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Emerging technology supply chain model for additive manufacturing

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EMERGING TECHNOLOGY SUPPLY CHAIN MODEL FOR ADDITIVE MANUFACTURING

by

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ABSTRACT

This research concerns developing an emerging manufacturing technology, additive manufacturing (AM), into a mature and flexible, cost-effective supply chain for aerospace production. The field of additive manufacturing is an approach to low volume manufacturing of plastic or metal parts using three dimensional Computer Aided Design data. As an emerging technology, AM's supply chain is not established compared to conventional aerospace manufacturing technologies, such as injection molding or composite manufacturing. Technical and business challenges limit the robustness of the additive manufacturing system for aerospace applications. The overall intent of this research is to: first, provide an introduction to two main polymer based AM methods, Fused Deposition Modeling and Selective Laser Sintering. Second, illustrate how AM benefits aerospace and third, develop a comprehensive framework that captures technical and non-technical issues surrounding the deployment of an emerging technology, such as AM, into a complex aerospace specific supply chain. Highlighted areas of research include both technical and business based challenges. In addition, the importance of machine flexibility is addressed. Areas of technical contribution include appropriate costing development, AM process and material development, part candidate screening and selection, and the establishment of a robust methodology that will be used as a model for aerospace emerging technology supply chain deployment for the future.

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NOMENCLATURE

Symbol	Description
AM	Additive Manufacturing
ABS	Acrylonitrile Butadiene Styrene
CNC	Computer Numerical Control
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
LENS	Laser Engineered Net Shaping
RM	Rapid Manufactuirng
SLA	Stereolithography
SLM	Selective Laser Melting
ECS	Environmental Control System
PC	Polycarbonate
RT	Rapid Tooling
JIT	Just in Time Manufacturing
FMS	Flexible Manufacturing Systems
TRL	Technology Readiness Level
DoD	Department of Defense
MRL	Manufacturing Readiness Level
QA	Quality Assurance
AMT	Advanced Manufacturing Technology
DOE	Design of Experiments

QLF	Quality Loss Function
MRA	Manufacturing Readiness Assessment
S/N	Signal to Noise
VSM	Value Stream Mapping
LS	Laser Sintering
FDM	Fused Deposition Modeling
EOS	Electro Optical Systems
SLS	Selective Laser Sintering
FUCE	Function Based Cost Estimation
DFM	Design for Manufacturing
DFA	Design for Assembly
OEE	Overall equipment effectiveness
P	Pressure
d_L,	Diameter of the liquefier
L_L	Length of the liquefier
d_T,	Diameter of the tip
L_T	Length of the tip
μ	Material viscosity at temperature
T	Temperature
V	Volumetric flow rate
F	Force
A	Area
T_a	Total Time for Adding Powder in the SLS process

H	Height of the overall SLS build height
L_R	Travelling distance of the roller
V_R	Roller travel speed
T_h	Specified thickness of the powder layer,
T_X	Time delay between parts.
T_S	Total laser scan time for a single part
V_{STL}	The bounding box volume of the single part
HS	Laser scan spacing in the Y direction
$f(\rho)$	Correction factor for the variations of laser mirror scan speed
V_J	Mirror jump speed
V_S	Mirror scan speed
W_p	Distance of the laser travel in the Y direction of a cross section
H_p	Height of an individual part
T_{Ldelay}	Mirror stabilization and laser switching delay
T_{Jdelay}	Jump speed to scan speed delay.
A_N	Amount of incident radiation per unit surface area
P_w	Laser power
BS	Beam speed and
$SCSP$	Laser scan spacing
σ_x	FDM fibrous stress in the X direction
σ_y	FDM fibrous stress in the Y direction
τ_{xy}	FDM shear stress in the X-Y plane
c	Cosine theta (θ)

s	Sine theta (θ)
ε_x	Laminate axis strain in the X direction
ε_y	Laminate axis strain in the Y direction
γ_{xy}	Laminate axis shear strain in the X,Y plane
k	Proportionality constant
μ	Product's mean functional characteristic
T	Target quality performance
Δ	Tolerance given at both sides of target mean
C_i	Cost of indirect labor ($)
C_d	Cost of direct labor ($)
M_r	Overhead Machine Rate ($/hr)
t_b	Time of Build (hr)
C_m	Cost of the Machine ($)
O_p	Cost of Production Overhead ($)
O_a	Cost of Administrative Overhead ($)
t_p	Period of time for specific accounting cycle (Months, Quarters, Annual)
C_{mat}	Direct Cost of the Material in a Batched Build ($)
L_T	Labor Rate of the Technical Staff ($/hr)
L_Q	Labor Rate of the Inspection Quality Staff ($/hr)
n_p	Number of Parts in the Batched Build (integer)
C_p	Cost of Sintered Material ($)
C_{rec}	Cost of Recycled Material ($)
C_{wst}	Cost of Wasted Material ($)

C_{mod}	Cost of Model Material ($)
C_{sup}	Cost of Support Material ($/in^3)
v_p	Volume of the Part Produced (in^3)
v_s	Volume of Support Material Consumed (in^3)
A_{face_down}	Area of the Downward Facing Surface of the Part Produced
$A_{overhang}$	Area of features that overhang the part produced
$Z_{overhang}$	The Z height of the overhanging features
p[A]	Size flexibility
p[B]	Shape flexibility
p[C]	Materials flexibility
p[D]	Machine flexibility
p[E]	Material Handling flexibility
p[F]	Process flexibility
p[G]	Routing flexibility
p[H]	Production range flexibility
$\overline{SLS}_{Flex}$	Average SLS flexibility score
$\overline{FDM}_{Flex}$	Average FDM flexibility score
W_s	Weighted score of each individual row within the MRL matrix
W_R	Individual risk weight assessed for each row
i_r	Number of red cells within the criteria row
i_y	Number of yellow cells within a criteria row.
W_s	Total weighted MRL score

MRL_R Total relative amount of manufacturing maturity risk

i_c Number of criteria rows being evaluated.

1. INTRODUCTION

1.1. RESEARCH OBJECTIVE

The overall objective of this body of knowledge is a clear establishment of a roadmap for transitioning emerging technologies into a low production volume based supply chain. The roadmap offered provides a comprehensive phased and gated system for emerging technology deployment. Individual tools are discussed and verified as critical elements of emerging technology development. These tools include, robust parameter design and optimization, manufacturing flexibility assessment, manufacturing maturing assessment, economic analysis, part candidate screening, and exploiting the technologies' benefits.

The field of Additive Manufacturing (AM) is a new approach to direct fabrication of limited, low volume production of plastic or metal parts using three-dimensional computer aided design definition. As an emerging technology, AM's supply chain is not very established, technical and business challenges limit the robustness of the process.

This body of knowledge provides a case example of emerging technology transition by using Additive Manufacturing (AM) as an example. The application of the tools identified throughout the roadmap to AM provides guidance to a practitioner looking to implement emerging technologies. In addition, as an example of low production volume based industry, the aerospace sector is offered as a platform for deployment of AM technologies and provides examples of emerging technology supply chain development.

The work provided will sequentially cover; an introduction to AM, a comprehensive literature review, technology description and motivation for the research, robust parameter design, economic analysis, proposed supply chain model, results from the tools used in the supply chain, contribution to the field, and conclude with a summary and future research opportunities.

1.2. BACKGROUND OF ADDITIVE MANUFACTURING

Additive Manufacturing is the ability to build parts directly from digital definition files using an additive construction approach. The use of these additively constructed parts to serve a specific function, such as, direct part fabrication or direct tooling is commonly known as Rapid Manufacturing (RM). Advantages of additive manufacturing lie in the ability to produce highly complex parts that require no tooling and thus reduce the costs of manufacture, especially for low volumes. As high volumes do not need to be manufactured to offset the cost of tooling, then the possibility for affordable, highly complex, custom parts becomes apparent (Tuck et al., 2007). AM was developed from the field of Rapid Prototyping (RP) and is sometimes used with the term interchangeably. The separation of the definition between Rapid Prototyping and Rapid Manufacturing is not the specific technologies used, but how the technology is applied and materials used.

As a predecessor to RM, Rapid Prototyping was developed to build parts directly from digital definition, for designers to fit-check their designs before moving into final production. This field was largely held by the prototyping technology known as

Stereolithography (SLA).[1] Gradually, Laser Sintering[2] (LS) and Fused Deposition Modeling[3] (FDM) were developed as AM alternatives to Stereolithography as each process offered other polymer choices other than the ultraviolet reactive photopolymers used in Stereolithography. Laser Sintering uses nylon powder in the form of Nylon 12 to achieve RP quality parts. FDM uses amorphous polymers, such as acrylonitrile butadiene styrene (ABS) to prototype for designers.

Recognizing that many prototype parts could be used for direct use item for low volume applications, rapid prototyping machine manufacturers began developing stronger material solutions for their rapid prototyping equipment. Instead of show and tell prototypes to check for design intent, highly customized parts started to become

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1 Commercially introduced in 1987, Stereolithography is defined as a method and apparatus for making solid objects by successively "printing" thin layers of the ultraviolet curable material one on top of the other. A concentrated beam of ultraviolet light focused onto the surface of a vat filled with liquid photopolymer draws the object onto the surface of the liquid layer by layer, causing polymerization or crosslinking to give a solid 3D object.

2 LS uses a powder which is melted with a CO2 laser so that the surface tension of the particles is overcome and they fuse together. Before the powder is sintered, the entire bed is heated to just below the melting point of the material in order to minimize thermal distortion and facilitate fusion to the previous layer . A layer is drawn on the powder bed using the laser to sinter the material. The bed is then lowered and the powder-feed cartridge rose so that a covering of powder can be spread evenly over the build area by a roller mechanism.

3 FDM systems consist of two movable heads (one for building the part and one for the supports) which deposit threads of molten material onto a substrate. The material is heated just above its melting point so that it solidifies immediately after extrusion and cold-welds to the previous layers.

constructed on RP machines to create functional items. This development was a critical strategic inflection point in the AM technology life cycle. The catalyst for this development was the lack of tooling required to build parts and the ability to take advantage of RP's build flexibility to overcome conventional manufacturing restrictions by integrating several parts into one part. Depending on the complexity of the part being built, breakeven analysis being conducted against conventional manufacturing started to favor RP, thus, creating a completely new field known as Rapid Manufacturing, Solid Free-Form Fabrication, and Additive Fabrication. For the reason of clarity and consistency, this research will describe Rapid Manufacturing and Rapid Prototyping as Additive Manufacturing (AM). This strategy is consistent with a universal definition of AM offered by academia and industry experts.

First, by using AM, Computer Aided Design (CAD) data may directly replace detailed drawings within industry. As an extension of digital file modeling, Choi and Chan (2004) propose a virtual reality system that incorporates RP technology as an output of the virtual reality system. As CAD geometry is directly constructed using AM processes, no need exists for design drawings to be printed. CAD geometry becomes the digital definition of the part. When a part is revised, it is revised in CAD and then labeled with a change. Parametric features of CAD allow dramatic changes to part geometry with relative ease. However, it is unlikely blueprint drawings will disappear completely. In most CAD packages, it is cumbersome to label digital definition with tolerances and geometric dimensioning and tolerance callouts. It is far easier to create a quick drawing from the CAD package and label the part with key dimensional criteria. In addition, quality inspection personnel need to be able to verify a part's dimensional accuracy using a blueprint and a variety of inspection techniques.

Second, Mansour and Hague (2003) reference AM's ability to replace traditional prototyping techniques. Prototypes are generally expensive to produce and require highly skilled technical labor to master. AM offers substantial inroads into prototyping a part on the same machine as production of a final product. AM processes will not completely eliminate the need for artisans to develop prototype articles. Consider a need for a six-foot span prototype pressure vessel to be developed to function under a specified amount of pressure to demonstrate a new product development concept. In such a case, no AM process currently on the market will accommodate such design considerations. It is simply easier for a prototyping artisan to obtain a pressure tank and fabricate the prototype by hand. AM augments traditional prototyping, but does not replace it completely.

Third, Mansour and Hague (2003) state that AM will affect numerical control or computer numerical control programs. According to Mansour and Hague (2003) "there will be no need to create and test numerical control or computer numerical control (CNC) programs, either for tool production purposes or product manufacturing purposes." Again, consider a case where a twenty-two foot wing structure is machined out of titanium for an aircraft. No current AM technology is capable of building the structure; therefore, CNC is required and cost effective.

Despite unbridled optimism for AM in the early 2000s, currently, AM is not viewed by most industries as a viable method of manufacturing. With regard to AM, "these devices were developed, and are still seen, mostly as a concept modeler"

(Dimitrov et al., 2006). Improving the technology to the point of changing this mindset is a critical target for the next 10-12 years (Bourell et al., 2009). Without a doubt AM technology offers potential to change the essence of traditional design and manufacturing; however, the development of those emerging technologies to the point of profitable application is still far ahead (Drizo and Penga, 2006).

Although there are many AM technologies in existence both in metals and polymer arenas, the breadth of the research included will cover two emergent polymeric additive manufacturing technologies, Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) as shown in Figure 1.1.

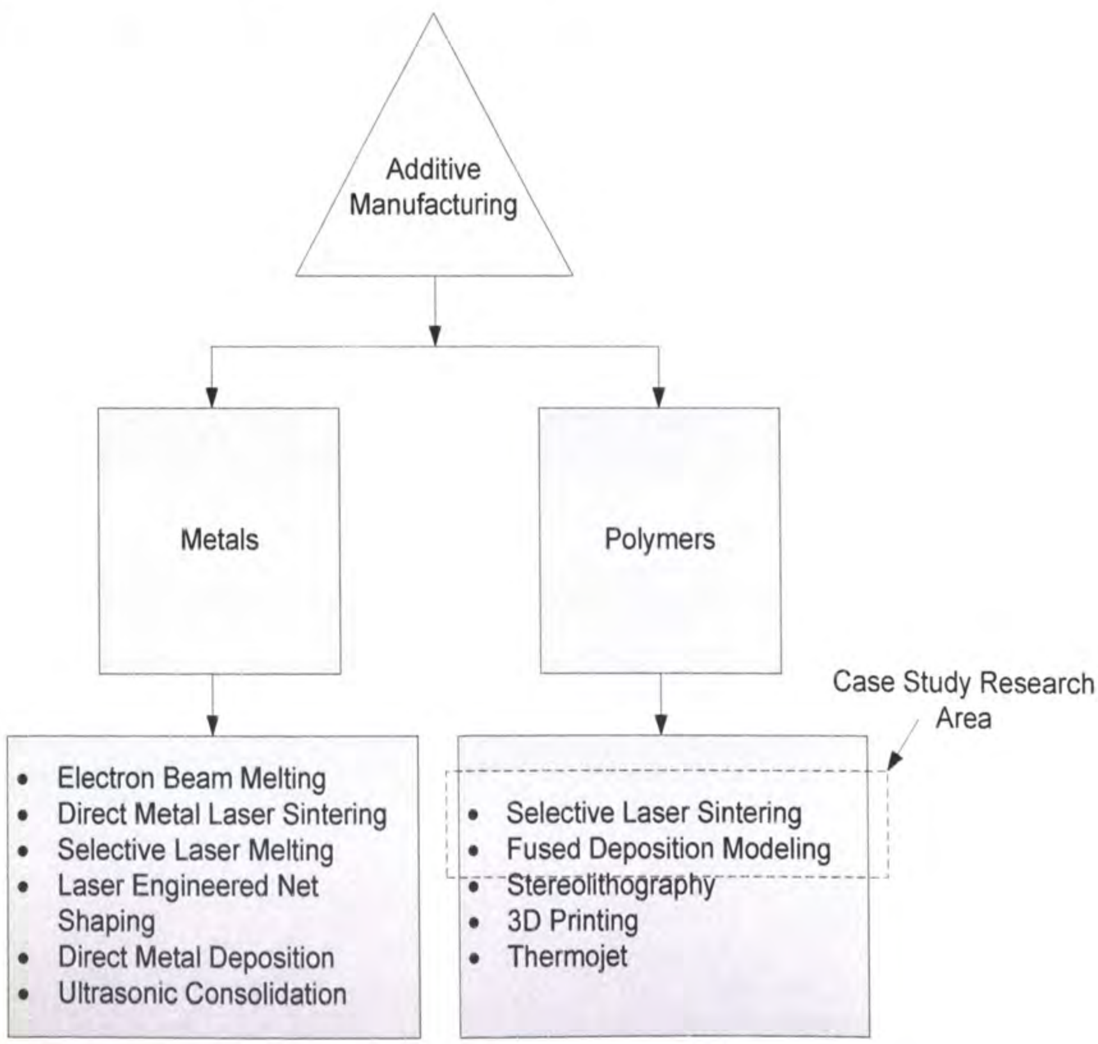

Figure 1.1. Elements of Additive Manufacturing

As there are a number of manufacturing methods employed for aerospace production, these methods range in levels of sophistication and maturity. A few examples of conventional manufacturing methods utilized include, but are not limited to, composite fabrication, three and five axis machining, injection molding, rotational molding, welding, drilling. These manufacturing methods are generally considered mature, used often in industries with well-established supply chains.

1.2.1. The Introduction of Selective Laser Sintering. Two laser sintering companies exist at the current point in time, 3D Systems of Rock Hill, South Carolina and Electro Optical Systems (EOS) of Krailling, Germany. Several raw materials may be used for the process, including polymers, ceramic, and metals. A process schematic of a 3D Systems styled machine using plastic powder is provided in Figure 1.2.

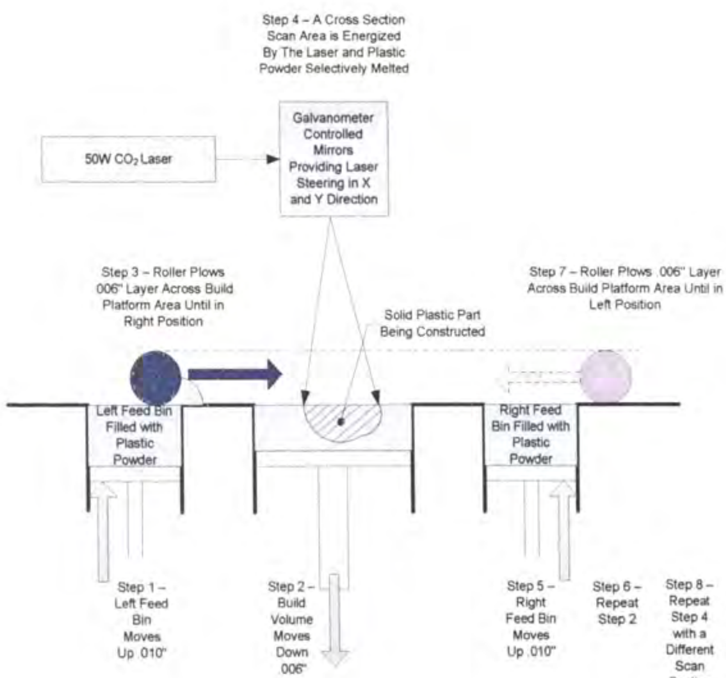

Figure 1.2. Schematic of the Selective Laser Sintering Process

In order to fabricate parts, a number of steps are required within the SLS process. The schematic shown in Figure 1.2 highlights the process in a stepped sequence. The entire process listed in the schematic is surrounded by a heated and N_2 inert build chamber environment to prevent oxidization of the powder before the build process is initialized. The build chamber is heated prior to the laser scanning process to bring the temperature of the powder up to a few degrees below the powder's sintering temperature. The build process sequence depicted in Figure 1.2 is as follows:

Step 1: The left feed bin stores the raw powdered plastic material. The powder contained within this powder feed bin is indexed up .010" inch vertically via a piston.

Step 2: As Step 1 occurs, concurrently Step 2 occurs. This step requires that the piston located in the center of the machine moves down .006" inch, creating a small cavity in the part build area. This incremented amount acts as the layer thickness of the fabricated part produced in the center of the machine.

Step 3: Once Step 1 and 2 have occurred, Step 3 is executed. Step 3 involves a roller, or re-coater rake in the case of EOS machine, pushing and plowing the raised powder from Step 1 across the build area cavity created in Step 2. A certain amount of excess powder, known as overflow, exists at the end of the roller travel which falls down in an overflow bin. At the end of this step, the roller is then parked at the right side of the machine, just to the right of the right feed bin.

Step 4: Once the roller, or re-coater, is parked to the right of the feed bin, a 50 Watt, CO_2 laser is energized at a specified watt. A series of galvanometer mirrors reflect and steer the laser beam at a specified velocity to the part build area. A specific cross section of digital geometry is scanned across the powder, thus, selectively melting a single layer of powder.

Step 5: The right feed bin moves up .010" inch to provide more material to be scanned.

Step 6: Concurrent to Step 5, the part build area moves down .006" inch to accommodate the powder spread from Step 5.

Step 7: The roller, or re-coater, pushes the powder across the build area to the left position and parks to the left of the left feed bin. The process loops back to Step 1 and repeats until all layers within the digital file are processed.

After processing all layers, the build chamber is set to cool until the geometry may be safely removed from the build cake.[4] The build cake of loose powder surrounding parts acts as a support mechanism for parts as they are additively constructed.

1.2.1.1. Materials Processed Using SLS. Semi-crystalline polymers are generally used for SLS. Specifically, polyamide nylons are commercialized as the main polymer of choice. These grades of nylons exist as neat resin cryogenically ground to 50μm and 80μm spherical shape. In an AM production environment, these polymer powders are quality checked using batched lot testing procedures with particle size analysis and melt flow indexing from samples conducted. In addition, versions of different nylon blends exist with glass, aluminum, and carbon fiber shavings dry blended

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4 The build cake is defined as the plastic powder volume that contains parts built during the SLS process. This cake of powder is evacuated from the build chamber once the chamber is cooled to room temperature. The parts are dug out of the part cake and the loose powder is removed from parts and recycled.

with the nylon base material (Liou, 2007). The blends increase modulus and/or tensile strength properties, often at the sacrifice of elongation percentage.

However, service bureaus[5] often sacrifice quality procedures to gain cost competitiveness. For example, a survey conducted by Munguia et al., (2008) canvassed SLS service bureaus and found that one-hundred percent of the respondents with SLS equipment perform material recycling, so the main topic concludes what mix ratios were used. The majority of the respondents to the survey responded with variable mixing ratios; therefore, the final part quality structural integrity would also become variable due to the inconsistency in raw material input properties. "Furthermore, the number of centres that measure and control particle size, powder viscosity, melt flow index and material humidity was minimum and a clear majority of the surveyed users undertake their normal operations without considering these concepts." (Munguia et al., 2008)

On a smaller scale, various metals and ceramics may be utilized, with limited success, in the SLS process. 3D Systems offered a method of metal sintering that included polymer based binders mixed with metals powders to sinter a form of part that is heated in a post processing operation. The lower polymer binder is then melted away to produce metal parts. EOS also offered a similar method using a sand mixed polymer

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[5] Companies specializing in fabrication of additively manufacturing parts for a wide variety of customers who wishes to use the technology solely for design intent. A general focus of the Service Bureau resides on processing as many Rapid Prototyping parts as quickly as possible at the lowest possible price for customers

binder sintered in the laser-sintering machine.[6] At current date, neither SLS company recommends or markets each technology.

Once constructed, the sand-polymer binder shape was then heated and the binder melted away, giving way to more successful methods of additive metal processing, such as Direct Metal Laser Sintering (DMLS)[7], Electron Beam Melting (EBM)[8], Laser Engineered Net Shaping (LENS)[9], and Selective Laser Melting (SLM).

1.2.1.2. SLS Process. Many machine models have been released by both EOS and 3D Systems. Each model released offers improvements over previous models in the areas of process efficiency, thermal control stability, laser accuracy, and system monitoring. Specific material limitations exist depending on the specific model. Each model also has limitations with respect to build volume. One of the largest differences among SLS machines is the build volume scale. This difference in scale is often refered to large frame and small frame machines. According to Wohlers (2009), the respective sizes between the large frame and small frame machines is noted in Table 1.1, which illustrates all SLS models available for purchase on the current market.

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[6] SLM – Originally developed by Fraunhofer Institutes, SLM is a process similar to SLS but fully melts metal or ceramic powders to form high density parts.

[7] DMLS is defined as a process that EOS developed that is a variation of SLS in which a laser liquid phase changes direct metal powder without the use of a polymer binder (Hopkinson et al., 2005)

[8] EBM - this process uses an electron beam to melt metal powder in a layer-by-layer process to build the physical part.

[9] Laser Engineered Net Shaping uses computer-controlled lasers that weld air-blown streams of metallic powders into parts directly from digital data

Table 1.1. SLS Machines Available

Polymer Based Selective Laser Sintering Machine					
Company	**Model Name**	**Build Volume (inches)**	**Compatible Materials**	**Initial Investment Price**	**Currency Type**
3D Systems	Sinterstation HiQ	13 X 15 X 18	Polystyrene, polyamide, glass and aluminum filled polyamides	350,000	$ (US)
3D Systems	sPro 230	22 X 22 X 30	Polystyrene, polyamide, glass and aluminum filled polyamides	850,000	$ (US)
3D Systems	sPro 140	22 X 22 X 18	Polystyrene, polyamide, glass and aluminum filled polyamides	725,000	$ (US)
EOS	Formiga P100	8 X 10 X 13	Polystyrene, polyamide, glass and aluminum filled polyamides	150,000	€'s
EOS	EOSINT P390	13 X 13 X 24	Polystyrene, polyamide, glass, aluminum, and carbon fiber filled polyamides	290,000	€'s
EOS	EOSINT P730	28 X 15 X 23	Polystyrene, polyamide, glass and aluminum filled polyamides	720,000	€'s
EOS	EOSINT P800	28 X 15 X 23	PEEK	905,000	€'s

* Sourced From Wohlers Report 2009 pg. 246

All manufacturing processes may be analyzed using output elements of throughput, cost, quality performance, and manufacturing flexibility. Specifically, the SLS process has been well researched with respect to time and performance, but not as well researched with respect to cost and flexibility as flexibility metrics are difficult to define (Beamon, 1999) and specific cost metrics are held proprietary by many industries.

With regard to process throughput, the processing time algorithm included within the SLS software often is inaccurate in determining estimated completion times. However, total throughput may be determined using various methods of analysis proposed by Pham and Wang (2000). In order to process a SLS part, the entire process requires a warm up stage, a build stage, and a cool-down stage. Within the build stage, the total time, T_a, for adding powder is defined as:

$$T_a = \left(\frac{L_R}{V_R} + T_X\right)\frac{H}{A} \tag{1}$$

Where H is the overall build height, L_R is the travelling distance of the roller, V_R is the roller travel speed, A is the specified thickness of the powder layer, and T_X is the time delay between parts. Also within the build stage, Pham and Wang developed a technique for estimating the total scan time of the SLS build, known as T_S that relates the volume of the smallest rectangular box formed by the X, Y, and Z boundaries, also known at the bounding box volume with $T_{h.}$ the thickness of the powder.

Once the part is completely analyzed, T_a and T_s are added together to determine an SLS build time for a single part. If multiple parts are built at the same time then each of the individual parts, T_s, are summed and added to T_a. Once all of the parts are analyzed together, the total time for an entire build may then be determined. Understanding the throughput of the SLS system allows a manufacturing facility to queue work intelligently within the manufacturing system process.

Research conducted in the area of SLS points to a basic equation known as the Andrew number, A_N, which represents the amount of incident radiation per unit surface area. The Andrew number has been correlated to the penetration depth of melting in SLS (Thompson, 1997).

$$A_N = \frac{P_W}{BS \times SCSP} \tag{2}$$

Where P_w is laser power, *BS* is beam speed and *SCSP* is scan spacing. Layer thickness is independent of A_N. Industry tends to use the Andrew number as an easy tuning equation for mechanical property performance of SLS.

However, during the sintering phase of the process, the thermal control of the build chamber environment is of critical importance to the quality of parts produced in the SLS process. Coupled with thermal variation, variables including power and speed of the laser affect the mechanical integrity of the parts produced in SLS. These variables are not accounted for in A_N. To answer this need, Dong et al., (2009) successfully developed a model for the simulation of SLS process, coupling the equations of the heat transfer and powder sintering together to form a more robust representation of the SLS process, but the depth of Dong et al.'s research is beyond the scope of this research.

For AM applications, several forms of testing methods are used to determine if the process is operating within its control limits. These testing methods may include tensile specimen testing, flexural testing, impact testing, density analysis, and compression testing. For aerospace production, the Boeing Company gives an idea of how tensile bars are used in production batch processing of SLS. Each tensile specimen indicates critical areas of challenge within the build volume. Taken from the patent application, Figure 1.3 gives a layout of a typical SLS production build with respective tensile specimen layout nested around the production part.

