	2	0.8
Minimal maintenance cost	4		$5,000	9	36	$14,500	6	24	$18,130	5	20	$35,000	0	0	$35,000	0	0	$17,500	5	20
Powerful Software	5			6.7	33		7.6	38		7.6	38		7.6	38		7	35		7	35
Ability to join smaller parts to make larger part without Magics		0.16	no	2	0.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Ability to stack parts		0.06	no	2	0.1	no	2	0.1	no	2	0.1	no	2	0.1	yes	8	0.5	yes	8	0.5
Ability to nest parts		0.12	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	9		216	7	63	487	1	9	325	6	54	487	1	9	180	8	72	120	9	81
Company Profile	3			8.5	26		8.5	26		8.5	26		8.5	26		5.5	17		5.5	17
Years in business		0.50	17	7	3.5	17	7	3.5	17	7	3.5	17	7	3.5	18	8	4	18	8	4
Number of all models worldwide		0.50	7013	10	5	7013	10	5	7013	10	5	7013	10	5	656	3	1.5	656	3	1.5

Appendix C
Decision Matrix
Weighted Decision - Cost and Time

Objective	Weight	Sub Weight	SinterStation HiQ			InVision XT			ProJet HD 3000		
These weights represent the machine that values time & cost above all else					537			626			645
Easy to maintain and operate	8			3.5	28		5.8	46		6	48
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1.8
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0.1
Time for set-up inbetween jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0.5
Time for set-up inbetween jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0.2
On-board diagnostics		0.07	low	2	0.1	low	2	0.1	low	2	0.1
Good up-time statistics			not available	0	0	not available	0	0	not avail	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	8			7.8	62		9	72		9	72
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	2
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	3
Durable materials	4			6.8	27		1.8	7.2		1.8	7.2
Tensile Strength		0.30	6961	6	1.8	4900	4	1.2	4900	4	1.2
Flexural Strength		0.20	19000	10	2	7500	2	0.4	7500	2	0.4
Impact Strength		0.30	1.4	4	1.2	not avail		0	not avail		0
Heat Deflection Temperature (at .45MPa)		0.20	370	9	1.8	114.8	1	0.2	114.8	1	0.2
High tolerance	5		0.002	8	40	0.002	8	40	0.001	10	50
Variety of materials	4	1.00		4	16		1.5	6		2.1	8.4
Color Variety		0.10	2	2	0.2	1	1	0.1	3	3	0.3
Quantity of different types of materials		0.40	7	7	2.8	1	1	0.4	2	2	0.8
Ability to print in different colors without changing cartridges			no			no			no		
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	7		3510	7	49	686	2	14	686.2	2	14
Minimal facility requirements	6			4.3	26		8	48		8	48
Runs on 110V		0.18	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6
Humidity can be above 75%		0.14	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	yes	8	1.6	yes	8	1.6
Material compatible with flight hardware	2			7.5	15		3.6	7.2		3.6	7.2
Low occurrence of FOD/Shatterability		0.50	excellent	10	5	poor	4	2	poor	4	2
Has a fire-resistant grade of material		0.30	HB	3	0.9	none	0	0	none	0	0
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	8		$365,930	1	8	$71,500	9	72	$74,900	9	72
Minimal consumables cost (most basic material & support cost/cu in)	10		$2.33	8	80	$3.79	6	60	$3.79	6	60
Minimal operator time	9			5.6	50		8	72		8	72
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	10		$28,100	1	10	$9,000	8	80	$9,600	8	80
Powerful Software	5			7	35		4.9	25		6	30
Ability to join smaller parts to make larger part without Magics		0.16	yes	8	1.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	no	2	0.3	no	2	0.3	no	2	0.3
Ability to stack parts		0.06	yes	8	0.5	no	2	0.1	yes	8	0.5
Ability to nest parts		0.12	yes	8	1	no	2	0.2	yes	8	1
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	7		260	6	42	338	4	28	est. 338	4	28
Company Profile	6			8	48		8	48		8	48
Years in business		0.50	20	10	5	20	10	5	20	10	5
Number of all models worldwide		0.50	3934	6	3	3934	6	3	3934	6	3

Objective	Eden 500V			Connex 500			Z450		
These weights represent the machine that values time & cost above all else			548			524			616
Easy to maintain and operate		5.8	46		5.8	46		5.6	45
Time spent per month cleaning & servicing	150 minutes	6	1.1	150 minutes	6	1.1	110 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	no	2	0.2	no	2	0.2
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Time for set-up inbetween jobs	10 minutes	8	0.7	10 minutes	8	0.7	127 minutes	2	0.2
Time for set-up inbetween jobs with different material	15 minutes	7	0.6	15 minutes	7	0.6		2	0.2
On-board diagnostics	low	2	0.1	low	2	0.1	good	8	0.6
Good up-time statistics	95%	8	0	95%	8	0	not available	0	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		4.5	36		4.5	36		9	72
Little or no parts that the warranty doesn't cover	no	2	1	no	2	1	yes	8	4
Close service technician	Atlanta	7	1.4	Atlanta	7	1.4	Jupiter, FL	10	2
Difficulty in sending a service technician	medium	7	2.1	medium	7	2.1	easy	10	3
Durable materials		4.5	18		4.5	18		2.1	8.4
Tensile Strength	8744	8	2.4	8744	8	2.4	3480	3	0.9
Flexural Strength	10991	5	1	10991	5	1	6236	1	0.2
Impact Strength	0.79	3	0.9	0.79	3	0.9	not avail		0
Heat Deflection Temperature (at .45MPa)	120	1	0.2	120	1	0.2	239	5	1
High tolerance	0.004	4	20	0.004	4	20	0.005	2	10
Variety of materials		5.9	24		8.3	33		2.4	9.6
Color Variety	3	3	0.3	3	3	0.3	thousands	10	1
Quantity of different types of materials	7	7	2.8	28	10	4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			yes			yes		
Ability to mix materials	no	2	0.4	yes	8	1.6	no	2	0.4
Ability to change out materials mid way thru build	yes	8	2.4	yes	8	2.4	no	2	0.6
Large build envelope	2348	5	35	2443	5	35	640	1	7
Minimal facility requirements		3.7	22		3.7	22		6.1	36
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	no	2	0.4	no	2	0.4	yes	8	1.6
Humidity can be above 75%	no	2	0.3	no	2	0.3	no	2	0.3
Temperature can change up to 20 degrees	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require ventilation/dust collector	yes	8	0.8	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	no	2	0.4	no	2	0.4	yes	8	1.6
Material compatible with flight hardware		3.6	7.2		3.6	7.2		2.6	5.2
Low occurrence of FOD/Shatterability	poor	4	2	poor	4	2	worst	2	1
Has a fire-resistant grade of material	none	0	0	none	0	0	none	0	0
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$196,000	7	56	$261,000	4	32	$60,270	9	72
Minimal consumables cost (most basic material & support cost/cu in)	$6.74	3	30	$6.74	3	30	$1.94	8	80
Minimal operator time		8	72		8	72		5.6	50
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	yes	8	3.2	yes	8	3.2	no	2	0.8
Minimal maintenance cost	$9,900	7	70	$13,900	6	60	$5,500	9	90
Powerful Software		5.7	28		5.7	28		6	30
Ability to join smaller parts to make larger part without Magics	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts	no	2	0.3	no	2	0.3	no	2	0.3
Ability to stack parts	no	2	0.1	no	2	0.1	yes	8	0.5
Ability to nest parts	yes	8	1	yes	8	1	yes	8	1
Knows how much material you have onboard	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need	yes	8	1	yes	8	1	yes	8	1
Can inport STL files	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	141	9	63	141	9	63	94	10	70
Company Profile		3.5	21		3.5	21		5	30
Years in business	7	3	1.5	7	3	1.5	12	5	2.5
Number of all models worldwide	878	4	2	878	4	2	3003	5	2.5

Objective	Z510			SST 1200			Elite		
These weights represent the machine that values time & cost above all else	SRB Element		607	Boeing Space Station		572			587
Easy to maintain and operate		4.9	39		6.9	55		6.9	55
Time spent per month cleaning & servicing	330 minutes	4	0.7	110 minutes	8	1.4	110 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	25 minutes	4	0.3	25 minutes	4	0.3
Time for set-up inbetween jobs		2	0.2	30 seconds	10	0.9	30 seconds	10	0.9
Time for set-up inbetween jobs with different material		2	0.2	10 minutes	8	0.6	10 minutes	8	0.6
On-board diagnostics	good	8	0.6	medium	6	0.4	medium	6	0.4
Good up-time statistics	not available	0	0	3500 hours b	8	0	3500 hours b	8	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		9	72		9	72		9	72
Little or no parts that the warranty doesn't cover	yes	8	4	yes	8	4	yes	8	4
Close service technician	Jupiter, FL	10	2	Palm Coast,	10	2	Palm Coast,	10	2
Difficulty in sending a service technician	easy	10	3	easy	10	3	easy	10	3
Durable materials		2.1	8.4		3.7	15		4.2	17
Tensile Strength	3480	3	0.9	3200	3	0.9	5295	5	1.5
Flexural Strength	6236	1	0.2	6000	1	0.2	7604	2	0.4
Impact Strength	not avail		0	2	6	1.8	1.8	5	1.5
Heat Deflection Temperature (at .45MPa)	239	5	1	205	4	0.8	204	4	0.8
High tolerance	0.005	2	10	0.005	2	10	0.003	6	30
Variety of materials		3.2	13		2.3	9.2		1.5	6
Color Variety	thousands	10	1	7	9	0.9	1	1	0.1
Quantity of different types of materials	3	3	1.2	1	1	0.4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			no			no		
Ability to mix materials	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	1120	2	14	1200	3	21	768	2	14
Minimal facility requirements		5.5	33		5.6	34		5.6	34
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	yes	8	1.6	no	2	0.4	no	2	0.4
Humidity can be above 75%	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	yes	8	1.6	no	2	0.4	no	2	0.4
Material compatible with flight hardware		2.6	5.2		5.5	11		6	12
Low occurrence of FOD/Shatterability	worst	2	1	fair	6	3	fair	7	3.5
Has a fire-resistant grade of material	none	0	0	HB	3	0.9	HB	3	0.9
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$75,465	9	72	$39,700	10	80	$43,050	9	72
Minimal consumables cost (most basic material & support cost/cu in)	$1.86	8	80	$8.80	1	10	$8.80	1	10
Minimal operator time		5.6	50		8	72		8	72
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	$7,900	8	80	$3,600	9	90	$3,950	10	100
Powerful Software		6	30		6	30		6	30
Ability to join smaller parts to make larger part without Magics	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts	no	2	0.3	yes	8	1.4	yes	8	1.4
Ability to stack parts	yes	8	0.5	no	2	0.1	no	2	0.1
Ability to nest parts	yes	8	1	no	2	0.2	no	2	0.2
Knows how much material you have onboard	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need	yes	8	1	yes	8	1	yes	8	1
Can inport STL files	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	94	10	70	365	4	28	365	4	28
Company Profile		5	30		6	36		6	36
Years in business	12	5	2.5	6	2	1	6	2	1
Number of all models worldwide	3003	5	2.5	7013	10	5	7013	10	5

Appendix C
Decision Matrix
Weighted Decision - Cost and Time

Objective	Weight	Sub Weight	Prodigy Plus			Vantage SE			400mc			900mc			EOS P390			EOS Formiga P100		
These weights represent the machine that values time & cost above all else			**NSLD**		**586**	**NASA Prototype Lab**		**571**			**603**			**482**			**541**			**585**
Easy to maintain and operate	8			6	**48**		6	**48**		6.1	**49**		6.1	**49**		4.1	**32**		4.5	**36**
Time spent per month cleaning & servicing		0.18	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	660 minutes	2	0.4	660 minutes	2	0.4
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	2 hours	2	0.1	2 hours	2	0.1
Time for set-up inbetween jobs		0.09	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	45 minutes	3	0.3	45 minutes	3	0.3
Time for set-up inbetween jobs with different material		0.08	15 minutes	7	0.6	15 minutes	7	0.6	10 minutes	8	0.6	10 minutes	8	0.6	1 1/2 hours	2	0.2	1 1/2 hours	2	0.2
On-board diagnostics		0.07	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4
Good up-time statistics			unknown	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	8			8.4	**67**		8.4	**67**		8.4	**67**		8.4	**67**		7.8	**62**		7.8	**62**
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Novi, MI	4	0.8	Novi, MI	4	0.8
Difficulty in sending a service technician		0.30	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials	4			3.7	**15**		6.9	**28**		8	**32**		8	**32**		7.6	**30**		7.6	**30**
Tensile Strength		0.30	3200	3	0.9	7600	7	2.1	8000	8	2.4	8000	8	2.4	6962	6	1.8	6962	6	1.8
Flexural Strength		0.20	6000	1	0.2	14000	9	1.8	15900	10	2	15900	10	2	10733	5	1	10733	5	1
Impact Strength		0.30	2	6	1.8	2.3	6	1.8	2.6	6	1.8	2.6	6	1.8	4.12	10	3	4.12	10	3
Heat Deflection Temperature (at .45MPa)		0.20	195	4	0.8	280	6	1.2	372	9	1.8	372	9	1.8	350	9	1.8	350	9	1.8
High tolerance	5		0.005	2	**10**	0.005	2	**10**	0.005	2	**10**	0.005	2	**10**	0.004	4	**20**	0.004	4	**20**
Variety of materials	4	1.00		2.3	**9.2**		4.9	**20**		4.6	**18**		4.2	**17**		4.9	**20**		4.9	**20**
Color Variety		0.10	7	9	0.9	7	9	0.9	1 & custom	2	0.2	1 & custom	2	0.2	3	3	0.3	3	3	0.3
Quantity of different types of materials		0.40	1	1	0.4	3	3	1.2	4	4	1.6	3	3	1.2	9	9	3.6	9	9	3.6
Ability to print in different colors without changing cartridges			no			no			no			no			no	2		no	2	
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	no	2	0.6	yes	8	2.4	yes	8	2.4	yes	8	2.4	no	2	0.6	no	2	0.6
Large build envelope	7		640	1	**7**	3584	8	**56**	3584	8	**56**	31104	10	**70**	4381	9	**63**	1006	2	**14**
Minimal facility requirements	6			5.6	**34**		5.4	**32**		5.4	**32**		5.4	**32**		4.3	**26**		4.3	**26**
Runs on 110V		0.18	yes	8	1.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require drainage		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4
Humidity can be above 75%		0.14	yes	8	1.1	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	yes	8	0.8	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Material compatible with flight hardware	2			5.5	**11**		7.1	**14**		8.6	**17**		8.6	**17**		7.5	**15**		7.5	**15**
Low occurrence of FOD/Shatterability		0.50	fair	6	3	good	8	4	good	8	4	good	8	4	excellent	10	5	excellent	10	5
Has a fire-resistant grade of material		0.30	HB	3	0.9	V2	5	1.5	V0	10	3	V0	10	3	HB	3	0.9	HB	3	0.9
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	8		$40,000	10	**80**	$182,850	6	**48**	$184,645	6	**48**	$406,370	0	**0**	$380,000	1	**8**	$200,000	5	**40**
Minimal consumables cost (most basic material & support cost/cu in)	10		$8.92	1	**10**	$7.61	2	**20**	$7.61	2	**20**	$7.61	2	**20**	$1.09	9	**90**	$1.09	9	**90**
Minimal operator time	9			8	**72**		8	**72**		8	**72**		8	**72**		5.6	**50**		5.6	**50**
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	yes	8	3.2	yes	8	3.2	yes	8	3.2	yes	8	3.2	no	2	0.8	no	2	0.8
Minimal maintenance cost	10		$5,000	9	**90**	$14,500	6	**60**	$18,130	5	**50**	$35,000	0	**0**	$35,000	0	**0**	$17,500	5	**50**
Powerful Software	5			6.7	**33**		7.6	**38**		7.6	**38**		7.6	**38**		7	**35**		7	**35**
Ability to join smaller parts to make larger part without Magics		0.16	no	2	0.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Ability to stack parts		0.06	no	2	0.1	no	2	0.1	no	2	0.1	no	2	0.1	yes	8	0.5	yes	8	0.5
Ability to nest parts		0.12	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	7		216	7	**49**	487	1	**7**	325	6	**42**	487	1	**7**	180	8	**56**	120	9	**63**
Company Profile	6			8.5	**51**		8.5	**51**		8.5	**51**		8.5	**51**		5.5	**33**		5.5	**33**
Years in business		0.50	17	7	3.5	17	7	3.5	17	7	3.5	17	7	3.5	18	8	4	18	8	4
Number of all models worldwide		0.50	7013	10	5	7013	10	5	7013	10	5	7013	10	5	656	3	1.5	656	3	1.5

Appendix C
Decision Matrix
Weighted Decision - Large Thermoform Molds

Objective	Weight	Sub Weight	SinterStation HiQ			InVision XT			ProJet HD 3000		
These weights represent the use of a finished product for LARGE Thermoform Molds					529			467			490
Easy to maintain and operate	7			3.5	25		5.8	41		6	42
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1.8
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0.1
Time for set-up inbetween jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0.5
Time for set-up inbetween jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0.2
On-board diagnostics		0.07	low	2	0.1	low	2	0.1	low	2	0.1
Good up-time statistics			not available	0	0	not available	0	0	not avail	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	6			7.8	47		9	54		9	54
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	2
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	3
Durable materials	10	1.00		8.3	83		1.3	13		1.3	13
Tensile Strength		0.10	6961	6	0.6	4900	4	0.4	4900	4	0.4
Flexural Strength		0.10	19000	10	1	7500	2	0.2	7500	2	0.2
Impact Strength		0.10	1.4	4	0.4	not avail		0	not avail		0
Heat Deflection Temperature (at .45MPa)		0.70	370	9	6.3	114.8	1	0.7	114.8	1	0.7
High tolerance	5		0.002	8	40	0.002	8	40	0.001	10	50
Variety of materials	5	1.00		4	20		1.5	7.5		2.1	11
Color Variety		0.10	2	2	0.2	1	1	0.1	3	3	0.3
Quantity of different types of materials		0.40	7	7	2.8	1	1	0.4	2	2	0.8
Ability to print in different colors without changing cartridges			no			no			no		
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	10		3510	7	70	686	2	20	686.2	2	20
Minimal facility requirements	6			4.3	26		8	48		8	48
Runs on 110V		0.18	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6
Humidity can be above 75%		0.14	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	yes	8	1.6	yes	8	1.6
Material compatible with flight hardware	2			7.5	15		3.6	7.2		3.6	7.2
Low occurrence of FOD/Shatterability		0.50	excellent	10	5	poor	4	2	poor	4	2
Has a fire-resistant grade of material		0.30	HB	3	0.9	none	0	0	none	0	0
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	4		$365,930	1	4	$71,500	9	36	$74,900	9	36
Minimal consumables cost (most basic material & support cost/cu in)	8		$2.33	8	64	$3.79	6	48	$3.79	6	48
Minimal operator time	5			5.6	28		8	40		8	40
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	4		$28,100	1	4	$9,000	8	32	$9,600	8	32
Powerful Software	10	1.00		5	50		3.7	37		4.5	45
Ability to join smaller parts to make larger part without Magics		0.08	yes	8	0.6	no	2	0.2	no	2	0.2
Ability to scale		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4
Ability to build sparse filled parts		0.50	no	2	1	no	2	1	no	2	1
Ability to stack parts		0.04	yes	8	0.3	no	2	0.1	yes	8	0.3
Ability to nest parts		0.10	yes	8	0.8	no	2	0.2	yes	8	0.8
Knows how much material you have onboard		0.08	yes	8	0.6	yes	8	0.6	yes	8	0.6
Knows how much material you need		0.10	yes	8	0.8	yes	8	0.8	yes	8	0.8
Can inport STL files		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4
Fast Build Speed (Machine Run Time Only)	5		260	6	30	338	4	20	est. 338	4	20
Company Profile	3			8	24		8	24		8	24
Years in business		0.50	20	10	5	20	10	5	20	10	5
Number of all models worldwide		0.50	3934	6	3	3934	6	3	3934	6	3

Objective	Eden 500V			Connex 500			Z450		
These weights represent the use of a finished product for LARGE Thermoform Molds			437			433			480
Easy to maintain and operate		5.8	40		5.8	40		5.6	39
Time spent per month cleaning & servicing	150 minutes	6	1.1	150 minutes	6	1.1	110 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	no	2	0.2	no	2	0.2
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Time for set-up inbetween jobs	10 minutes	8	0.7	10 minutes	8	0.7	127 minutes	2	0.2
Time for set-up inbetween jobs with different material	15 minutes	7	0.6	15 minutes	7	0.6		2	0.2
On-board diagnostics	low	2	0.1	low	2	0.1	good	8	0.6
Good up-time statistics	95%	8	0	95%	8	0	not available	0	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		4.5	27		4.5	27		9	54
Little or no parts that the warranty doesn't cover	no	2	1	no	2	1	yes	8	4
Close service technician	Atlanta	7	1.4	Atlanta	7	1.4	Jupiter, FL	10	2
Difficulty in sending a service technician	medium	7	2.1	medium	7	2.1	easy	10	3
Durable materials		2.3	23		2.3	23		3.9	39
Tensile Strength	8744	8	0.8	8744	8	0.8	3480	3	0.3
Flexural Strength	10991	5	0.5	10991	5	0.5	6236	1	0.1
Impact Strength	0.79	3	0.3	0.79	3	0.3	not avail		0
Heat Deflection Temperature (at .45MPa)	120	1	0.7	120	1	0.7	239	5	3.5
High tolerance	0.004	4	20	0.004	4	20	0.005	2	10
Variety of materials		5.9	30		8.3	42		2.4	12
Color Variety	3	3	0.3	3	3	0.3	thousands	10	1
Quantity of different types of materials	7	7	2.8	28	10	4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			yes			yes		
Ability to mix materials	no	2	0.4	yes	8	1.6	no	2	0.4
Ability to change out materials mid way thru build	yes	8	2.4	yes	8	2.4	no	2	0.6
Large build envelope	2348	5	50	2443	5	50	640	1	10
Minimal facility requirements		3.7	22		3.7	22		6.1	36
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	no	2	0.4	no	2	0.4	yes	8	1.6
Humidity can be above 75%	no	2	0.3	no	2	0.3	no	2	0.3
Temperature can change up to 20 degrees	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require ventilation/dust collector	yes	8	0.8	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	no	2	0.4	no	2	0.4	yes	8	1.6
Material compatible with flight hardware		3.6	7.2		3.6	7.2		2.6	5.2
Low occurrence of FOD/Shatterability	poor	4	2	poor	4	2	worst	2	1
Has a fire-resistant grade of material	none	0	0	none	0	0	none	0	0
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$196,000	7	28	$261,000	4	16	$60,270	9	36
Minimal consumables cost (most basic material & support cost/cu in)	$6.74	3	24	$6.74	3	24	$1.94	8	64
Minimal operator time		8	40		8	40		5.6	28
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	yes	8	3.2	yes	8	3.2	no	2	0.8
Minimal maintenance cost	$9,900	7	28	$13,900	6	24	$5,500	9	36
Powerful Software		4.3	43		4.3	43		4.5	45
Ability to join smaller parts to make larger part without Magics	no	2	0.2	no	2	0.2	no	2	0.2
Ability to scale	yes	8	0.4	yes	8	0.4	yes	8	0.4
Ability to build sparse filled parts	no	2	1	no	2	1	no	2	1
Ability to stack parts	no	2	0.1	no	2	0.1	yes	8	0.3
Ability to nest parts	yes	8	0.8	yes	8	0.8	yes	8	0.8
Knows how much material you have onboard	yes	8	0.6	yes	8	0.6	yes	8	0.6
Knows how much material you need	yes	8	0.8	yes	8	0.8	yes	8	0.8
Can inport STL files	yes	8	0.4	yes	8	0.4	yes	8	0.4
Fast Build Speed (Machine Run Time Only)	141	9	45	141	9	45	94	10	50
Company Profile		3.5	11		3.5	11		5	15
Years in business	7	3	1.5	7	3	1.5	12	5	2.5
Number of all models worldwide	878	4	2	878	4	2	3003	5	2.5

Objective	Z510			SST 1200			Elite		
These weights represent the use of a finished product for LARGE Thermoform Molds	**SRB Element**		481	**Boeing Space Station**		465			474
Easy to maintain and operate		4.9	34		6.9	48		6.9	48
Time spent per month cleaning & servicing	330 minutes	4	0.7	110 minutes	8	1.4	110 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	25 minutes	4	0.3	25 minutes	4	0.3
Time for set-up inbetween jobs		2	0.2	30 seconds	10	0.9	30 seconds	10	0.9
Time for set-up inbetween jobs with different material		2	0.2	10 minutes	8	0.6	10 minutes	8	0.6
On-board diagnostics	good	8	0.6	medium	6	0.4	medium	6	0.4
Good up-time statistics	not available	0	0	3500 hours b	8	0	3500 hours b	8	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		9	54		9	54		9	54
Little or no parts that the warranty doesn't cover	yes	8	4	yes	8	4	yes	8	4
Close service technician	Jupiter, FL	10	2	Palm Coast,	10	2	Palm Coast,	10	2
Difficulty in sending a service technician	easy	10	3	easy	10	3	easy	10	3
Durable materials		3.9	39		3.8	38		4	40
Tensile Strength	3480	3	0.3	3200	3	0.3	5295	5	0.5
Flexural Strength	6236	1	0.1	6000	1	0.1	7604	2	0.2
Impact Strength	not avail		0	2	6	0.6	1.8	5	0.5
Heat Deflection Temperature (at .45MPa)	239	5	3.5	205	4	2.8	204	4	2.8
High tolerance	0.005	2	10	0.005	2	10	0.003	6	30
Variety of materials		3.2	16		2.3	12		1.5	7.5
Color Variety	thousands	10	1	7	9	0.9	1	1	0.1
Quantity of different types of materials	3	3	1.2	1	1	0.4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			no			no		
Ability to mix materials	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	1120	2	20	1200	3	30	768	2	20
Minimal facility requirements		5.5	33		5.6	34		5.6	34
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	yes	8	1.6	no	2	0.4	no	2	0.4
Humidity can be above 75%	no	2	0.3	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees	no	2	0.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector	no	2	0.2	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	yes	8	1.6	no	2	0.4	no	2	0.4
Material compatible with flight hardware		2.6	5.2		5.5	11		6	12
Low occurrence of FOD/Shatterability	worst	2	1	fair	6	3	fair	7	3.5
Has a fire-resistant grade of material	none	0	0	HB	3	0.9	HB	3	0.9
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$75,465	9	36	$39,700	10	40	$43,050	9	36
Minimal consumables cost (most basic material & support cost/cu in)	$1.86	8	64	$8.80	1	8	$8.80	1	8
Minimal operator time		5.6	28		8	40		8	40
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	no	2	0.8	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	$7,900	8	32	$3,600	9	36	$3,950	10	40
Powerful Software		4.5	45		6.7	67		6.7	67
Ability to join smaller parts to make larger part without Magics	no	2	0.2	no	2	0.2	no	2	0.2
Ability to scale	yes	8	0.4	yes	8	0.4	yes	8	0.4
Ability to build sparse filled parts	no	2	1	yes	8	4	yes	8	4
Ability to stack parts	yes	8	0.3	no	2	0.1	no	2	0.1
Ability to nest parts	yes	8	0.8	no	2	0.2	no	2	0.2
Knows how much material you have onboard	yes	8	0.6	yes	8	0.6	yes	8	0.6
Knows how much material you need	yes	8	0.8	yes	8	0.8	yes	8	0.8
Can inport STL files	yes	8	0.4	yes	8	0.4	yes	8	0.4
Fast Build Speed (Machine Run Time Only)	94	10	50	365	4	20	365	4	20
Company Profile		5	15		6	18		6	18
Years in business	12	5	2.5	6	2	1	6	2	1
Number of all models worldwide	3003	5	2.5	7013	10	5	7013	10	5

Appendix C
Decision Matrix
Weighted Decision - Overall Best Machine

Objective	Weight	Sub Weight	Vantage SE			400mc			900mc			EOS P390			EOS Formiga P100			Dimension 1200es SST		
			NASA Prototype Lab		565			595			535			544			547			513
Easy to maintain and operate	10			6	60		6.1	61		6.1	61		4.1	41		4.5	45		6.9	69
Time spent per month cleaning & servicing		0.18	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	660 minutes	2	0.4	660 minutes	2	0.4	110 minutes	8	1.4
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	yes	8	0.6	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	2 hours	2	0.1	2 hours	2	0.1	25 minutes	4	0.3
Time for set-up inbetween jobs		0.09	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	45 minutes	3	0.3	45 minutes	3	0.3	30 seconds	10	0.9
Time for set-up inbetween jobs with different material		0.08	15 minutes	7	0.6	10 minutes	8	0.6	10 minutes	8	0.6	1 1/2 hours	2	0.2	1 1/2 hours	2	0.2	10 minutes	8	0.6
On-board diagnostics		0.07	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4
Good up-time statistics			not available	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0	3500 hours t	8	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	9			8.4	76		8.4	76		8.4	76		7.8	70		7.8	70		9	81
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Novi, MI	4	0.8	Novi, MI	4	0.8	Palm Coast,	10	2
Difficulty in sending a service technician		0.30	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials	9			6.9	62		8	72		8	72		7.6	68		7.6	68		4.2	38
Tensile Strength		0.30	7600	7	2.1	8000	8	2.4	8000	8	2.4	6962	6	1.8	6962	6	1.8	5295	5	1.5
Flexural Strength		0.20	14000	9	1.8	15900	10	2	15900	10	2	10733	5	1	10733	5	1	7604	2	0.4
Impact Strength		0.30	2.3	6	1.8	2.6	6	1.8	2.6	6	1.8	4.12	10	3	4.12	10	3	1.8	5	1.5
Heat Deflection Temperature (at .45MPa)		0.20	280	6	1.2	372	9	1.8	372	9	1.8	350	9	1.8	350	9	1.8	204	4	0.8
High tolerance	8		0.005	2	16	0.005	2	16	0.005	2	16	0.004	4	32	0.004	4	32	0.005	2	16
Advertised Tolerance			0.005	2		0.005	2		0.005	2		0.004	4		0.004	4		0.005	2	
Average Deviation of Tolerance of Benchmark Sample			0.0132			0.0034									0.0031					
Minimum Deviation of Tolerance of Benchmark Sample			0.0015			0.0000									0.0000					
Max Deviation of Tolerance of Benchmark Sample			0.0470			0.0150									0.0080					
Variety of materials	8			4.9	39		4.6	37		4.2	34		4.9	39		4.9	39		2.3	18
Color Variety		0.10	7	9	0.9	1 & custom	2	0.2	1 & custom	2	0.2	3	3	0.3	3	3	0.3	9	9	0.9
Quantity of different types of materials		0.40	3	3	1.2	4	4	1.6	3	3	1.2	9	9	3.6	9	9	3.6	1	1	0.4
Ability to print in different colors without changing cartridges			no			no			no			no	2		no	2		no		
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	yes	8	2.4	yes	8	2.4	yes	8	2.4	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	7		3584	8	56	3584	8	56	31104	10	70	4381	9	63	1006	2	14	1200	3	21
Minimal facility requirements	7			5.4	38		5.4	38		5.4	38		4.3	30		4.3	30		5.6	39
Runs on 110V		0.18	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4
Doesn't require drainage		0.20	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4	no	2	0.4
Humidity can be above 75%		0.14	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4	yes	8	1.1
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Material compatible with flight hardware	7			7.1	50		8.6	60		8.6	60		7.5	53		7.5	53		6	42
Low occurrence of FOD/Shatterability		0.50	good	8	4	good	8	4	good	8	4	excellent	10	5	excellent	10	5	fair	7	3.5
Has a fire-resistant grade of material		0.30	V2	5	1.5	V0	10	3	V0	10	3	HB	3	0.9	HB	3	0.9	HB	3	0.9
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	6		$182,850	6	36	$184,645	6	36	$406,370	0	0	$380,000	1	6	$225,000	5	30	$45,100	9	54
Minimal consumables cost (most basic material & support cost/cu in)	5		$7.61	2	10	$7.61	2	10	$7.61	2	10	$1.09	9	45	$1.09	9	45	$8.80	1	5
Minimal operator time	5			8	40		8	40		8	40		5.6	28		5.6	28		8	40
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	yes	8	3.2	yes	8	3.2	yes	8	3.2	no	2	0.8	no	2	0.8	yes	8	3.2
Minimal maintenance cost	4		$14,500	6	24	$18,130	5	20	$35,000	0	0	$35,000	0	0	$17,500	5	20	$4,100	9	36
Powerful Software	4			7.6	31		7.6	31		7.6	31		7	28		7	28		6	24
Ability to join smaller parts to make larger part without Magics		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Ability to stack parts		0.06	no	2	0.1	no	2	0.1	no	2	0.1	yes	8	0.5	yes	8	0.5	no	2	0.1
Ability to nest parts		0.12	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	no	2	0.2
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	3		487	1	3	325	6	18	487	1	3	180	8	24	120	9	27	365	4	12
Company Profile	3			8.5	26		8.5	26		8.5	26		5.5	17		5.5	17		6	18
Years in business		0.50	17	7	3.5	17	7	3.5	17	7	3.5	18	8	4	18	8	4	6	2	1
Number of all models worldwide		0.50	7013	10	5	7013	10	5	7013	10	5	656	3	1.5	656	3	1.5	7013	10	5