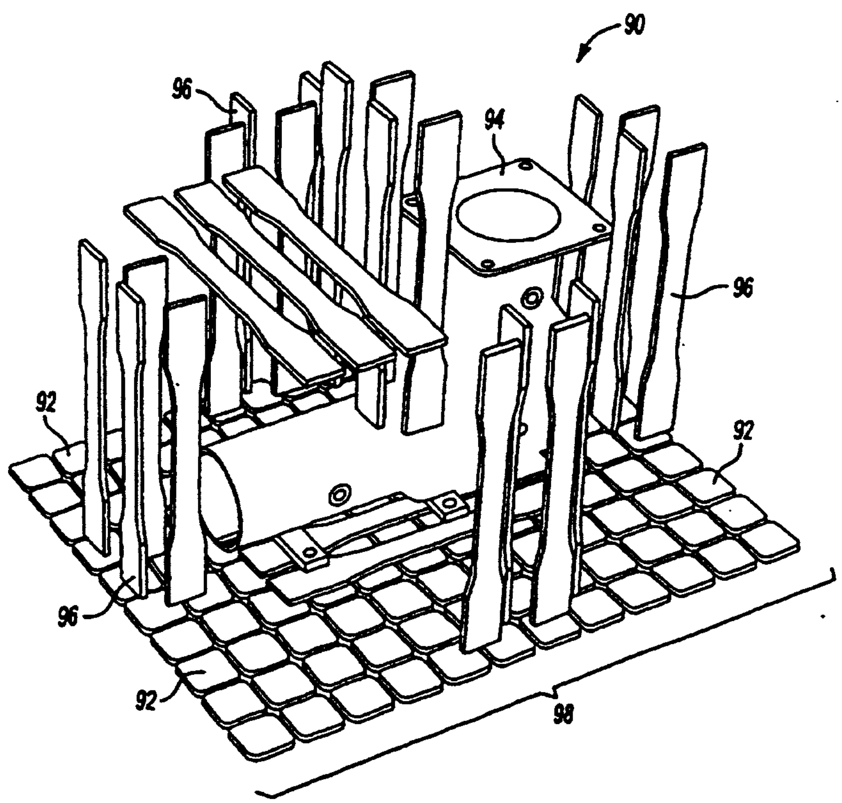

Figure 1.3. Aerospace SLS Production Build Layout

1.2.2. History of Selective Laser Sintering. SLS was invented in 1979 by Ross Householder, who holds the first patent of the technology, according to Hopkinson et al, (2005). Dr. Carl Dekkard at the University of Texas-Austin first commercialized the SLS process in 1989, which led to the development of the Desktop Manufacturing (DTM) Corporation. DTM Corporation was the first to develop a machine in 1992. DTM is now part of 3D Systems. In 1994, EOS released their EOSINT machine for sale (Hopkinson et al., 2005). Following other Rapid Prototyping technologies lead of the 1990s, SLS looked to penetrate the Rapid Prototyping industry by offering an alternative to the anisotropic mechanical properties exhibited in the SLA resins at the time. Although less accurate than SLA, by offering nylon parts that were more impact resistant compared to more brittle SLA resins and requiring no additional support material, SLS gained a foothold into the Rapid Prototyping market. Not only does SLS offer improved mechanical performance, it also offers the ability to pack many parts into a batch run, thus, lowering the material costs compared to alternative RP technologies. The material that remains after processing may be recycled offering another element of cost reduction. However, laser sintering is not without its shortfalls. The surface finish of laser sintering is rough compared to Stereolithography and not as dimensionally stable as FDM. In addition, LS requires highly skilled technical labor to operate, unlike FDM

In the 1990s, Service Bureaus located in the United States began to construct parts from SLS technology. Notably, companies such as Harvest Technologies, Solid Concepts, and Paramount Industries developed entire business models based on quick response, low cost prototype SLS parts for wide varieties of industries. In response to growing demand, SLS machine manufacturers began to struggle to develop quick response equipment service capability to meet the needs of the Service Bureaus.

1.2.3. Applications for SLS. Many industries are adopting SLS for direct part fabrication, which represents a dramatic shift from the traditional Rapid Prototyping model for the technology. Instead of a focus on speed and low cost of additively manufacturing parts, a focus shifts to quality control documentation and structural part integrity. As directly manufactured parts become candidates for the SLS, structural evaluation of parts acts as a forcing function to evaluate a deeper technical understanding of the SLS manufacturing process. Out of the current range of RP/AM processes, Laser Sintering appears to be the most appropriate for AM. In fact, the materials used in LS have better and more stable mechanical properties compared with most of the other RM materials (Ruffo, 2006).

1.2.4. An Introduction to Fused Deposition Modeling. Developed by Stratasys Inc. in 1991, FDM patents were first awarded to Scott Crump, the company founder (Hopkinson et al., 2005). Stratasys has outsold all other rapid prototyping machines manufacturers. According to Wohlers (2009), in 2008, Stratasys reached a milestone by installing its 10,000th FDM system. Stratasys has positioned FDM well for rapid prototyping applications; however, FDM is also a contender in the field of AM. According to Wohlers (2009), "Stratasys recently branded its high-end systems as Fortus 3D Production Systems for production applications. Production applications of FDM have become the fastest growing revenue source at Stratasys."

Comb et al. (1994) offers that the basic FDM process consists of small direct current motors that drive feed wheels to provide up to 10lbs of force to push a filament-based thermoplastic material to a machine. The machine interprets a sliced 3-dimensional CAD model from an exported tessellated file, and builds the geometry layer-by-layer at .005"-.013" 'Z' or slice heights. The FDM machine feeds the filament into a head assembly containing a heater element. The material is brought to its melt point and then is pushed out through a tip. The head moves on an X-Y gantry/plane which 'draws' the defined tool path while extruding the material in a semi-liquid state onto the previously layered tool path, building up the part, layer by layer. A completed build is subsequently removed from the build chamber and any required support material is removed manually. The part is considered complete at this point and can be finished to customer requirements by sealing, painting, or sanding.

The FDM head assembly consists of two separate material feed systems. One system is for the model or part material. The other is for a complimentary support material system. Since the FDM process is not a self-supporting system, any overhanging features require a support material to give the model material a base on which to build from. The break-away support material removes easily from the model material after the build is complete. The equipment and material supplier, Stratasys, also provides a water-solvable support system that can be used on a few of their commercially-available model materials. Figure 1.4 highlights the FDM process.

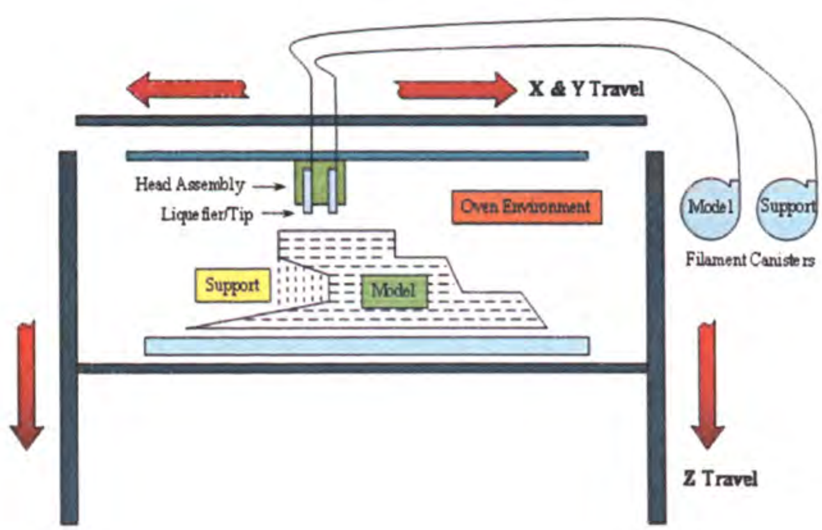

Figure 1.4. Fused Deposition Modeling Schematic

Because FDM technology is a relatively simple extrusion based process, its simplicity offers advantages over competing AM technologies such as SLS. A few of the most basic advantages include, but are not limited to, capable of being used in an office environment, less service and maintenance, and easy to relocate and move to other locations.

1.2.4.1. Materials Processed Using FDM. There are a large range of polymers available for FDM. However, all polymers available for FDM must be more amorphous than semi-crystalline due to the relatively wide thermal melt range of the FDM process. At the present time, the following base material grades available for FDM include acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), polyphenylsulfone (PPSF), and ultem (PEI). It is worth noting that blends of the base materials listed above are also available for FDM. Each amorphous material compatible with FDM systems offers an inherent viscosity during processing. According to Rauwendaal (2001), the viscosity of amorphous materials is described by a two-exponential equation:

$$\mu = A_1 \cdot T \cdot \left[1 + A_2 \cdot e^{\frac{B}{RT}}\right] \cdot \left[1 + C \cdot e^{\frac{D}{RT}}\right] \qquad (3)$$

Where μ is viscosity, A_1, A_2, B, C, and D are related to thermodynamic parameters of joining bonds among amorphous materials.

Each material processed using the FDM process has advantages and disadvantages. For example, ABS offers the ability to have a complimentary support material that is water-soluble; however, the mechanical properties of ABS are often the weakest of the FDM materials. PPSF can withstand the highest amount of thermal exposure, but often at the sacrifice of being more brittle than the other materials. PEI seems to offer the best combination of mechanical and thermal performance; however, it is priced higher than the other materials. Knowing process material tradeoffs affords an AM system manufacturer the ability to cater individual customer performance requests to the optimum material system.

1.2.4.2. The FDM Process. Several control parameters affect the FDM process. These consist of bead width, slice height, speed of deposition, and a volumetric flow rate of the specific material described in § 1.2.4. These specific control parameters are controlled in the liquefier deposition portion of the FDM process located in the head assembly. Comb et al. (1994) describe the pressure (P) of the material within the liquefier and tip is dependent upon the length and diameter of the liquefier (d_L, L_L) and tip (d_T, L_T) as well as the material viscosity (μ) at temperature (T), and volumetric flow rate (V). Tip diameter will be related to pressure drop in the liquefier. This effect is due to the smaller size of the tip diameter relative to the liquefier diameter. Pressure drop associated with the material within the liquefier is shown in Equations 4 and 5:

$$P = \frac{128 * \mu * V}{\pi} \left[\frac{L_T}{{d_T}^4} + \frac{L_L}{{d_L}^4} \right] \tag{4}$$

$$P = \frac{F}{A} \tag{5}$$

Because force (F) is fundamentally related to pressure (P) via area (A), the force of the feed wheels are known as well. Various FDM machines are offered for sale from Stratasys that encompass a variety of build volumes and material compatibility.

According to Wohlers (2009), Table 1.2 illustrates the various FDM machines for sale by Stratasys.

Table 1.2. FDM Machines Available

Polymer Based Fused Deposition Modeling Machine					
Company	**Model Name**	**Build Volume (inches)**	**Compatible Materials**	**Initial Investment Price**	**Currency Type**
Stratasys	Fortus 200mc	8 X 8 X 12	ABSplus, soluble support	50,000-55,000	$ (US)
Stratasys	Fortus 360mc	16 X 14 X 16	ABS-M30, soluble support	80,000-150,000	$ (US)
Stratasys	Fortus 400mc	16 X 14 X 16	ABS-M30, PC-ISO,PC, PC-ABS, PPSF, soluble support	100,000-200,000	$ (US)
Stratasys	Fortus 900mc	36 X 24 X 36	ABS-M30, PC, PPSF, soluble support	350,000-450,000	$ (US)
Stratasys	Dimension SST	10 X 10 X 12	ABSplus, soluble support	32,900	$ (US)
Stratasys	Dimension Elite	8 X 8 X 12	ABSplus, soluble support	29,900	$ (US)

* Sourced From Wohlers Report 2009 pg. 243

For both FDM and SLS, the Z-axis orientation of parts are generally weaker than both X and Y directions. This anisotropic condition is derived from the build-up of residual thermal stresses as new layers are deposited onto existing layers of the part (Bueth and Narayan, 1996). This Z-axis limiting effect is due primarily to the additive nature inherent in most AM processes. Due to the Z-axis limitation, design engineers must limit the technology to the weakest anisotropic plane and place emphasis on Z-axis testing. This emphasis on Z-axis testing is relevant for many testing types. Kridli (2006) describes several mechanical property evaluation techniques for AM such as uniaxial tensile, impact toughness, flexure, hardness, and creep tests.

Mahesh et al. (2004) developed a test specimen geometry that assists in benchmarking among AM technologies. However, this test specimen geometry focuses mainly on surface finish and dimensional accuracy criteria for inspection among AM processes. Their research does not address mechanical property performance among AM processes. Aerospace design engineers evaluate manufacturing performance on mechanical property performance of the parts built from manufacturing processes.

In addition, due to budget constraints, industry often focuses on one or two types of testing techniques that simulates physical conditions of applications and a large population of samples. This constraint has led to an overall decision to test for both uniaxial tensile and flexural tests. The research included will cover only uniaxial tensile testing.

FDM extrudes an amorphous plastic, does not offer a meta-support structure, and lays a user defined orientation pattern during fabrication. By not offering a meta-support structure within the build chamber, such as SLS powder, tensile specimens and directly manufactured parts must be built within the same plane. In addition, the user defined orientation pattern may be altered to optimize strength for a design engineer. This manipulation of a layered extruding tool path may be altered for each layer, thus, this manipulation of pattern must be captured. Also, due to the lack of a meta-support structure, a single tensile bar built in Z would most likely topple over during the build process due to the vibration induced from the extruding head moving back and forth at a relatively high frequency. Therefore, multiple tensile bars must be built at the same time and attached together to form a larger mega-structure that is not as susceptible to the vibration inherent in the FDM process.

Given that FDM Z axis tensile properties are generally lower than X-Y tensile properties, design engineers must design to the weakest parameter for direct manufacturing of parts. Therefore, a test specimen must be designed to optimize the FDM system relative to Z strength. To address this need in the most efficient manner possible, Dietrich et al. (2010) designed a test specimen to capture the structural integrity and robustness of the FDM process. This specimen geometry is illustrated in Figure 1.5.

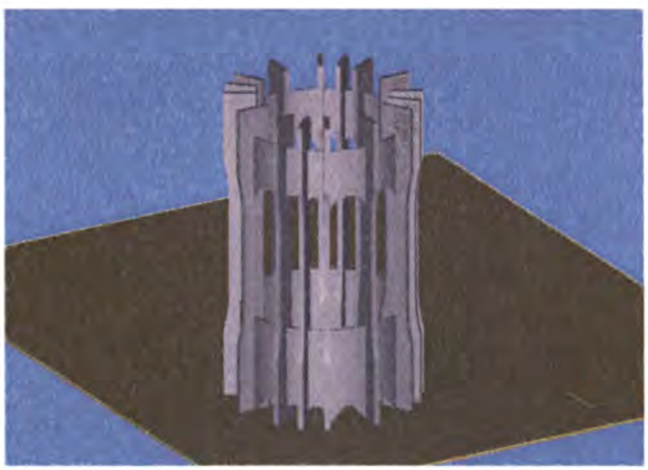

Figure 1.5. Fused Deposition Modeling Schematic

The specimen geometry shown in Figure 1.5 is a grouping of American Society for Testing and Materials (ASTM) D638 Type I tensile specimens oriented in the Z direction. The tensile specimen may be constructed from any FDM material. Through tensile testing, the tensile specimen grouping also acts as a process performance checkThe ASTM D638 Type I callout describes a tensile specimen that is illustrated in Figure 1.6.

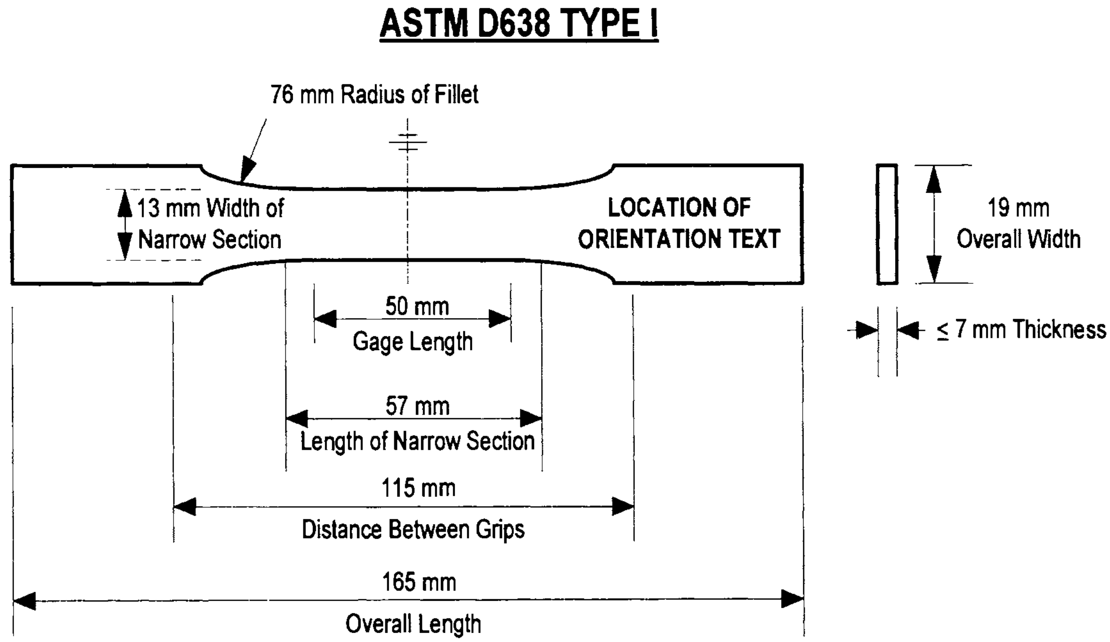

Figure 1.6. ASTM D638 TYPE I, Callout Diagram

The geometry highlighted in Figure 1.6 serves several functions. One function replicates the layered pattern of any part built concurrently in the FDM process. The arched geometry connecting tensile specimens acts as a self-supporting feature to eliminate the need for support material to be constructed for the tensile bar grouping. Without the arching feature, the requirement for support material would double the estimated build time. In addition, by eliminating the need for support material, the specimen requires 45% less material.

This connecting arched geometry also acts as a rigid body for the construction of the tensile bar group to prevent a tensile bar from toppling over during building. In addition, this rigid body also prevents the vibration inherent within the FDM process from manifesting itself as rough surfaces within the neck of the tensile bar during construction. Note the individual tensile bars are labeled. The labeled tensile bars define the tensile bar's relative position during construction and assists a test technician to accurately label data generated from the tensile specimen group. Ultimately, the tensile specimen grouping acts as a quality control device for production by nesting the tensile specimen group with production parts built within the FDM process as shown in Figure 1.7.

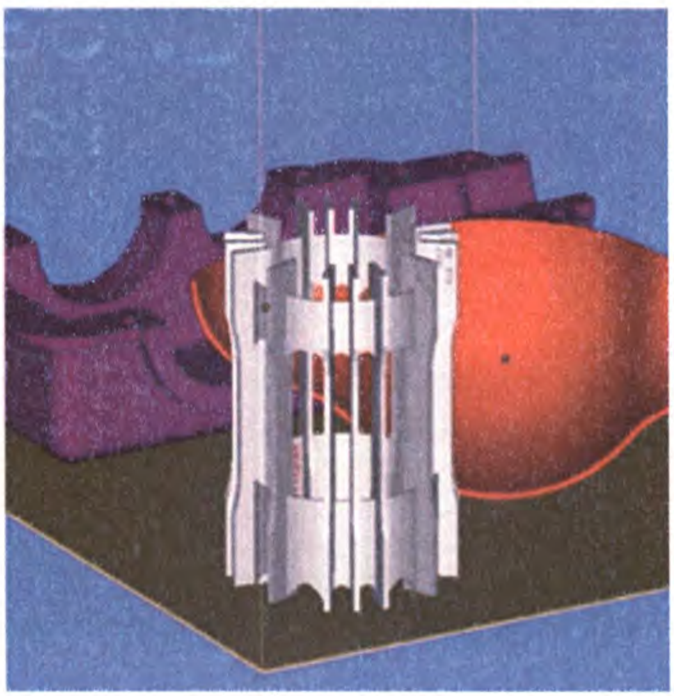

Figure 1.7. FDM Tensile Specimen Nested with Production Parts

Kulkarni and Dutta (2001) observed that with each FDM deposited layer is a bonded, close-packed fibrous lamina, similar to fiber-reinforced composites. Ahn et al. (2003) theorized that a FDM bead width might be compared to fiber orientation of classic laminate theory. This theory proposes that the mechanical properties of the laminate are defined along the fiber, or, x-direction and perpendicular to the fiber, or, y-direction.

Each layer of a tensile bar is found to be similar to an individual ply in laminate theory. Another common aspect of FDM to composite manufacturing involves the failure mode of parts. Beuth and Narayan (1996) note that "delamination is one of the principal sources of failure in laminated composites." This observation acts as a corollary to Z-axis layer bonding in the FDM process.

Expounding on these observations and recognition of classic composite laminate theory (Baker et al., 2004); material properties are listed relative to on-axis coordinates. Consider the properties of an off-axis ply, anything other than zero degrees, can be calculated by transforming the properties of the 0-degree ply. Let zero be the x-axis, and note that the angle θ is measured from the x-axis to the laminate axis and is positive in the counterclockwise direction; the y-axis is perpendicular to the x-axis and in the plane of the ply, see Figure 1.8. All subsequent calculations are made using the x-y, or laminate axes; therefore, it is necessary to transform the stress-strain law from the material axes to the laminate axes. If the stresses in the laminate axes are denoted by σ_x, σ_y, and τ_{xy}, then these are related to the stresses referred to the material axes by the usual transformation equations:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} c^2 & s^2 & -2cs \\ s^2 & c^2 & 2cs \\ cs & -cs & c^2 - s^2 \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{6}$$

where c denotes cos θ and s denotes sin θ. Also, the strains in the material axes are related to those in the laminate axes, namely, ε_x, ε_y, and γ_{xy}, by what is essentially the strain transformation:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix}=\begin{bmatrix}c^2 & s^2 & cs\\ s^2 & c^2 & -cs\\ -2cs & 2cs & c^2-s^2\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix} \tag{7}$$

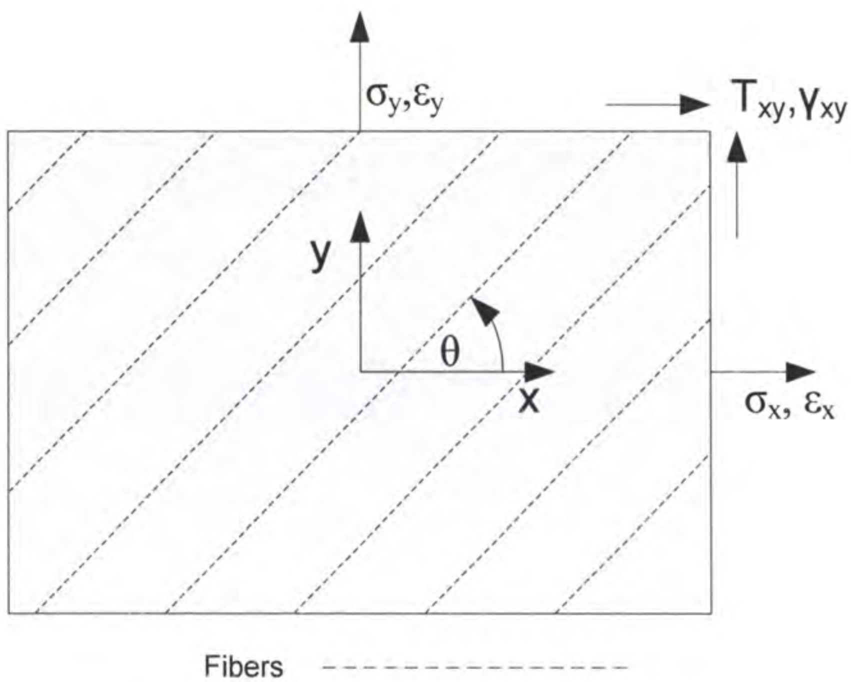

Figure 1.8. Fiber Placement, Single Layer of FDM

Consider a similar approach using FDM whereas the tensile specimen highlighted in Figure 1.7 is shown from a top view perspective in Figure 1.9. Raster orientations are additively constructed in the FDM process. Therefore, a natural expansion of thought would be to consider that each ply in composite laminate theory may be thought of as a raster pattern layer in the FDM process and by specifying each layers orientation to 0° each ply, or layer, the specimen may be defined to serve as a function of loading for multi-directionally loaded parts.

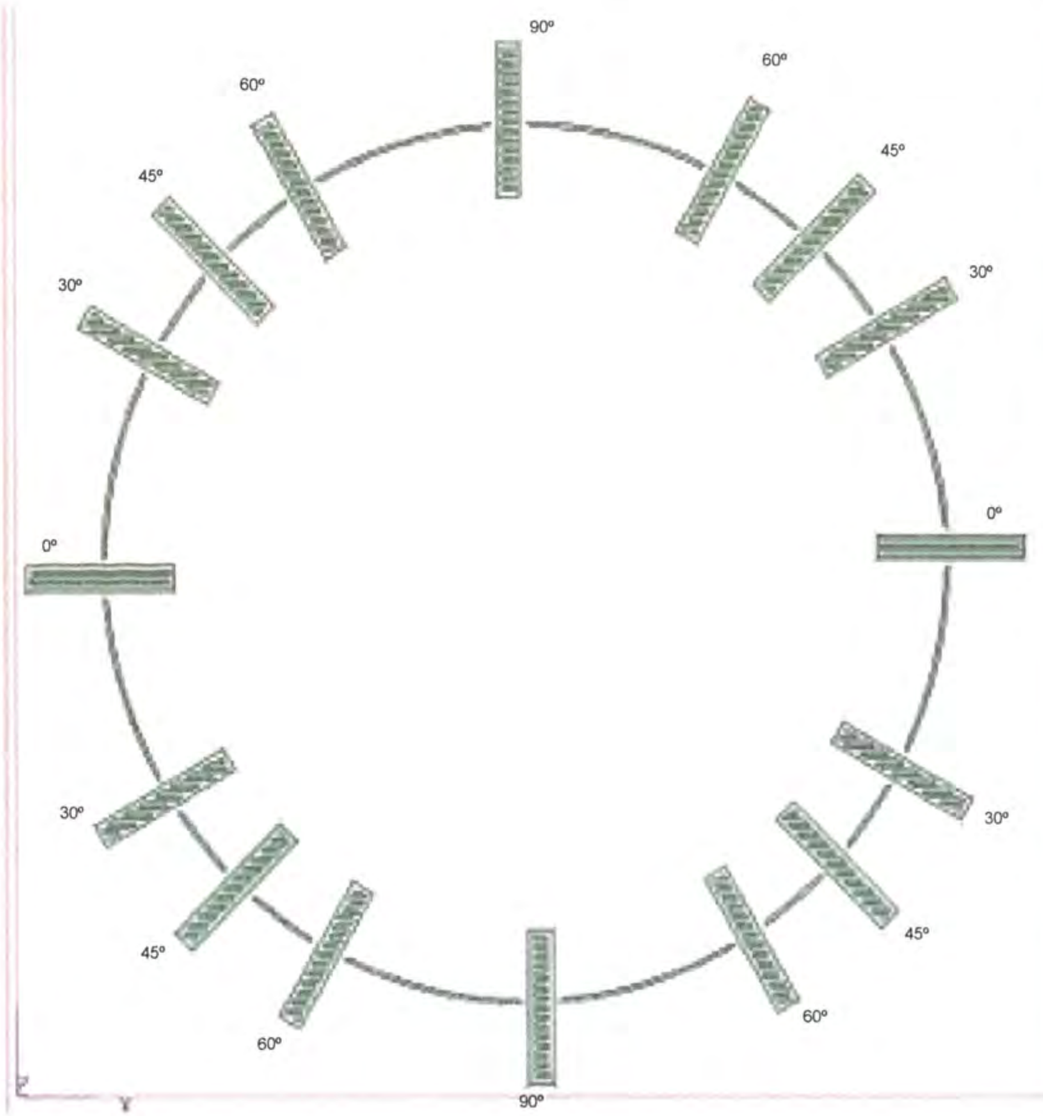

Figure 1.9. Multi-Directionally Loaded Raster Orientation Tensile Specimen

Each specimen offers unique orientations to correlate to the laminate theory fundamental principles listed above. By tailoring several orientations within the same tensile specimen in a circular pattern, the specimen shown in Figure 1.9 represents a multi-directionally loaded part. From a testing perspective, each multi-directionally loaded specimen would yield the following quantity of tensile bars listed in Table 1.3.

By gaining raster orientation direction mechanical property data relative to the Z axis, a thorough knowledge capture may be attained for the FDM process.