Appendix C
Decision Matrix
Weighted Decision - Overall Best Machine

Objective	Weight	Sub Weight	SinterStation HiQ			InVision XT			ProJet HD 3000			Eden 500V			Connex 500		
					542			538			565			489			486
Easy to maintain and operate	10			3.5	35		5.8	58		6	60		5.8	58		5.8	58
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1.8	150 minutes	6	1.1	150 minutes	6	1.1
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0.6	no	2	0.2	no	2	0.2
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0.1	yes	8	0.6	yes	8	0.6
Time for set-up inbetween jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0.5	10 minutes	8	0.7	10 minutes	8	0.7
Time for set-up inbetween jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0.2	15 minutes	7	0.6	15 minutes	7	0.6
On-board diagnostics		0.07	low	2	0.1	low	2	0.1	low	2	0.1	low	2	0.1	low	2	0.1
Good up-time statistics			not available	0	0	not available	0	0	not avail	0	0	95%	8	0	95%	8	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	9			7.8	70		9	81		9	81		4.5	41		4.5	41
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	no	2	1	no	2	1
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	2	Atlanta	7	1.4	Atlanta	7	1.4
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	3	medium	7	2.1	medium	7	2.1
Durable materials	9			6.8	61		1.8	16		1.8	16		4.5	41		4.5	41
Tensile Strength		0.30	6961	6	1.8	4900	4	1.2	4900	4	1.2	8744	8	2.4	8744	8	2.4
Flexural Strength		0.20	19000	10	2	7500	2	0.4	7500	2	0.4	10991	5	1	10991	5	1
Impact Strength		0.30	1.4	4	1.2	not avail		0	not avail		0	0.79	3	0.9	0.79	3	0.9
Heat Deflection Temperature (at .45MPa)		0.20	370	9	1.8	114.8	1	0.2	114.8	1	0.2	120	1	0.2	120	1	0.2
High tolerance	8		0.002	8	64	0.002	8	64	0.001	10	80	0.004	4	32	0.004	4	32
Advertised Tolerance			0.002	8		0.002	8		0.001	10		0.004	4		0.004	4	
Average Deviation of Tolerance of Benchmark Sample			0.0082			0.0155						0.0035					
Minimum Deviation of Tolerance of Benchmark Sample			0.0000			0.0010						0.0000					
Max Deviation of Tolerance of Benchmark Sample			0.0280			0.0403						0.0120					
Variety of materials	8			4	32		1.5	12		2.1	17		5.9	47		8.3	66
Color Variety		0.10	2	2	0.2	1	1	0.1	3	3	0.3	3	3	0.3	3	3	0.3
Quantity of different types of materials		0.40	7	7	2.8	1	1	0.4	2	2	0.8	7	7	2.8	28	10	4
Ability to print in different colors without changing cartridges			no			no			no			yes			yes		
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.6
Ability to change out materials mid way thru build		0.30	no	2	0.6	no	2	0.6	no	2	0.6	yes	8	2.4	yes	8	2.4
Large build envelope	7		3510	7	49	686	2	14	686.2	2	14	2348	5	35	2443	5	35
Minimal facility requirements	7			4.3	30		8	56		8	56		3.7	26		3.7	26
Runs on 110V		0.18	no	2	0.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4
Humidity can be above 75%		0.14	no	2	0.3	yes	8	1.1	yes	8	1.1	no	2	0.3	no	2	0.3
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Doesn't require ventilation/dust collector		0.10	no	2	0.2	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4
Material compatible with flight hardware	7			7.5	53		3.6	25		3.6	25		3.6	25		3.6	25
Low occurrence of FOD/Shatterability		0.50	excellent	10	5	poor	4	2	poor	4	2	poor	4	2	poor	4	2
Has a fire-resistant grade of material		0.30	HB	3	0.9	none	0	0	none	0	0	none	0	0	none	0	0
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	6		$365,930	1	6	$71,500	9	54	$74,900	9	54	$196,000	7	42	$261,000	4	24
Minimal consumables cost (most basic material & support cost/cu in)	5		$2.33	8	40	$3.79	6	30	$3.79	6	30	$6.74	3	15	$6.74	3	15
Minimal operator time	5			5.6	28		8	40		8	40		8	40		8	40
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	no	2	0.8	yes	8	3.2	yes	8	3.2	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	4		$28,100	1	4	$9,000	8	32	$9,600	8	32	$9,900	7	28	$13,900	6	24
Powerful Software	4			7	28		4.9	20		6	24		5.7	23		5.7	23
Ability to join smaller parts to make larger part without Magics		0.16	yes	8	1.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale		0.14	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts		0.17	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
Ability to stack parts		0.06	yes	8	0.5	no	2	0.1	yes	8	0.5	no	2	0.1	no	2	0.1
Ability to nest parts		0.12	yes	8	1	no	2	0.2	yes	8	1	yes	8	1	yes	8	1
Knows how much material you have onboard		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need		0.13	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files		0.09	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	3		260	6	18	338	4	12	est. 338	4	12	141	9	27	141	9	27
Company Profile	3			8	24		8	24		8	24		3.5	11		3.5	11
Years in business		0.50	20	10	5	20	10	5	20	10	5	7	3	1.5	7	3	1.5
Number of all models worldwide		0.50	3934	6	3	3934	6	3	3934	6	3	878	4	2	878	4	2

Objective	Z450			Z510			SST 1200			Elite			Prodigy Plus		
			486	SRB Element		484	Boeing Space Station		515			542	NSLD		502
Easy to maintain and operate		5.6	56		4.9	49		6.9	69		6.9	69		6	60
Time spent per month cleaning & servicing	110 minutes	8	1.4	330 minutes	4	0.7	110 minutes	8	1.4	110 minutes	8	1.4	30 minutes	8	1.4
Can the machine run unattended	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer	no	2	0.2	no	2	0.2	yes	8	0.6	yes	8	0.6	no	2	0.2
Designed to be left on all the time	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time	yes	8	0.6	yes	8	0.6	25 minutes	4	0.3	25 minutes	4	0.3	4 hours	1	0.1
Time for set-up inbetween jobs	127 minutes	2	0.2		2	0.2	30 seconds	10	0.9	30 seconds	10	0.9	5 minutes	9	0.8
Time for set-up inbetween jobs with different material		2	0.2		2	0.2	10 minutes	8	0.6	10 minutes	8	0.6	15 minutes	7	0.6
On-board diagnostics	good	8	0.6	good	8	0.6	medium	6	0.4	medium	6	0.4	medium	6	0.4
Good up-time statistics	not available	0	0	not available	0	0	3500 hours b	8	0	3500 hours b	8	0	unknown	0	0
Can be hooked up to the network	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan		9	81		9	81		9	81		9	81		8.4	76
Little or no parts that the warranty doesn't cover	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician	Jupiter, FL	10	2	Jupiter, FL	10	2	Palm Coast,	10	2	Palm Coast,	10	2	Atlanta	7	1.4
Difficulty in sending a service technician	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials		2.1	19		2.1	19		3.7	33		4.2	38		3.7	33
Tensile Strength	3480	3	0.9	3480	3	0.9	3200	3	0.9	5295	5	1.5	3200	3	0.9
Flexural Strength	6236	1	0.2	6236	1	0.2	6000	1	0.2	7604	2	0.4	6000	1	0.2
Impact Strength	not avail		0	not avail		0	2	6	1.8	1.8	5	1.5	2	6	1.8
Heat Deflection Temperature (at .45MPa)	239	5	1	239	5	1	205	4	0.8	204	4	0.8	195	4	0.8
High tolerance	0.005	2	16	0.005	2	16	0.005	2	16	0.003	6	48	0.005	2	16
Advertised Tolerance	0.005	2		0.005	2		0.005	2		0.003	6		0.005	2	
Average Deviation of Tolerance of Benchmark Sample	0.0146									0.0039			0.0144		
Minimum Deviation of Tolerance of Benchmark Sample	0.0000									0.0000			0.0000		
Max Deviation of Tolerance of Benchmark Sample	0.0500									0.0100			0.0425		
Variety of materials		2.4	19		3.2	26		2.3	18		2.3	18		2.3	18
Color Variety	thousands	10	1	thousands	10	1	7	9	0.9	9	9	0.9	7	9	0.9
Quantity of different types of materials	1	1	0.4	3	3	1.2	1	1	0.4	1	1	0.4	1	1	0.4
Ability to print in different colors without changing cartridges	yes			yes			no			no			no		
Ability to mix materials	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build	no	2	0.6	no	2	0.6	no	2	0.6	no	2	0.6	no	2	0.6
Large build envelope	640	1	7	1120	2	14	1200	3	21	768	2	14	640	1	7
Minimal facility requirements		6.1	43		5.5	38		5.6	39		5.6	39		5.6	39
Runs on 110V	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require drainage	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4	no	2	0.4
Humidity can be above 75%	no	2	0.3	no	2	0.3	yes	8	1.1	yes	8	1.1	yes	8	1.1
Temperature can change up to 20 degrees	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector	yes	8	0.8	no	2	0.2	yes	8	0.8	yes	8	0.8	yes	8	0.8
Doesn't require plumbing (air, nitrogen, water)	yes	8	1.6	yes	8	1.6	no	2	0.4	no	2	0.4	no	2	0.4
Material compatible with flight hardware		2.6	18		2.6	18		5.5	39		6	42		5.5	39
Low occurrence of FOD/Shatterability	worst	2	1	worst	2	1	fair	6	3	fair	7	3.5	fair	6	3
Has a fire-resistant grade of material	none	0	0	none	0	0	HB	3	0.9	HB	3	0.9	HB	3	0.9
Little to no off-gassing	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	$60,270	9	54	$75,465	9	54	$39,700	10	60	$43,050	9	54	$40,000	10	60
Minimal consumables cost (most basic material & support cost/cu in)	$1.94	8	40	$1.86	8	40	$8.80	1	5	$8.80	1	5	$8.92	1	5
Minimal operator time		5.6	28		5.6	28		8	40		8	40		8	40
Machine does not need attending	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time	no	2	0.8	no	2	0.8	yes	8	3.2	yes	8	3.2	yes	8	3.2
Minimal maintenance cost	$5,500	9	36	$7,900	8	32	$3,600	10	40	$3,950	10	40	$5,000	9	36
Powerful Software		6	24		6	24		6	24		6	24		6.7	27
Ability to join smaller parts to make larger part without Magics	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
Ability to scale	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1	yes	8	1.1
Ability to build sparse filled parts	no	2	0.3	no	2	0.3	yes	8	1.4	yes	8	1.4	yes	8	1.4
Ability to stack parts	yes	8	0.5	yes	8	0.5	no	2	0.1	no	2	0.1	no	2	0.1
Ability to nest parts	yes	8	1	yes	8	1	no	2	0.2	no	2	0.2	yes	8	1
Knows how much material you have onboard	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Knows how much material you need	yes	8	1	yes	8	1	yes	8	1	yes	8	1	yes	8	1
Can inport STL files	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7	yes	8	0.7
Fast Build Speed (Machine Run Time Only)	94	10	30	94	10	30	365	4	12	365	4	12	216	7	21
Company Profile		5	15		5	15		6	18		6	18		8.5	26
Years in business	12	5	2.5	12	5	2.5	6	2	1	6	2	1	17	7	3.5
Number of all models worldwide	3003	5	2.5	3003	5	2.5	7013	10	5	7013	10	5	7013	10	5

Appendix C
Decision Matrix
Weighted Decision - Large Thermoform Molds

Objective	Weight	Sub Weight	Prodigy Plus			Vantage SE			400mc			900mc			EOS P390			EOS Formiga P100		
These weights represent the use of a finished product for LARGE Thermoform Molds			**NSLD**		464	**NASA Prototype Lab**		530			576			525			570			545
Easy to maintain and operate	7			6	**42**		6	**42**		6.1	**43**		6.1	**43**		4.1	**28**		4.5	**32**
Time spent per month cleaning & servicing		0.18	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	30 minutes	8	1.4	660 minutes	2	0.4	660 minutes	2	0.4
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3	yes	8	1.3
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3	no	2	0.3
No need for a dedicated computer		0.08	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	no	2	0.2	yes	8	0.6
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Low Cold Start Warm Up Time		0.07	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	4 hours	1	0.1	2 hours	2	0.1	2 hours	2	0.1
Time for set-up inbetween jobs		0.09	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	5 minutes	9	0.8	45 minutes	3	0.3	45 minutes	3	0.3
Time for set-up inbetween jobs with different material		0.08	15 minutes	7	0.6	15 minutes	7	0.6	10 minutes	8	0.6	10 minutes	8	0.6	1 1/2 hours	2	0.2	1 1/2 hours	2	0.2
On-board diagnostics		0.07	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4	medium	6	0.4
Good up-time statistics			unknown	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0	not available	0	0
Can be hooked up to the network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Good maintenance service plan	6			8.4	**50**		8.4	**50**		8.4	**50**		8.4	**50**		7.8	**47**		7.8	**47**
Little or no parts that the warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Close service technician		0.20	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Atlanta	7	1.4	Novi, MI	4	0.8	Novi, MI	4	0.8
Difficulty in sending a service technician		0.30	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3	easy	10	3
Durable materials	10	1.00		3.8	**38**		6.4	**64**		8.7	**87**		8.7	**87**		8.4	**84**		8.4	**84**
Tensile Strength		0.10	3200	3	0.3	7600	7	0.7	8000	8	0.8	8000	8	0.8	6962	6	0.6	6962	6	0.6
Flexural Strength		0.10	6000	1	0.1	14000	9	0.9	15900	10	1	15900	10	1	10733	5	0.5	10733	5	0.5
Impact Strength		0.10	2	6	0.6	2.3	6	0.6	2.6	6	0.6	2.6	6	0.6	4.12	10	1	4.12	10	1
Heat Deflection Temperature (at .45MPa)		0.70	195	4	2.8	280	6	4.2	372	9	6.3	372	9	6.3	350	9	6.3	350	9	6.3
High tolerance	5		0.005	2	**10**	0.005	2	**10**	0.005	2	**10**	0.005	2	**10**	0.004	4	**20**	0.004	4	**20**
Variety of materials	5	1.00		2.3	**12**		4.9	**25**		4.6	**23**		4.2	**21**		4.9	**25**		4.9	**25**
Color Variety		0.10	7	9	0.9	7	9	0.9	1 & custom	2	0.2	1 & custom	2	0.2	3	3	0.3	3	3	0.3
Quantity of different types of materials		0.40	1	1	0.4	3	3	1.2	4	4	1.6	3	3	1.2	9	9	3.6	9	9	3.6
Ability to print in different colors without changing cartridges			no			no			no			no			no	2		no	2	
Ability to mix materials		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Ability to change out materials mid way thru build		0.30	no	2	0.6	yes	8	2.4	yes	8	2.4	yes	8	2.4	no	2	0.6	no	2	0.6
Large build envelope	10		640	1	**10**	3584	8	**80**	3584	8	**80**	31104	10	**100**	4381	9	**90**	1006	2	**20**
Minimal facility requirements	6			5.6	**34**		5.4	**32**		5.4	**32**		5.4	**32**		4.3	**26**		4.3	**26**
Runs on 110V		0.18	yes	8	1.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Doesn't require drainage		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	yes	8	1.4	yes	8	1.4
Humidity can be above 75%		0.14	yes	8	1.1	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Temperature can change up to 20 degrees		0.18	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4	yes	8	1.4
Doesn't require ventilation/dust collector		0.10	yes	8	0.8	yes	8	1.4	yes	8	1.4	yes	8	1.4	no	2	0.4	no	2	0.4
Doesn't require plumbing (air, nitrogen, water)		0.20	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4	no	2	0.4
Material compatible with flight hardware	2			5.5	**11**		7.1	**14**		8.6	**17**		8.6	**17**		7.5	**15**		7.5	**15**
Low occurrence of FOD/Shatterability		0.50	fair	6	3	good	8	4	good	8	4	good	8	4	excellent	10	5	excellent	10	5
Has a fire-resistant grade of material		0.30	HB	3	0.9	V2	5	1.5	V0	10	3	V0	10	3	HB	3	0.9	HB	3	0.9
Little to no off-gassing		0.20	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6	yes	8	1.6
Minimal initial cost (machine + addl equip)	4		$40,000	10	**40**	$182,850	6	**24**	$184,645	6	**24**	$406,370	0	**0**	$380,000	1	**4**	$200,000	5	**20**
Minimal consumables cost (most basic material & support cost/cu in)	8		$8.92	1	**8**	$7.61	2	**16**	$7.61	2	**16**	$7.61	2	**16**	$1.09	9	**72**	$1.09	9	**72**
Minimal operator time	5			8	**40**		8	**40**		8	**40**		8	**40**		5.6	**28**		5.6	**28**
Machine does not need attending		0.60	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8	yes	8	4.8
Little or no post-processing time		0.40	yes	8	3.2	yes	8	3.2	yes	8	3.2	yes	8	3.2	no	2	0.8	no	2	0.8
Minimal maintenance cost	4		$5,000	9	**36**	$14,500	6	**24**	$18,130	5	**20**	$35,000	0	**0**	$35,000	0	**0**	$17,500	5	**20**
Powerful Software	10	1.00		7.3	**73**		7.8	**78**		7.8	**78**		7.8	**78**		7.5	**75**		7.5	**75**
Ability to join smaller parts to make larger part without Magics		0.08	no	2	0.2	yes	8	0.6	yes	8	0.6	yes	8	0.6	no	2	0.2	no	2	0.2
Ability to scale		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Ability to build sparse filled parts		0.50	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4	yes	8	4
Ability to stack parts		0.04	no	2	0.1	no	2	0.1	no	2	0.1	no	2	0.1	yes	8	0.3	yes	8	0.3
Ability to nest parts		0.10	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8
Knows how much material you have onboard		0.08	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6	yes	8	0.6
Knows how much material you need		0.10	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8	yes	8	0.8
Can inport STL files		0.05	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4	yes	8	0.4
Fast Build Speed (Machine Run Time Only)	5		216	7	**35**	487	1	**5**	325	6	**30**	487	1	**5**	180	8	**40**	120	9	**45**
Company Profile	3			8.5	**26**		8.5	**26**		8.5	**26**		8.5	**26**		5.5	**17**		5.5	**17**
Years in business		0.50	17	7	3.5	17	7	3.5	17	7	3.5	17	7	3.5	18	8	4	18	8	4
Number of all models worldwide		0.50	7013	10	5	7013	10	5	7013	10	5	7013	10	5	656	3	1.5	656	3	1.5

Appendix C
Decision Matrix
Weighted Decision - Compiled Scores

	Overall Good Machine		Flight Hardware Compatability & End Use		Presentation and Visual Aid		Cost & Time & Facility Mods		Thermoform Molds & Large Volume	
Machine	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
HiQ	541.88	6	544.69	4	495.59	13	536.66	13	529.05	5
InVision XT	538.16	8	501.36	9	517.7	7	625.5	2	467.1	11
ProJet HD	564.88	3	530.8	6	549.22	1	644.58	1	489.62	7
Eden 500V	488.9	13	481.86	11	503.04	11	548.26	11	437.4	14
Connex 500	486.1	14	483.86	10	496.04	12	523.86	14	433.4	15
Z450	485.94	15	446.68	15	548.22	2	615.98	3	480.08	9
Z510	483.94	16	449.64	14	545.78	3	606.82	4	481.44	8
SST 1200	514.84	10	478.86	12	506.02	10	572.28	9	464.92	12
Elite	541.84	7	507.86	8	488.02	14	587.08	6	473.92	10
Prodigy +	502.22	12	474.62	13	520.5	5	586.2	7	463.8	13
Vantage SE	565.46	2	551.46	2	520.5	5	571.2	10	529.6	4
400mc	595.26	1	586.02	1	535.46	4	603.04	5	575.66	1
900mc	535.06	9	525.02	7	447.46	15	482.44	15	524.66	6
EOS P390	543.7	5	543.41	5	509.53	9	541.32	12	570.27	2
EOS P100	546.5	4	544.77	3	516.89	8	585.16	8	544.63	3
SST 1200es	512.84	11								

Appendix D:

Companies Contacted or Interviewed

Companies Contacted or Interviewed

3D Systems Corporation
333 Three D Systems Circle
Rock Hill, SC 29730
Telephone: (803) 326-3900
http://www.3dsystems.com

Stratasys, Inc.
7665 Commerce Way
Eden Prairie, MN 55344-2080 U.S.A.
+1 888.480.3548 US Toll Free
http://www.stratasys.com

Z Corporation
32 Second Avenue
Burlington, MA 01803 USA
Phone: +1 781 852 5005
http://www.zcorp.com

EOS GmbH
Electro Optical Systems
Robert-Stirling-Ring 1
D-82152 Krailling / Munich
Germany
Tel.: +49 89 893 36 - 0
www.eos.info

Objet Geometries Ltd.
2 Holtzman St.,
Science Park,
P.O. Box 2496,
Rehovot 76124,
Israel
T: +972 8 931 4314

Quantum Leap Associates, Inc.
5651 Corporate Way, Suite #4
West Palm Beach, FL 33407
561-491-3200

WB Engineering
780 NE 69th Street, Suite 204
Miami, FL 33138
305-756-4401
www.wb-3d.com

Prototyping Solutions
2076 Valleydale Terrace
Birmingham, AL 35244
407-446-2120
www.prototypingsolutions.com

Review, Selection and Installation of a Rapid Prototype Machine

IEN 694 Master's Project
University of Miami
Industrial Engineering Department
Caryl McEndree
October 19, 2008

Outline

- Objective
- Background
  - Terms and Concepts
  - USA's Current Capabilities and Resources
- Comparison of Conventional Methods to the Rapid Prototyping Process
- Design Involving Rapid Prototyping
- Potential Uses Identified within United Space Alliance, LLC
- Benefits of Owning a Rapid Prototyping System
  - Cost Benefits
  - Non-Realized Benefits
- How Other Companies Utilize Rapid Prototyping
- Evaluation of Selected Machines
  - Benchmarking
  - Decision Making Process
  - Results
- Proposal for a New Facility
- Conclusion

Objective

- To impress upon the reader the benefits and advantages of investing in rapid prototyping (additive manufacturing) technology
  - Thru the procurement of one or two new rapid prototyping machines
  - The creation of a new Prototype and Model Lab at the Kennedy Space Center (KSC).
- This new resource will be available to all of United Space Alliance, LLC (USA), enabling engineers from around the company to pursue a more effective means of communication and design with our co-workers, and our customer, the National Aeronautics and Space Administration (NASA).

Terms and Concepts

- The name "Rapid Prototyping" is really a misnomer. It is much more than prototypes and it is not always rapid.
- Rapid Prototyping (RP) is the name given to a host of related technologies that are used to fabricate physical objects directly from CAD data sources.
- The technology is broad, but basically consists of fabricating an object in layers by adding material instead of machining away material.
- Also known as:
  - Direct Digital Manufacturing (DDM)
  - Rapid Manufacturing (RM)
  - Desktop Manufacturing (DTM)
  - Solid Freeform Fabrication (SFF)
  - Freeform Fabrication (FFF)
  - Solid Imaging
  - Layered Manufacturing
  - Additive Fabrication

Types of Rapid Prototyping Technology

- **Stereo Lithography (SLA)**
  - Acrylic blend parts that can simulate ABS, Polycarbonate, Nylon and Polypropylene
- **Selective Laser Sintering (SLS)**
  - Nylon blend parts that can simulate ABS, Elastomers and Polypropylene.
- **Inkjet Systems or Multi-Jet Modeling (MJM)**
  - Acrylic blend parts
- **Fused Deposition Modeling (FDM™)**
  - Can use ABS, Polycarbonate, ABS-Polycarbonate blend, Polyphenylsulfone
- **Three Dimensional Printing (3DP™)**
  - Plaster like parts, but variations exist thru use of different powders, binders and infiltrants
  - Only technology that is full color

USA's Current Capabilities and Resources

- **USA currently owns four rapid prototyping machines**
  - **Limited in function and size**
  - **Not recommended for increased usage**
  - **One machine is owned by Integrated Logistics**
  - **Two machines are owned by SRB Element**
  - **One machine is owned by Flight Operations Engineering**
  - **The technology of the machines has been surpassed and there is better technology available**

USA's Current Capabilities

- Integrated Logistics NSLD Machine Shop
  - Stratasys Prodigy Plus
    - 8" x 8" x 12" build size
    - ABS Plastic

  - Disadvantage: The envelope size of the NSLD machine is very small and a lot of applications will have to be split into at least two to three pieces to be fabricated in the smaller sized machine

USA's Current Capabilities

- SRB Element Design Engineering
  - Z-Corporation Spectrum Z510
    - Full color
    - 10" x 14" x 8" build size
    - Plaster parts
  - Disadvantages:
    - Powder creates dust
    - Part Strength
    - Finishing
  - While their 3D printer works well for non-functional prototypes and visual models, it does not work well for end use items.

USA's Current Capabilities

- **Flight Operations Engineering**
  - **3D Systems InVision XT**
    - **Full color**
    - **11.75" x 7.3" x 8" build size**
    - **Acrylic parts**
  - **Disadvantages:**
    - **Small Build Chamber**
    - **Part Strength**

USA's Current Resources

- **Why not use the KSC NASA Prototype Lab?**
  - **The NASA lab owns a Stratasys FDM Vantage SE machine that produces excellent parts. We have used them in the past fabricate some of our parts and they have done a great job.**
  - **Their machine is in constant use. The lab is so busy that they have a hard time carving out the necessary machine time to fabricate some of our parts.**

- **Why not use RP Service Bureaus?**
  - **Service Bureaus are companies that own several rapid prototyping machines and will fabricate your part from an STL file for a fee**
  - **Purchasing items off-base is a slow process.**
  - **Transmission of design information to outside vendors is a concern (many firms are brokers and send the work to other firms).**

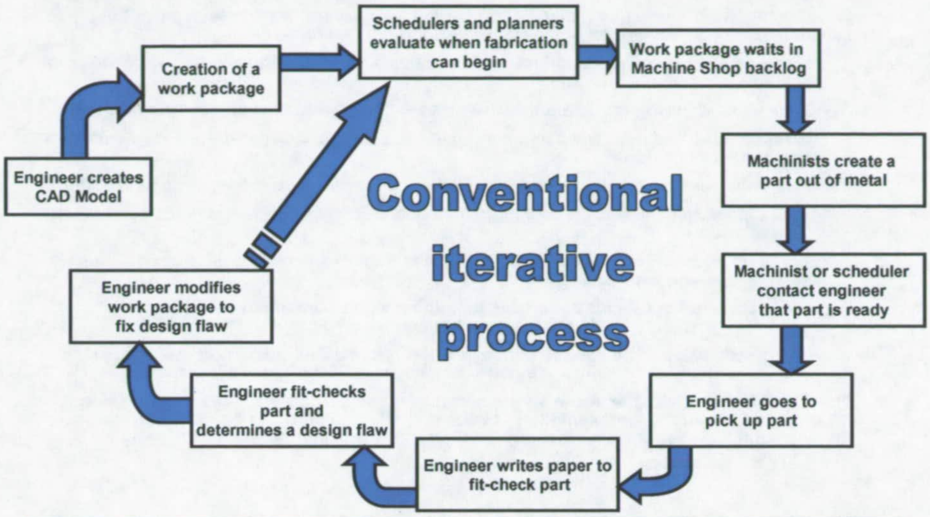
Comparison of Conventional Methods to the Rapid Prototyping Process

- The real advantage to purchasing a rapid prototyping machine is that engineers can have access to the ability to create physical models and prototypes in real time without the time consuming method of requesting the services of the machine shop.
- With the ability to create their own prototypes and models, engineers can reduce time taken in the iterative process of fabrication-fitcheck/evaluation-modification-fitcheck/evaluation...
- With some machines, it takes only slightly longer to create two models as it does to create one model. This allows engineers to create several versions of a model at the same time, reducing the iterative process even further.
- Rapid prototyping gives engineers the opportunity to detect any design flaws or come up with improvements prior to any metal cutting
- But the machines available today can do much more than just create prototypes and models. They can be used to create fully functional end-use parts because of the strength of materials that are utilized in some machines.
- The additive layer process also allows the creation of parts that would be impossible with conventional methods, such as fully integrated, captured fasteners.
- Assemblies can be built all in one shot. Parts do not have to be fabricated separately and then joined with fasteners or welding.

Comparison of Conventional Methods to the Rapid Prototyping Process

- The fabrication of a shop aid special tool made at the Launch Equipment Shop (LES) was compared with the fabrication of the same shop aid in a Stratasys 400mc FDM machine.
  - LES Machine Shop time = 81 hours
    - Includes tool path programming, jig fabrication and set-up, material set-up and tool fabrication
  - Stratasys 400mc machine run time = 63.5 hours
    - Includes 62 hours and 47 minutes machine run time
    - 45 minutes of machine set-up and part finishing.
- The great thing about Rapid Prototype machines is that fabrication jobs can run on their own without constant watching. Machine Shop workers cannot leave their machines unattended. So in essence, the above time for the FDM machine is only 45 minutes for labor, where the full 81 hours of the Machine Shop time is labor, a savings of over $3000.
- If we average the time savings of all four of the shop aid jobs, we end up with an average labor savings of 96%.

Conventional Iterative Process



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Tales of the Conventional Iterative Process

- Recently, shop aid SA-2K7-005 was fabricated at the Launch Equipment Shop (LES) Machine Shop.
  - This new shop aid was to be a work stand tool tray that gave tile techs someplace to rest tools while up on the smaller work stands
  - The attachment method of the new tool tray included a clamping foot that would clamp around one of the lower handrail bars.
  - The tool tray was designed in CATIA and then sent off to the LES.
  - Unfortunately, the clamping foot did not work as planned and needed revision.
  - A change in the drawing was made and a new work order was written to modify one clamping foot, allow for a fit-check and then modify the other twenty clamping feet.
  - The first modification did not go well, and the work package was re-written (and all necessary signatures were obtained) to include a new step to further modify the first clamping foot.
  - The second modification worked better, but did not completely work. The work order was again re-written (and all necessary signatures were obtained) to include another step to modify the clamping foot further and then modify the other twenty clamping feet.
- This entire process (post initial design) took over three months. This could have been avoided and would have taken a lot less time if a rapid prototyping machine had been used.
- The design of the clamping foot could have also been designed differently using the additive layer manufacturing technique because of the ability to create assemblies all in one build and fully integrate and capture fasteners.

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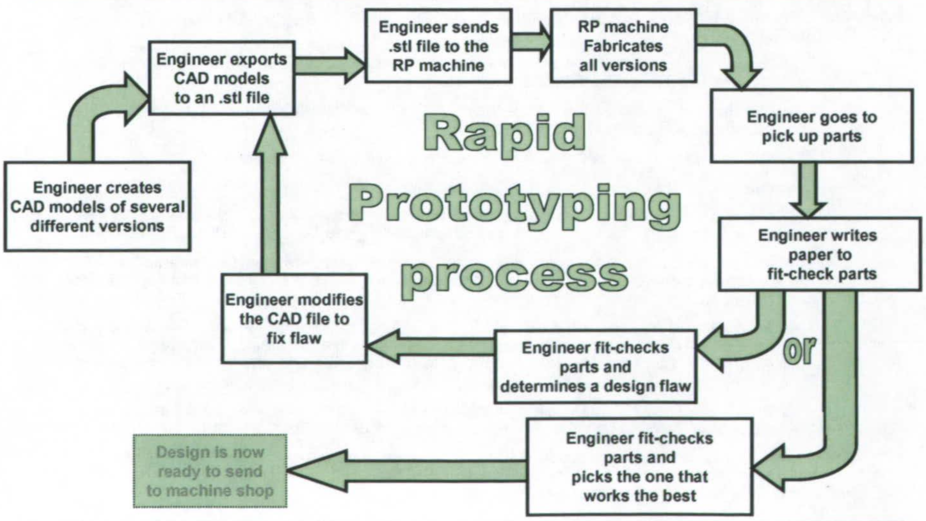
Design Involving Rapid Prototyping

- Avoiding the need to create machine shop work packages and waiting for a permitting schedule is a huge advantage of the Rapid Prototyping machines.
  - Small details that can be overlooked during design and drafting can be caught prior to sending it to the machine shop
  - Errors found during fabrication, usually means that materials and labor are scrapped.
  - Waste of time and money when a part needs to be fabricated more than once during first stages of design.
  - Additional waste of time due to re-scheduling, new signature loop and documentation.
  - Avoid juggling schedule on backlogged milling machines and lathes, which is a much slower process
- Another huge advantage to Rapid Prototyping is the ability to create design review models for use in discussion with customers.
  - There is no substitute for being able to hold an exact scale model of a concept, especially where no hardware exists yet to compare it to.
  - The prototypes can be used to convey design information much more quickly and efficiently than 2D drawings, isometric drawings, or 3D software screen shots.
- The Rapid Prototype Machine can also assist the Machine Shop machinists by allowing machinists to "print" a representation of what they need to fabricate out of metal, giving them the ability to see the best method of fabrication and determination of assembly sequences.