Table 1.3. Quantity of Tensile Bars Produced from Multi-Directional Specimen

Test Specimen Layout for Multi-Directional Loaded Geometry	
	Quantity of Tensile Bars Per Specimen
0°	2
90°	2
30°	4
45°	4
60°	4

By adjusting the raster pattern into different angled orientations, a designer may feel confident that all orientation patterns have been accounted for in the design of the part. After the orientation pattern is constructed, the tensile specimens are tested for strength and measured.

In addition, consider if a design engineer designed a part to only take loads solely in a bi-directional format, such as X and Z or, Y and Z axis, an alternative tensile specimen configuration may be required, as shown in Figure 1.10. In such a situation, a raster pattern layout with all rasters constructed at 0° shown in Figure 1.10, may be appropriate. Using a bi-directional design requirement may yield sixteen 0° tensile specimens, as opposed to two 0° specimens using the multi-directional design requirement. It is also important to note that the ring pattern may be adjusted to accommodate a variety of samples. For example, the 30° and 60° specimens may be eliminated to leave only the 0°, 90°, and 45° specimens.

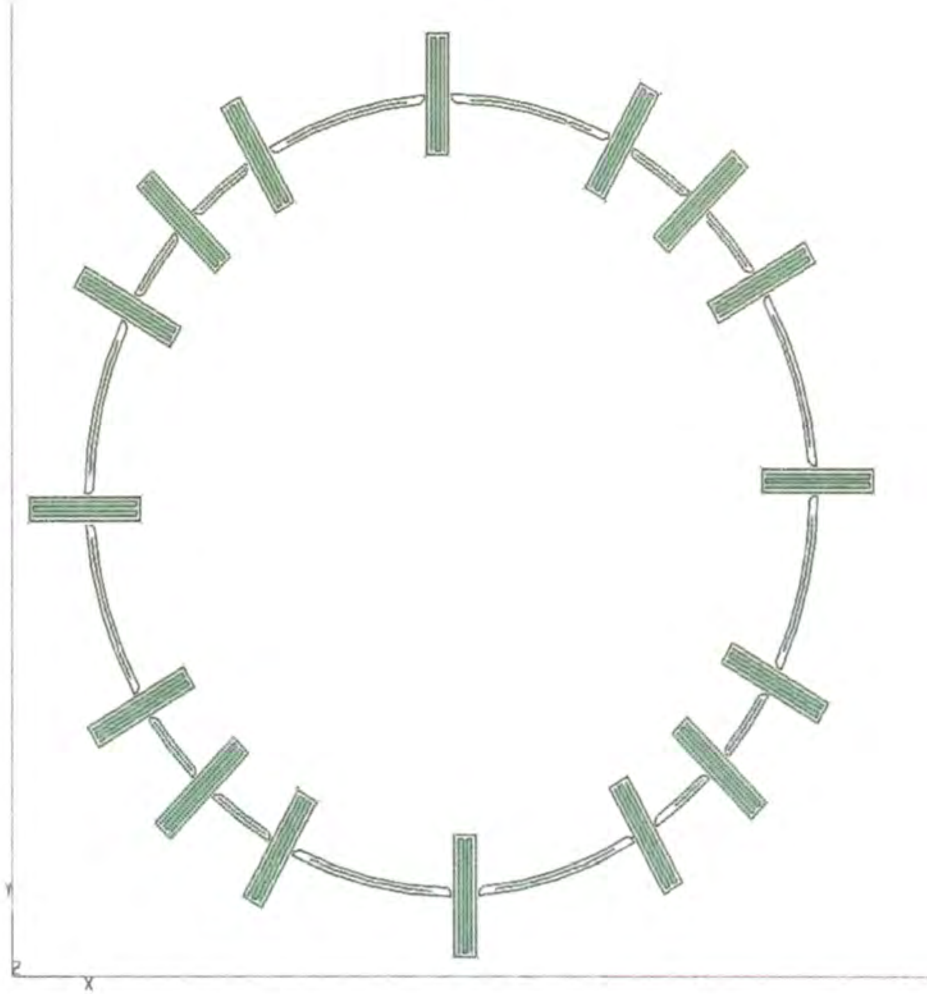

Figure 1.10. Bi-Directionally Loaded Raster Orientation Tensile Specimen

In summary, FDM orientation of the raster pattern may be tailored to the specific design function needs required by the design engineer. These tensile specimens shall then be constructed concurrently with the production part and tested to ensure product performance has been established. However, before any part is produced for production, the process must be optimized for structural integrity.

However, according to Federal Aviation Administration (1984) documentation, the extent of testing and analysis required for each part will change for each specific structure. This change is based on the expected service usage, the material selected, and the design allowable, and failure criteria.

1.3. ADDITIVE MANUFACTURING IN AEROSPACE

Large aerospace manufacturing companies strive to produce flight hardware with stringent quality standards. As global manufacturing integration continues to proliferate throughout the commercial airplane sector, manufacturing technologies, such as AM, have emerged to meet the evolving needs of the company. The aerospace industry is one of the first commercial users of AM for direct part fabrication. Rigorous testing and certification is necessary before it is possible to use materials and processes for the manufacture of aerospace components. Boeing in Canoga Park, California has successfully used AM technology to manufacture hundreds of parts for the international space station and Boeing has used AM for the F/A-18 (Walter et al., 2004).

Aerospace parts have relatively stringent design requirements compared with parts in other applications, primarily due to operating environments having extremely high loads and temperatures in addition to a relatively high amount of parts in a relatively small volume. For example, aerospace parts must be as lightweight as possible to meet performance measures, subjected to a large range of operating temperatures, fluid exposure, positive and negative pressure cycling, and prolonged fatigue loads.

In addition, aerospace parts such as environmental control system (ECS) ducts consist of complex shapes bending and shaping around other parts and aircraft systems inside a tightly spaced aircraft. Moreover, aerospace structures must be capable of withstanding impact loads from maintenance, handling, and in the case of military aerospace structures, from threats such as armor piercing incendiaries or high explosive incendiaries. Accordingly, aerospace parts must be designed to accommodate a variety of operating environments and thus have design requirements that are beyond those of non-aerospace parts.

Due to the inherent nature of the process, AM responds to critical customer needs such as manufacturing flexibility, which is achieved through AM's ability to respond to changing demand for parts by building parts quickly and to change product design without taking a tooling time penalty. Specifically, the aircraft spares parts aspect of the aerospace company benefits from this quick response ability the most. In addition, manufacturing risk reduction in terms of schedule is seen as a major impact of AM. This is facilitated by shorter lead times associated with error correction and adjustments compared to traditional manufacturing of injection mold tooling and composite manufacturing. Part integration, or the ability to combine several parts conventionally manufactured into a single piece, offers tremendous opportunities for aerospace through part count reduction. By reducing the number of components in assemblies, aircraft weight and assembly labor throughout the supply chain may be reduced.

In addition to part count reduction, AM also offers a unique logistical advantage over conventional technologies. With AM close to the point of use the costs of warehousing and delivery is eliminated. The problem of expensive and difficult delivery to remote locations disappears. The US Military is in the process of evaluating the opportunities for the distributed production of spare parts near the point of combat (Walter et al., 2004).

1.3.1. The Deployment of AM in an Aerospace Supply-Chain. Deploying such a promising manufacturing technology into a global supply chain effectively, while concurrently managing technological and economic risk associated with AM is a challenge. There are both technical and economic challenges facing the technology while a potential savings incurred through its use concurrently exists. The research provided offers a methodology that roadmaps challenges and benefits of AM in terms of cost, manufacturing flexibility, lead-time savings, and targeted performance enhancements through the application of industry proven engineering management tools.

If a large demand exists for the technology, or customer pull is established, the organization must also identify how quickly their suppliers can invest and ramp up production while, at the same time, maintain appropriate quality standards associated with the end products produced from the proposed technology. If the technology is simply emerging, as in the case of AM, suppliers must either be trained and/or persuaded to take the risk of capital procurement of the technology.

While manufacturing maturity continues to proceed, of equal importance is the ability to develop a proposed supply chain for the emerging technology at hand. This supplier development action is taken by the supplier management arm of the aerospace enterprise. Supplier chain managers offer a unique position for emerging technology development. Positioned to be a unique component in emerging technology development, supply chain managers have the ability to identify and use quality tools and values. Tools commonly used by supply chain managers include benchmarking, complaint resolution, design for the environment, ERP, supplier development, focus groups and supply chain management (Foster and Ogden 2008). Each tool mastered by a technically proficient supply chain manager provides assistance for developing emerging technologies. Traditional engineering functions may not have extensive training in the business development arm of supply chain development. In addition, engineers may not be exposed to many of the tools that supply chain managers use on a daily basis for technology evaluation. Therefore, it is generally agreed upon, within aerospace, that a concurrent engineering approach must be taken for emerging technology development to include design engineers, system engineers, and supply chain managers.

Generally, a supplier trying to obtain aerospace production business does not start out directly building flight-worthy hardware for a production platform. Aerospace OEM companies have a choice to either invest in suppliers who have taken the initiative to adopt the emerging technology and teach them aerospace quality standards, or, invest in existing aerospace suppliers with existing aerospace quality standards in place and teach them the new technology. Maturing manufacturing technology is a lengthy and expensive process that requires a proper identification of a risk path for the technology to mature to the capability of producing flight-worthy hardware. A method for identifying risk relative to manufacturing maturity is required to gain a level of executive understanding for technology evaluation; this method is then used to assess future funding and resource allocation to each manufacturing technology being developed in the enterprise.

Once a supply chain is deployed, the chain must maintain an appropriate level of quality improvement within the company offering AM. The critical success factors for the maintenance of quality includes management commitment, customer focus, quality culture, supplier relationships, involvement and empowerment, training and education, teaming, communication, vision and strategy, and measurement tools and rewards (Bullington et al., 2002). Without elements of these critical success factors established within the AM supply chain, developing or training a supplier to accept AM may prove challenging.

1.3.2. Part Candidate Screening. Fundamental elements of different AM manufacturing processes must be taken into account when selecting the appropriate AM technology for the part application. "It should be recognized that AM is not a panacea and the correct identification of appropriate parts that can/could be manufactured is essential. There will be parts that are suitable for AM, parts that are competitive with conventional techniques and some parts that can only be manufactured additively – it is these last two categories that should be pursued, but a robust methodology for identifying these applications should be investigated." (Bourell et al., 2009)

For SLS, the lack of tooling required, the additive layered build approach, and the self-supporting nature of the powder build cake offer opportunities for part candidate geometry. Figure 1.11 highlights the fundamental elements of the SLS process shown in circles. Due to each element, specific attributes of parts may be focused on for part candidate searches. These specific elements are shown as rectangles in Figure 1.11. Because of the fundamental elements of the SLS process, an optimum directly manufactured candidate part would be a part design that exhibits low production volume requirements, is in need of a quick response, exhibits high complexity and has the opportunity for part integration[10].

---

[10] Part Integration is defined as the practice of redesigning an assembly of parts into a single part.

Breaking down a manufacturing process, such as SLS, to a fundamental level of competitive elements shows an opportunity to qualitatively match candidate part geometries to what works best for the technology. See Figure 1.11 for an example of SLS element breakdown.

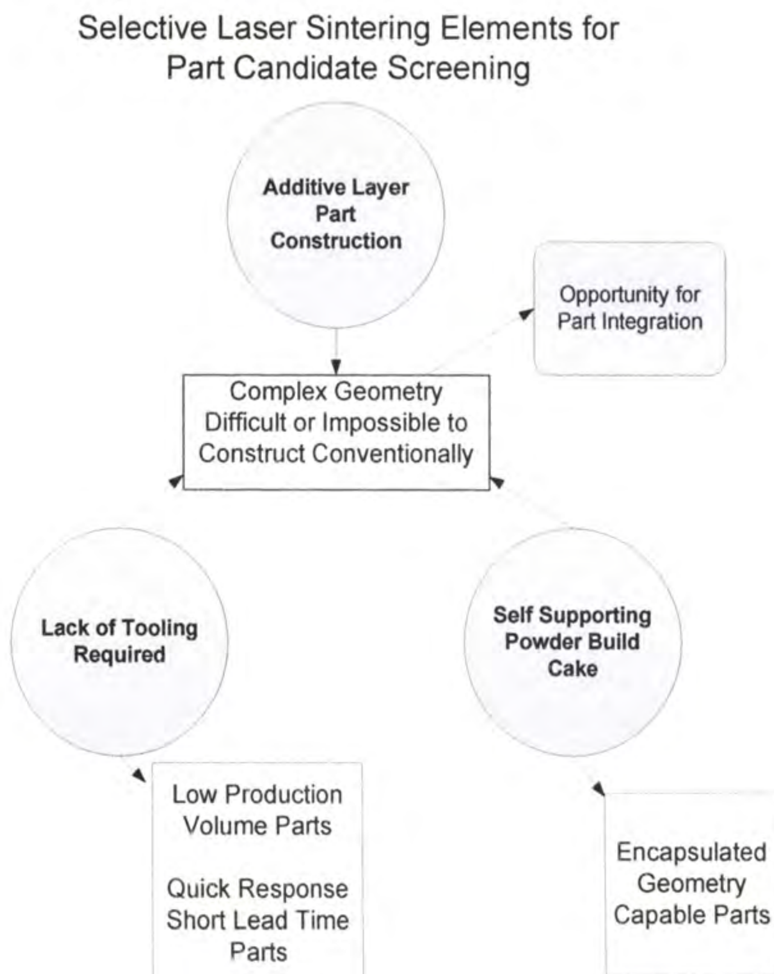

Figure 1.11. SLS Part Candidate Screening Elements

As a case example for SLS, consider a need for an example from the highly competitive formula racing industry. A racing company has a need to evaluate a fiberglass manifold duct that is difficult to tool for production and time consuming to install. The required production volume is two ducts needed on an annual basis. However, if the manifold duct fails, a replacement is needed within days to replace on a car en route to another race. Due to these requirements, SLS is selected as the manufacturing method due to its fundamental elements of additive layer part construction, lack of tooling, and self supporting powder build cake. Figure 1.12 illustrates the case example part.

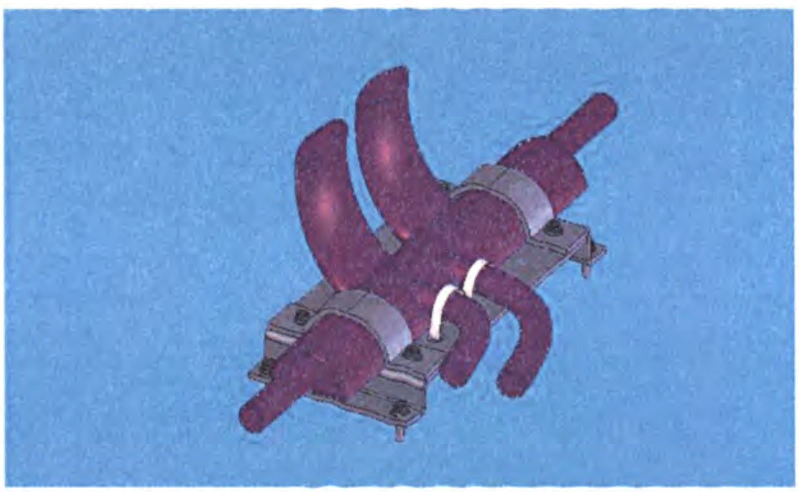

Figure 1.12. Case Example Existing Manifold Subsystem

When evaluating the manifold duct for SLS, the design engineer selects SLS because it affords a high level of design complexity. Therefore, the design engineer analyzes the entire manifold duct subassembly for design integration opportunity and proposes a single part design built using SLS. By eliminating brackets, screws, plastic retaining clips and mounting brackets, the design engineer is allowed to reduce the weight of the entire subassembly and design the manifold duct for ease of installation and optimized performance function as shown in Figure 1.13.

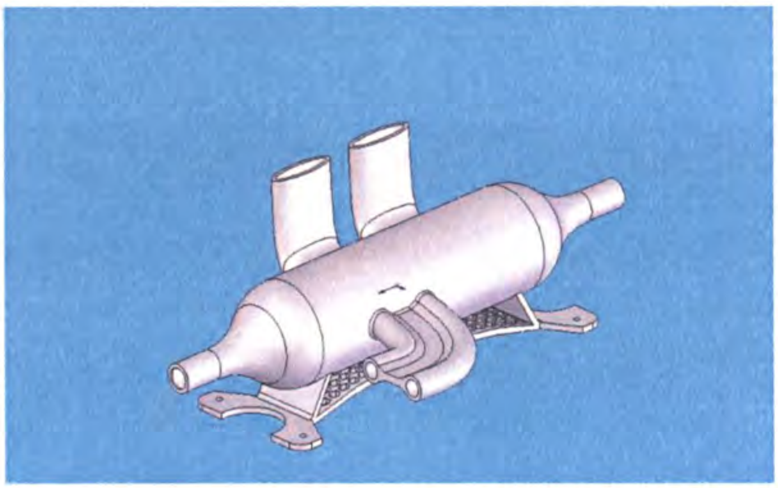

Figure 1.13. Redesigned SLS Integrated Assembly

Fundamental elements surrounding FDM are inherently different than SLS. Although both technologies may construct highly complex geometry, SLS's strength lies in the ability to make geometry largely encapsulated. FDM's strength is aligned with tooling, fixtures, and parts with higher temperature need requirements and Rapid Tooling (RT)[11]. RT techniques are categorized into direct and indirect tooling based on whether the AM technology is used to fabricate a mold or a pattern for direct part fabrication. Often used to AM net-shape patterns such as injection molding and investment casting,

[11] Rapid Tooling – Tooling driven from an additive process. An indirect approach to part fabrication, rapid tooling accelerates the tooling process by quickly producing geometry capable of producing other end-use non AM parts (Jacobs, 1996).

the practice of Rapid Tooling reduces tooling lead time from weeks to days (Sambu et al., 2004). Levy and Schindel (2002) also state that the impact of RT technologies relative to complex geometry is very positive.

Due to FDM's ability to accommodate several materials that operate in many manufacturing thermal conditions, provide a relatively high amount of accuracy and relative quick turnaround of parts, FDM is generally best suited for RT and aerospace fixture applications. Figure 1.14 highlights the fundamental elements of FDM.

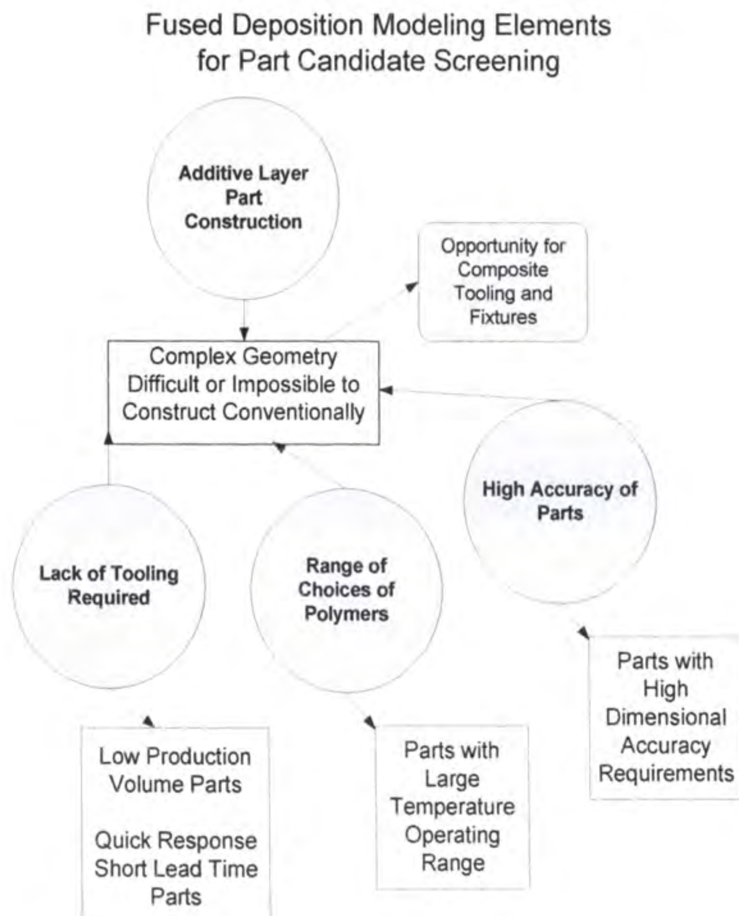

Figure 1.14. FDM Part Candidate Screening Elements

Another case example involves a need for an aerospace manufacturer to construct a tooling fixture for testing a composite part in elevated temperature regimes. The fixture must be fabricated quickly as a test schedule has been compressed to meet tight deadlines. The fixture must be capable of withstanding a 93° Centigrade sustained operating temperature and offer accuracy comparable to basic fixture tooling. The fixture geometry is shown in Figure 1.15.

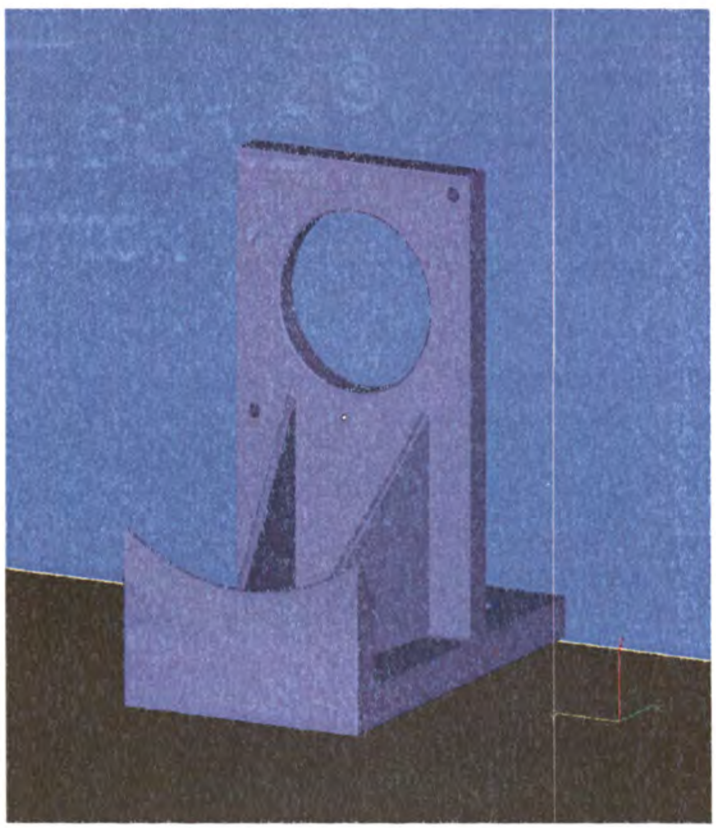

Figure 1.15. FDM Candidate Fixture Part

FDM was chosen due to the ability to build parts with high complexity quickly. A higher temperature capable material, polyphenelsulfone (PPSF), was chosen to accommodate the temperature requirements. In addition, due to the geometry flexibility, design engineers engraved text work instructions and quality inspection requirements directly into the CAD model to aid test technicians with integrating the part in the test.

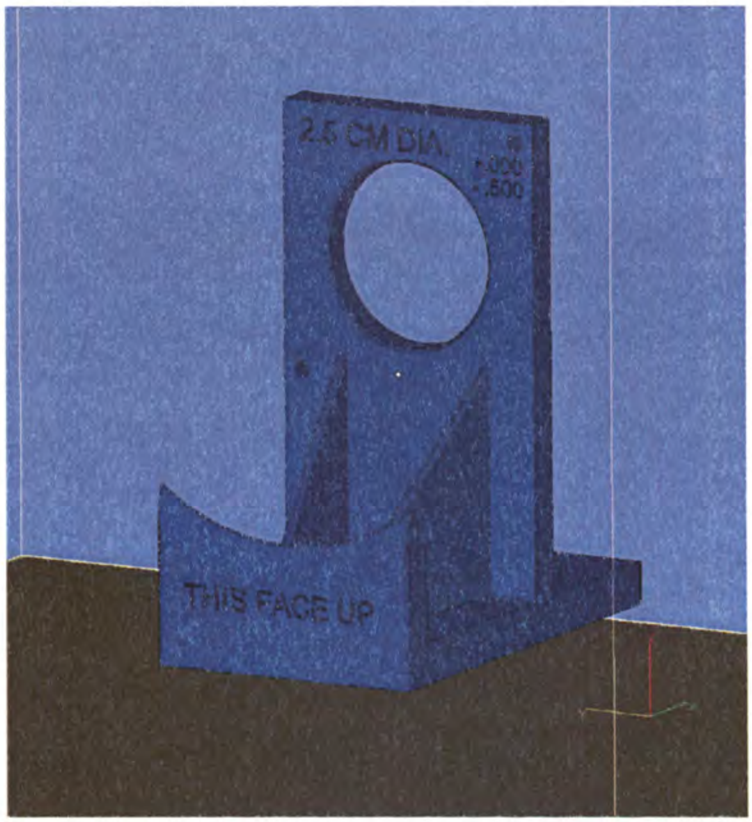

Figure 1.16. FDM Candidate Part Design with Text

1.4. TECHNICAL HURDLES OF ADDITIVE MANUFACTURING

A number of technical barriers exist for AM to become known as mainstream production. In 2009, a technical workshop was held in Alexandria, VA by Dave Bourell, Ming Leu, and David Rosen. Funding was provided by the National Science Foundation (NSF) and the Office of Naval Research (ONR). The intention of the meeting was to develop and articulate a roadmap for research in the area of AM for the next 10-12 years. Several experts from both academia and industry noted several technical barriers associated with AM technology, which grouped around different themes such as design, process modeling and control, materials, process, machines, education, and outreach recommendations (Bourell et al., 2009).

1.4.1. Design. The CAD systems available currently act as a constraint for AM technology. In the current state, .stl files are generated from commercially available parametrically controlled digital definition software. The STL format approximates the CAD digital definition with triangles. Each triangle consists of three vertices and a normal vector describing its orientation to the global coordinate system (Choi and Samavedam, 2002). The difficulty of the STL format lies in the inflexibility to adapt to changing designs. This inflexibility is especially true when emulating very complex geometries and several materials used on the same geometry. A new file format needs to be developed to take advantage of building gradient materials and incredibly complex algorithm driven geometry.

Another design related hurdle to overcome for AM involves product-process design improvements for multifunctional design. Currently, in order to generate a multifunctional design as pictured in Figure 1.13, a designer must modify an existing assembly of files in order to integrate the digital geometry into a singular file. Improving CAD software to generate highly complex shapes based on multi-functional designs is critical to the evolution of AM.

1.4.2. Process Modeling and Control. A large need exists for performance requirements associated with AM to become repeatable. Both process variability and sensitivity to process variation must be minimized to add manufacturing credibility to AM. According to two-step optimization, the process variation must be minimized first, then the system performance be placed on the customer focused target (Fowlkes and

Creveling, 1995). In order to achieve a high confidence of system performance, closed-loop control systems that monitor and offer feedback to the operator must be integrated within the AM system design. For aerospace production, quality systems developed at the supplier level must correlate with the system controls of the AM process.

1.4.3. AM Materials, Processes and Machines. Machine throughput must be improved to accommodate the AM technology. As AM technology works in a batched production system, the entire AM process needs to be modified to integrate into a leaner, more agile production system. This displacement of production theory may be realized by moving away from the batched process to favor more of a Just–In–Time (JIT) palletized production format. By offering a more responsive production format, inventory levels would be reduced and the process would become more aligned to customer demand instead of supplier push.

Another thought expressed in the Bourell et al., (2009) roadmap included the need for AM to differentiate from conventional manufacturing processes by exploiting the unique characteristics associated with AM. These characteristics include taking advantage of the anisotropic nature associated with AM, fabricating functionally gradient materials, and embedding components during fabrication processes.

One of the most significant hurdles involves the lack of understanding associated with material compatibility screening. It is known that the materials and properties of AM often fail to match their molded or machined counterparts. Often, this general assumption is known to be true for AM, especially in the Z-axis orientation but it is not known as to why materials are not compatible with the AM process. However, if material properties for AM parts were known in detail, then functional parts could be designed to be manufactured by AM processes. The basic assumption is that the current limitation in material properties lies in the lack of information regarding AM materials, not necessarily that they are functionally inadequate (Hopkinson and Dickens, 2003). Other than the basic amorphous versus semi crystalline processing requirements associated with FDM and SLS, it is difficult to understand why some materials work well with AM and others do not. According to Bourell et al. (2009), other common barriers include:

- There are significant geometric and property variations between identical parts built on different machines. This effect is known as 'intra-machine' repeatability. In addition, mechanical property variation exists among several machines, calling 'inter-machine' repeatability into question

- Many processes require highly skilled operators or need careful periodic tuning to operate well, thus, limiting the amount of workforce available for production

- Machines lack long-term hardware reliability with respect to production systems

- Most machine vendors have a closed architecture, which restricts researchers from optimizing parameters to processing conditions

- Even the lowest-cost platforms cost more than $10,000, which limits adoption by educational institutions and general consumers; and

- Although many processes are inherently capable of multi-material deposition, few have hardware and software implementations, which enable simple, effective use of these capabilities.