Rapid Prototyping Process



Design Involving Rapid Prototyping

- The parts can also be used to evaluate designs via form, fit, and functional testing and as a design tool used to identify design errors not obvious when viewing 3D CAD files on the screen or 2D paper printed drawings.
- This type of technology can be used, not just for prototypes, but for visual aids, presentation models, fit-check and assembly, training aids, ergonomic studies, fixtures and manufacturing aids
- Failure to properly communicate is often the root cause of problems in new product development. Additive fabrication offers a quick, clear, and concise description of a new design that improves comprehension and communication between interested parties. Better communication leads to the development of better products, along with possible reductions in time and cost.
- Some of the machine produce parts that are so robust and strong that they can be used as end-use parts and assemblies that can be used on flight hardware instead of a metal part machined at the machine shop.
- The obvious advantage of Rapid Prototyping machines is that parts can be fabricated with very little labor. The RP machines can be started on Friday afternoon and can run unattended over the night and weekend and on Monday morning, the part(s) are complete.

Potential Uses Identified within USA

- Ground Operations
  - Shop Aids and Shop Aid prototypes
  - Thermoform molds for flight hardware protective covers
  - Ergonomic study models for Safety and Human Factors Engineering
  - Machine Shop evaluation models
  - Training aids for servicing of flight hardware
  - Optical targets for field metrology
- Program Integration
  - Quick fabrication of models of payloads for storage to be used to fit-check packaging requirements.
- Constellation
  - Scale models of ARES hardware for visualization and training purposes
- Flight Operations
  - Scale models of payloads and new flight hardware for training and visualization purposes
  - Prototypes of discontinued vendor parts for reverse-engineering processes

Potential Uses Identified within USA

- Integrated Logistics
  - Pre-machining models to determine tool paths and best fabrication methods
  - Protective fixtures for use when repairing flight hardware
- SRB Element
  - Evaluate designs via form, fit, and functional testing and as a design tool used to identify design errors
  - Communication of stress / strain information with a physical model whose colors correlate to a stress plot
- Flight Software
  - Rapid connector fabrication and assembly to help in meeting and beating schedules
- FCE/EVA Processing
  - Early in the design cycle for anything requiring on-station maintenance [both IVA and EVA], a volumetrically accurate prototype should be available for time and motion studies of the crew performing maintenance. This approach should allow better, faster, and cheaper prototypes to be available for use.

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Benefits of Owning a Rapid Prototyping System

- The advantages of using rapid prototyping technology are numerous, and are limited only by the ingenuity and innovativeness of its users. The key advantages as explained above include:
  - Less time waiting for the machine shop
  - Saving resources at the machine shop
  - Saving labor and expensive materials
  - Saving engineering design hours and reducing design errors
  - Saving scheduling time due to faster product development
- Non-realizable savings include:
  - The ability to communicate more effectively with customers
  - Improvements in product design thru higher capabilities
  - More effective design evaluation
  - The ability to show customers results throughout the design process and not just at the end.

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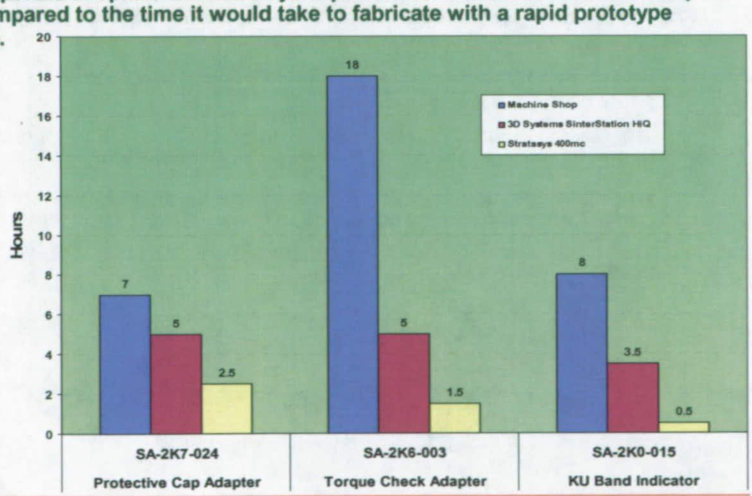
Cost Benefits

- Most companies have difficulty in justifying the cost benefits of a rapid prototyping facility.
  - It is difficult to quantify the benefits, because many arise from what is avoided rather than what is eliminated or improved.
- Unlike the purchase of a new machine tool, which is justified in faster throughput and decreased cost per piece
- Rapid prototyping often offers the benefit of
  - Avoiding mistakes
  - Improving quality
  - Decreasing time to product implementation

Cost Benefits

- Three separate shop aid fabrication jobs performed at the LES machine shop were compared to the time it would take to fabricate with a rapid prototype machine.

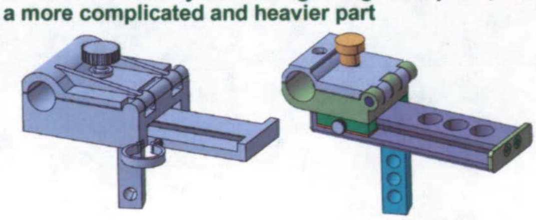


Non-Realized Benefits

- Non-realized benefits include how engineers design new products.
- Before the advent of additive layer manufacturing, engineers had to account for tool paths and manufacturing methods when designing new products.
- Additive layer manufacturing opens up a new method of fabrication, one in which tool paths are obsolete.
- This creates the ability to design more complex and functional parts.

Non-Realized Benefits

- Recently, USA Ground Operations Tool Design was given the task of creating a protective shield for the External Tank insulative foam up at the forward attach fitting to the solid rocket boosters.
  - A clamping fixture was designed to hold together an upright support beam and a horizontal beam.
  - The easiest method of design, fabrication and assembly of this clamping fixture was clearly that of additive layer manufacturing
  - When faced with limited time and difficulty of sending the fabrication of these parts out to a service bureau, a re-design was completed
  - The result was an assembly consisting of eighteen parts, and one weld; creating a more complicated and heavier part



How Other Companies Utilize Rapid Prototyping

- Architectural firms produce scale models of buildings and landscapes
- Formula 1 racing teams fabricate scale models of vehicles for wind tunnel testing.
- The European-built Vega launcher will include FDM polycarbonate parts in each of the engines in all three stages of the rocket.
- SAAB Avitronics is using additive fabrication to produce electronic surveillance devices. The company uses laser sintering to manufacture antenna RF boxes for unmanned aircraft.
- AdvaTech Manufacturing uses laser sintering to fabricate an airplane windshield defroster out of one piece instead of three parts and six rivets.
- Boeing subsidiary, On-Demand Manufacturing, fabricates hard to manufacture ECS ducts for F-18 military jets.
- EOIR technologies produced a battle-ready ABS camera mount for the M1 Abrams tank.
- Caterpillar used laser sintering to manufacture hundreds of complex wire harness covers.

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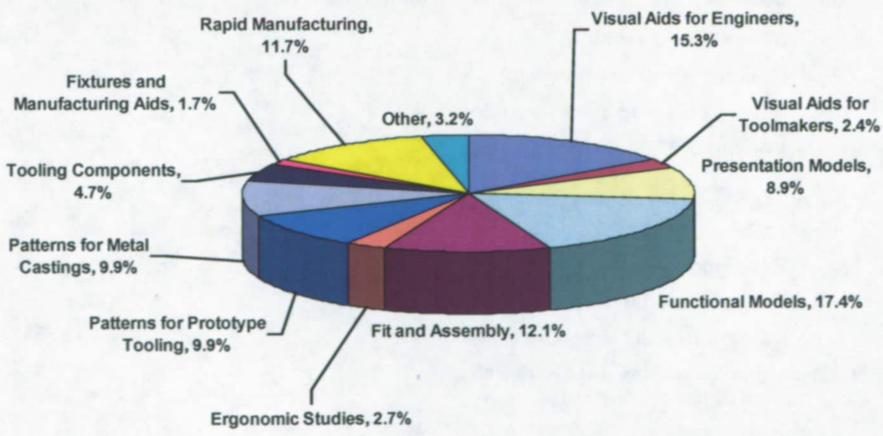
How Companies Are Applying Additive Processes



Source: Wohlers Report 2007

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Evaluation of Selected Machines

- USA Ground Operations Tool Design Engineering researched and compiled a list of fourteen different rapid prototyping machines, comparing them to one another. These fourteen machines come from six different manufacturers and range in price from $38,000 to $406,000. There were three SLS machines, four MJM machines, two 3DP machines and five FDM machines.

- Selective Laser Sintering Machines
  - 3D Systems SinterStation HiQ
  - EOS P390
  - EOS Formiga P100
- Multi-Jet Modeling Machines
  - 3D Systems InVision XT
  - 3D Systems ProJet HD 3000
  - Objet Eden 500V
  - Objet Connex 500
- Three Dimensional Printing Machines
  - Z-Corp Z450
  - Z-Corp Z510
- Fused Deposition Modeling Machines
  - Dimension SST 1200
  - Dimension Elite
  - Stratasys Vantage SE
  - Stratasys 400mc (large tray)
  - Stratasys 900mc

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Benchmarking

- Each company was sent an STL file of a shop aid inspection mirror holder created in CATIA and asked to collect the data from that fabrication process
  - Setup Time (hrs:min)
  - Machine Run Time (hrs:min)
  - Post-Processing Time (hrs:min)
  - Volume of Material Used (cubic inches)
  - Volume of Support Material Used (cubic inches)
  - Resolution used/layer thickness
  - Cost of material used
  - Cost of Support Material Used
- Benchmark samples were acquired from ten of the machines

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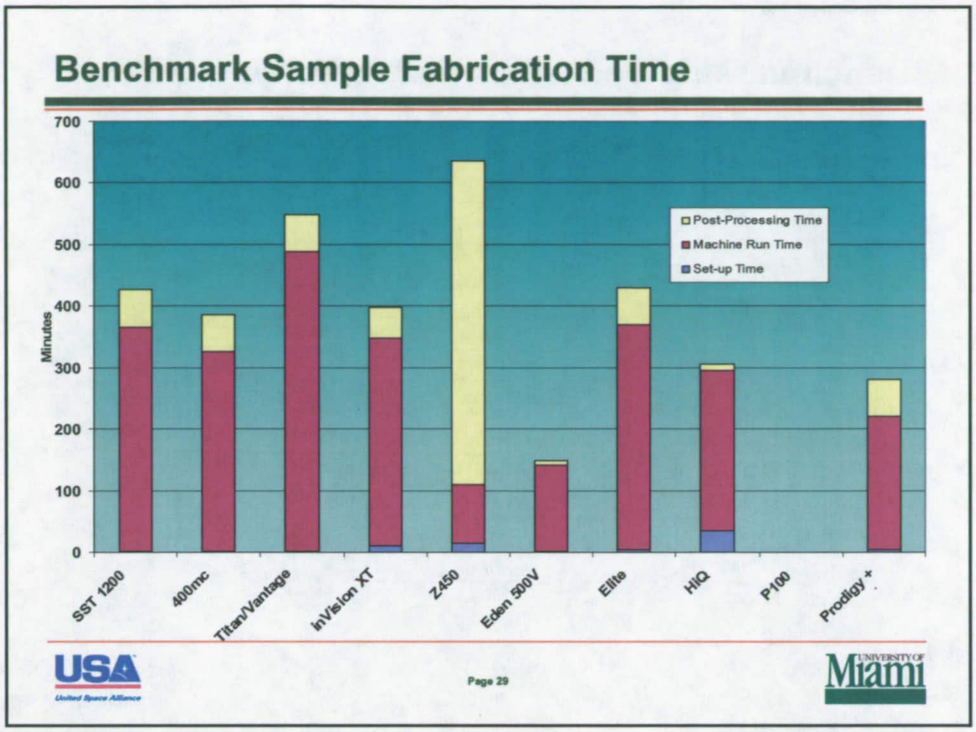
Benchmark Sample Fabrication Time
700
600
500
400
300
200
100
0
Minutes
Post-Processing Time
Machine Run Time
Set-up Time
SST 1200
400mc
Titan/Vantage
inVision XT
Z450
Eden 500V
Elite
HiQ
P100
Prodigy +
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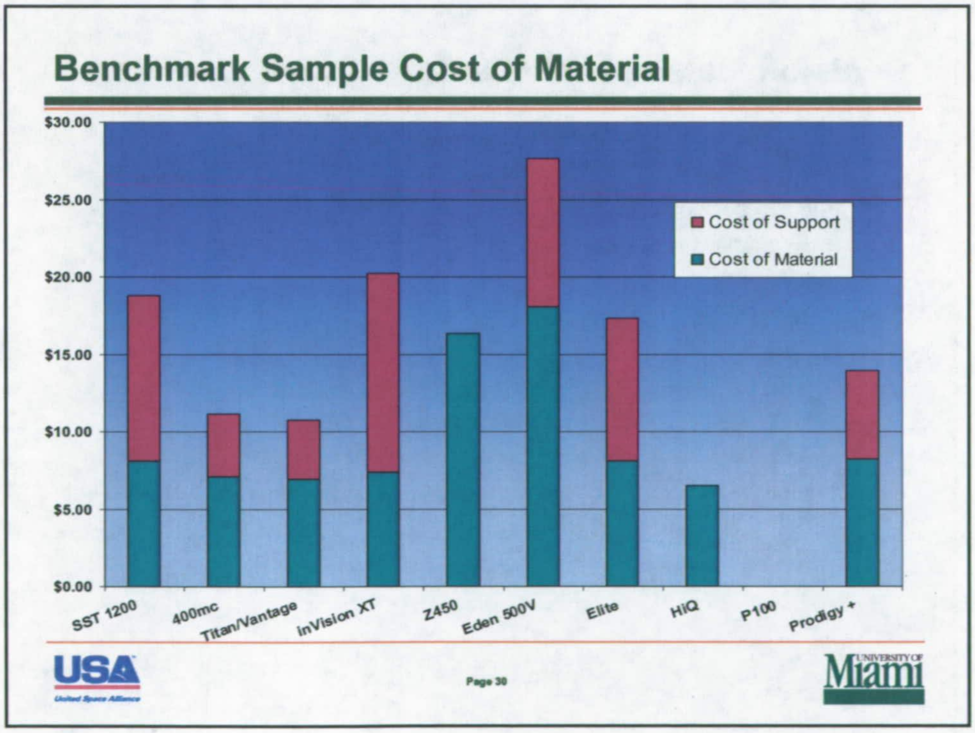
Benchmark Sample Cost of Material
$30.00
$25.00
$20.00
$15.00
$10.00
$5.00
$0.00
Cost of Support
Cost of Material
SST 1200
400mc
Titan/Vantage
inVision XT
Z450
Eden 500V
Elite
HiQ
P100
Prodigy +
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Benchmarking Comparison of Accuracy

- Each mirror holder was measured in sixteen different locations and compared to the computer model to determine the accuracy of the machine.