In addition, a large amount of research funding is needed to establish material interaction process models that encompass AM processes. Similar to phase diagrams in the metallurgical field, materials processed within the AM process must be mapped to illustrate finite melt points inherent that highlight the interaction of AM materials and processes.

1.5. ECONOMIC CHALLENGES OF ADDITIVE MANUFACTURING

In addition to the technical challenges, economic challenges confront Additive Manufacturing. As both process and supplier, structure varies among AM technologies, a universal costing model is difficult to establish. In addition, the supply chain for AM is immature, with many supplier themselves not truly understanding their own costs of the process. Therefore, each process must be detailed to understand the process flow and assign costs appropriately.

Fundamentally, costs are broken down into specific process steps and assigned into direct, indirect, reoccurring and non-reoccurring costs. The field of activity based accounting is aligned to assigning costs to each activity performed (Arieh and Qian, 2003). Since design engineers create the demand for production volume of AM technologies, one must view economic analysis from the perspective of a design engineer conducting a simple economic breakeven analysis between AM and conventional

manufacturing technologies. Therefore, an effective way to economically compare conventional manufacturing technologies with AM is to generate process flow diagrams for both conventional technologies and AM, then assign costs to each activity.
Once costs of an AM process are understood, an overall arching cost model for the process may be developed. The intent of the overall cost model is to provide design engineers evaluating the AM process knowledge on how costs are assigned. For example, if a design engineer learns that powder recycling affects the overall cost of a laser sintered part, then that design engineer may redesign the part to allow it to nest among other parts, thus, lowering its piece price.

Consider at the same time, a supplier manager receives vast quoting inconsistency from AM suppliers and needs to use a cost model map to understand where costs vary. To use cost model maps of manufacturing processes as a communication tool that aids design engineers in part design and supplier managers in cost risk reduction truly represents the core discipline of concurrent engineering. Using AM as an example, the derivation of costs from process flow diagram development, spreadsheet construction, and the resulting steps involved in developing the model is provided in § 6.0. The process decomposes activities associated with the technology into individual cost elements. These cost elements then roll-up to form direct and indirect costing. The idea is to build up a structure to activate a critical function of the technology. In the case of laser sintering, the critical function is processing one build. Figure 1.17 illustrates a costing model map for the laser sintering process that breaks down the direct and indirect costs to form a total cost. The total cost is then assigned as the total cost of the build and each build is then cost accounted.

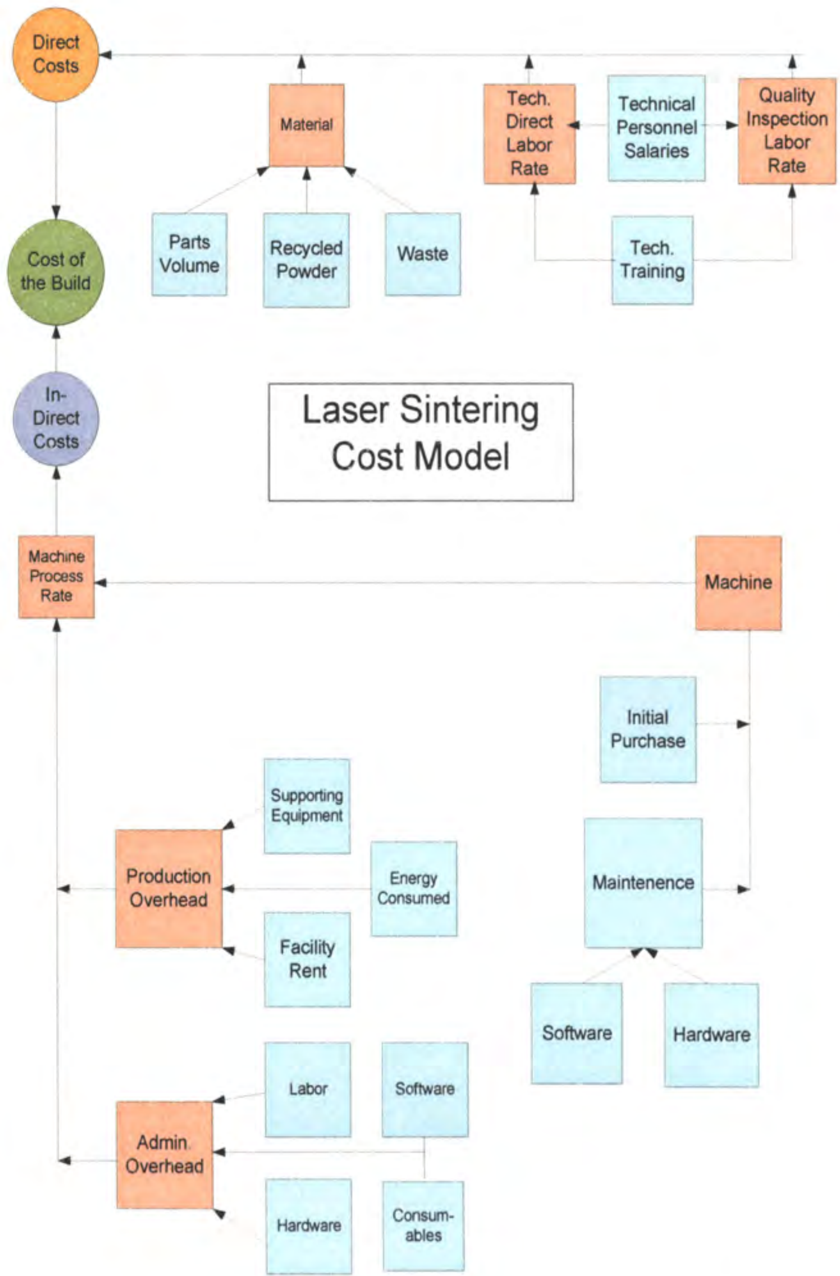

Figure 1.17. Laser Sintering Cost Model Map

1.5.1. Comparative Economic Analysis. In order to understand AM costing structure, a comparison must be made to conventional manufacturing technologies. Injection molding is often compared to AM technologies as an alternative manufacturing process. The commonality between the two technologies extends to materials. However, injection molding includes mold tool construction costs. This mold construction cost often requires large production volumes of parts in order to justify the initial tooling costs. Design engineers and supplier managers must understand the economic comparison of conventional manufacturing processes in order to pick the best manufacturing process for the candidate geometry. Using appropriate cost models, breakeven analysis may be conducted to illustrate the economic cross over point between manufacturing processes for piece price versus quantity demanded.

Although theories on how to appropriately compare technologies differ for economic evaluation, Hopkinson, et al. (2005), Hopkinson and Dickens (2003), and Ruffo (2005) all use a similar techniques of evaluating economic analysis comparisons of AM technologies and injection molding. The original Hopkinson and Dickens (2003) model uses a straight line to depict SLS piece price costs over quantities. Ruffo (2005) suggests a saw-toothed pattern to describe SLS. Figure 1.18 shows the comparison between the SLS costing theories.

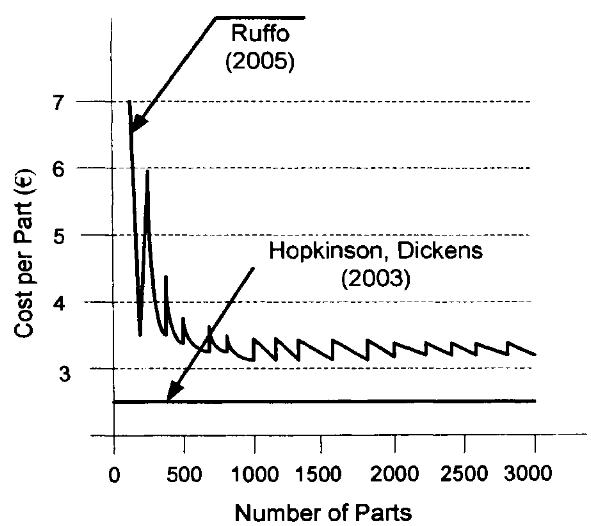

Figure 1.18. Comparison of Ruffo SLS Costs and Hopkinson Dickens Costs

Using a methodology developed by Poli (2005), an economic analysis is constructed to gauge injection molding tooling costs based on design complexity. A simple methodology for comparison exists by using geometry case studies. Injection molding piece price is driven from relative tooling costs and relative part costs. Injection mold costs are a function of part design complexity and scale. In addition, relative part costs are a function of material choice and quantity of parts being produced.

This research suggests that both the Ruffo (2005) and Hopkinson and Dickens (2003) models are appropriate ways of evaluating SLS costs. However, the appropriation of which model is accurate is based on the specific geometry being evaluated and the SLS machine being evaluated. Neither the Ruffo nor the Hopkinson and Dickens model considers different SLS machine sizes. For example, Figure 1.19 illustrates the difference between a small frame SLS machine a large frame SLS machine and injection molding.

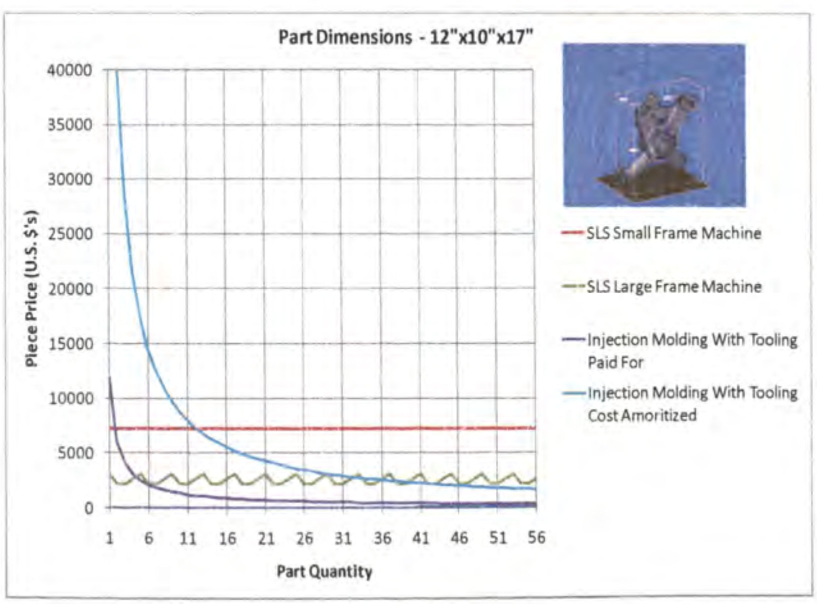

Figure 1.19. Economic Analysis of SLS versus Injection Molding

Two elements are compared to injection molding. One scenario captures a case where the injection mold tooling already exists and a second scenario shows tooling needing to be constructed. Because the size of the part being evaluated consumes the build volume of a small machine, only one part may be built in the small frame machine. Therefore, the economic model creates a straight line for the small machine which follows the Hopkinson and Dickens model. However, because approximately five parts fit inside of the large machine, a saw-toothed pattern is established for the large SLS machine which is similar to Ruffo's model. Therefore, both the saw-toothed pattern and the straight lined pattern may represent the geometry processed in the SLS machine and the scale of the SLS machine. Specifics regarding the cost model development are found in § 6.0.

1.5.2. Flexibility of Batched Production. According to Gunasekaran et al. (2002), to compete effectively in a global market, manufacturing industries need to maintain a high level of flexibility to attain agility and remain competitive. All AM processes use a batched production queuing system in which the amount of batching required depends on the individual technology and the production volume demanded. For example, SLS's cost reduction element stems from the ability to pack several parts into a single batch in all three global coordinate axes. Two items are needed to justify SLS batching, (1) a large supply of parts are needed to be produced, and (2) short lead times are necessary to justify batching the parts together. However, FDM has the freedom to pack parts into a build volume or build parts one at a time without penalizing throughput or cost performance. This is due to nature of the FDM process only costing what is consumed. In a supplier production realm, most CAD files are integrated into a single build volume for processing as depicted in Figure 1.20.

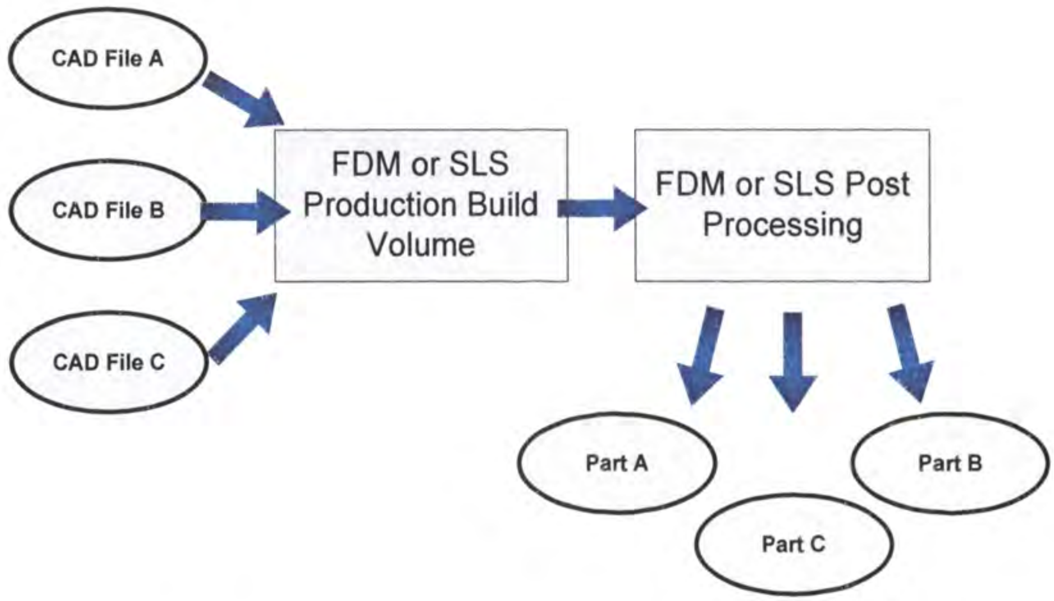

Figure 1.20. Illustration of Batched Processing for Additive Manufacturing

Information should be made transparent across the supply chain. This helps in developing an integrated network. OEMs should develop an integrated network with a minimal number of suppliers that promote flexibility, responsiveness, and minimum cost (Sinha et al., 2004). Flexibility is a well-researched topic for general manufacturing systems, but not with respect to AM.

According to Beamon (1999), flexibility, infrequently used in supply chain analysis, may analyze a system's ability to receive production volume and schedule fluctuations from suppliers, manufacturers, and customers. Throughout literature, it is generally understood that flexibility is defined as the ability to change or react with little penalty in time, effort, cost, or performance. Sethi and Sethi (1990), Slack (1991), Detoni and Tonchia (1998), Beamon (1999) and Zhang and Tseng (2009) cite range[12] and response[13] flexibility as two main dimensions to manufacturing flexibility.

De Treville et al. (2007) acknowledges that although much of the flexibility literature has tended to focus only on range, mobility and uniformity are of tremendous importance at the tactical level. Mobility is concerned with setup time reduction, as well as with scheduling and training of workers. Uniformity also is concerned with setups, as it is common for nonconforming product to be produced immediately after a setup. In addition, process documentation adds elements of uniformity.

Sethi and Sethi (1990) point out a method to measure ranges of volumes in which the organization can run profitably. The downfall with Sethi and Sethi's volume flexibility model is that the supply chain of interest needs sufficient historical production data on demand volumes. For a new emerging technology, such as AM, historical data regarding demand volume would most likely not be available. Therefore, effectively measuring the flexibility of the new manufacturing process being proposed for deployment may prove difficult.

In measuring AM performance relative to the dimensions of flexibility, range flexibility favors the AM approach. For example, measurement of flexibility adopted by Stockton and Bateman (1995) measures separate aspects of production range flexibility. Within the model, a flexible manufacturing system (FMS) rates against several aspects of

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[12] Range Flexibility is defined as the total envelope of capability or range of states which the manufacturing system is capable of achieving, i.e. short-term flexibility (Stockton, Bateman, 1995).

[13] Response Flexibility is the ease with which the operation can be changed, in terms of cost or schedule impact or both (Beamon, 1999).

range flexibility relative to probability of occurrences. Table 1.4 highlights several aspects of flexibility measurement with corresponding definitions as defined by Stockton and Bateman (1995).

Table 1.4. Range Flexibility Definition

Symbol	Flexibility Type	Definition
p[A]	Size Flexibility	The limitation of a part physically fitting within the FMS boundaries
p[B]	Shape Flexibility	The limitation of a part being processed within the FMS, due to its shape
p[C]	Materials Flexibility	The limitation of a part being processed within the FMS, due to its material processing capacity
p[D]	Machine Flexibility	The limitation of a part being processed within the FMS, due to the operations required
p[E]	Material Handling Flexibility	The limitation of a FMS to move components from one area to another via a material-handling route
p[F]	Process Flexibility	The limitation of a FMS to process a part due to its physical characteristics.
p[G]	Routing Flexibility	The limitation of a FMS achieving appropriate process routing
p[H]	Production Range Flexibility	The limitation of the FMS providing full production

Applying the flexibility definitions listed in Table 1.4 to AM, SLS and FDM may be evaluated with respect to several aspects of flexibility that are covered in more detail in § 3.1.2.

1.6. QUALIFYING MANUFACTURING PROCESSES

The qualification of any manufacturing technology for aerospace is an arduous task. Emerging technologies are particularly challenging for aerospace applications due to the unknown ability of the technologies to perform to specific performance requirements repeatedly. Currently, aerospace supply chains exist as a global entity; both geographic and cultural boundaries exist for manufactured components. Each component must mate to another component produced in, perhaps, a completely different hemisphere. In order to control vast differences in produced components, material and process specifications are concurrently generated to capture the process capability to reduce manufacturing variation due to inherent global supply chain challenges. Material and process specifications are closely interrelated. A material specification typically defines the material and its qualification tests. Many of the tests require specimens fabricated using the process specification. Once qualification is completed, requirements in the material specification are finalized. The material specification is used to procure the production material and maintain levels of quality attained at certification (FAA, 2003).

In order to evaluate manufacturing technology performance, Hon (2005) suggests evaluating performance based on the manufacturing elements of time, quality, cost, productivity, and process flexibility. From an aerospace OEM's perspective, developing an emerging technology is a large resource demand. However, by researching and developing the emerging technology in-house, an OEM can easily control how the supply chain is developed for the technology. If the technology were outsourced from an OEM to a partnership, resources are reclaimed, but control over the supply chain is reduced. A major balance in sourcing strategy occurs daily for large aerospace OEM's. Each technology's criticality to the OEM is evaluated on a case-by-case basis. Proprietary information agreements may be placed with outsourced suppliers to curtail commercialization outside the OEM, however, this strategy is generally avoided to completely eliminate the possibility of information leaks. Supplier partnerships must be put in place and looked upon as collaboration efforts for all parties involved in the supply chain development. Trust among all parties must be established to develop intercompany relations effectively. Figure 1.21 offers a notional concept of emerging technology development from the perspective of an aerospace OEM.

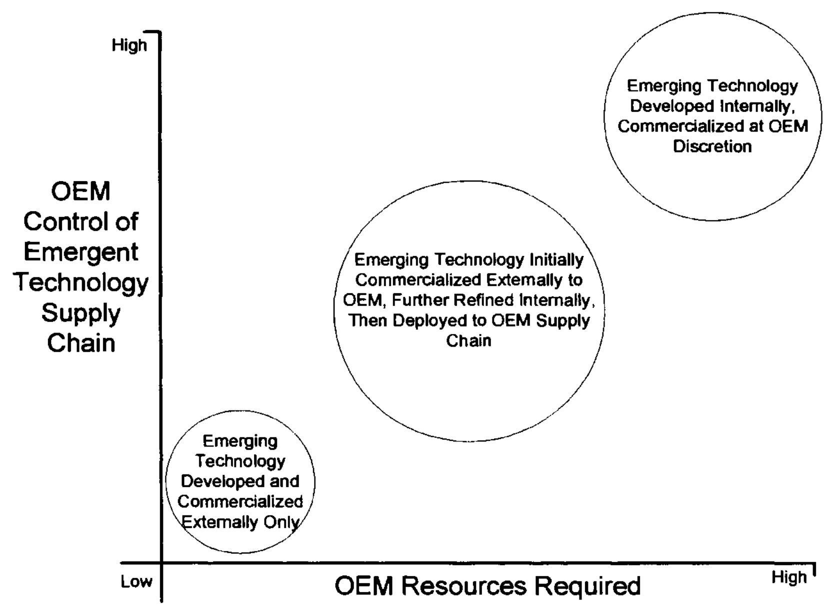

Figure 1.21. OEM Perspective of Emerging Technology Development

Collaboration can be beneficial and even a survival factor for industrial companies. But it can also be risky; therefore, it is important to assess the readiness of potential partners that will become the emergent technology's suppliers. When partnerships are critical to the success of technology development, Rosas and Camarinha-Matos (2009) describe a metric to consider for the supply chain known as collaboration readiness. According to Rosas and Camarinha-Matos (2009), although most research in the past was focused on 'hard' factors such as competency matching or technological preparedness, the probability of success of a collaborative process depends on other factors of a 'soft' nature such as an organization's character, willingness to collaborate, or the affectivity/empathy relationships. However, understanding how an emerging technology reacts to each collaborative performance metric before a technology is implemented into production is difficult.

1.6.1. Technology Readiness Levels. Expected technology performance of an emerging technology can be forecasted by mapping out the maturation levels associated with the emerging technology level. The act of mapping a technology's maturation level is known as technology assessment. A tool that is used to gauge technology maturation relative to a universal set of technology maturation definitions is known as technology readiness level[14] (TRL) for the emerging technology. First developed by the United States Department of Defense (DoD), the TRL system ranks a candidate emerging technology's ability to perform given its level of maturity. Sourced from the DoD's Manufacturing Readiness Level Deskbook (2009), Technology Readiness Levels are defined as:

- **TRL 1 -** Basic principles observed and reported. An example might include paper studies of a technology's basic properties.
- **TRL 2 -** Technology concept and/or application formulated. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.

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[14] Technology Readiness Level – defined as measure used by United States government agencies and many industries to assess the maturity of evolving technologies' materials, components, devices, processes prior to incorporating that technology into a system or subsystem.

- **TRL 3 -** Analytical characteristic proof-of-concept. Active research and development is initiated. Examples include components that are not yet integrated or representative.
- **TRL 4 -** Component/subsystem validation in laboratory environment. Basic technological components are integrated to establish that the pieces will work together. Examples include integration of pieced hardware in a laboratory.
- **TRL 5 -** System/subsystem/component validation in environment. Pieced hardware becomes more robust and repeatable. Examples include high fidelity laboratory integration of components.
- **TRL 6 -** System/subsystem model or prototyping demonstration in relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
- **TRL 7 -** System prototyping demonstration in an operational environment. Prototype near or at planned operational system. Examples include testing the prototype in a flight test environment.
- **TRL 8 -** Actual system completed and qualified through testing. Technology has been proven to work in its final form and under expected conditions. Examples include developmental test and evaluation of the system in its operating environment to determine if it meets design specifications.

- **TRL 9 -** Actual system proven through successful missions. Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

It is important to note that the TRL takes into account a singular process, material, subsystem, or component. In the case of AM, each technology such as SLS or FDM may be considered at different levels. In addition, the customer perspective of the evaluator may also influence a TRL score for an individual technology. For example, a prototyping company that primarily sells SLS technology as prototyping design pieces may rate SLS at a higher value than an aerospace OEM that is relying on the technology to produce performance specific flight hardware.

A major key to transitioning technology, whether developed by industry or government, is the availability of sufficient funds to mature technology through each level of the TRL system. Ideas generated in the laboratory many times do not translate easily into workable manufacturing systems. A major downfall of using the TRL evaluation process is often the amount of risk and funding to advance the technology is overlooked or underestimated.

1.6.2. Manufacturing Readiness Levels. Though useful, the TRL also falls short of identifying the feasibility to deploy the technology as a sustainable manufacturing base. For example, TRL will not address the cost of the candidate technology, the feasibility of a production environment or availability of components or materials. An evaluation technique known as the Manufacturing Readiness Level (MRL) addresses the challenge of gauging a manufacturing supply chain's robustness. MRL definitions were developed by a joint DoD/industry working group under the sponsorship of the Joint Defense Manufacturing Technology Panel (JDMTP). The goal of the panel was to develop a metric scale that would serve the same purpose for manufacturing readiness as Technology Readiness Levels serve for technology readiness. TRL serves to provide a common metric and vocabulary for assessing and discussing manufacturing maturity, risk and readiness. Table 1.5 offers an example of a sample evaluation of FDM from an aerospace OEM's perspective. The green cells indicate that the gate for each thread with respect to the MRL level criteria has been satisfied. The yellow cells indicate the current level in process and the red cells indicate what has not been completed to-date.

Table 1.5. Sample MRL Matrix Assessment of FDM

	Fused Deposition Modeling (FDM) Manufacturing Readiness Level Assessment									
Threads	1	2	3	4	5	6	7	8	9	10
1. Technology (From TRL Assessment)	Green	Green	Green	Green	Green	Green	Green	Yellow	Red	
2. System Design for Modularity	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red
3. Materials	Green	Green	Green	Green	Green	Green	Yellow	Red	Red	Red
4. Cost and Funding	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	Red
5. Process Capability and Control	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	Red
6. Quality Management	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	Red
7. Operator Training	Green	Green	Green	Green	Green	Yellow	Red	Red	Red	Red
8. Facilities Installation	Green	Green	Green	Green	Green	Green	Yellow	Red	Red	Red
9. Manufacturing Management (ERP System)	Green	Green	Green	Green	Green	Green	Green	Yellow	Red	Red

Similar to TRL, each column's criteria definition acts as gates for each thread. The Joint Defense Manufacturing Technology Panel's (2009) definition for each MRL column is as follows:

- **MRL 1 -** Basic manufacturing implications identified. Begin basic research in the form of studies to identify producibility and material solutions.

- **MRL 2 –** Manufacturing concepts identified. Begins by demonstrating the feasibility of producing a prototype product/component with very little support/data available.
- **MRL 3 –** Manufacturing proof of concept developed. Materials have been characterized for manufacturability and availability but further evaluation and demonstration is required.
- **MRL 4 –** Capability to produce the technology in a laboratory environment. At this point, required investments, such as manufacturing technology development have been identified; processes to ensure manufacturability, producibility and quality metrics are in place; and manufacturing risks have been identified for prototype build. Manufacturing cost drivers have also been identified.
- **MRL 5 –** Capability to produce prototype components in a production relevant environment. Manufacturing technology development efforts have been initiated or are ongoing. A cost model has been constructed which is based upon a detailed end-to-end value stream map.
- **MRL 6 -** Capability to produce a prototype system or subsystem in a production relevant environment. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes.
- **MRL 7 -** Capability to produce systems, subsystems, or components in a production representative environment. Supply chain and supplier quality

assurance (QA) elements have been assessed and long lead procurement plans are in place.

- **MRL 8 -** Pilot production line capability demonstrated. Ready to begin low rate production. All materials are available to meet the planned low rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment.
- **MRL 9 -** Low rate production demonstrated. Capability in place to begin full rate production. Manufacturing processes and procedures are established and controlled in a low rate production environment to three-sigma.
- **MRL 10 -** Full rate production demonstrated and lean production practices in place. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level.

1.6.3. Developing the Process and Material Specifications. Within aerospace production, parts receive flight certification when design engineers, structural engineers, systems engineers, electrical engineers, and manufacturing engineers are satisfied that performance requirements have been reached for a material and matching process. These individuals may be considered the process customers. If performance requirements are not known or not developed for the emerging technology, Griffin and Hauser (1993) provide examples of how to relate customer voices to performance requirements through quality function deployment.

For AM, examples of performance requirements include, but are not limited to, structural integrity, cost benefit analysis, weight analysis, electrical conductivity, lead time performance, etc. However, each zone on an aircraft where parts reside may exhibit unique performance requirements specific to that particular zone. Therefore, design engineers are grouped to individual subsystems. For example, it is common to have a design engineer design parts for air control ducting and another design engineer who designs interior paneling. It is the job of the systems engineer to ensure that performance requirements that are met in one zone of the aircraft translate to an adjacent zone without cross-functional conflict.