	Advertised Accuracy (inches)	Actual Accuracy (inches	Difference (inches)
Formiga P100	0.004	0.003	-0.001
400MC	0.005	0.003	-0.002
Eden 500V	0.004	0.004	0.000
Dimension Elite	0.003	0.004	0.001
SinterStation HiQ	0.002	0.008	0.006
Vantage SE	0.005	0.013	0.008
Z-Printer 450	0.005	0.015	0.010
InVision XT	0.002	0.016	0.014
Prodigy Plus	unknown	0.019	-

Decision Making Process

- Based on Kepner-Tregoe Decision Analysis Procedure
  - Step 1: State decision
  - Step 2: Develop objectives
  - Step 3: Classify objectives into MUSTS and WANTS
  - Step 4: Weigh the WANTS
  - Step 5: Generate alternatives
  - Step 6: Compare alternatives against the WANTS
    - Establish a rating scale for each criterion
  - Step 7: Multiply each alternative's rating by the weight
  - Step 8: Add up all the points for each alternative
- The option with the highest score will not necessarily be the one to choose, but the relative scores can generate meaningful discussion and lead the team toward consensus

Step 1: State Decision

- Choose a rapid prototyping machine or combination of machines to purchase for the use within United Space Alliance, LLC for the Space Shuttle Contract engineers and management while also considering Constellation development.
  - The rapid prototyping system is intended to be utilized for visualization, functional testing and manufacturing of tools, ground support equipment and training aides
  - The owning directorate(s) and location of installation(s) to be determined at a later date
  - Ability to create detailed show and tell/visualization models
  - Ability to create full-scale parts for fit-checks and functional testing

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Step 2: Develop objectives

- To help develop a representative list of objectives, invitations to a brainstorming session were sent out to engineers, technicians, and management from all different parts of the company.
- From the brainstorming session, the ensuing discussions, and e-mails, a list of objectives were compiled and refined over the next few weeks.
- Fourteen objective categories were developed, in which nine of those categories were broken down into further elements.
  - Easy to maintain and operate
  - Good maintenance service plan
  - Durable Materials
  - High Tolerance
  - Variety of Materials
  - Large Build Envelope
  - Minimal Facility Requirements
  - Material Compatible with Flight Hardware
  - Minimal Initial Cost
  - Minimal Consumables Cost
  - Minimal operator time
  - Minimal maintenance cost
  - Powerful Software
  - Fast Build Speed
  - Company Profile

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Step 2: Develop objectives

Easy to maintain and operate

- Time spent per month cleaning & servicing
- Can the machine run unattended
- Part continuance after a power failure beyond capability of a UPS
- No need for a dedicated computer
- Designed to be left on all the time
- Low Cold Start Warm Up Time
- Set-up Time
- On-board diagnostics
- Good up-time statistics
- Can be hooked up to the network

Good maintenance service plan

- Little or no parts that the warranty doesn't cover
- Close service technician
- Difficulty in sending a service technician

Durable materials

- Tensile Strength
- Flexural Strength
- Impact Strength
- Heat Deflection Temperature (at .45MPa)

Variety of materials

- Color Variety
- Quantity of different types of materials
- Ability to print in different colors without changing cartridges
- Ability to mix materials
- Ability to change out materials

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Step 2: Develop objectives

Minimal facility requirements

- Runs on 110V
- Doesn't require drainage
- Humidity can be above 75%
- Temperature can change up to 20 degrees
- Doesn't require ventilation/dust collector
- Doesn't require plumbing (air, nitrogen, water)

Material compatible with flight hardware

- Low occurrence of FOD/Shatterability
- Has a fire-resistant grade of material
- Little to no off-gassing

Minimal operator time

- Machine does not need attending
- Little or no post-processing time

Powerful Software

- Ability to join smaller parts to make larger part
- Ability to scale
- Ability to build sparse filled parts
- Ability to stack parts
- Ability to nest parts
- Knows how much material you have onboard
- Knows how much material you need
- Can inport STL files

Company Profile

- Years in business
- Number of all models worldwide

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Step 3: Classify objectives into MUSTS and WANTS

- The purchase of a rapid prototype machine is more of a desire to improve existing capabilities. The added benefit of its procurement and implementation is not a necessity, and therefore all of the objectives were determined to be WANTS.

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Step 4: Weigh the WANTS

- To help determine the decision weights, a short questionnaire was put together
  - Sent to all the participants of the brainstorming session
  - Also sent to few others who did not attend.
  - The questionnaire asked each person to rate some of the attributes of a Rapid Prototyping System that they felt was most important to United Space Alliance, LLC
- Due to the lack of response, the results from the questionnaires were used only as a guide to determining the weights used in the final decision analysis.

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Step 4: Weigh the WANTS

Easy to maintain and operate	10	→ Further breakdown
Good maintenance service plan	9	→ Further breakdown
Durable Materials	9	→ Further breakdown
High Tolerance	8	
Variety of Materials	8	→ Further breakdown
Large Build Envelope	7	
Minimal Facility Requirements	7	→ Further breakdown
Material Compatible with Flight Hardware	5	→ Further breakdown
Minimal Initial Cost	6	
Minimal Consumables Cost	5	
Minimal operator time	5	→ Further breakdown
Minimal maintenance cost	4	
Powerful Software	4	→ Further breakdown
Fast Build Speed	3	
Company Profile	3	→ Further breakdown

Step 5: Generate Alternatives

- **Internet research resulted in over 60 machines available on the market. From this list, 14 machines were chosen from six different manufacturers, based upon availability and functionality**

Machine	Manufacturer	Type
InVision XT	3D Systems Corporation	MJM
SinterStation HiQ	3D Systems Corporation	SLS
ProJet HD 3000	3D Systems Corporation	MJM
Elite	Dimension (a business unit of Stratasys Inc.)	FDM
SST 1200	Dimension (a business unit of Stratasys Inc.)	FDM
EOSINT P 390	Electro Optical Systems (EOS) GmbH	SLS
Formiga P 100	Electro Optical Systems (EOS) GmbH	SLS
Connex 500	Objet Geometries Ltd.	MJM
Eden 500V	Objet Geometries Ltd.	MJM
400mc (large tray)	Stratasys Inc.	FDM
900mc	Stratasys Inc.	FDM
Vantage SE	Stratasys Inc.	FDM
Z450	Z Corporation	3DP
Z510	Z Corporation	3DP

Step 6: Compare alternatives against the WANTS

- The scoring is based on a 1 to 10 scale
- The alternative which best fulfills that objective receives a 10
- The rest are given scores based on how well they compare to the best alternative.
- Yes or no questions are assigned 8 and 2 respectively
- For those objectives which were further broken down, each sub-objective was given a percentage of the major objective's weight.

Step 7: Multiply each alternative's rating by the weight

- Each machine then was given a score from 1 to 10 based
  - That score was then multiplied by the percentage of the sub-weight
  - All the sub-weights were summed together
  - Then multiplied by the objective weight to get a score for the objective.
- As an example, consider the EOS P390 machine's score for Durable Materials

Objective		Weight	Sub Weight	EOS P390		
Durable materials		9			7.6	68.4
	Tensile Strength		0.30	6962	6	1.8
	Flexural Strength		0.20	10733	5	1
	Impact Strength		0.30	4.12	10	3
	Heat Deflection Temperature (at .45MPa)		0.20	350	9	1.8

Step 8: Add up all the points for each alternative

Objective	Weight	Sub Weight	SinterStation HiQ		542	InVision XT		578	ProJet HD 3000		6(
Easy to maintain and operate	10			3.5	35		5.8	58		6	6
Time spent per month cleaning & servicing		0.18	770 minutes	2	0.4	0	10	1.8	0	10	1
Can the machine run unattended		0.16	yes	8	1.3	yes	8	1.3	yes	8	1
Part continuance after a power failure beyond capability of a UPS		0.15	no	2	0.3	no	2	0.3	no	2	0
No need for a dedicated computer		0.08	no	2	0.2	yes	8	0.6	yes	8	0
Designed to be left on all the time		0.07	yes	8	0.6	yes	8	0.6	yes	8	0
L... Time		0.07	no	2	0.1	no	2	0.1	4hours	2	0
Ti... jobs		0.09	>3 hours	1	0.1	20 minutes	6	0.5	20 min	6	0
Ti... jobs with different material		0.08	> 3 hours	1	0.1	n/a		0	>60 min	2	0
O...		0.07	low	2	0.1	low	2	0.1	low	2	0
G...			not available	0	0	not available	0	0	not avail	0	
C... network		0.05	yes	8	0.4	yes	8	0.4	yes	8	0
Good m...	9			7.8	70		9	81		9	8
Li... warranty doesn't cover		0.50	yes	8	4	yes	8	4	yes	8	
Close service technician		0.20	Austin, TX	4	0.8	Orlando	10	2	Orlando	10	
Difficulty in sending a service technician		0.30	Easy	10	3	easy	10	3	easy	10	
Durable materials	9			6.8	61		1.8	16		1.8	1
Tensile Strength		0.30	6961	6	1.8	4900	4	1.2	4900	4	1
Flexural Strength		0.20	19000	10	2	7500	2	0.4	7500	2	0
Impact Strength		0.30	1.4	4	1.2	not avail		0	not avail		
Heat Deflection Temperature (at .45MPa)		0.20	370	9	1.8	114.8	1	0.2	114.8	1	0
High tolerance	8		0.002	8	64	0.002	8	64	0.001	10	8
Variety of materials	8			4	32		1.5	12		2.1	1
Color Variety		0.10	2	2	0.2	1	1	0.1	3	3	0
Quantity of different types of materials		0.40	7	7	2.8	1	1	0.4	2	2	0
Ability to print in different colors without changing cartridges			no			no			no		

- <1 minute = 10
- 1 to 5 min = 9
- 6 to 10 min = 8
- 11 to 15 min = 7
- 16 to 20 min = 6
- 21 to 25 min = 5
- 26 to 30 min = 4
- 31 to 60 min = 3
- >60 min = 2

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Breaking down the scores

- During the meeting on 2/18/08, it was suggested that we change the weights on our decision matrix to reflect different scenarios.
- Four different scenarios were created in addition to the "Best Overall"
  - Need for a machine to produce parts that will be used on flight hardware or will be used for end use parts
  - Need for a machine to produce only visual and presentation aids
  - Need for a machine that cost the least, saves man hours and has minimal facility modifications to get it functional
  - Need for a machine that can produce large thermoform molds

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Weights of Objectives

Objective	Best Overall	Fit Hdwr & End Use	Visual	Cost & Time	Thermo Molds
Easy to maintain and operate	10	7	7	8	7
Good maintenance service plan	9	6	6	8	6
Durable Materials	9	10	4	4	10[2]
High Tolerance	8	9	7	5	5
Variety of Materials	8	10	10[1]	4	5
Large Build Envelope	7	7	7	7	10
Minimal Facility Requirements	7	5	4	6	6
Material Compatible with Flight Hardware	7	10	2	2	2
Minimal Initial Cost	6	6	6	8	4
Minimal Consumables Cost	5	5	7	10	8
Minimal operator time	5	5	10	9	5
Minimal maintenance cost	4	4	4	10	4
Powerful Software	4	4	5	5	10[3]
Fast Build Speed	3	3	9	7	5
Company Profile	3	3	3	6	3

1) Color variety was bumped up to 50% of the variety of materials weight
2) Heat deflection temperature was bumped up to 70% of the durable materials weight
3) Ability to sparse fill parts was bumped up to 50% of the powerful software weight

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Results

	Overall Good Machine		Flight Hardware Compatibility & End Use Parts		Presentation and Visual Aid		Cost & Time & Facility Mods		Thermoform Molds & Large Volume	
Machine	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
HiQ	541.9	6	544.7	4	495.6	13	536.7	13	529.1	5
InVision XT	538.2	8	501.4	9	517.7	7	625.5	2	467.1	11
ProJet HD	564.9	3	530.8	6	549.2	1	644.6	1	489.6	7
Eden 500V	488.9	12	481.9	11	503.0	11	548.3	11	437.4	14
Connex 500	486.1	13	483.9	10	496.0	12	523.9	14	433.4	15
Z450	485.9	14	446.7	15	548.2	2	616.0	3	480.1	9
Z510	483.9	15	449.6	14	545.8	3	606.8	4	481.4	8
SST 1200	514.8	10	478.9	12	506.0	10	572.3	9	464.9	12
Elite	541.8	7	507.9	8	488.0	14	587.1	6	473.9	10
Prodigy +	502.2	11	474.6	13	520.5	5	586.2	7	463.8	13
Vantage SE	565.5	2	551.5	2	520.5	5	571.2	10	529.6	4
400mc	595.3	1	586.0	1	535.5	4	603.0	5	575.7	1
900mc	535.1	9	525.0	7	447.5	15	482.4	15	524.7	6
EOS P390	543.7	5	543.4	5	509.5	9	541.3	12	570.3	2
EOS P100	546.5	4	544.8	3	516.9	8	585.2	8	544.6	3

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Best Overall Scores

#1
Stratasys 400mc large tray

#2
Stratasys Vantage SE

#3
3D Systems ProJet HD 3000

#4
3D Systems SinterStation HiQ

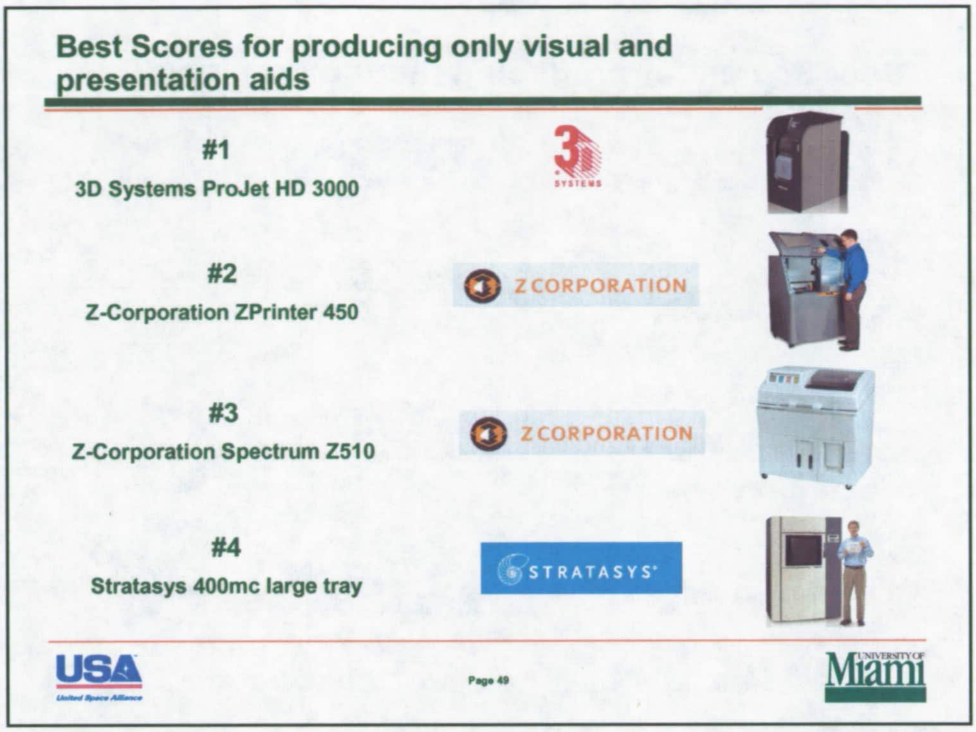
Best Scores for parts that will be used on flight hardware or will be used for end use parts

#1
Stratasys 400mc large tray

#2
Stratasys Vantage SE

#3
3D Systems SinterStation HiQ

#4
EOS INT P390


Best Scores for producing only visual and presentation aids
#1
3D Systems ProJet HD 3000
#2
Z-Corporation ZPrinter 450
Z CORPORATION
#3
Z-Corporation Spectrum Z510
Z CORPORATION
#4
Stratasys 400mc large tray
STRATASYS
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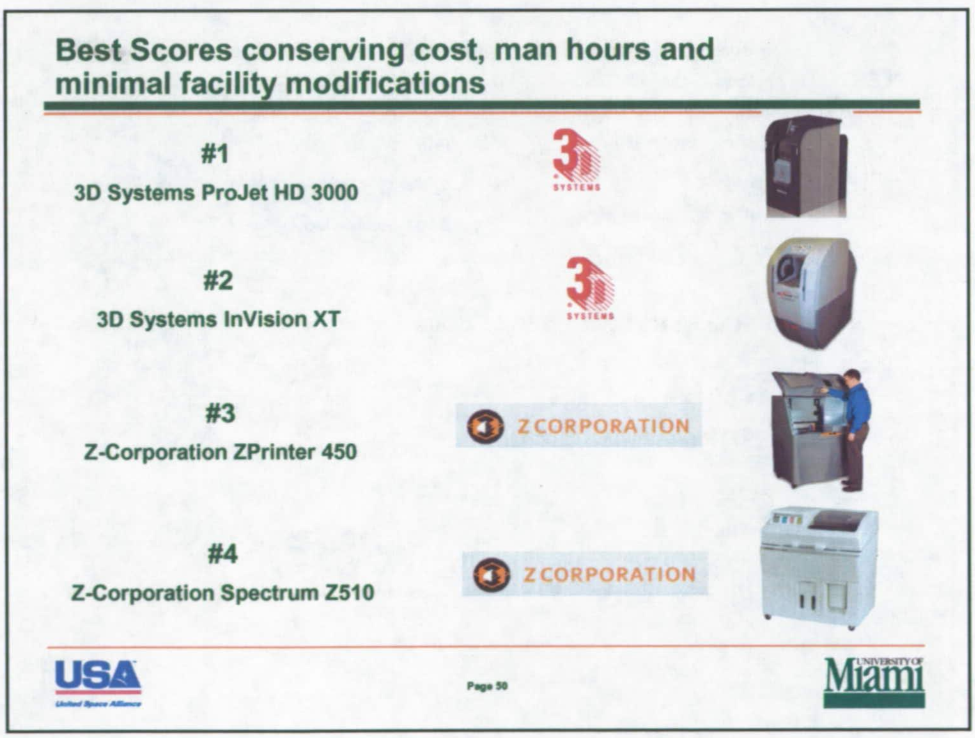
Best Scores conserving cost, man hours and minimal facility modifications
#1
3D Systems ProJet HD 3000
#2
3D Systems InVision XT
#3
Z-Corporation ZPrinter 450
Z CORPORATION
#4
Z-Corporation Spectrum Z510
Z CORPORATION
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Best Scores for producing thermoform molds