Specifications for individual geometry are written to environmentally satisfy the requirements of the zone where the part resides. This satisfaction may come from a space packaging constraint, pressure constraint, operating temperature constraint, point loading constraint, handling, or an electrical constraint. In order for parts produced from of an emerging technology, such as AM, to receive flight certification, data are recorded to provide design engineers guidance on whether the process offers the performance to meet the design needs. Once the emerging technology meets minimum mechanical property requirements repeatedly, a large amount of funding is set aside to pay for design allowable generation. Defined in the Department of Defense military (MIL-17) handbook, design allowables[15] offer a sense of security for an aerospace program and

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[15] Statistically determined materials property values derived from test data. They are limits of stress, strain, or stiffness that are allowed for a specific material, configuration, application, and environmental condition.

come in the form of 'A' basis[16] and 'B' basis[17] (Department of Defense, 2002). The specific values for the technology are set by the design engineering community evaluating the process and material.

Once basis allowables are produced, specifications are written to control the process through documentation. Hastings (2007), a supplier manager within Boeing, describes a manufacturing and quality plan that details elements of process and material specifications to transition a RP company to an AM based company. Table 1.6 illustrates the two types of specifications with descriptions of items that each may include.

Table 1.6. Example Items Found in Process and Material Specifications.

Examples of Items Found in a Process Specification	**Examples of Items Found in a Material Specification**
Specific Machine Settings	Environmental Exposure Regulations
Statistical Process Control Specification Limits	List of Acceptable Materials
Tensile Bar Layout Parameters	Material Receiving
Scrap Procedure	Material Inspection
Proprietary Information Protection	Pre-Build Material
Records Control and Retention	Material Control
Nonconformance Disposition	Contaminant Identification
Corrective Action	Material Disposal and/or Recycling
Scrap Procedure	
Production Flow Chart	
Production Machine Certification	
Production Machine Monitoring and Calibration	
Production Machine Maintenance and Repair	
Part Post Processing	
Mechanical testing	
Dimensional Inspection of Parts	
Coatings	
Surface Finishing	
Parts Identification	
Parts Packaging	

[16] A-Basis: At least 99% of the population of material values is expected to equal or exceed this tolerance bound with 95% confidence.

[17] B-Basis: At least 90% of the population of material values is expected to equal or exceed this tolerance bound with 95% confidence (redundant load path with load redistribution)

2. LITERATURE REVIEW

2.1. LITERATURE REVIEW INTRODUCTION

A large amount of literature was reviewed to cover the breadth of research. First, technology evaluation methods were reviewed to gauge the amount of published research on this topic. Specifically, the fields of manufacturing technology maturation and manufacturing flexibility were researched.

Second, the field of AM was investigated to include SLS, FDM, RT, and cost modeling conducted for all AM fields. Third, the field of robust design was evaluated with regard to application of parameter design for SLS and FDM. Finally, a literature review of supply chain strategies was conducted to include; six sigma implementation, quality function deployment, emerging technology integration and agile manufacturing topics.

2.1.1. Technology Evaluation Research Justification. In order to capture the implementation of an emerging technology within a supply chain, a thorough literature review was conducted to evaluate what has been published to date in the field. Additive Manufacturing is considered an emerging technology in the field of aerospace. When deploying complex manufacturing technologies, such as AM, within a complex global supply chain, a systematic approach is needed to evaluate the technology. Specifically, an approach is needed that would rank individual technologies within an emerging technology portfolio. Technology and Manufacturing Readiness Levels are used throughout advanced system industries as common tools for evaluating technologies in development. Known as pioneers in the field of technology and manufacturing evaluation, the work conducted by the Department of Defense and the National Aeronautics and Space Administration (NASA) was researched.

Since the industrial revolution, time, cost, and performance have been common metrics used to evaluate manufacturing performance. According to Zhang and Tseng (2009), "Today, more and more companies are providing a large variety of products to meet diversified customer needs. With increasing product variety and dynamic demand fluctuation, it can be observed that manufacturing is moving towards a configure-to-order and make-to-order environment with high product mix and low order volume." As commercial aircraft parts are no longer sourced from a common supplier, but rather a global network, manufacturing flexibility is fast becoming a fourth metric to be used in rating technology systems.

AM is one of the most advantageous technologies with respect to manufacturing flexibility as it allows for complex shaped geometries, incapable of being built using conventional technologies, to be produced rapidly without tooling iterations. Therefore, the field of research surrounding manufacturing flexibility was studied to gauge AM's flexibility rating relative to conventional manufacturing technologies.

2.1.2. Additive Manufacturing Research Justification. AM is a dynamic field and much has been published regarding rapid prototyping, rapid manufacturing and AM. As the intent of this research includes the deployment of AM technology into an aerospace supply chain, naturally, the field of AM was scoured to find the latest information regarding FDM and SLS.

2.1.3. Robust Design Research Justification. Often overlooked as a key component in technology development for a supply chain, parameter optimization focuses on robustness of the process. When deploying an emerging technology, the optimization of the system robustness must be addressed to most effectively limit the variation that exists with the process. For example, a major goal of supply chain development is to minimize the amount of performance variation existing within the process; if two machines were deployed at different suppliers, one supplier in Germany and another in Japan, it is expected that each machine would perform the same. When the emerging technology exhibits process variation, robust parameter optimization techniques must be used to mature the technology through the technology readiness level assessment tollgates. Therefore, a thorough literature review of robust design should be conducted to determine what has been researched to-date in optimization of AM technologies.

2.1.4. Supply Chain Research Justification. In terms of deploying an emerging technology into a supply chain, research was conducted to discover the most current literature existing for six sigma deployment, quality function deployment, emerging technology integration, agile manufacturing, and aerospace specific supply chains. Using a blend of elements from each field offers a unique and significant literature review when applied to AM supply chain deployment. Cheng (2008) offers a comprehensive review of Total Quality Management (TQM) and Six Sigma and applies many concepts of Six Sigma applied through TQM. Concepts that apply toward emerging technology development include, but are not limited to, C_p and C_{pk} derivation, statistical process control, variation analysis, reliability calculations, variation analysis, linear regression analysis and designed experiments.

2.2. TECHNOLOGY EVALUATION REVIEW

The development of emerging technology and subsequent deployment into an existing supply chain offers significant challenges for companies looking to gain a competitive edge in the marketplace. Tools exist that describe an approach to technology development and evaluation.

2.2.1. Manufacturing Technology Maturation Review. The Department of Defense and NASA offer the most comprehensive toolset for evaluating technology maturation and supply chain maturation. A dataset published by the Joint Defense Manufacturing Technology Panel (JDMTP) published a deskbook manual for technology integration in 2009. This manual covers appropriate MRL, TRL levels and their respective definitions. In addition, the deskbook covers the application of technology matrices.

Although rare, journal articles have been found on the subject of technology readiness. Stratton and Warburton (2003) claim that development of a supply chain centered on a manufacturing technology requires a holistic perspective of the enterprise. Gindy et al., (2006) describe levels of maturity that draws parallels to a TRL matrix by providing Emerging, Pacing, Key and Base categories. Like the TRL, Gindy et al., claim a technology starts in the 'Emerging' category in the form of a research state. Once graduated to a 'Pacing' category, other competing companies are investigating the same technology. Next, moving to the 'Key' category, technologies are now well embodied within product and production services. Finally, the 'Base' category is defined as a commodity technology with highly competitive environments. Each defined category is as a corollary to TRL level charting.

Muchiri and Pentelon (2008) provide performance measurement criteria for individual technologies by measuring overall equipment effectiveness (OEE). Specifically, they described one such performance-measurement tool that measures different types of production losses and indicates areas of process improvement. In addition, a methodology for grouping and measuring production loss for overall production effectiveness is proposed. This approach may be more aligned with application to an established AM supply chain, not a supply chain in its infancy.

Dangayach and Deshmukh (2005) surveyed one hundred twenty two companies spanning the automobile, electronics, machinery and process sectors of Indian small and medium sized enterprises. The survey aimed to report propensities of the businesses to accept advanced manufacturing technologies (AMT) and rankings of resulting metrics. AMT is a term that covers a broad spectrum of computer-controlled automated process technologies. Per the AMT definition, AM would then be considered an AMT. The survey asked to rank quality, delivery, flexibility and cost. The survey reported that of the one hundred twenty two small and medium enterprises, the majority focused the most on production quality and least on flexibility. Based on this analysis, when deploying an emerging technology, such as AM into an emerging economy supply chain, such as India, quality would most likely remain the number one priority for the evaluation of the technology. Acknowledging that manufacturing metrics may change based on the country manufacturing the product recognizes the differing perspectives in understanding how AM might deploy globally within an aerospace supply chain.

Schroder and Shohal (1999) surveyed Australian and New Zealand manufacturing to determine the differences between firms in terms of AMT investment, planning, and implementation based on firm size and principle ownership. A few of their main findings included:

- Larger companies make larger AMT investments than smaller ones.
- Larger companies take longer to decide to invest and implement their AMT investment than smaller ones.
- Top and senior management, despite ownership and company size, spearhead much of the drive to invest in AMTs.

On a similar front, Chen and Small (1994) concluded that AMT deployment is far more limited to managerial concerns and less on the technology robustness. Chen and Small (1994) conclude that funding AMT remains a high-gain, but potentially high-risk adventure. Many manufacturing companies that have invested in these new technologies were not able to reap all the expected benefits. Since the technical abilities of the AMTs are relatively well-proven, there is a growing belief that managerial issues, from planning to implementation, present the major barrier to employing these technologies effectively.

When a company decides when to deploy an emerging technology, such as AM into a supply chain, decisions are made foremost with respect to planning, justification and implementation. After a thorough literature review of deploying AMTs, Small and Yasin (1997) acknowledge the following eight phases of deployment. These phases offer a practical sense of technology deployment from industry best practices. Below, application for AM is provided for each phases:

- Recognition of an increasingly complex and competitive global and national business environment. AM technology must be able to accommodate this increasingly complex global environment by accommodating manufacturing flexibility.

- Need for strategic responses (which includes the adoption of advanced manufacturing technology) to meet these competitive demands, along with careful planning for the adoption of these technologies. AM technology inherently offers a competitive edge by allowing parts to be manufactured without tooling. Careful planning must be used when adopting AM technology.
- The need to establish organizational goals and performance measures during the strategy formulation and planning phases. When first deploying AM technology globally, common performance measures attained by AM must be setup so that a common benchmark may be used for comparing AM globally.
- The need for structural (process) changes to meet organizational goals. Questions must be asked to determine the amount of supplier commitment to AM within the supply chain. How many structural changes must be met to adopt AM technology and how much are the organizational goals tied to AM technology are fundamental questions that need to be addressed when initially setting up a global AM technology supply chain.
- The need for infrastructural adjustments to support the new technology structure. In unsupportive environments AMT can quickly lead to the unraveling of an organization. It is for this reason that manufacturers are wisely cautioned against making premature adoption decisions of AM technology. AM technology is a significant investment in capital, training and material costs for a supplier, given the costliness of these systems and the potential risks involved. Other less costly

infrastructural innovations and interventions should be investigated prior to, or in conjunction with, consideration of deploying AM.

- Investment justification of advanced manufacturing technology. Investment justification for AM should be attempted only after a firm has identified the benefits that they require, investigated alternative AMT that offers the same benefits, and considers the organizational infrastructure changes that are required to implement successfully the varying types of AMT or AMT portfolios. Using the MRL risk assessment tool, covered in section 3.3.1. offers a solution to mitigate AMT deployment risk relative to initial investment.
- Next is choice of technology. All choices of AM technology, including both SLS and FDM, should be thoroughly reviewed and reflect both the expected benefits of the organization and the quality of support for the adoption of the chosen system.
- The evaluation of AMT performance. Measurement of AM performance must be focused on assessing progress towards the original strategic, business and organizational objectives for implementing the systems. For example, SLS or FDM performance should not only be based on mean time before failure rates, or tensile property performance, but also focused on relative cost savings, new business wins and marketing potential tied to strategic goals associated with the supply chain.

The objective of developing the goals of evaluation stems from a need to document industry best practices during technology deployment.

2.2.2. Manufacturing Flexibility Review. Flexibility of a system is its adaptability to a wide range of possible situations it may encounter during its phase of production. Due to the inherent definition of flexibility, AM processes are found to accommodate the definition of manufacturing flexibility through customized build setups, on-the fly build manipulation, multiple material systems, etc. However, measuring flexibility with respect to manufacturing systems is nebulous. Various authors have attempted to capture the definition of flexibility, list aspects of flexibility, and promote metrics to measure flexibility. El Maraghy (2007) claims flexible manufacturing systems are more robust, but on the other hand, have high initial capital investment requirements. Sharifi and Zhang (1999) offer other types of flexibility not associated with manufacturing processes; some examples include people flexibility and organizational flexibility.

Several types of flexibility performance measures exist. Acting as an elegant approach to the definition of flexibility and by capturing the multidimensionality effect of manufacturing flexibility, Sethi and Sethi (1990) offer solutions to measure flexibility performance based on individual elements such as; machine flexibility, material handling flexibility, operation flexibility, process flexibility, product flexibility, routing flexibility, volume flexibility, expansion flexibility, program flexibility, production flexibility, and market flexibility.

De Toni and Tonchia (1998) attempts to summarize many of the forms of flexibility discussed in research by offering a comprehensive literature review of manufacturing flexibility and lists the topic of flexibility in terms of: (1) definition of flexibility, (2) request for flexibility, (3) classification in dimensions of flexibility, (4) measurement of flexibility, (5) choices for flexibility, (6) interpretation of flexibility. Though none of offer an applied format to measure flexibility.

Stockton and Bateman (1995) measure separate aspects of range flexibility. Within the model, a flexible manufacturing system (FMS) is rated against several aspects of range flexibility relative to probability of occurrences. Beamon (1999) extends the concept of flexibility beyond manufacturing system performance to an entire supply chain by establishing performance metrics at the supply chain level and categorizing supply chain performance measures. This categorization results in the identification of three types of performance measures that are necessary components in any supply chain performance measurement system: resource, output and flexibility.

In terms of AM, combining the general terms of flexibility presented in literature, a systematic evaluation of flexible manufacturing systems becomes clear. When classifying AM systems in terms of flexibility using various performance metrics discussed, a methodology is found in Section 3.1.2.

2.3. ADDITIVE MANUFACTURING REVIEW

The basis of the research provided incorporates Additive Manufacturing into an aerospace supply chain. As mentioned earlier, there are various aspects to Additive Manufacturing ranging from 3D printing to the additive processing of metals. However, the scope of the research is to investigate FDM and SLS as emerging candidates for an aerospace supply chain. Therefore, despite the number of Additive Manufacturing references available in academia, FDM and SLS were only considered for the article review.

2.3.1. Selective Laser Sintering Review. A variety of research conducted over the past twenty years highlights a number of technical reviews of Selective Laser Sintering, or Laser Sintering. One of the first bodies of knowledge research of SLS came from a dissertation for the University of Texas - Austin authored by Nelson, J. (1993) in which several aspects of the SLS technology are discussed in technical detail. This work covers computer and operator controlled parameters, machine specific parameters, material properties, physical modeling and computer modeling of the process, and control and optimization techniques.

With regard to throughput of SLS, Pham and Wang (2000) developed mathematical formulas based on laser scan speeds and process time associated with the SLS process that predicts and reduces build time for the SLS process, thus increasing throughput.

Based off work conducted by Thompson et al. (1997), Singhal et al. (2009) developed a model for optimum part orientation using several customer requirements that balance part integrity with build speed. Using this approach, the developed simulation gives the idea of surface roughness variation over the part's surface well in advance before going for actual part fabrication. Therefore, the modification in the part design can be carried out at very early stages to improve its functionality. Optimizing build orientation up front in the design process affords the supply chain an opportunity for cost reduction and performance gains with respect to SLS aerospace parts.

In addition to proper part orientation, inter-layer bonding is also being studied in detail to gain an idea of how to improve mechanical property performance of the SLS process. Dong et al, (2009) highlights a method in which a transient three-dimensional finite element model is developed to simulate the phase transformation during the selective laser sintering process; taking into account the thermal and sintering phenomena involved in this process. Using the mathematical model referenced, SLS users may understand the relative importance of thermal gradients within the process and use approaches offered by Dong et al, (2009) to increase mechanical property performance of parts, thus increasing yield percentage of parts per batch.

From a business aspect, the work of Ruffo (2005), Hopkinson and Dickens (2003) highlight the economic evaluation conducted by the research group at Loughborough University with regard to the SLS process. This information is critical in understanding when design engineers must select SLS over conventional manufacturing techniques. Also, suppliers may gain from understanding the breakeven analysis to effectively market the technology to niche markets rather than marketing a process incorrectly, only to be supplanted by conventional manufacturing technologies at a later time.

2.3.2. Fused Deposition Modeling Review. Similar to SLS, most of the literature specific to FDM focuses on quality enhancements and optimization techniques of the process. Wang et al (2007) focused on improving methods for the reduction of warp deformation for FDM. Factors affecting FDM integrity include the material characteristics, setup of the fabrication parameters, geometrical structure of the CAD model, and deposition path planning. Using such an approach would allow FDM suppliers to gain an understanding of the process to achieve maximum part integrity.

Others (Agrawal and Dhande, 2007; Ahn and Baek, 2003; Rodriquez et al., 2000; Kulkarni and Dutta, 1997; Pandey et al., 2003; Comb et al., 1994; Beuth and Narayan, 1996; Agarwala et al., 1996) extensively researched the anisotropic nature of the FDM process, with each researcher modeling and offering paths for FDM optimization. Due to the inherent anisotropic nature of FDM, this research is critical in process optimization of FDM and ultimately, the FDM supply chain.

The only economic model found regarding FDM was published by Hopkinson et al (2005), which referenced a straight-line economic model for FDM. The author feels the lack of published work regarding FDM economic analysis comes from a dual challenge. (1) The FDM supply base is virtually non-existent compared to SLS. Stratasys, the manufacturer that produces FDM machines, also sells the materials to be processed within the system. The markup on the raw material filament limits material sourcing, thus making supplier development difficult due to material markup. (2) Stratasys also owns a separate business, known as RedEye.com (Wohlers, 2009) that chooses to sell parts using a large inventory of machines. Since Stratasys owns RedEye.com and controls all filament material sourcing to customers, RedEye.com will always offer the lowest pricing of any parts produced from the FDM process due to lack of profit margin applied to the consumption of their own material. The business structure of a FDM machine manufacturer locking out other material systems and suppliers restricts the maturity of a FDM supply chain for industry.

2.3.3. Rapid Tooling Review. Direct parts fabricated out of AM technologies are not the only means of AM for aerospace. Indeed, Rapid Tooling (RT) offers significant opportunities for aerospace without the risk and qualification procedures necessary for direct part manufacture. Therefore, many suppliers may find RT an easier entry into the aerospace market.

Because of suppliers' propensity to adopt RT, a review of the latest in RT technology was in order. Violante et al. (2007) provides a novel use of rapid tooling for component inspection fixtures. Using Magics software, tooling pegs are generated via a computerized macro. These peg geometry match to the conformal surface of the geometry being inspected, the other end of the peg features a boss peg that mates to a standardized size breadboard fixture. Due to the complex shapes and patterns generated from a large portion of aircraft geometry, fixtures may be produced using AM and implemented within a supply chain to save time and costs for inspection fixtures.

Pham and Dimov (2003) segregate RT into two distinct classes, direct tooling and indirect tooling. Indirect RT allows tool validation to be conducted before changes become very costly. The aim of these RT methods is to fill the gap between RP and hard tooling by enabling the production of tools capable of short prototype runs of parts made from RT technologies. An example of this technology would be investment casting[18]. FDM may be used to create a pattern, traditionally laboriously sculpted or machined by hand. This pattern is then used in an investment casting process to form a shape that is melted away for metal castings. Cooper (2001) references FDM directly for investment casting. "If prototypes are needed in a metal form, the parts can be prototyped using the investment-casting wax and then carried through the traditional investment-shell casting

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[18] Also known as lost foam casting, investment casting is an industrial process that creates aluminum, copper and steel parts by (1) creating a master mold pattern, (2) creating a mold, (3) producing a wax pattern, (4) coating the pattern with ceramic, (5) dewaxing the pattern, (6) burnout of the wax, (7) pouring the metal, (8) removal of the pattern (Degarmo, 2003).

process to obtain usable metal components." Direct tooling, on the other hand, affords the ability to produce tooling directly from the AM process itself by producing tools capable of short prototype runs of approximately fifty to a hundred parts using the same material and manufacturing process as for final production parts. An example of this would be using FDM or SLS parts for direct inspection fixtures as earlier described.

Although SLS and FDM were not included in their study, Hanumaiah and Ravi (2007) evaluated other AM technologies for RT. Specifically, SLA and Direct Metal Laser Sintering technologies were investigated for form accuracy of direct tooling. Feature aspects of flatness, circularity, straightness were evaluated relative to form accuracy. The research offers a methodology of process selection based on dimensional capability and may translate for SLS and FDM direct tooling applications as well. By quantifying RT tolerance design based on manufacturability considerations, OEM design engineers may assist the AM supply chain by providing case studies and a common methodology for intelligent RT deployment.

2.3.4. Cost Modeling. Critical to the knowledge base of emerging technologies, understanding the relative cost information specific to AM allows collaborative learning of the emerging process. This information assists potential suppliers, OEM supplier managers, and design engineers in understanding appropriate part candidate selection and manufacturing process selection.

The most accurate cost information is derived from actual case studies of part candidates driven through industry. However, manufacturing companies see AM technologies as strategic growth opportunities. Due to this perception, companies have been unwilling to publish internal cost information regarding the appropriation of costs associated with the technology. As an alternative, models may be setup using academic references and cost modeling techniques. The only work published regarding AM costing comes from Loughborough Universities' Rapid Manufacturing Research Group. Ruffo (2005), Ruffo et al., (2006) Ruffo and Hague (2007), and Hopkinson and Dickens (2003) provide basic guidelines when comparing a single geometry in a small frame SLS machine versus injection molding. However, no mention of cost differentiation relative to multiple size SLS machines, scaled geometry and part integration exist within published literature.

Knowing that a thorough cost model for AM processes must first be developed in order to assist the maturation of the AM supply chain, the author-selected activity based costing (ABC) guidelines to establish process costs. Also used by Ruffo (2005), ABC offers fundamental costing guidelines that seem to work well with flexible manufacturing systems, such as AM, by breaking down the process in terms of individual steps.

Rezaie et al. (2008) details a case study of applying ABC to a flexible manufacturing system in the forging industry. "Traditional cost systems are known to distort cost information by using traditional overhead allocation methods. Activity-based costing, on the other hand, has gained recognition as a more accurate cost estimation and calculation method." ABC costing systems differ from traditional systems by cost pools being defined as activities rather than production cost centers. Cost drivers are used to assign activity costs differ structurally from those used in traditional cost systems, leading to less confusion and double costing. Reszaie et al. (2008) also highlights the implementation of ABC in an actual system by illustrating how activities and their respective costs were decomposed and assigned as drivers. Applying this same approach to AM systems allows for intelligent cost development from the ground up. This research has modified a similar approach for SLS cost development and FDM cost development.

Roy et al. (2008) proposes a different costing structure known as function based cost estimating (FUCE) in which function decomposition identification of product parameters are related to a top-level function. The end step involved in FUCE associates product costs to the function using past knowledge and data. The difficulty in FUCE approach for emerging technologies is the reliance on historical data, which is generally non-existent for an emerging technology.

2.4. ROBUST DESIGN AND QUALITY ENGINEERING REVIEW

Parameter optimization is a key component of emerging technology development. A well-researched field, parameter optimization affords the ability for emerging technologies to be optimized prior to deployment into a supply chain. Thomas et al. (2009) claim that the application of Taguchi's experimental design techniques allows for increased quality problem resolution.

Kiemele et al. (1999) cite designed experiments as purposefully making changes to inputs (or factors) in order to observe corresponding changes in the outputs (or responses). In order to progress the maturation of an emerging technology, designed experiments should be conducted by an OEM for the purpose of system optimization before deploying the technology into a supply chain. Taguchi and Clausing (1990) initially describe the effect of designing quality within a product as robust quality.

"Strengthening design increases the signal-to-noise ratio of component parts, which simultaneously improves the robustness of a product as a whole."

Another fresh approach to quality engineering comes by applying Taguchi's concept of quality loss function to selective assembly[19] techniques. Kannan et al. (2008) introduces a methodology that allows operators to segregate individual parts into groups of dimensional deviation. All of the parts are assembled together with the goal in mind to reduce dimensional variation on the mating surfaces of part through dimensional inspection techniques. The functional performance of an assembled product and its manufacturing cost are directly affected by the individual component tolerances.

Nevertheless, the selective assembly method can achieve tight assembly tolerance through the components manufactured with wider tolerances. The components are segregated by the selective groups (bins) and mated according to a purposeful strategy rather than being at random, so that small clearances are obtained at the assembly level at lower manufacturing cost. (Kannan et al., 2008). Consider that if dimensional segregation of parts is possible to lower dollars lost due to poor quality, AM could possibly have even a greater impact to quality loss through part integration of designs.

Fowlkes and Creveling (1995) highlight the work of Taguchi in parameter design optimization as a generally accepted approach to parameter design. Although primarily intended for product design, many of the concepts offered by Fowlkes and Creveling

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[19] Selective assembly involves sorting individual parts that make up an assembly by grouping batches of adjacent parts together to produce the least amount of tolerance stackup during assembly (Kannan et al, 2008).

(1995) could be directly applied to emerging technology, such as AM. For example, Fowlkes and Creveling (1995) discuss product design segmented into three distinct phases of concept design, parameter design and tolerance based design.

Others have applied Taguchi's work of optimization for other technologies. For example, Oktem et al. (2007) discuss the application of Taguchi optimization techniques applied to injection molding process parameters. In addition, Huang and Tai (2001) and Tang et al. (2007) discuss solving injection-molding warping challenges using Taguchi optimization techniques. Berginc et al. (2006) highlight the use of Taguchi optimization practices to strengthen injection-molding parameters.

The Juran Trilogy[20] requires quality planning, quality control, and quality improvement. During the quality-planning phase, Juran (1992) declares that in order to produce product features critical to customer requirements, one must develop processes that are able to produce these features repeatedly. Although generally held to manufacturing product, quality improvement strategies may be applied to business processes, manufacturing processes, support operations, and production operations (Juran, 1989). Using this strategy of universal quality improvement, product design quality tools can directly correspond to AM deployment into the supply chain. If AM were thought of as a product, process variation may be driven out of AM before supply chain deployment using quality engineering tools and techniques. These quality engineering tools and techniques offer a way to view the AM technology as a complete

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[20] Defined as Planning, Control and Improvement, Juran claims these areas as fundamental to modern quality engineering (Juran, 1992).

system that is interrelated to the maturation of the technology. Table 2.1 offers a comparison to quality engineering application towards product design versus the author's application of the same tools for emerging technology development.

Table 2.1. Quality Engineering Tools Applied to AM Maturation

Quality Engineering Steps for Product Design	Applied to Additive Manufacturing Supply Chain Deployment
Concept Design Phase	**Emerging Technology Discover Phase**
Quality Function Deployment	Measuring Customer Expectations of Technology, Competitive Analysis Conducted for Competing Technologies
Design of Experiments	Initial Screening Technique for Optimizing AM quality through basis mechanical property assessment
Competitive Technology Assessment	Understanding Conventional Mfg. Technology from Technical and Economic Aspect
Pugh Concept Selection	Weighting Customer Expectations Defined in QFD versus SLS, FDM, Conventional Mfg.
Parameter Design Phase	**Pre-Supply Chain Deployment Phase**
Engineering Analysis	Using training, experience, and experimentation to discover the sources of variability and effective countermeasures for SLS or FDM
The System P-Diagram	Represents the Various Parameters Influencing the SLS or FDM System Output, Main Quality Metric Defined (i.e., mechanical properties)
Dynamic and Static S/N Optimization	Optimization of Parameters Defined from P Diagram
Crossed Array Experiments	Exploits Interactions Among Control Factors and Noise Factors to Enhance System Robustness
Tolerance Design Phase	**Supply Chain Deployment Phase**
Quality Loss Function	Equation to Determine the Amount of $'s Lost to Poor FDM or SLS Quality
Analysis of Variation	Quantitatively Determines the Amount of Contribution Each Control Factor Affects SLS or FDM

2.5. SUPPLY CHAIN REVIEW

Globalization has increased market segregation and customers are requiring smaller quantities of more customized products (Maskell, 2001). AM technology answers the call to construct highly customized products. Therefore, a comprehensive literature review of fundamental supply chain principles was performed in attempt to grasp the latest research conducted within the field of supply chain management.

2.5.1. Six Sigma Strategies. Surveying the latest advancements in Six Sigma strategies yielded an overwhelming amount of data. Narrowing down to supply chain management with regard to six sigma practices that could be applied to AM produced the following:

Cudney and Drain (2007) concluded that C_{pk} measurement techniques might be adapted to account for batch effects, an area of critical application for SLS processing. The Define, Measure, Analysis, Improve and Control process methodology fundamental to six sigma practices may be used for technology development for an emerging technology such as AM. As machine-to-machine variation exists within both FDM and SLS technology, six sigma tools and techniques may be effectively utilized to quantify the variation and provide process change suggestions.

2.5.2. Quality Function Deployment. QFD is a set of product development processes utilizing cross-functional teams that use a series of matrices to map customer concepts across design, production and service functions (Griffen and Hauser, 1993). Currently, companies cannot be certain of their product quality until the product is built and tested (Suh, 1995). In order to ensure quality in an emerging process, such as AM, prior to technology deployment, the four-phase approach to QFD offers the most structure when applying emerging technology deployment. Maritan and Panizolo (2009) identify business practice priorities using QFD. During the development of business priorities, it is important to note that the four-phase approach of product planning, part deployment, process planning and production planning may be applied to emerging technology with the only alteration to the model being sequence changes.

Fung et al. (2003) constrain the amount of QFD deployed at the supply chain level and propose a mathematical model for operational QFD planning with resource allocations kept in mind. The Fung et al. (2003) model plans for the capture of technical attributes by allocating various resources among them hoping to achieve maximum overall customer satisfaction. The technical and resources constraints, including limited design budget, are incorporated into the proposed QFD planning process. Application of this model may be used for upfront emerging technology deployment of AM technology at the supply chain level. Shen et al. (2001) recognize linguistic variables of importance to a customer and relationship strength as fuzzy inputs into the QFD model and propose a model that marginalizes the fuzziness of these attributes by offering crisp quantitative measures to assist in weighting the variables. Jiang et al. (2007) offer guidelines on how to integrate design for excellence and design for six sigma theories into a QFD method. By integrating the methods, manufacturers can differentiate a product in terms of quality prior to the actual production process. In terms of emerging technology deployment, process design must effectively prevent a recurrence of the existing process's design problems through the evaluation of the potential design problems of the emerging process through multifunctional product development teams. For example, using tools like failure mode effect analysis tables and cause and effect diagrams prior to technology deployment are valuable ways to foreshadow potential supply chain issues before the emerging technology is implemented.

2.5.3. Integrating Emerging Technologies into a Supply Chain. A host of external and internal change drivers may exist and affect the manufacturing enterprise at various levels from strategic planning to re-position the actual production facilities to achieve a high degree of adaptability (ElMaraghy, 2007). AM technologies achieve the high degree of adaptability necessary to react to the external and internal change drivers of an enterprise. Naylor et al. (1999) discuss an integration of lean and agile manufacturing and the resulting effect on the supply chain.

To ensure a high quality product and on time delivery, an effective relationship with the component suppliers is vital (Karim et al, 2008) AM suppliers should be seen as partners to an aerospace OEM. However, as a supplier provides value to different aerospace OEMs, the supplier is exposed to more risk due to each supply chain having different objectives. Members of the chain may have requirements placed upon them by one supply chain that conflicts with another. (Sinha et al, 2004). Childerhouse and Towill (2000) emphasize the need for all members of the supply chain to work as a team, so facilitating the dynamic and ongoing re-engineering of each value stream to best match customer requirements becomes easier. Fraser et al (2003) developed a collaboration maturity model that describes seven key process areas. AM applicability is expanded upon these areas by the following:

- *Collaboration strategy* – OEM and supplier development strategy
- *Structured development process* – Outlines AM testing integration

- *System design and task partitioning* – Tasks are assigned based on shared resource competency between OEM and AM supplier
- *Partner selection* – Prospective partners are carefully screened, motives are aligned between OEM and potential AM suppliers
- *Partnership formation and project initiation* – Roles and responsibilities of suppliers and OEM are clearly defined and communicated, intellectual property challenges are defined.
- *Partnership and project management* – Communication is open and frequent, management styles are compatible, and both the supplier and OEM feel they are gaining from the technology, risk equity management plan enacted.
- *Partnership development* – The exit conditions between the OEM and supplier are clearly defined and understood, mutual understanding that an investment in the relationship will pay dividends in the long term. Both partners are consciously learning about the collaborative process.

Each of the seven areas may then be subjected to a four-level maturity model to determine the amount of relationship bonding the OEM and AM supplier are engaged in. Fraser et al. (2003) also indicate the management of the design chain presents particular challenges with collaborations. In addition, a conclusion may be drawn that it takes time for a supplier and OEM to develop collaborative maturity with a supply base.

Despite an abundance of theoretical suggestions regarding supply chain development, implementation problems occur. For example, the methodologies currently used in supplier selection processes have a number of issues including much emphasis on subjective assessments, the evaluation mechanism being solely based on performance outcomes, and a failure to take supplier capabilities into consideration (Wu and Blackhurst, 2009). The problem is not how to transform the supply chains but how to convince the controllers of OEM resources that changes are needed at the supply chain level (Barker, 1996). Ideally, this will not be reactive change in response to competitive pressure but a change that begins with a visionary mindset driven by individuals to invest in emerging technologies. People with vision who create a culture to promote the energy for change in all parts of the business will no doubt be the most successful at emerging technology supply chain deployment.

On a similar topic of leadership of emerging technology, Hirtz et al. (2007) investigated the relationship between leadership characteristics, such as transformational, transactional and non-transactional attributes of top management and subordinate employees' perceptions of quality management implementation and concluded that top management support for quality management programs spreads among followers. Expanding on this principle, AM technology deployment should also receive full support from OEM and supplier top management in order to ensure the successful development of a supplier – OEM partnership. However, it should be noted that an aerospace enterprise is a dynamic system, and long-term solutions in complex product environments inevitably have ramifications at the strategic level based on part design modularity, the structure of enterprise processes and confounding performance metrics established at different levels of the organizational structure among suppliers and OEMs (Hurd, 2004).

Once a technology is deployed and a competent quality system put in place at an AM supplier, initial quality must match quality maintenance in the long term. For example, FDM initial quality at the supplier level must perform to established metrics as long as parts are being demanded at the OEM level. While many suppliers start out with motivated employees and focused initiatives, their ability to maintain the quality initiative set by the OEM often dwindles with time. Bullington et al. (2002) suggest critical success factors for maintaining performance quality from initial technology deployment through production. Their research indicates that significant falloff occurs in the areas of management commitment, supplier - OEM relationships, training and education and the use of teams, tools and rewards. Using this information, specific long-term focus must be provided by the OEM that augments each critical success factor listed above. This effort will ensure quality consistency at the AM supplier level.

In order for efficient AM supplier development to occur, the aerospace OEM must first set a manufacturing strategy for AM that accommodates an international manufacturing network. Currently a company's sources of competitive advantage are not within its immediate boundaries; they are generally located within the structure of a network of facilities and companies that represents an enterprise. (Miltenburg, 2009) Strategies for international manufacturing are often viewed as responses to pressure for globalization and pressure for local responsiveness within the OEM enterprise.

Miltenburg (2009) claims that in addition to cost, quality, delivery, performance, flexibility and innovativeness measures used to gauge factor performance, output such as accessibility, thriftiness, mobility and learning affect global supply networks. AM can add value to each global network factor listed above by allowing accessibility into other markets, acting as a common resource center to illustrate thriftiness, easily moved from one location to the next to represent mobility. Also, with a common workforce-training package, offers an element of learning. By addressing each aspect of the global network outputs, AM can become a potential for global supplier deployment within an OEM enterprise.

2.6. SUMMARY OF LITERATURE REVIEW

After reviewing the literature available regarding the areas of technology evaluation, additive manufacturing, robust design, supply chain analysis and emerging technology integration, a conclusion may be drawn. This conclusion is that despite individual tools being used to measure, model and develop methodologies for each area described above, a significant gap exists to provide a roadmap for additive manufacturing, or any emerging technology, to develop aerospace suppliers.

Given the evidence of a lacking technique, the research provided will attempt to roadmap a strategy, using a toolbox set of analysis tools for emerging technology development.

3. TECHNOLOGY DESCRIPTION AND MOTIVATION

3.1. BENEFITS OF ADDITIVE MANUFACTURING

Starting in 2007, a multi-year project was established within Boeing Research & Technology to identify challenges existing within the emerging SLS supply chain to respond directly to production needs creeping up during production infancy. During the discovery phase of the project, cost-modeling analysis indicated an inconsistent methodology across the supply chain. In response to this discovery, the scope changed to include other polymer additive processes, such as FDM. This research effort attempts to cover the breadth of content developed to drill to the marrow of AM supply chain challenges and provide a strategy for supply chain maturation that assists both AM and future emerging technologies.

As discussed in Section 1, there are many advantages for AM technology. Without the need to fabricate intermediate tooling, the construction of parts directly from CAD digital definition allows for manufacturing flexibility, design flexibility risk reduction via design revisions and dramatically shortened lead times of direct parts. In addition, the additive nature of AM processes allows unbridled design creativity to manifest itself into a part previously unable to be manufactured using any other method. This design element enables AM technology to integrate several individual pieces into a singular unit.

3.1.1. Part Consolidation. Due to the additive nature of AM technologies, parts conventionally manufactured as separate entities and assembled together to form a subassembly may now be constructed as a single piece complex entity. This is a vast departure for many part design evaluation techniques that highlight design for manufacturing, design for assembly (DFM & DFA). These techniques are integrated within University curricula as standard techniques used in industry to reduce manufacturing costs (Aurand et al., 1998). This training directly contrasts with AM principles of integrating designs to make them more complex. In addition, Rosen et al. (2003) claim that DFM is difficult for mechanical parts because a high level of manufacturing knowledge is required to change designs that assist manufacturing processes. "By thinking about the production process at the same time the product design is being evaluated, it's possible to optimize both." (Womack, pp.45, 2007)

Recognized as a main element of AM technology, design complexity extends AM technology beyond simple lack of tooling advantages and into a realm of true value added savings for aerospace applications. When conventionally manufactured aerospace flight hardware is design integrated into a single unit and built using AM, some of the following savings occur:

- Weight is often reduced of the overall assembly
- Part count is reduced and less parts need to be maintained and managed logistically within the OEM
- Direct labor is less for assembly into the aircraft
- Less parts need to be shipped from suppliers to OEM destinations for assembly
- Direct material costs are saved due to less parts being used
- As an aggregate unit, less carbon emissions are produced to manufacture
- For the unit, the cost of poor quality loss due to tolerance stack up is reduced

- Lead time risk for the subassembly is reduced by relying on only one process to make the part, not several processes
- More aircraft space is available in the installation space for the unit. This space and weight reduction helps allow room for critical subcomponents in the future
- Hard tooling is not required to build the unit. Thus, there are substantial lead time savings for delivery of the unit
- Tooling is not required; therefore, master tooling no longer needs to be warehoused for long periods. Parts are rebuilt directly from digital definition stored on hard drives when needed.

Using a notional case study of a support spacer subassembly to illustrate the effect of integrated design, an assembly of parts is presented in Figure 3.1. The subassembly consists of two sheet metal brackets attached to an injection molded support structure that supports air ducts within an aircraft. Twelve bolts are used to fasten the support structure to the airframe.

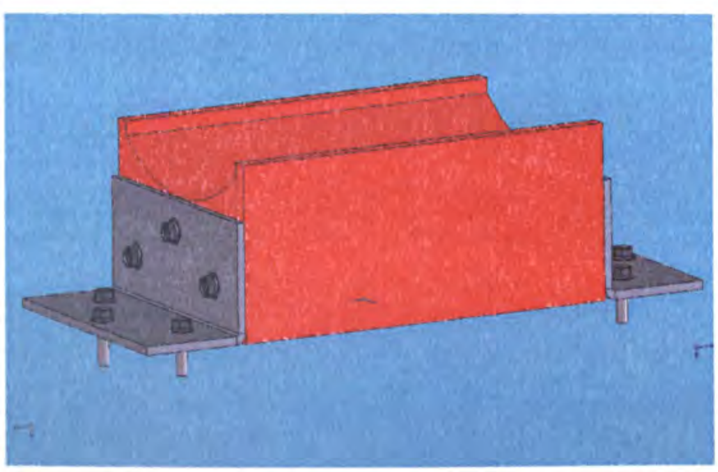

Figure 3.1. Example Geometry Subassembly

With a goal to reduce part count and weight, the spacer subassembly was redesigned to become function based, as opposed to manufacturing based design. During the redesign, the aerospace design engineer optimized the design with a goal to minimize the total weigh of the part, thus resulting in many honeycomb holes in the part to allow for both structural integrity and minimal weight performance. In addition, ten fasteners were eliminated with the integrated design and four were replaced with snap-fit plugs designed directly to the part. With this type of redesign, proof may be offered as to how AM becomes a disruptive technology for aerospace. The redesigned spacer support article is pictured in Figure 3.2.

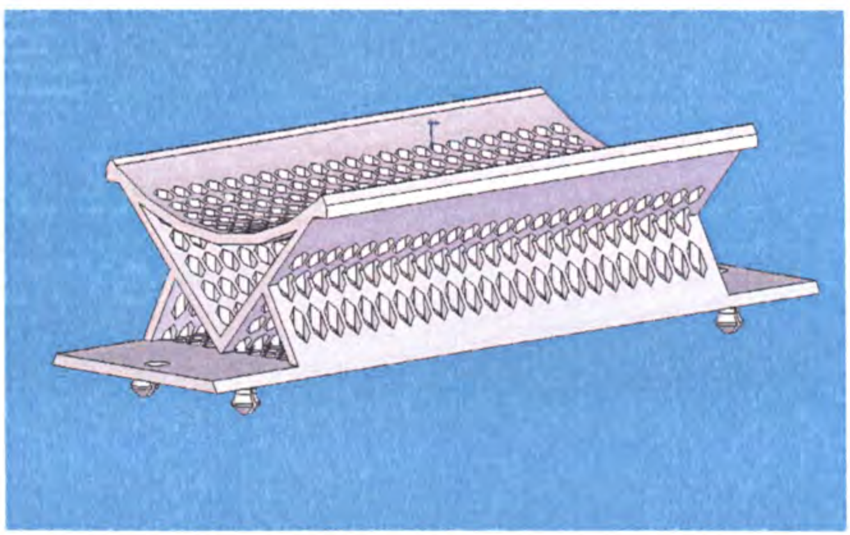

Figure 3.2. Redesigned Geometry for AM

3.1.1.1. The Effect of Quality Loss and Part Integration. Before the introduction of Taguchi's quality loss function (QLF) concept, cost due to poor quality was considered a nebulous concept. By quantifying the cost of poor quality through a simple formula, it helps engineers translate poor quality measurements into dollars of loss for management to evaluate (Taguchi and Clausing, 1990). The quality loss function is detailed as Figure 3.3.

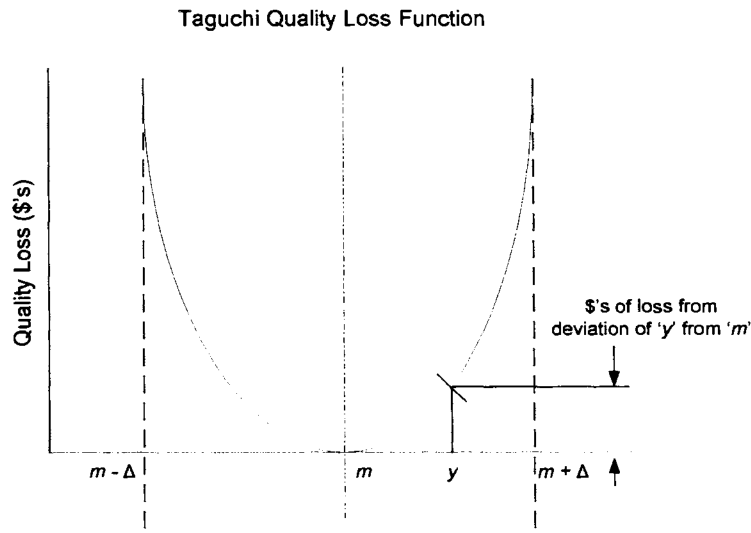

Figure 3.3. Taguchi Quality Loss Function Relationship

Quality loss caused by deviation equals zero when the functional characteristic is on target (y = m). The loss increases when the value of functional characteristic deviates from the target of m. Δ is the tolerance given to both sides of the target mean of m. The loss increases when the value of functional characteristic, y, exceeds either one of the allowable tolerance limits m + Δ or m - Δ. The quality loss is equal to the cost of product disposal or rework. The quadratic equation is then defined as:

$$L(y) = k(y - m)^2 \tag{8}$$

Where,

k = proportionality constant

y = product's functional characteristic

m = target mean

Δ = tolerance given at both sides of target mean

When the deviation of y is an amount Δ from the target value m, the quality loss equals the cost of a product's disposal, A. At that point, $A = k\Delta^2$ (Kannan et al., 2008). Thus, the loss function is given as:

$$(L) = \frac{A}{\Delta^2}(y - m)^2 \tag{9}$$

3.1.1.2. Additive Manufacturing Applied to QLF. Applying the QLF to part integration of AM, loss due to quality is significantly reduced. Using the geometries introduced in Section 1, the following provides an example of how QLF may be applied to part integration facilitated through AM technologies. Figure 3.4 illustrates a notional case example of quality loss applied to the manifold subassembly.

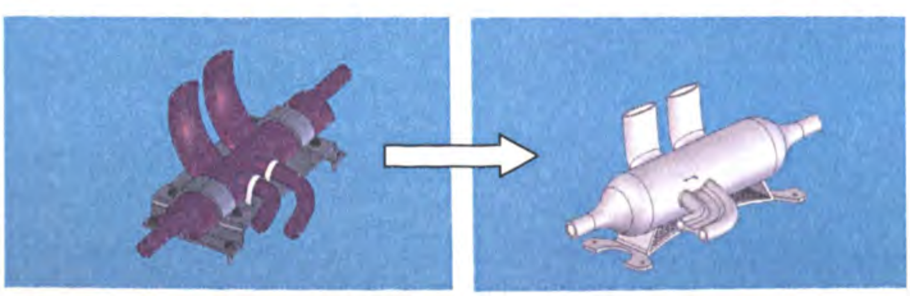

Figure 3.4. Part Integration QLF Example

Recall using AM technology, the part pictured on the left consists of (8) fasteners, (2) strap brackets, (1) support bracket and (1) composite manifold. All parts pictured on the left of Figure 3.4 could be manufactured conventionally using sheet metal brake press technology, fastener fabrication technology, and composite fabrication with wash out tooling methods. Each technology used to fabricate the assembly on the left inherently offers tolerance deviations from each part produced. By assembling the part together as a subassembly, all the tolerances inherent to each part add together to form tolerance stack-up[21]. Consider that the cost of poor quality of each subcomponent within the assembly can be measured using the QLF technique. Consider the price to replace each component and tolerances associated with random sampling of parts used in the subassembly. Each piece within the assembly is measured to be within tolerance specification limits of +-. 025" for the Manifold; +-.015" for the Support Bracket; and Strap Bracket. Due to each component's ability to perform off target mean of $m = 0$, a total subassembly cost due to poor quality may be derived to \$574.

Each item within the assembly is analyzed for tolerance deviation. Figure 3.5 highlights the cost of a conventionally manufactured subassembly with definition of the supporting hardware's tolerances associated with the entire assembly.

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[21] arithmetic tolerance stack-ups use the worst-case maximum or minimum values of dimensions and tolerances to calculate the maximum and minimum distance (clearance or interference) between two features or parts (Wikipedia, 2009). Tolerance stack-ups can cause mechanical problems after assembly due to customer wear of the product, operational temperature fluctuations to the assembly, deflection of components being loose, etc.

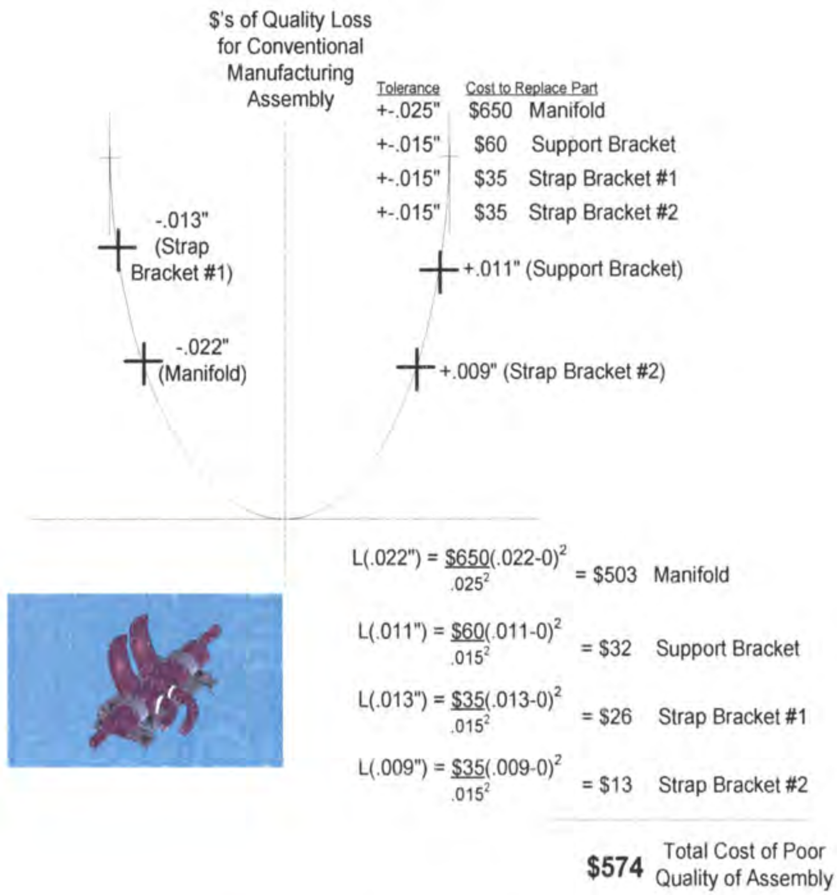

Figure 3.5. QLF Analysis of Manifold Subassembly

On the other hand, consider a case where the subassembly were integrated into a single design, constructed out of an AM process and reevaluated with respect to QLF. Using the SLS cost model discussed in Section 5.1, a cost for the manifold redesigned as a single piece, shown on the right picture of Figure 3.5, is developed to be $405 with a standard tolerance set to +-.015" as defined through Boeing internal testing. Using the same QLF methodology, due to the lower piece price of integrated design, even if a random sampled integrated design sample piece were inspected to still be acceptable at -.0149", its resulting loss at $405 is still less than the assembled manifold subassembly initial cost of $780 [$650+$60+$35+$35]. Figure 3.6 illustrates the QLF applied to a single piece unit.

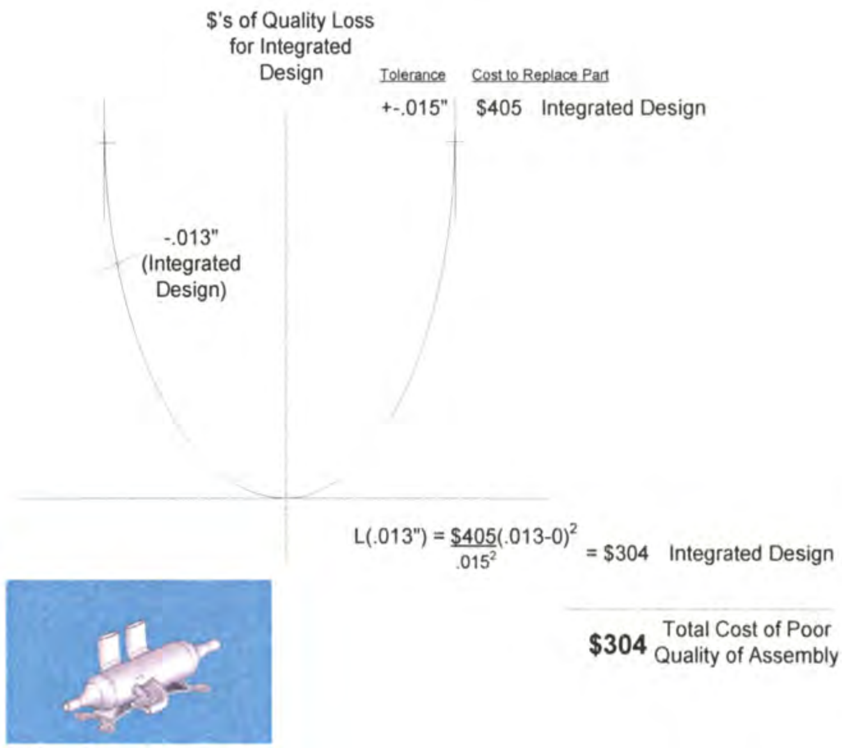

Figure 3.6. QLF Analysis of Manifold Subassembly

Therefore, it can be generalized that comparing conventional tolerance deviations in traditional manufacturing processes in an aggregate subassembly form to AM technology, a conclusion may be drawn that AM technology may also allow for looser dimensional control when parts are integrated and built as a single piece.

3.1.1.3. Part Integration and Tolerance Stackup. There is significant opportunity to research the use of tolerance stackup equations to the field of additive manufacturing (AM) part design integration. The paper offered by Lin and Zhang (2001) is a significant contribution to the formulation of geometrical tolerancing. Within the paper, Equation 10 and 11 are defined as:

$$\Delta d = \sum_{i=1}^{l} \left|\frac{\partial f}{\partial x_i}\Delta x_i\right| + \sum_{j=1}^{m} \left|\frac{\partial f}{\partial y_j}\Delta y_j\right| + \sum_{k=1}^{n} \left|\frac{\partial f}{\partial z_k}\Delta z_k\right| \quad (10)$$

$$\Delta d = \left[\sum_{i=1}^{l}\left(\frac{\partial f}{\partial x_i}\Delta x_i\right)^2 + \sum_{j=1}^{m}\left(\frac{\partial f}{\partial y_j}\Delta y_j\right)^2 + \sum_{k=1}^{n}\left(\frac{\partial f}{\partial z_k}\Delta z_k\right)^2\right]^{\frac{1}{2}} \qquad (11)$$

Where Δd is the variation of the resultant dimension, Δx_i, Δy_j, Δz_k are variations of component dimensions.

Although research has been conducted by Huang, et al. (2005) to correlate the Taguchi Loss Function and geometric tolerance stackup, in practice the theory is rarely applied. To explicitly define an example of tolerance stackup savings by applying Equations 10 and 11 to an integrated design case study would significantly illustrate the power of integrated design from a quality perspective.

However, within the field of tolerance design, equations 10 and 11 may be too restrictive in their nature for application. For example, Musa et al. (2004) claim that equation 10 only assumes a worst case scenario where all tolerances simultaneously occur at their worst limit and is considered too pessimistic in calculating tolerance stackup. Using the statistical analysis approach of Equation 11, individual tolerances are considered to be independent and have a normal distribution, which allows the stochastic use of the root sum of squares for stackup calculation. This statistical analysis method may also lead to conservative results due to tolerances being a function of machining, not necessarily distributed normally. The problem is that it assumes normal distribution, while a machined dimension usually has a flat top distribution. In addition, the major causes of tolerance deviation, namely process errors, are not taken into account (Muse et al., 2004). Also, according to Taylor, (1995) worst-case tolerancing tends to overestimate the variation of the output. Cost suffers when the variation of the output is overestimated. Statistical tolerancing tends to underestimate the output variation. Quality suffers when the variation of the output is underestimated.

Taylor (1995) suggests using process tolerancing. It is possible to accurately predict the behavior of the output, providing the desired quality at a lower cost. These types of specific challenges must be overcome in order to apply AM to the equations.

Despite the controversy in using these equations, in order to relate the stackup Equations 10 and 11 to AM single piece integrated design, a test would need to be conducted where sample geometry is selected to be manufactured conventionally. The sample geometry would represent a subassembly of conventionally manufactured components. After a thorough gage capability analysis is conducted of the measuring equipment, each component within the subassembly would be decomposed and analyzed for tolerance deviation. Dimensional tolerance deviation would be recorded for all of the critical features in the subassembly in all three axis so that data may be gathered for the, Δx_i, Δy_j, Δz_k values from nominal critical feature positioning.

In a similar fashion, a corresponding single piece integrated design would also be constructed to mirror the same features as the conventionally manufactured assembly. Upon completion of the single piece integrated design, inspection would commence on the part and data are then recorded for the resulting , Δx_i, Δy_j, Δz_k values from nominal critical feature positioning. Upon completion of the experiment, data are gathered and compared.

Since AM geometries are generally complex in nature, it may be useful to digitally scan the geometry using commercially available reverse engineering equipment and print out the dimensional deviations rather than measurement systems using calipers, only after conducting a thorough gage R&R of the digital scanning equipment. For practical application, it may be worthwhile to analyze both the conventionally manufactured subassembly and the integrated design listed in the experiment using the 3D geometric stackup analysis technique referenced by Lin and Zhang (2001) on page 261.