#1
Stratasys 400mc large tray

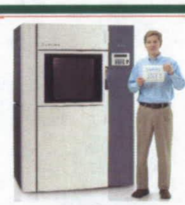
#2
EOS INT P390

#3
EOS INT Formiga P100

#4
Stratasys Vantage SE

Recommendations

- **Stratasys 400mc large tray** — **$184,645**
  - **4 materials**
  - **16" x 14" x 16" build size**
  - **Accuracy: ± .005 inch**



- **3D Systems ProJet HD 3000** — **$74,900**
  - **2 materials**
  - **11.75" x 7.3" x 8" build size**
  - **Accuracy: ± .001 inch**

- **EOS INT P390** — **$380,000**
  - **9 materials**
  - **13.4" x 13.4" x 24.4" build size**
  - **Accuracy: ± .0042 inch**

Proposal for a New Facility

- In order to effectively use the new rapid prototyping resources that USA will procure, a new facility, called the Prototype and Model Lab (PML) should be created.
  - Will be a resource to all of USA, enabling engineers from around the company to pursue a more effective means of communication and design.
  - The PML will house a majority of USA's assets in rapid prototyping technology and knowledge
  - Will be employed by one or more dedicated technicians or engineers.
  - PML staff would process orders for models and prototypes for those who are unable to run the software and machine.
  - PML is to serve as a facility that [properly trained] engineers could run themselves, freeing up the need for a large staff.
- The new Prototype and Model Lab will need to be located in a building that is accessible by most USA engineers
  - Processing Control Center (PCC)

Proposal for a New Facility

- Regardless of location and machine, the following requirements are necessary.
  - Three phase, 240 volt power (for the rapid prototype machine)
  - Single phase, 240 volt power (for periphery equipment)
  - Air conditioning\humidity controls
  - Storage area
  - Access to waste streams
  - Access to basic shop tools and machinery
  - Computer network access
  - Adequate lighting
  - Work bench\tables
  - Double door\rollup door (required for installation)

Proposal for a New Facility (option 1)

- Purchase a new Fused Deposition Modeling Machine
  - $185,000 initial machine investment + approximately $5000 in accessories and facility upgrades
- Re-locate one of SRB Element's Z-Corporation Z510's

- Accuracy: ± .005 inch
- Envelope: 16 x 14 x 16
- Limitations:
  - No flexible materials
  - Anisotropic parts
- Uses:
  - Templates
  - Working prototypes
  - Models
  - End-use products
  - Thermoform Molds

- Accuracy: ± .005 inch
- Envelope: 10 x 14 x 8
- Limitations:
  - Plaster material lacks strength
  - Long and labor intensive post-processing
  - High maintenance
- Uses:
  - Full color models

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Proposal for a New Facility (option 2)

- Purchase a new Laser Sintering Machine
  - $380,000 initial machine investment + approximately $10,000 in accessories and facility upgrades
- Re-locate one of SRB Element's Z-Corporation Z510's

- Accuracy: ± .004 inch
- Envelope: 13.4 x 13.4 x 24.4
- Limitations:
  - Some post processing
- Uses:
  - Templates
  - Working prototypes
  - Models
  - End-use products
  - Thermoform Molds
  - Flexible Models

- Accuracy: ± .005 inch
- Envelope: 10 x 14 x 8
- Limitations:
  - Plaster material lacks strength
  - Long and labor intensive post-processing
  - High maintenance
- Uses:
  - Full color models

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Conclusion

- The advantages of using a rapid prototyping system seems to be outweighed by the cost of investment and training, but in the long run, it gives engineers an incredible opportunity
  - Communicate more effectively with customers
  - Correct mistakes before production
  - Fabricate new products and tools that are impossible using conventional means
- There are over 60 rapid prototype machines available on the market today.
  - Deciphering which machine will work the best is a tough endeavor
  - A Kepner-Trego based decision analysis
    - The best machine for United Space Alliance, LLC is the Stratasys 400mc.
      - Can make products out of several different [known] plastics
      - It requires the use of a support material
      - parts have a tendency to break across the layers.
    - Other machines that rise to the top include the
      - 3D Systems ProJet
      - EOS INT P390
- Aside from helping the shuttle program develop new and better tools and equipment, a rapid prototyping machine will help USA as it transitions itself from the shuttle program to the constellation program, allowing this company to remain at the front of the technology curve.

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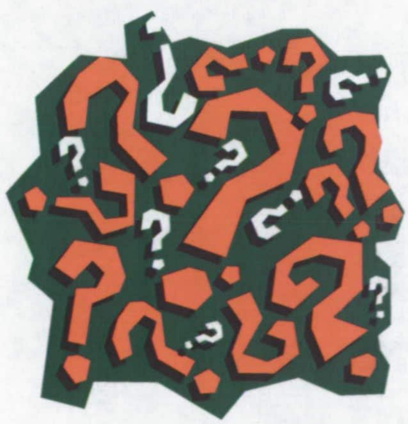
Questions



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Master's project: Rapid Prototyping/Additive Manufacturing and Recommendations on to United Space Alliance, LLC.

October 16th, 2007 (3 hours):

Met with Mike Lane of the NASA Prototype Lab. Discussed their Stratasys Vantage SE machine and other technologies.

We also traveled to the NSLD and spoke with Ray Porter and his machine, the Stratasys Prodigy Plus.

October 19th, 2007 (3 hours):

Wrote e-mail to Dr. Asfour explaining project opportunity:

> -----Original Message-----
> From: McEndree, Caryl N
> Sent: Friday, October 19, 2007 2:31 PM
> To: 'Asfour, Shihab S'
> Subject: Master's Project
>
> I am planning on doing my Master's project in the spring, but I am working on a project here at work that I think will work well as a Master's project. You said that we could write a "research" paper instead of doing an experimental project.
>
> Our department designs and oversees fabrication of specialty hand tools and various other equipment for use on the space shuttle. We are in the beginning stages of trying to figure out if we want to spend money on a rapid prototyping/rapid manufacturing machine. We are going to be evaluating what type of technology is available and which technology would work best for us. We will also have to put together some kind of ROI estimate. I was thinking about applying this to my master's project by writing a paper on the various technologies available in rapid prototyping/rapid manufacturing and how they have effected the industry. I will also include in the paper, our search for a machine that will fit our needs with examples of how we will be using it.
>
> Does this sound like a good master's project to you?
>
> Caryl McEndree
> IE Student out of Cape Canaveral

Reply back from Dr. Asfour was to proceed.

Also on October 19th, we met with Rod Ostoski at the ARF and discussed their Z-corp Spectrum machine and its uses and advantages and disadvantages.

Also on October 19th, through e-mails determined who in the SSPF owns an RP machine

October 22nd, 2007 (2 hours):

Compiled a list of shop aids that would have benefited from the use of Rapid Prototyping technologies and those shop aids that have already benefited.

October 25th, 2007 (2 hours):

Met with Met with Rudy Santamaria with Boeing GSE Design at the space station building. They purchased a Dimension SST1200 about a month ago and have only used the machine for one assembly. It has around 60 hours accumulated time.

October 26th, 2007 (3 hours):

Received a quote from Milt Martini of Stratasys. Spent time working on a new spreadsheet that includes all the machines I can find and what their attributes are. Also a second spreadsheet of the materials used in each machine and what their properties are (as I can find them).

October 29th, 2007 (3 hours):

Worked on presentation and definitions. Inputted cost data into spreadsheet worked on idea for a survey.

October 30th, 2007 (3 hours):

Created a brief presentation on the idea and asked for permission to continue. Also sent e-mails to Rick Davignon, USA's Engineering Process Owner and chairman of the New Technologies Integration Forum, asking his opinion on the matter.

October 31st, 2007 (1/2 hour):

Spoke with Werner Blumenthal of WB engineering in West Palm Beach who does sales and service for the 3D Systems machines. Also spoke with Ken Brace who owns some Dimension machines in Satellite beach who is willing to do one part for free

November 2nd, 2007 (3 hours):

Visited with Davignon and discussed RP and CAD standardizations. Has linked me with Bill Anderson who will bet back with me on Monday. Did some additional research online on stereolithography and machines out there. Found book online thru KSC library.

November 5th, 2007 (3 hours):

Wrote up project charter and started a WBS.

November 8th, 2007 (3 hours):

Online research and compiled more info in matrix

November 9th, 2007 (2 hours)

Online research and compiled more info in matrix.

November 13th, 2007 (6.8 hours)

Went to see Z-corp vendor demo in Melbourne.

November 14th, 2007 (1 ½ hours)

Spoke with Bill Anderson on the phone. He likes my idea of having a sit down meeting with design engineering around the company and getting a sense of priorities. Worked on an intro presentation for that sit down meeting.

November 15th, 2007 (6 hours):

Talked with Mark Menninger and Werner Blumenthal, both with 3D Systems Sales (distributors). Set up a meeting with Mark for Thurs, Dec 6th at 11am. Set up meeting for Brainstorming session on Friday December 7th. Worked on intro presentation for the brainstorming session. Also spoke with Rick Serfozo and Dan Cicciterri in regards to my endeavour.

November 16th, 2007 (1 hour):

Rescheduled brainstorming session. Spent time looking for conference room.

November 27th, 2007 (1 hour):

Sent out invitations to brainstorming meeting. Confirmed next Wed meeting with Mark from 3D sys. Tried to locate a meeting room for 3Dsys meeting.

December 5th, 2007 (3 ½ hours):

Brought Mark Menninger from 3D Systems out to do a vendor presentation. Also worked on presentation for Monday and technology matrix.

December 7, 2007 (3 hours):

Worked on presentation for Monday. Looked for information on Brainstorming and Nominal Group Technique.

December 10, 2007 (4 hours):

Got ready for presentation and had a one hour meeting with the following people. Wrote notes in an excel spreadsheet. From this meeting we need to work on completing the technology matrix and determining which option is best.

Antonio Rodriguez - Tool Design
Don Runaas - NSLD
Tim Kelley - NSLD
Joe Jacoby - IE
Bill Drummond - old process innovations group
Rod Ostoski - SRB Element Mech design
Dwyane Conklin - MFS
Robert Jordan - EPO
Rick Davignon - EPO
Bill Anderson - EPO (Houston)
Dan Sawin
Paul Lucas
Lloyd Hoffmann
Marty Martin
Dan Ciccateri - GO engineering
Mike Stackpole - TDE
Lynda Pileggi - ET/SRB GSE
Rick Serfozo - ET/SRB
Gary Rohrkaste - Constellation
Rory Duncan - Constellation
Todd Brooks - Optics
Leslie Roche
Doc Pepper
Graham O'Neil
James Orr

December 12, 2007 (2 hours):

Reviewed the e-mails of those who had comments on the presentation I gave on Monday. Also, worked on inputting more information into the Matrix. Mainly focusing on the following machines:

- SinterStation HiQ
- InVision XT
- Connex 500
- Zprinter 450
- Spectrum Z510
- Dimension SST 1200
- FDM Vantage SE
- FDM Titan
- FDM 400mc large tray
- FDM Maxum
- FDM 900mc

E-mailed some of the vendors for some missing specifications.

December 13, 2007 (2 hours):

Received e-mails back from vendors on missing specifications and entered them into the Matrix. Also spoke with Ron Tucker (VAB Facility Manager) about finding a new room/rooms for a brand new Prototype Shop. I put together some facility requirements and put them in a spreadsheet and sent them to Ron.

December 14, 2007 (2 hours):

Developed a questionnaire asking those people who were at the meeting what they thought the priorities in terms of the machine attributes, then e-mailed the questionnaire. Got four responses back, started an Excel spreadsheet tabulating the results.

January 2, 2008 (2 hours):

Received two more responses to the survey. Inputted them into the spreadsheet. To this point, It looks like a good service/maintenance plan is the most important. E-mailed Mark Minninger and Werner Blumenthal of 3DSystems, Milt Martini of Stratasys, the rep from Dimension and the Rep from Z-corp with STL files asking for sample parts with details on how long each part took and how much it costs. I have already heard back from Mark Menninger that he might have something back in his hands in 7 to 10 days.

January 7, 2008 (1 hour):

Received more responses to survey. Inserted results into spreadsheet. E-mailed Milt Martini and the rep from Dimension on clarifications to request. Received an e-mail from Milt Martini on the data I requested; still need to input into spreadsheet. Researched Decision Analysis from Kepner-Tregoe.

January 11, 2008 (3 hours):

Received results of benchmark Mirror Holder from Tom Sattler and Z-corp. Created a new spreadsheet with the results. Also entered in the information that I received from Milt Martini and Stratasys. Spoke with Danny with WB engineering. He will make us the benchmark parts and will bring them on Friday of next week and do a presentation. Also spoke with Tom Rochford with the Dimension machines (prototyping solutions), we set up a meeting for the 22nd of January and he will be bringing with him the manufacturer of the dimension machines. Tom Rochford recommended the Objet printers if we go with two different kinds of machines and not the Z-corp machine. Spoke with Tom Sattler who had sent me some files on accuracy and material properties. A lot of good information. He sent me some files on benchmarks with the Dimension machine. Called Mark Menninger of 3D Systems and they will run the part sometime next week. He mentioned that a group called Varak (sp?) who is part of Phillips Federal is interested in our interest. They supply all the HOS machinery to the LES and does GSA contracts. Mark said he thought the fellow's name was John Harna.

January 14, 2008 (1 hour):

Received package from Tom Sattler of Quantum Leap with the parts made on the Zprinter 450. Also received results of the printing of these parts. Rescheduled meeting with Tom Rochford to Wednesday the 23rd.

January 15, 2008 (1 hour):

CATIAdigest has a compilation of articles on rapid prototyping. And I have started looking thru them. I spent some time trying to figure out how to get Daniel Plazas with WB engineering a badge to come see us on Friday (since he is a foreign national). Also spoke with Tim Kelley who is doing his capstone project in rapid prototyping. He is working on his masters degree from Webster University in info sys.

January 18, 2008 (3 hours):

Werner Blumenthal and Danny Plazas from WB engineering came up today and talked to us about their InVision machines. I then wrote my meeting notes.

January 23, 2008 (3 hours):

Antonio, Mike and I met with Tom Rochford of Prototyping Solutions and Ned Bradham of Stratasys in the OSB, starting at 1 pm today. They brought the benchmark sample piece we asked them to build. They built it on the Dimension Elite machine and made it out of the ABS plus plastic, which is 43% stronger than regular ABS. I spent some time inputting the information into the database

January 25, 2008 (2 hours):

Made tags for all different benchmark samples so that we would not get them confused. Also entered in more information into the database from what Tom Rochford sent me. Rusty McDonald from Objet sent the statistics on his benchmark piece and he will bring that on the 31st when he comes to visit.

January 28, 2008 (8 hours):

Generated charts for cost, material variety and tolerance for selected machines. Also generated charts for the benchmarked samples. Started working on objective weighting and weighted scores. Started presentation for a follow-up meeting of the December 10th meeting. Scheduled follow-up meeting for February 11th.

January 29, 2008 (4 hours):

Worked on decision matrix, filling in scores and weights. Also adding additional information. Found out about 3D Systems ProJet machine which is brand new. Spoke with Danny with WB Engineering, and he will forward me some information.

January 30, 2008 (6 hours):

Worked on decision matrix and developing the presentation for the February 11th meeting. Sent out meeting notice to key people to make sure they can make it. Researched other manufacturers online, including EOS and SinterMask.

January 31, 2008 (6 hours):

Rusty McDonald with Objet came and did a presentation on his machine. Entered the new information into the spreadsheets. Refined decision matrix and spoke with Scott Daniel with 3D systems who is an applications engineer about some of the questions I had.

February 1, 2008 (6 hours):

Continued to work on decision matrix, by cleaning up the objectives, adding some and re-arranging some. I also got opinions on the weights from Antonio, Mike and Robert Jordan. I spoke at length with Andy Snow who is the EOS North American Sales rep. He sent me some information on their machines and materials. I added the Formiga P100 and the P390 it to the decision matrix for EOS as well as added the new ProJet from 3M and added the Prodigy Plus as a baseline.

February 4, 2008 (3 hours):

Frank Baldwin from USA M&P and Bill Wendorff of Boeing M&P came up to discuss the various materials from the machines with Antonio and I. The consensus was that Nylon based materials would probably be the best, then Polycarbonate, then ABS and then Acrylic. However, the difference between them is not much. Bill seemed to think that any one of them could get a MUP with not much of a problem. They are more worried about toxicity when the material is burned. Also with if the material is going to shatter instead of break at one point. Nylon tends to just break at the one point, where polycarbonate and acrylic will probably shatter. I questioned this because Lexan does not shatter, but Bill said that Lexan has an additive that allows it to bend instead of shatter.

Continued to work on decision matrix. Added EOS information and filled in some blanks.