Using Equation 12;

$$\Delta d = \left[\sum_{i=1}^{l}\left(\frac{\partial f}{\partial x_i}\Delta x_i\right)^2 + \sum_{j=1}^{m}\left(\frac{\partial f}{\partial y_j}\Delta y_j\right)^2 + \sum_{k=1}^{n}\left(\frac{\partial f}{\partial z_k}\Delta z_k\right)^2\right]^{\frac{1}{2}} \tag{12}$$

as l, m, and n values are increased due to the number of component dimensions increasing, the amount of tolerance deviation, Δd, increases due to the summation of each x, y, and z axis. Because the x, y and z terms are summed individually and then summed together as an axis aggregate, any increase in the number of component dimensions, l, m, and n would result in an increase in tolerance deviation. As a result, as the number of components increase, tolerance stackup risk increases.

By setting the partial derivatives equal to one, the rate of change of f with respect to each axis is eliminated and Equation 12, essentially becomes:

$$\Delta d = \left[\sum_{i=1}^{l}(\Delta x_i)^2 + \sum_{j=1}^{m}(\Delta y_j)^2 + \sum_{k=1}^{n}(\Delta z_k)^2\right]^{\frac{1}{2}} \tag{13}$$

To highlight the magnitude of this tolerance stackup effect, a simplified example may be written by finding the volume of a single simplified box with respect to error stackup of a box. This simplified example correlates because in Lin and Zhang's (2001) paper, tolerance stackup analysis is based on error stackup analysis as well.

Larson et al. (1999) example: The possible error involved in measuring each dimension of a rectangular box is ±0.1 mm. The dimensions of the box are $x = 50$ centimeters, $y = 20$ centimeters, and $z = 15$ centimeters. The volume of the box is given as $V = xyz$ and thus,

$$dV = \frac{\partial V}{\partial x}dx + \frac{\partial V}{\partial y}dy + \frac{\partial V}{\partial z}dz \tag{14}$$

Which decomposes into;

$$= (y * z * dx) + (x * z * dy) + (x * y * dz) \tag{15}$$

Using 0.1 millimeter = .01 centimeter, you have $dx = dy = dz = \pm 0.01$, and the variation is approximately

$$dV = (20)(15)(\pm 0.01) + (50)(15)(\pm 0.01) + (50)(20)(\pm 0.01)$$

$$= 300(\pm 0.01) + 750(\pm 0.01) + 1000(\pm 0.01)$$

$$= 2050(\pm 0.01) = \pm 20.5 \text{ cm}^3$$

Similar to Equation 10 and 11, if the partial differentials were set to one in this case, the length of the box becomes irrelevant and the tolerance alone becomes that driving force behind the equation. Thus,

$$dV = dx + dy + dz \tag{16}$$

Whereas in Equation 15, the dimensions of the box represented $\frac{2}{3}$ of the equation, and the tolerance only $\frac{1}{3}$. In Equation 16, the tolerance is the fundamental aspect of the equation.

As a corollary, by setting the partial differentials in equation 10 and 11 to one, an increase in emphasis is placed on the tolerance deviation aspect, thus, increasing the risk due to tolerance deviation.

To continue with the example, imagine if more than one box were evaluated, thus, altering equation 14, to become;

$$dV = \sum_{i=1}^{n} \left(\frac{\partial V}{\partial x} dx + \frac{\partial V}{\partial y} dy + \frac{\partial V}{\partial z} dz \right) \tag{17}$$

Again assuming that the partial differentials were set to one with several boxes evaluated for dimensional variation the equation now transforms into;

$$dV = \sum_{i=1}^{n} (dx + dy + dz) \tag{18}$$

Equation 18, illustrates the example of simple tolerance stackup of variance of the volume of a box when the partial differentials are set to one and more than one box is present. Now, consider if all of the boxes were to be redesigned as a single complex box and built using AM, the risk due to tolerance stackup drastically diminishes. This simplified example of tolerance stackup, coupled with the QLF example, illustrates the power of integrated design through tolerance stackup reduction, and as a result, the potential role AM plays towards impacting manufacturing quality.

3.1.2. Manufacturing Flexibility. As discussed in § 1.5.2, AM technology offers incredible flexibility for the supply chain. The Law of Industrial Dynamics states that if demand for products can be amplified, it will. Due to this effect, suppliers will have alternating periods of stock-outs and surpluses that result in an increase in total costs to manufacturing (Wikner et al, 1991). One way to smooth supply chain dynamics is to offer processes that can accommodate demand fluctuations through the element of manufacturing flexibility. Table 3.1 illustrates the different types of flexibilities associated with manufacturing and their respective definitions.

Table 3.1. Different Aspects of Process Flexibility

Symbol	Flexibility Type	Definition
p[A]	Size Flexibility	The limitation of a part physically fitting within the FMS boundaries
p[B]	Shape Flexibility	The limitation of a part being processed within the FMS, due to its shape
p[C]	Materials Flexibility	The limitation of a part being processed within the FMS, due to its material processing capacity
p[D]	Machine Flexibility	The limitation of a part being processed within the FMS, due to the operations required
p[E]	Material Handling Flexibility	The limitation of a FMS to move components from one area to another via a material-handling route
p[F]	Process Flexibility	The limitation of a FMS to process a part due to its physical characteristics.
p[G]	Routing Flexibility	The limitation of a FMS achieving appropriate process routing
p[H]	Production Range Flexibility	The limitation of the FMS providing full production

By slightly adjusting manufacturing flexibility assessment techniques proposed by Stockton and Bateman (1995), AM is evaluated with respect to each characteristic of flexibility. In Table 3.2, two SLS machines and two FDM machines are compared to injection molding to determine how AM technology ranks relative to size flexibility, p[A]. Table 3.2, indicates the ratio of each ranked process accommodating part volumes. Each process is evaluated to different m^3 part volumes ranging in orders of magnitude. If the process can accommodate the part volume spatially, a 'Y' is placed within the cell.

The L/D or d/b ratio is a ratio of the depth dimension of the part relative to the length dimension of the part, or the depth dimension of the part relative to the base dimension.

Table 3.2. p[A] – Size Flexibility

Size Flexibility p[A]

AM Technology		m^3 part capacity 0-.001	.001-.01	.01-.1	.1-1	L/D or d/b ratio <1	1 thru 5	>5	p[A] Score
SLS	P730	Y	Y	Y	N	Y	Y	Y	0.857142857
SLS	Vanguard	Y	Y	N	N	Y	Y	Y	0.714285714
FDM	400MC	Y	Y	N	N	Y	Y	Y	0.714285714
FDM	900MC	Y	Y	Y	N	Y	Y	Y	0.857142857
n/a	Injection Molding	Y	Y	Y	N	Y	Y	N	0.714285714
p[A] = # of Ys / Opportunities									

Shape flexibility p[B], is the ratio of a part being built in the process, based solely on its shape. Injection molding is limited by the number of different shapes that may be produced from its process. Table 3.3 indicates a strong ability of AM processes to generate all shapes listed.

Table 3.3. p[B] – Shape Flexibility

Shape Flexibility p[B]

AM Technology		Rotational	Flat	Complex Entrapped Tubing	Box-like	Extrusion	Spherical	Complex Features (undercuts)	p[B] Score
SLS	P730	Y	Y	Y	Y	Y	Y	Y	1
SLS	Vanguard	Y	Y	Y	Y	Y	Y	Y	1
FDM	400MC	Y	Y	Y	Y	Y	Y	Y	1
FDM	900MC	Y	Y	Y	Y	Y	Y	Y	1
n/a	Injection Molding	Y	Y	N	Y	N	Y	N	0.5714
p[B] = # of Ys / Opportunities									

Material flexibility, p[C], is the ability of the process to produce different kinds of materials. Several engineered thermoplastics were listed as criteria for processing. As noted in the introduction, it is not entirely understood why materials processed in one

AM process does not work well in other types of AM processes. Note, the ability of injection molding to process all of the materials listed in Table 3.4.

Table 3.4. p[C] – Material Flexibility

Material Flexibility p[C]

AM Technology		Polycarbonate	PA	ABS	PEI	PPSF	p[C] Score
SLS	P730	Y	Y	N	N	N	0.4
SLS	Vanguard	Y	Y	N	N	N	0.4
FDM	400MC	Y	N	Y	Y	Y	0.8
FDM	900MC	Y	N	Y	Y	Y	0.8
n/a	Injection Molding	Y	Y	Y	Y	Y	1
p[C] = # of Ys / Opportunities							

Machine flexibility, p[D], encompasses the ability of the machine to produce different part requirements based on feature detail. In Table 3.5, all processes evaluated scored the same for machine flexibility.

Table 3.5. p[D] – Machine Flexibility

Machine Flexibility p[D]

AM Technology		Specified Surface Finish	Integrated Designs	Keyway and slots	Bosses	Capable of Text	p[A] Score
SLS	P730	N	Y	Y	Y	Y	0.8
SLS	Vanguard	N	Y	Y	Y	Y	0.8
FDM	400MC	N	Y	Y	Y	Y	0.8
FDM	900MC	N	Y	Y	Y	Y	0.8
n/a	Injection Molding	Y	N	Y	Y	Y	0.8
p[D] = # of Ys / Opportunities							

Material handling flexibility, p[E], offers a sense of the amount of effort necessary when switching among materials system listed in p[C]. Switching materials in a large frame SLS machine is much more difficult than switching materials in a small frame machine. As the material change mechanism is the same for each FDM machine, the ease of material switching does not differ between FDM machines. Table 3.6 illustrates the same p[E] score among all processes evaluated.

Table 3.6. p[E] – Material Handling Flexibility

Material Handling Flexibility p[E]

AM Technology		Automated Delivery of Material	Quick Material Changes?	Environmental Conditioning of Material Required	p[E] Score
SLS	P730	Y	N	Y	0.666667
SLS	Vanguard	N	Y	Y	0.666667
FDM	400MC	Y	Y	N	0.666667
FDM	900MC	Y	Y	N	0.666667
n/a	Injection Molding	Y	N	Y	0.666667
p[E] = # of Ys / Opportunities					

Process flexibility, p[F], offers a an evaluation of the individual processes in terms of response to size p[A], shape p[B] and material p[C] changes. Table 3.7 shows that the 900MC FDM machine offers the greatest score for process flexibility.

Table 3.7. p[F] – Process Flexibility

Process Flexibility p[F]

AM Technology		p[A] Score	p[B] Score	p[C] Score	p[F] Score
SLS	P730	0.857143	1	0.4	0.342857
SLS	Vanguard	0.714286	1	0.4	0.285714
FDM	400MC	0.714286	1	0.8	0.571429
FDM	900MC	0.857143	1	0.8	0.685714
n/a	Injection Molding	0.714286	0.571429	1	0.408163
Process Flexibility p[F] = p[A] x p[B] x p[C]					

Routing flexibility, p[G], is a product of machine and material handling flexibility. Given the equal scores for all the technologies evaluated, Table 3.8 shows even scoring for all processes with regard to routing flexibility.

Table 3.8. p[G] – Routing Flexibility

Routing Flexibility p[G]

AM Technology		p[D] Score	p[E] Score	p[G] Score
SLS	P730	0.8	0.666667	0.533333333
SLS	Vanguard	0.8	0.666667	0.533333333
FDM	400MC	0.8	0.666667	0.533333333
FDM	900MC	0.8	0.666667	0.533333333
n/a	Injection Molding	0.8	0.666667	0.533333333
Routing Flexibility p[G] = p[D] x p[E]				

Production range flexibility, p[H], is the ultimate metric for ranking machine processes in terms of flexibility. Evaluating the different AM technologies against injection molding yields a result of higher production range flexibility relative to FDM processes, next, injection molding, and then finally SLS technology, shown in Table 3.9.

Table 3.9. p[H] – Production Range Flexibility

Production Range Flexibility

AM Technology		p[G] Score	p[F] Score	p[H] Score
SLS	P730	0.533333	0.34285714	0.18285703
SLS	Vanguard	0.533333	0.28571429	0.15238086
FDM	400MC	0.533333	0.57142857	0.30476171
FDM	900MC	0.533333	0.68571429	0.36571406
n/a	Injection Molding	0.533333	0.40816327	0.21768694
Production Range Flexibility p[H] = p[F] x p[G]				

Quantifying the amount of production range flexibility among the processes evaluated yields the following logic with respect to SLS and FDM flexibility:

$$\overline{SLS}_{Flex} = \frac{\sum_{i=0}^{n_{SLS}} p[H]_{SLS}}{n_{SLS}} \qquad (19)$$

Where, n_{SLS} is the number of SLS technologies evaluated, $p[H]_{SLS}$ is the individual p[H] scores associated with SLS technology. Using the data generated from the production range flexibility of SLS yields:

$$\overline{SLS}_{Flex} = \frac{.183 + .152}{2} = .167$$

Similarly, evaluating FDM flexibility yields the following:

$$\overline{FDM}_{Flex} = \frac{\sum_{i=0}^{n_{FDM}} p[H]_{FDM}}{n_{FDM}} \qquad (20)$$

Where, n_{FDM} is the number of FDM technologies evaluated, $p[H]_{FDM}$ is the individual p[H] scores associated with FDM technology.

$$\overline{FDM}_{Flex} = \frac{.305 + .366}{2} = .336$$

Using the defined production range flexibility amount of injection molding of .218, found in Table 3.9, and comparing the average production range flexibility, the following pie chart in Figure 3.7 may be developed to describe the amount of production flexibility existing among the technologies compared.

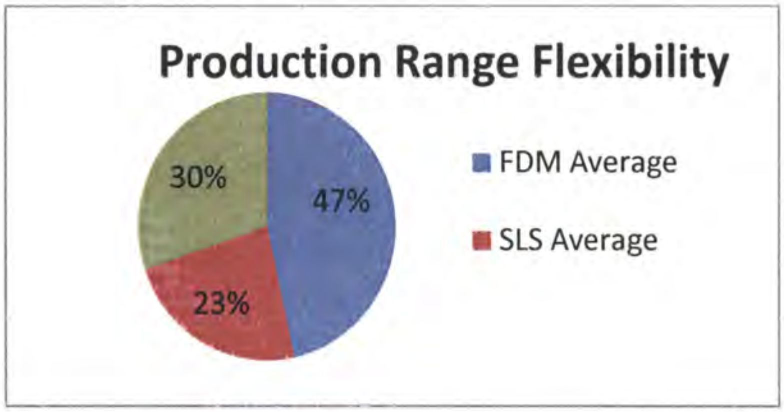

Figure 3.7. Production Range Flexibility of AM technologies

Using the information derived from the production range flexibility calculations, a generalized observation may be concluded that FDM appears to offer the most flexibility when using the attributes defined for each flexibility listed in p[A] through p[E]. Specifically, the 900MC offers the maximum amount of manufacturing flexibility when compared to other technologies.

3.1.3. Lead Time Comparison. Other than part integration, another major beneficial element of AM comes from part lead-time reduction facilitated through the lack of tooling necessary to build a part using AM technology. This lead time reduction offers benefits in not only time shaved from delivery estimates within the supply chain, but also acts as a buffer for tooling redesigns and offers substantial risk reduction opportunities for tooling errors. To illustrate this point of lead-time reduction, SLS is compared to composite manufacturing to highlight discrepancies between the two processes. Composite manufacturing was chosen as a competitive technology to SLS due to the reliance on tooling and many aerospace parts are made from composites.

First, a composite manufacturing supplier is consulted to develop a process flow diagram of a traditional composite manufacturing process. The process flow diagram for a composite process is located in A.5. Next, each step within the process is analyzed with respect to an optimistic lead-time and a pessimistic lead time. In addition, this difference between the optimistic and pessimistic lead-times could be replaced with non-complex and highly complex part attributes for the composite process.

Next, the supplier assists with developing lead-time data for each step based on over 50 years of composite manufacturing expertise. Table 3.10 indicates the number of days it typically takes for each task associated with producing a composite part from order to delivery.

Table 3.10. Typical Composite Manufacturing Company Process

Lead Time (Days)			
	a	m	b
Find and Ship Existing Tooling	8	12	30
Design Tooling	2	6	10
Fabricate Tooling	4	4.5	5
Trim/Drill	10	13.5	25
Tooling Quality Assurance	1	1.5	2
Mold Preparation	1	1.5	2
Material Cutting	0.5	0.75	1
Lay Up	0.5	0.75	1
Bagging	0.1	0.2	0.5
Cure	0.5	0.75	1
Demolding	0.2	0.4	1
CNC Trim	0.2	0.35	0.5
Hand Trim	0.05	0.525	1
Surface Prep	0.5	2.75	5
Assembly	0.8	1.5	3
Final Assembly Quality Assurance	0.25	1	3
Packaging	0.25	1.625	3
Shipping	1	3	5
Sum	22.85	40.60	69.00

The format for Table 3.10 is as follows, 'a' represents the optimistic lead time in days for the step to take, this is generally sought to be non- complex parts with little geometric difficulty for tooling. Next, 'm' is thought to be the average of time it takes for the step to be performed. Finally, 'b' is thought to be the pessimistic lead time for the step to take in days; this is thought to represent geometry that is difficult to construct for aerospace.

Next, data are placed in Crystal Ball™ Monte Carlo simulation software to determine the probability of receiving parts within specified acceptable lead times. The lead time specifications are then agreed upon by both supplier managers within the OEM and the suppliers producing the parts. Within Crystal Ball™, each step may be specified with regard to probability assumptions. For example, the step known as 'Find and Ship Existing Tooling' has a triangle distribution assumption associated with it that looks like Figure 3.8.

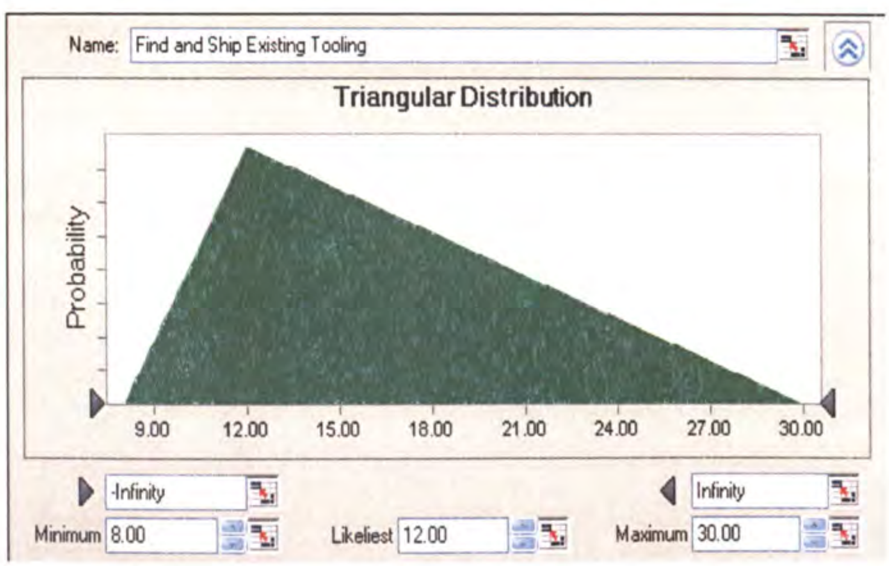

Figure 3.8. Triangle Distribution of Finding and Shipping Tooling Step.

Next, each step listed in Table 3.10 is then assigned distributions agreed upon by coupling both the supplier managers of the OEM perspectives and the suppliers' perspectives with historical referenced data. Next, Crystal Ball™ simulates over 10,000 trials using a randomization algorithm to develop a graph of the composite process shown in Figure 3.9.

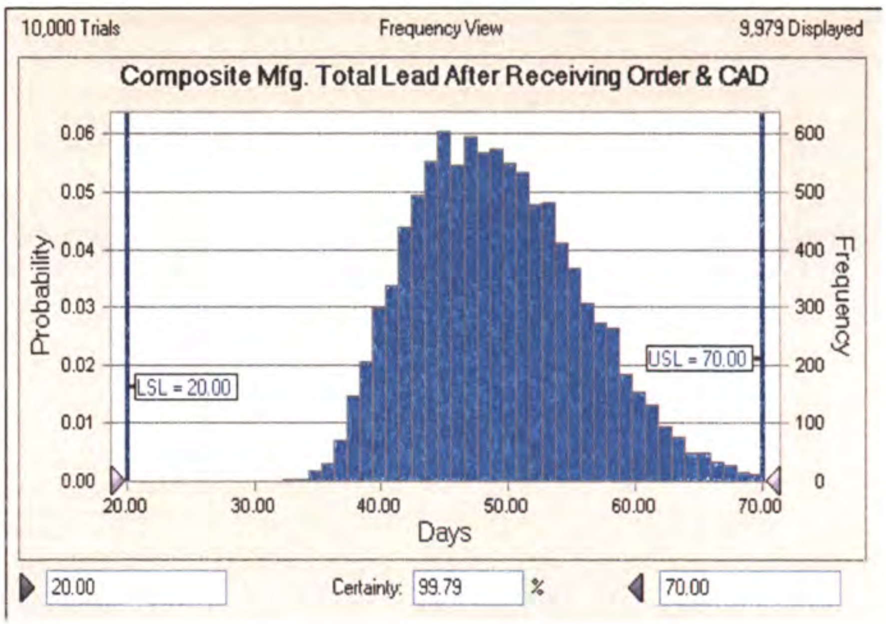

Figure 3.9. Composite Manufacturing Lead Time

Next, using the specification limits within the software, the probability of receiving composite parts within a specified period of time may be realized. This period of time may then be compared to AM. By using the vendor supplied information coupled to the Monte Carlo simulation, an appropriate lead time may be realized that encompasses both optimistic and pessimistic estimates of lead time. Figure 3.10 indicates a 57% chance of receiving parts within 50 days from receiving an order at a composite supplier.

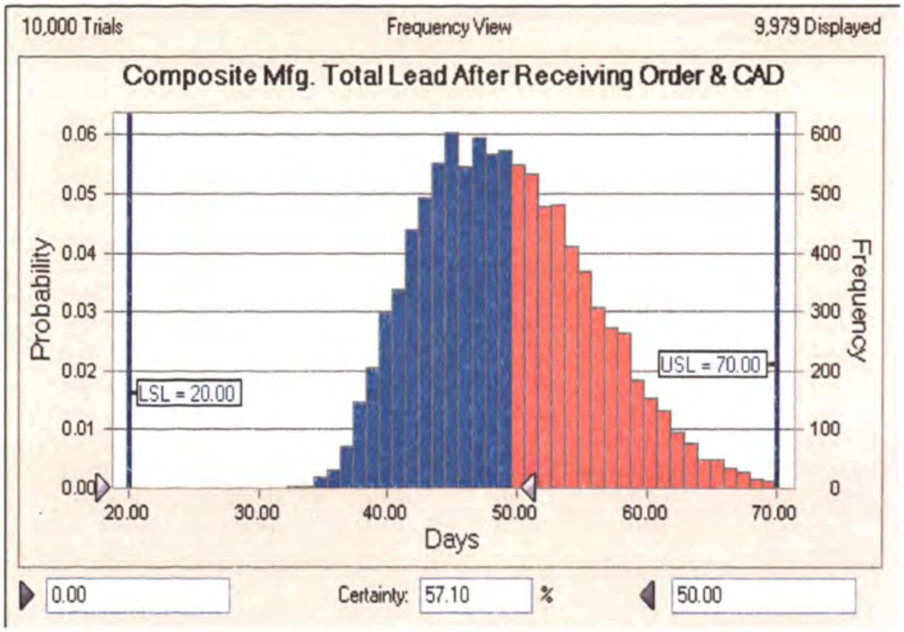

Figure 3.10. Probability of Receiving a Composite Part within Specified Days

Located in Appendix A.2, a process flow diagram was developed for Selective Laser Sintering in conjunction with SLS suppliers. Table 3.11, similar to the composite process, was developed with regard to process lead time for SLS.

Table 3.11. Typical SLS Manufacturing Process

Lead Time (Days)			
	a	m	b
Preparing the LS Machine	0.1	0.3	0.5
Create/Modify Build Setup	0.05	0.1	0.3
Splitting Work Orders	0.05	0.1	0.3
Generating Build Setup Sheet	0.01	0.05	0.1
File Paperwork for Build Work Order	0.01	0.1	0.2
Run Parts in Machine	1	1.5	2
Cooldown of Parts	0.75	1	2
Remove Parts from Machine	0.2	0.5	1
Inspect Parts and Tensile Test	0.25	1	3
Complete Paperwork	0.1	0.2	0.4
Verification the Work Order is Complete	0.05	0.05	0.1
Assembly of Parts for Shipping	0.1	0.5	1
Packaging	0.25	1.625	3
Shipping	1	3	5
Sum	3.92	10.025	18.9

Using the same distribution pattern strategy employed for the composite process, assumption cells were highlighted based on detailed conversations with a SLS supplier and OEM supplier management. Next, a forecast was created for SLS lead time for comparison to composite manufacturing. Figure 3.11 shows the SLS lead time result.

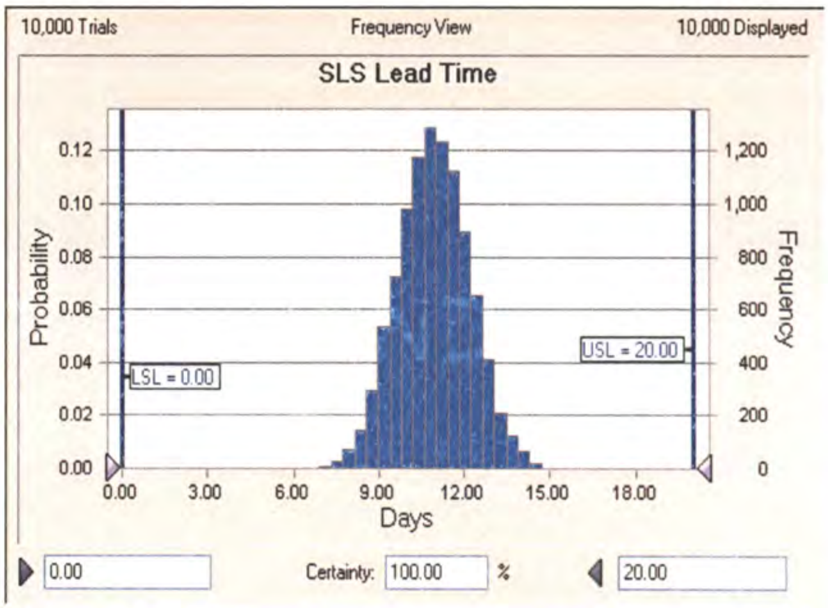

Figure 3.11. Typical SLS Lead Time Analysis

Given the comparison of Figure 3.10 and Figure 3.11, it can be determined that SLS is substantially faster than composite manufacturing. Statistics derived from the simulation highlights a mean SLS lead time of 11 days from order to delivery with a standard deviation of 1.2 days. On the other hand, composite manufacturing yielded a mean lead time of 50 days with a standard deviation of 6.6 days.

Using the comparative results, it may be concluded that SLS yields an approximate 78% decrease [(50 days -11days)/ (50 days)] in lead time over composite manufacturing and an 82% decrease [(6.6 – 1.2) / 6.6] in standard deviation over composite manufacturing. This estimate may be verified by checking AM technology lead-time to conventional composite manufacturing.

3.2. THE NEED FOR A TECHNOLOGY DEVELOPMENT ROADMAP

Despite the demonstrated success of AM technology, a roadmap to deploy the emerging technology is needed for the aerospace supply chain. Unfortunately, most aerospace aircraft maintenance scheduling procedures are held to be proprietary, looking at the main drivers for aerospace maintenance using an iterative probability calculation model (MacDonnell and Clegg, 2007), a typical part holding for part number 763810-1 = $f(MTBR, TAT, QPA, FLeetUtil, SL)$, where:

- MTBR = manufacturer's mean time between removal figures
- TAT = turnaround time, or, the time taken to route, maintain and replace item 763810-1 in inventory
- QPA = quantity per aircraft
- FleetUtil = total hours flown by the total number of aircraft of the same type in a fixed period of time
- SL = target service level, which is the probability of the part being available

Looking at AM with respect to each aerospace maintenance driver, it can be determined that TAT can be affected due to the reduced lead time to fabricate AM parts within the supply chain, as illustrated in section 3.1.3. In addition, the quick response manufacturing of flexible AM technology, illustrated in 3.1.2., also impacts the SL value by building parts on demand, rather than stocking inventory. Through using part integration design, shown in 3.1.1., the quantity of parts produced per aircraft may also be reduced.