February 7, 2008 (4 hours):

Read some in the Wohlers Report and created some graphics from the statistics contained therein. Also worked on the decision matrix.

February 13, 2008 (4 hours):

Worked on decision matrix. Read thru MSDS sheets for various materials and entered them into the tech available spreadsheet.

February 14, 2008 (6 hours):

Continued to work on decision matrix, correcting all the formulas and formats. Collected more info from vendors.

February 15, 2008 (6 hours):

Continued to work on decision matrix. Worked on Presentation for Monday's meeting.

February 18, 2008 (6 hours)

Finished presentation, gave presentation, collected facility requirements info.

February 20, 2008 (2 hours)

I prepared some models to send to vendors that we have previously made using the machine shop. Received one estimate back and input the results into a spreadsheet.

February 21, 2008 (4 hours)

I modified the decision matrix so that there is now a score for four different scenerios: use on flight hardware, lowest cost, visual aids, and thermoform molds. Compiled all the scores and made a short presentation and sent it out to the people who were at the presentation on 2/18. Also spent some time working on the helium tank cover molds and sending those out for time and material quotes from 3D systems and Stratasys. I got the numbers back from 3D systems, and it is not good. I then remembered the LH2 Cabletray elbow cover molds and then sent them to Stratasys to see what they could do.

February 22, 2008 (1 hour)

During my annual training, came across the proper form and OP for presenting my master's project to the class. I am to use USA Form 120-025, Information Release Request, and read FPP C-02-06.

February 25, 2008 (3 hours)

Started to prepare presentation for justification and recommendations. Compiled a list of "Team Members" and sent it to Robert Jordan. Robert has told me that Rick Davignon has asked him to head up the search for the new PML.

February 26, 2008 (2 hours)

Compiled a list of purchasing options for the PML.

February 27, 2008 (3 hours)

Collected thoughts on advantages and pulled them together in a presentation. Created two different flow charts depicting the conventional iterative process and the rapid prototyping process.

February 3, 2008 (4 hours):

Andy snow with EOS came to visit and we discussed what EOS has to offer over 3D Systems. I also took the knowledge I gained in our meeting and entered it into the appropriate spreadsheets.

February 6, 2008 (2 hours):

I had asked Antonio to measure the benchmark samples last Thursday and create a spreadsheet so that we can determine average and maximum deviation for all of the samples. Today I looked over that spreadsheet and made a few more observations and ranks.

April 9, 2008 (3 hours):

Drove over to Orlando to make a visit with Mydea Technologies, which is a service bureau that Antonio had encountered at the AmCon show earlier this month. Mike Siemer is the president and he showed us his little facilty. It is not that big. It is part of an incubator company supported by UCF. Pretty soon they will be moving to a new facility. They own a dimension BST 768 and an Objet Eden 333 and a Z-Corp Spectrum Z510. They also have companies they work with that can do SLA, SLS, DMLS and FDM. They also do some urethane casting as well, creating a mold from the Objet machine and then injecting the urethane into the mold under vacuum. Antonio discussed with him the possibility of their company producing the final parts for the mirror holder. Take aways from this encounter is interest in casting, the plausibility of SLA, and the knowledge that 3D systems should be stayed away from.

Also spoke with Robert Jordan. He is still trying to get results from Kathy about finding us a facility.

April 10, 2008

Sent e-mail to Ahmad and Ken asking if I could express our interest in obtaining a rapid prototyping machine up the management chain.

April 11, 2008

Scheduled meeting with Ahmad And Ken to go over results. Started preparing a formal report on our efforts

April 14, 2008 (8 hours)

Met with Ahmad and Ken today for a half hour to briefly go over what was in the report. Handed them copies of the report. Ken was very open to the idea, and suggested I move forward by talking with Davignon. Ahmad expressed interest in seeing more numbers in easy to see format on how much the company can save. He also expressed interest in seeing an abstract of the report at the beginning.

April 15, 2008 (4 hours)

Continued working on improvements to the report.

May 15, 2008 (1/2 hour)

I just met with Robert Jordan (Eng Process Owner office) and Johnny Cooper who is the facility planner for the PCC. We walked down room 1141, which is an old battery storage area. It is right across the street from the OSB, and has a separate entrance from the south side of the building. The batteries are still there, but there are work orders in place to have them removed. The room has water and drainage, nice high ceilings, a double door and on the first floor. There are breaker panels in the next room for 480 and 208 3 phase power. There is also AC controls in the room and an exhaust fan to the outside. If we select the room as our new prototype facility, we will need to run 110 outlets and network cable along with the 3 phase power, but that shouldn't be too difficult. The one thing that the room did not have, and is most likely not available in the building is compressed air. The room is fairly large, and could accommodate two or three machines, possibly more. There wouldn't be much room for an office, but the room is not really rated for office environment anyway; it is perfect, on the other hand, for a lab.

The question becomes if the NSLD and the SRB Element folks would be willing to re-locate their machines to this new facility. It would combine all of our capabilities into one place, which would make it easier for us to share. There are great attributes to all of the machines, and not just one machine will fulfill all of our needs. I think combining all of our machines into one location will be very beneficial.

My suggestion is that there be a select group of people, including those currently users of the NSLD and SRBE machines and Tool Design that have keys and access to the room. If a request comes in for a prototype, then one of those people can run the machine, or assist the requester in the use of the machine depending on their level of understanding. If more people want to have access to the room, then they must be trained on the use of each of the machines.

May 19, 2008 (4 hours)

Traveled to Orlando for the RAPID 2008 Conference:
The session was a workshop on 3D Scanning. They gave a bit of history and demonstrated four different scanners and three different software packages. I got a CD with the workshop and I will give it to any of you guys if you want it. One of the coolest things they talked about was scanning a 1940 Jeep BRC-40 (prototype to the Willie). They used an LDI laser scanner mounted on a 12' Faro arm and also used point probing. Their objective was to scan the 1940s chassis (which was old, rusted, bent and deformed) and come up with a CAD file of the intended design. Basically, the customer wanted a CAD file that would have been made during design if CAD was around in the 1940s. They used the software package RapidForm XOR which is able to create history trees and the history trees are fully exportable to Solidworks, Pro-E and NX.

They also spoke of a 1950s SAAB A-35 Draken that they had to scan so that they could make improvements and modifications (currently uses all its fuel within 9 minutes). They used a combination of technology to complete the scan. They used both short range and long range scanners and used a Konica Minolta scanner and a Leica 6000. One of these (hard to remember, my notes aren't that well) was a time of flight camera. I am not exactly sure what that is, but I would like to know more about it. For this project they used Polyworks Software which is good for AS-IS projects. If they had to do it all again, they would have used a Surfazor mid range scanner for the whole project.

May 20, 2008 (9 hours)

Today started out with a keynote speaker. General Halley gave us a motivational speech on leadership. The thing that impressed me the most, is that the success of the industry will be determined by Leadership as much, if not more than, the technology itself. In our situation, the growth of rapid manufacturing within USA will depend largely upon leadership. Leadership to show other engineers the capability of RM and the leadership to make RM available to those who need it. I think the hardest thing that we will have to overcome is letting engineers know that we have this capability and it can do wondrous things. It can change the whole way we design.

I visited the booths a bit, along with Ahmad, Antonio and Mike. I was really impressed by the Creaforms scanner. I encouraged Antonio to get with Todd to find out how to get the scanner approved to be brought into the Orbiter midbody for a demo. I would really like to see Antonio's water line project compared to how we would have done it had we had this scanner. Antonio, you may want to talk with Teresa Parrish about American citizens working for a foreign company.

The afternoon sessions were not all that exciting. The best one talked about Direct Digital Manufacturing and what kind of things people are using DDM for now a days.

May 21, 2008 (8 hours)

This morning's keynote was given by Todd Grimm who is one of the leaders in the industry. A few things I got from him was in simple terms, 3D Scanning is the process of going from physical to digital and DDM is the process of going from digital to physical. We also should not be trying to compare DDM and 3D Scanning to existing technologies and processes. Doing so masks all the things that they do not have in common and we will miss out on potential benefits. This is a very important statement, I believe, because DDM and additive layer manufacturing has the ability to completely change how parts are engineered and designed. But our greatest enemy is the resistance to change. Yes, there are only 2 more years left in the Shuttle program and why change now? If we add this technology now to USA's arsenal, it will allow us to improve ourselves tremendously and it will improve the process of servicing and preparing Ares, making design much better and easier.

The first session after the keynote was on ageing aircraft. It was interesting, and the presentation is available on the conference CD, but one of the things they did was to scan the cargo bay of a CA5 aircraft. They scanned it with a Surfazor and a laser tracker with tooling balls. It took them two days to scan with three setups with the tracker and 25 different setups with the Surfazor. I believe Todd did something similar with the Space Shuttle Payload Bay.

One of the sessions I attended gave me one ah-ha moment. That is that Rapid Technology means accessible fabrication. It allows engineers the opportunity to create the necessary prototypes without having to deal with the machine shop and waste time and money. I myself have made prototypes out of plastic shim stock or wood or things I find down in the thermoform lab. The prototypes are extremely cruel, and not very useful. The ability to print prototypes out on a rapid prototype machine would open up doors for us and many of the other engineers at USA.

The last session I attended was on 3rd Generation Modeling. 1st generation was to take point data and create cross sections and to loft them together. 2nd generation was to take point data and create "fish nets" over a surface with a polygomized mesh. Third generation is able to take point data and go directly to CAD. Which I thought was very interesting and has a huge potential for time savings. There is no need to clean up the point data, you just create the CAD model directly over the points, using them as guides. I don't know if other software does this, but the presenter was showing off the ability of the package called RapidForm.

I spent some time out on the exhibit floor today and talked with several people. I did talk with Andy Snow of EOS and he did say that a transformer is included in the price of the P390. They get a lot of problems with voltage compatibility, so they just make sure that the transformer is included in the package. So no worries there. I asked around about a softer flexible material we could use. Pretty much you are limited to Objet's Tango products or there are some SLS materials that can be flexible. I had an idea today that I would like to try for making a protective barrier for the ET intertank.

May 22, 2008 (5 hours)

The day started out with keynote speaker, Terry Wohlers, who is another industry leader. He discussed the progress of the direct digital manufacturing and 3D scanning community. He first iterated that DDM allows for labor reduction because of it's hands-off manufacturing. This may become critical as we transition to the new program. Since more and more people are leaving the shuttle program and since there will be less people here for the new program, it allows us to fabricate parts without having the huge labor force of the machine shop. I am not saying the machine shop is not necessary, because it is definitely needed. We just may need one or two less machinist because we have the ability to create parts directly on our additive layer machine. The engineers become the fabricators.

Terry then talked about some of the newer technologies out there. Some of them are using infrared radiation. One machine lays out a powder bed and then sprays out a pattern in black ink. Since the black ink absorbs infrared radiation much quicker, it allows just those spots to sinter together. EnvisionTec is using DLP technology (the tiny little mirror technology used in some HDTVs) and photopolymers. Solidica is using ultra high frequency sounds to make aluminum sheet metal.

Obstacles that are now facing the DDM/3D Scanning industry is the lack of standards, properties of materials, cost of materials, process control, repeatability and surface finish.

Terry explained to us his vision of the future where each home may have a $99 3D printer that our children may use to print out their own toys and figurines. Right now, there are companies that will print out your World of Warcraft characters. Some of the other uses of DDM is specialty foods. People have used 3D printers to "print" out specialty chocolates. "Fab at Home" has even allowed users to print out working actuators and batteries. RM/DDM also has the potential to be very green. Traditional fabrication produces 30 tons of waste per 1 ton of product.

From Terry Wohler's keynote, I went and sat in on a presentation that Joe Frascati of Mydea technologies in Orlando gave. For his master's thesis he did a study on the build position, orientation and various infiltrants have on parts that are fabricated in the Z-Corp Z510. This paper will prove useful if we are able to obtain the spare Z510 from the SRB Element folks.

Overall, I really enjoyed the conference and I appreciate the opportunity I had to attend.

May 28, 2008 (1 hour)

I sent STL files to EOS and 3DS so that they could do a benchmark sample on their flexible nylon product for me. I also e-mailed Objet and asked if they would make me something out of Tango Plus.

May 29, 2008 (8 hours)

Today I met with Ken, Ahmad, Rick and Robert Jordan. We discussed how we are going to go about getting funding and Rick said that he would like to approach Mark and Patty next week or so. He said that he would work on some selling points, and needed me to come up with technical info and location information. I started work on a presentation for Mark and Patty that includes a little on the advantages, but mainly what our two choices are and our three options of location. I took a walk over to the VAB to look at 3B17. I also stopped by and talked with Ron Tucker, and we went back and looked at the room. We looked next door, which is the GSE Engineering electronics lab and lo and behold, there was water and drainage in that room. I compiled all the installation requirements of both machines and what will be needed for all three location options and put them into the presentation. I also worked a little bit on the layout of the Thermoform Lab if we were to put a new humidity controlled room inside of it for the PML.
I also wrote Andy Snow of EOS e-mails with questions involving installation, and whats included in the price, along with some selling point differences between EOS and 3DS. He sent me a nice package on those differences.

June 2, 2008 (6 hours)

Continued working on the presentation for Mark and Patty. Worked mainly on what consumables there will be along with various room requirements.

June 3, 2008 (3 hours)

Contacted Pneumatics, Electrical and Structural folks about PCC and VAB. Robert Jordan is going to try and get NSLD and SRBE to invest some in the machine.

June 9, 2008 (3 hours)

Came up with list and cost of items we would need to purchase (besides the machine) to get the PML up and running. Added it to the FY'09 budget.

July 8, 2008 (1.5 hours)

Mark Menninger came to visit and bring duraflex part. Discussed differences between Sinterstation HiQ and EOS P390.

July 22, 2008 (7 hours)

Had a meeting this morning with Jim Cawby, Mike Orr, Vicky Lorick and Greg Crews. The meeting was encouraging. The action item from the group was to find out if there were any machines that could not be delivered and paid for by Sept 30th (end of fiscal year). I was able to talk with Mark Menninger, Andy Snow and Susan Scoritino and all three said that they could meet that deadline. The ball now seems to be in the financial corner. Carl McManis is the financial guru for Patty, and I talked with him briefly and sent him some information on payback and benefits. I also looked again at the differences between the HiQ and the P390. I think the P390 is the way to go.

July 24, 2008 (3 hours)

Started the PR yesterday, and today it was in the signature loop. Susan Ellsworth, our finance person, worked on trying to get this thru. She determined that this is an IT item and because of that fact it needed to be on the FY08 plan. She is going to talk with Carl McManis tomorrow who might talk with Ralph Esposito if there is any way around that issue. I met with Johnny Cooper today and walked down PCC 1141, took some measurements and put them into a MicroStation file for laying out the PML plan. Also drew up the EOS system parts in that same file.

Answered questions for Jim Melton, who I think has been asked by Mike Orr to investigate this further. He wanted to know the reason for choosing the EOS over the Stratasys or Dimension machine. He also inquired about the cleaning solution for the FDM products and if it could be disposed of in the drain. I sent an e-mail out to Mike Lane, Rusty McAmis and Rudy Santamaria asking them what they do.

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
28-10-2008	Master's Thesis	December 2007 to October 2008

4. TITLE AND SUBTITLE Review, Selection and Installation of a Rapid Prototype Machine	**5a. CONTRACT NUMBER** NNJ06VA01C
	5b. GRANT NUMBER none
	5c. PROGRAM ELEMENT NUMBER none
6. AUTHOR(S) Caryl McEndree	**5d. PROJECT NUMBER** none
	5e. TASK NUMBER none
	5f. WORK UNIT NUMBER none
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) United Space Alliance 8550 Astronaut Blvd Mailcode USK-708 Cape Canaveral, FL 32920	**8. PERFORMING ORGANIZATION REPORT NUMBER** No Report Number
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Kennedy Space Center	**10. SPONSORING/MONITOR'S ACRONYM(S)** KSC
	11. SPONSORING/MONITORING REPORT NUMBER No report number

12. DISTRIBUTION/AVAILABILITY STATEMENT

None

13. SUPPLEMENTARY NOTES

None

14. ABSTRACT

The rapid protoyping industry is growing rapidly, and it would be highly benefitial for United Space Alliance, LLC (USA) to invest in a highly capable rapid protoype machine. The benefits and advantages of investing in rapid prototyping (additive manufacturing) technology are discussed, including a brief overview and summary of existing rapid prototyping technology as well as a comparison between rapid prototyping and traditional manufacturing methods. To determine which machine would suit USA the best, decision making model is employed.

15. SUBJECT TERMS

Rapid Prototyping
Decision Making
Design Process

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19b. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Caryl McEndree
U	U	U	UU		**19b. TELEPHONE NUMBER** ***(Include area code)*** (321) 861-4972