Due to the ability to directly impact aircraft maintenance through integrated part design and quick response manufacturing, AM offers substantial opportunities for aircraft spares and maintenance arena of the aerospace sector. As a corollary to this thought process, Walter et al., (2004) cite that "A fast repair and maintenance service is essential to keep the planes in the air, and this requires good availability of spare parts. But it is nearly impossible for an airline to have all the necessary parts in their own warehouse. This is evident when one considers that big commercial airplanes built by Boeing or Airbus are each made up of 4 million parts." Therefore, many infrequently sourced parts need to be stored for a long period of time which increases inventory holding and logistical costs. Using conventional production technologies it costs too much time and money to produce the required parts on demand (Walter et al., 2004). The annual cost of holding inventory is equal to the organization's cost of capital multiplied by the value of the surplus parts. This cost adds up to millions of dollars for a large airline.

Also, product requirements differ between civil and military sectors of aircraft platforms. From a top level system requirement standpoint, military requirements include lethality, maneuverability and survivability which are subjected to a volatile defense spending budget. This volatility increases supply chain holding costs of obsolete parts that are being redesigned for every cost reduction initiative cycle. On the other hand, the civil aircraft platforms include technical product requirements that are more in line with many sector-specific types of demand, such as safety regulation, standardization, operational and lifecycle issues (Williams et al, 2002). Therefore, emerging technologies, such as AM, offer substantial opportunities to normalize part production between civil and defense market segments by focusing on offering solutions to different part requirements via flexible manufacturing methods that respond quickly. This approach serves to quantify the issues that will surface while developing new systems by focusing on objective thinking surrounding the emerging technology. "Objective thinking…is a fundamental characteristic of the systems approach and is exhibited or characterized by emphasis on the tendency to view events, phenomena, and ideas as external and apart from self-consciousness" (Meade and Farrington, 2008). By marrying dynamic part requirements to new emergent flexible manufacturing systems, the benefits for substantial gains in efficiency for production may be met. This holds especially true via large economies of scale of large OEM's that offer multiple product platforms that extend to both the civil and military platforms.

Strategic inter-organizational networks aid organizations in gaining competitive advantages and improving production efficiencies. "Network organizations, virtual corporations, and value-adding partnerships are envisioned by many experts as the epitome of inter-organizational networks for the 21st century." (Talluri et al, 1999) These multi-organizational structures are viewed as a solution for rapid introduction of products and emerging technologies while maintaining high quality and minimal costs. In order to deploy an emerging technology effectively, a roadmap is necessary to ensure efficient planning of global integration of the technology for the entire global enterprise.

This is known as enterprise technology roadmapping[22]. Gindy et al., (2006) discuss specific needs for consistency among technology roadmapping tools; citing several sources of inconsistency between business and technology development strategies.

Named the University of Nottingham Technology Roadmapping Methodology (UNTRM), Gindy et al (2006) propose a six-step process for consistent technology roadmapping that includes:

1. Requirements Capture – Evaluation of component families and manufacturing capabilities
2. Benchmarking – A comparison of other manufacturing technologies among the emerging technology, base technology, key technologies, and pacing technologies
3. Technology Watch – Focuses on timeline fishbone diagrams that relay the technology development benchmarked with respect to time.
4. Project Generation – A collection of steps 1,2 and 3 above result in a project generated for an emerging technology
5. Project Evaluation – Each project is assessed with respect to four categories, benefit, investment, opportunity and risk.
6. Project Portfolio Management and Optimization – Includes an analysis of resource requirements that includes, human, manufacturing resources, knowledge, and finance. Also, an outlook for future funding opportunities exists.

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[22] A management tool that aims to improve the strategic technology planning process, by linking the acquisition of emerging technology to strategic objectives and associated business and market drivers (Gindy et al, 2006)

3.2.1. Evaluation of Additive Manufacturing. Addressing the steps listed in the University of Nottingham Technology Roadmapping Methodology for an emerging technology, such as AM, can be challenging for a large aerospace OEM. For example, capturing customer requirements listed in step 1 can be challenging if the customer is unaware of what the emerging technology can do. Instead, this research proposes an iterative stepped process method designed to assess the feasibility of AM technology from both the technical and economic standpoint for part candidate screening. This methodology integrates many steps of the UNTRM, with the exception of project portfolio management and technology watch, into a single iterative process that maps AM capability with component families (Step 1) and compares economic and technical feasibility of AM relative to conventional manufacturing (Steps 2&5) . The part screening methodology developed specifically for AM consists of two main phases, the technical evaluation and the economic evaluation. See § 6.1 for more detail.

3.2.2. Manufacturing Readiness. In order to appropriately deploy an emerging technology, such as AM, into an aerospace supply chain an OEM must be able to assess the maturity of the technology and its corresponding supply chain appropriately. Several methods exist to assess manufacturing process maturity. One of the most common methods is the Technology Readiness Level technique developed by the National Aeronautics and Space Administration (NASA) and widely used by the Department of Defense (DoD). Although TRLs have found acceptance as a measure of technology maturity, both in government and industry, the TRL falls short in assessing manufacturing capability. A concern with the TRL is that it is somewhat limited with respect to overall technology definition. The TRL matrix doesn't address the relative difficulty, or even the possibility, of improving to a higher maturity level and the risk associated with moving from one level to the next. A second shortcoming is that TRLs alone do not give a comprehensive viewpoint of a technology, or of the risks in adopting a particular technology to the needs of the customer requirement definition. As defined by NASA and the Department of Defense's Joint Manufacturing Technology Panel (2009), the TRL scale measures maturity along a single axis, the axis of technology capability demonstration. A full measure of technology maturity, or in the commercial world product maturity, would be a multi-dimensional metric capable of not only measuring the technology readiness, but also the manufacturing readiness and risk associated with graduating to separate levels.

The U.S. Department of Defense offers an alternative technique for a specific manufacturing process called the Manufacturing Readiness Level evaluated by the Manufacturing Readiness Assessment (MRA) process. The MRA approach evaluates manufacturing risk and maturity from the aspect of a manufacturing process.

According to the U.S. Department of Defense Manufacturing Readiness Assessment Deskbook, Manufacturing Readiness Level (MRL) definitions were developed by a joint DoD/industry working group to create a measurement scale that would serve the same purpose for manufacturing readiness as Technology Readiness Levels serve for technology readiness. Overall, the objective was to provide a common metric and vocabulary for assessing and discussing manufacturing maturity using an easy to use numbering system similar to the TRL.

Within the aerospace community, both TRL and MRL are used together to determine the capability of emerging technologies and the overall risk assessment of the proposed emerging technology. This risk is assessed using a Manufacturing Readiness Assessment. According to the U.S. Department of Defense MRL Assessment Deskbook, "A Manufacturing Readiness Assessment (MRA), is a structured evaluation of a technology, component, or manufacturing process. It is performed to define the current level of manufacturing maturity, identify maturity shortfalls and provide the basis for manufacturing maturation and risk management (planning, identification, analysis, mitigation, implementation, and tracking)." The research included uses both the MRL and TRL jointly to assess emerging technology within aerospace by combining risk cube metrics with readiness level assessment techniques.

3.2.2.1. Qualitative Evaluation. The initial assessment phase includes a qualitative evaluation of the emerging technology. This survey includes a TRL assessment and a MRL assessment which are recorded using a matrix format. This matrix format includes a snapshot of a point of time for the technology. Using a team of technology experts from within the company, each row within the matrix is weighted according to the priority listing of the criteria defined by the company developing the technology. This criterion acts as pass/fail gates to move to the next cell. As a result, each cell within the matrix is colored green, red or yellow to give a status indicator of the technology at the point of time. Green indicates the criteria for the cell has been met; yellow means it is in process and red indicates that the content within the cell has not been addressed. In this case, it is probable that the technology TRL will not equal the MRL of the technology in question. For example, a technology may be seen as technically ready at a TRL of 7-8. However, it may have no industrial base (suppliers) to support the technology, thus limiting the MRL assessment.

The qualitative method is a simple way to understand where a technology is relative to other technologies. As a living document, upper management for evaluation of several technologies at once prefers the qualitative format. However, due to the overwhelming cost of capital associative with new technologies and the potential impact these technologies will have on the global supply chain an evaluation of the technology should go deeper than the qualitative method.

3.2.2.2. Quantitative Evaluation. Using the same matrix format, a Pugh method adaptation may occur to recognize individual risk weights associated with each row identified in the matrix. Like TRL matrix charts, MRL matrix charts fundamentally lack the ability to project a level of risk to move from one column to the next. Therefore, a modification to the widely accepted Manufacturing Readiness Level has been performed to account for risk perception when assessing the MRL. The following equations have been derived to serve as a model for risk assessment of manufacturing maturation.

$$W_s = W_R * \left[i_r + .5\left(i_y\right)\right] \tag{21}$$

Whereas, W_s is the weighted score of each individual criterion (row) within the matrix, W_R is the individual risk weight assessed for each criterion, i_r is the number of red cells within the criteria row and i_y is the number of yellow cells within the criteria row. After each row is evaluated to determine a W_s, each are summed to define a total weighted score and normalized to the number of criteria evaluated. This summation effect is expressed in equation 22.

$$MRL_R = \frac{\sum_i^{\infty} W_s}{(i_c * 10)} \quad (22)$$

Whereas, MRL_R is the total relative amount of risk associated with maturing the manufacturing process, or MRL risk. i_c is the number of criteria (rows) being evaluated.

W_R is assessed by the developing technology subject matter experts with regard to the manufacturing technology being evaluated and is scaled from 2-10. This risk assessment method is an adaptation of the standard risk cube method (Coleman, et al. 2006) as shown in Figure 3.13.

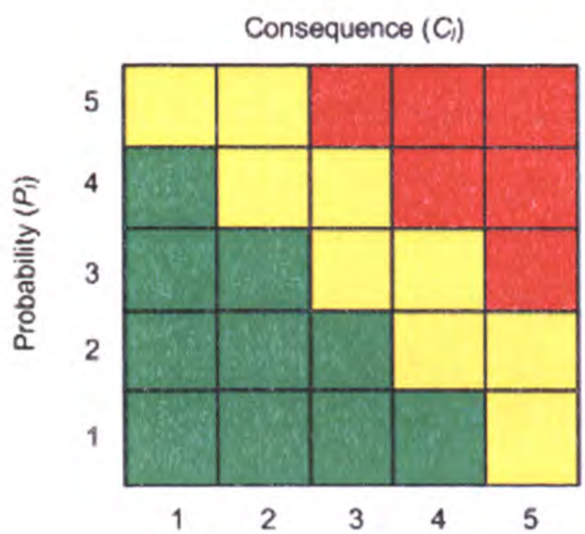

Figure 3.13. Risk Cube Evaluation Method

Offering 2-10 as a scale helps offer more fidelity in the amount of risk being assessed. To calculate the amount of risk being assessed, this research proposes a simple approach to developing (W_R) by adding the Probability Level (P_I) and the Consequence Level (C_I).

Tables 3.12 and 3.13 indicate the definition of risk associated with (P_I) & (C_I).

Table 3.12. Probability Level of Risk (P_l)

Probability Level (P_l)	Definition of Risk
1	Little to no likelihood
2	Low to Medium likelihood
3	Medium likelihood
4	Medium to high likelihood
5	High likelihood

Table 3.13. Consequence Level (C_l)

Consequence Level (C_l)	Schedule	Cost	Technical
1	No Impact	No Impact	No Impact
2	Slip 1 Month	< 1% of Budget	Minor Technical Setback
3	Slip 1 Month on Critical Path	< 5% of Budget	Moderate Technical Setback
4	Critical Path Delayed > 1 month	< 10% of Budget	Major Technical Setback, Alternative Option Available
5	Critical Path Delayed > 6 months	> 10% of Budget	Major Techical Setback, No other Options Available

Upon review of the Consequence Level and Probability Level for each criterion, each assessed level score is added to form W_R, the weighted risk for each row.

$$W_R = C_l + P_l \tag{23}$$

As shown in Table 3.14, the risk weights column (W_R), is at the far left hand side of the matrix. Each row within the Weights column now is scored from 2-10 using Equation 23, the score of 10 being most critical risk associated with technology evaluation, note that the risk weights are not scored relative to each row, rather each row is evaluated independently. Also, a column is added with a Relative MRL Score column, (W_S), on the far right of Table 3.14.

Table 3.14. True MRL Risk Evaluation Table Example

		FDM Manufacturing Readiness Level Assessment										
Threads	(W_R) Weighted Risk (C_I + P_I)	1	2	3	4	5	6	7	8	9	10	(Ws) Relative MRL Score
1. Technology (From TRL Assessment)	8	Green	Green	Green	Green	Green	Green	Green	Yellow	Red		12
2. System Design for Modularity	4	Green	Green	Green	Green	Green	Green	Green	Yellow	Red	Red	10
3. Materials	3	Green	Green	Green	Green	Green	Green	Yellow	Red	Red	Red	10.5
4. Cost and Funding	7	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	Red	38.5
5. Process Capability and Control	6	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	Red	33
6. Quality Management	9	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	Red	49.5
7. Operator Training	4	Green	Green	Green	Green	Green	Yellow	Red	Red	Red	Red	18
8. Facilities Installation	5	Green	Green	Green	Green	Green	Green	Yellow	Red	Red	Red	17.5
9. Manufacturing Management (ERP System)	3	Green	Green	Green	Green	Green	Green	Green	Yellow	Red	Red	7.5
											MRL Subtotal	196.5
											True MRL Risk	2.18

The Relative MRL score is derived from a simple technique. The scoring technique is as follows: each red cell with criteria listed in the cell is worth 1 point for every cell in each row, each yellow cell is worth 0.5 point, and each green cell is worth 0 points. Each row is summed and multiplied by the perceived risk weight (W_R).

For example, the first row in Table 3.14 concerns the TRL level for the manufacturing technology advancement being evaluated. This effort is currently evaluated at a MRL of 7 with work being done to move to 8, as indicated by the yellow cell. The W_R is currently assessed at a risk weight of 8. This risk rationale is based on the P_I of 2, which is a low to medium likelihood of risk associated with the MRL advancement to 7 and the C_I of 5 based on a proposed schedule slip of over 6 months and/or a 12% budget overrun to advance to MRL of 8.

Also in Table 3.14, row 1 is red in MRL level 9, and 10 is not used as the TRL scale is capped at 9 levels. Thus, using Equation 1, the W_s for the first row is calculated as $W_s = 8 * [1 + .5(1)]$. This process is repeated until all of the rows are evaluated. The relative MRL Subtotal score is summed to a value of 196.5 for the entire matrix. Finally, in order to normalize to other MRL charts that may have a lower or higher number of rows, the sum of 196 is divided by the number of rows being evaluated multiplied by 10, in this example 9 rows are evaluated. The true MRL risk score would then be 2.18, or 196.5/90.

If all technologies are evaluated using the same criteria listed in Table 3.14, then a relative risk-maturity comparison can be obtained among several technologies at once. The higher the true MRL risk score, the higher the perceived risk of maturing the manufacturing technology to full production standards.

4. ROBUST DESIGN FOR ADDITIVE MANUFACTURING

4.1. DOE SELECTION METHODOLOGY

When evaluating emerging technologies for supplier deployment, process optimization plays a key role in ensuring that the technology is optimized prior to manufacturing production deployment into the supply chain. It is recommended to establish the robust design phase hand in hand with potential and current suppliers of the emerging technology. There is a twofold reason for involving the supplier and OEM in the robust design process. First, verification of the process by both the OEM and emerging supplier allows for common learning of an otherwise immature process. Second, a larger data pool may be extracted for use in the designed experiments if both the OEM and supplier execute the same Designed Experiments. This data pool exposes process repeatability between the OEM and supplier.

The Taguchi system of process parameter design was used to characterize dimensional instability within the SLS process. A traditional process improvement method is design, build, and test the process. This is conducted to solve symptoms of process variations. According to industry experts Taguchi and Clausing (1990), this method of process testing is time consuming and inefficient. Another approach would be to test every variable within the process, resulting in a full factorial experiment (Kiemele et al., 1999). Although very exact, this process is very time consuming and the opportunity costs of the process being ready for production would prove inefficient.

The ideology of the Taguchi system focuses on energy transformation of the process and incorporates noise reduction, not symptom solving. This is achieved through a two-step optimization of product parameter design. The first step is to reduce variability within the system, and then, shift the now tighter variability on target to the mean. This proactive approach eliminates as much noise as possible early in the design phase. Taguchi methodology has been extensively used by the injection molding industry to enhance the robustness of the injection molding process (Oktem et al., 2007; Huang and Tia, 2001; Tang et al., 2006; Berginc et al., 2006). Within the Taguchi system of quality, there exists several elements. One of the main elements is the quality loss function, discussed in § 3.1.1.1. This theory application achieves the following:

1. The QLF quantifies dollars lost due to manufacturing tolerance variation during production. This particular theory applies to SLS by examining the tolerance variation of the existing process.
2. The loss function may be used to quantify the process quality. Applies to SLS by looking at build repeatability.
3. The loss function may be used to compare the expected cost of quality relative to the manufacturing cost. Used to compare SLS quality loss relative to a more mature manufacturing method.

In order to apply the quadratic loss function, a series of Design of Experiments was constructed and analyzed according to Taguchi methods. As a result of these experiments, two main metrics are established – the static signal to noise (S/N) ratio, Equation 24 and the dynamic signal to noise (S/N) ratio, Equation 25 (Fowlkes and Creveling, 1995).

$$S\ /\ N_{TypeI-NTB} = -10\log\left[\frac{\bar{y}^2}{S^2}\right] \tag{24}$$

$$S/_N = 10 \log \frac{\beta^2}{MSE} \tag{25}$$

In the SLS testing, an S/N ratio measures overall dimensional stability robustness in the form of a value. An S/N ratio produces a numeral, in which case, the higher the numeral, the better. The static S/N test used one signal factor input, in this case, the vector sintering of nylon powder. However, the response is not directly associated with the input, allowing the control and noise factors to vary to find an optimized point. These noise factors and control factors are essentially variables identified in the SLS process. The quality characteristic is the objective of the experiment. In the static experiment, the quality characteristic is dimensional accuracy of parts. Since deviation from dimensional target by percentage is the objective of the static case, Equation 24 represents the nominal is best, type I case. Where, $\bar{y}^2$ represents the mean squared and S^2 represents the variance of data.

The dynamic S/N test, defined in Equation 25, may use several signal factor inputs, in this case, changes in laser wattage and relates to the slope, β, of the quality characteristic over the mean square error (MSE). The dynamic test includes the same noise factors, control factors, and quality characteristics as the static S/N test, only at optimized levels. The static S/N test was run prior to the dynamic S/N test in order to determine the scale of variability that inherently exists in the SLS process.

4.1.1. DOE Setup of SLS. In an attempt to characterize the entire build volume, large amounts of data were harvested to illustrate the impact of dimensional variation. Because of immediate need to characterize an emerging AM technology prior to supplier deployment, there is a desire to discover what variation exists within the process. Within this document, a technical illustration is provided to highlight how production techniques like the Taguchi method of product parameter design may be applied to an immature process control scenario of the SLS system. Using the Taguchi system for the SLS process speeds the development cycle of production quality by reducing variability, while at the same time reducing the cost of SLS parts to the industry via scrap reduction.

4.1.2. Static Problem Description. The particular machine that will be analyzed within this document is the 3D Systems Vanguard High Speed with the Hi-Q upgrade. This specific system represents a popular SLS system that is currently being used as a production platform throughout the various industries mentioned in § 1.1.2.

The SLS process is in its infancy with respect to more mature mass production methods such as numerical control machining, injection molding, etc. As a result, more research needs to be completed to accurately gauge what physical transformation occurs to achieve the ideal function. Through fault tree analysis, A.16-A.19 highlights many variables identified in the SLS process.

There are two high level ideal functions regarding the SLS process. The first ideal function is dimensional accuracy of parts produced in the process and the second being suitable mechanical properties of parts produced in the process. A common noise that is shared between the two ideal functions is thermal instability.

The SLS process can vary thermally within the X,Y,Z build envelope. Figure 4.1. depicts a random sampled color map image of an X-Y cross sectional area of the build envelope. The thermal map shows a cooling effect in the blue corners and too much heat in the center area of the X-Y cross section. The thermal inconsistency is a direct function of heaters that are not directed properly to areas within the SLS process.

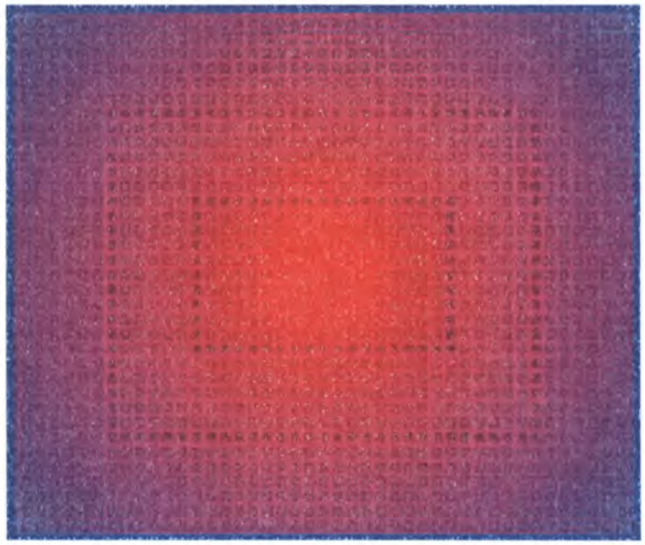

Figure 4.1. Thermal Inconsistency of the SLS Build Plane

Using the Taguchi system of quality engineering, a set of simulation builds is constructed to assess the impact of thermal variation to part dimensions. Not only is thermal inconsistency dramatic in the X-Y plane of the build envelope, but it is also noticeable throughout the Z-axis as well.

4.1.3. Dynamic Problem Description. Similar to plastic injection molding, the SLS process relies on its process to produce geometrically stable parts. Also similar to injection molding, the dimensional variation of these parts is a function of the geometry size and cooling rates. A main selling point of the SLS process is the ability to build very different geometry with varying cross-sections within the same run. However, Z-axis thermal instability is influenced by the amount of thermal mass of parts constructed within the SLS batch. For example, the more laser scanned cross sections change within a build volume, the more thermal inconsistency in the Z-axis, shown in Figure 4.2.

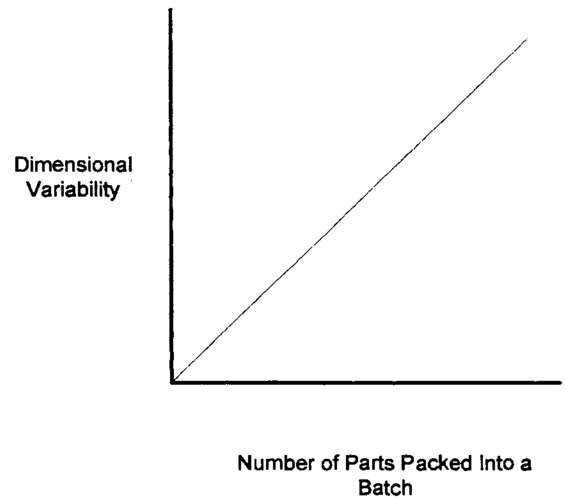

Figure 4.2. Dimensional Variation of Thermal Mass

This ability allows for flexible production, however, at the same time increases process variability, Figure 3 illustrates this relationship. Using the Taguchi system of Quality Engineering, the dynamic simulation will characterize this instability.

The main focus of the analysis is the characterization of SLS process in the X-Y area with respect to the Z direction. The overall goal of the simulation should yield the optimum area of the build envelope that expresses the least amount of dimensional variation.

4.2. THE STATIC EXPERIMENT

The P-diagram in Figure 4.3 depicts the relationships between signal factors, control factors, and noises and how they interact to produce quality characteristics. The main quality characteristic identified is dimensional stability of a part sintered in the SLS process. The ideal function is to achieve on-target nominal dimensional performance relative to the X,Y,Z planes of a part.

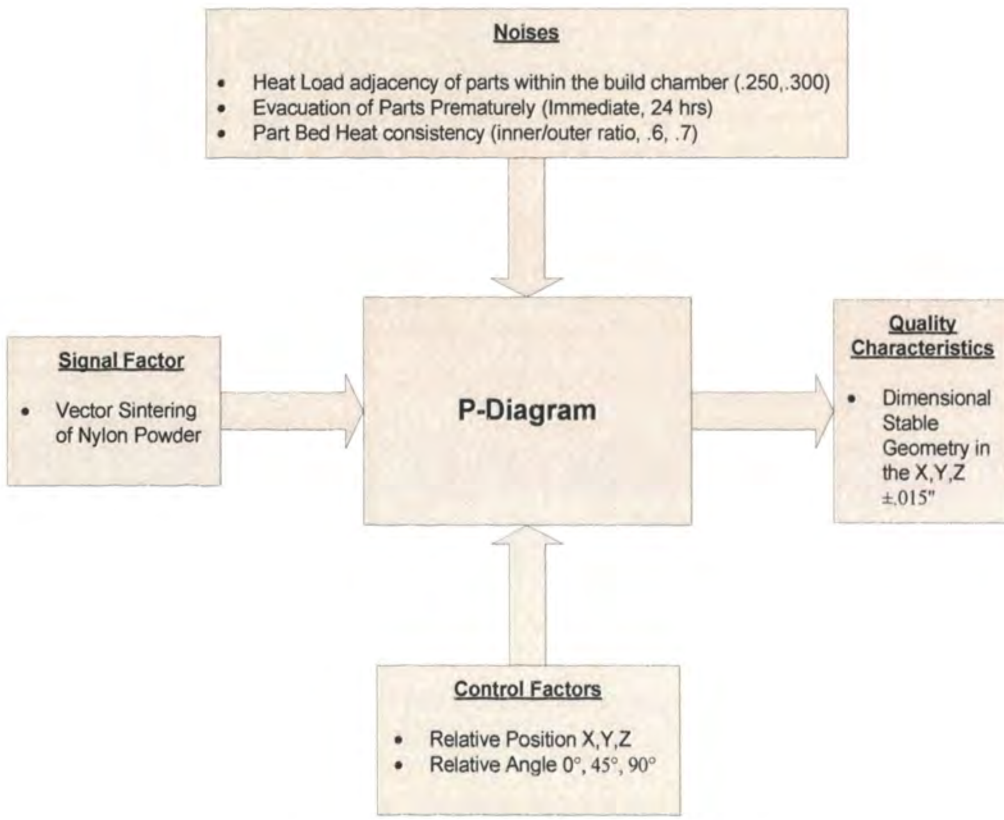

Figure 4.3. SLS Static Test P-diagram

4.2.1. Purpose of the Static Test. The main purpose of the static experiment is to highlight the dimensional variation that exists within the build envelope while subjected to a series of compound noises within the process. Once completed, the testing will reflect just how much variation exists in the presence of the noise conditions. Once determined, two-step optimization will reduce the variation and move the dimensional variation on target by using scaling algorithms associated with the software. Refer to the initial FAST diagram in A.7 for more information.

4.2.2. Signal Factor. One main signal factor exists to execute the SLS process. The signal factors identified include CO_2 laser energy input, controlled with analog galvanometer mirrors, which result in vector lasing of Nylon 80 micron powder.

4.2.3. Control Factors. The control factors identified simulate real world part positioning within the SLS build envelope. As CAD geometry is imported into the SLS software, the user controls where these objects are placed within the build envelope. The operator defines the X,Y,Z relative location of the part, as well as the angle of orientation.

4.2.4. Noises. As SLS is a relatively immature industry, there are many noises identified with the process. However, due to time considerations, only the thermal noises are taken into account. The first noise is premature evacuation of the build cake. Often times, the machine will allow a user to remove the build cake for part evacuation too early. This is a function of the temperature sensors measuring temperature at only the top and sides of the build cake. If large and thick parts remain in the part cake, the user may inadvertently remove the cake while the internal part of the cake is too hot, thus resulting in warped parts.

The second noise is heat load adjacency. If two parts are spaced too close together, the extra heat produced from the adjacent 'part B' will affect the dimensional performance of 'part A'; the third noise is uneven heating of the build envelope during the SLS build process. Attributed to the inconsistent output of the part heaters, uneven temperatures are a function of misdirected thermal energy.

4.2.5. Quality Characteristic. The ideal function is the dimensional stability of a processed SLS part in the X,Y, and Z. Current specifications hold the SLS process at ±.015" in X and Y.

4.2.6. Experimental Plan. A design of experiments was constructed to simulate variability within the build envelope. A three level - L18 orthogonal array was chosen to mimic the control factors in the outer array. The particular array was chosen to take advantage of the engineering distinction between the control and noise factors in the p-diagram listed in Figure 4.3. In addition, the array was chosen to highlight the various noises that naturally compound within a build.

Upon choosing the array, a representative geometry was designed to encompass the X-Y build plane. The intention was to construct a geometry that was easily measured. Figure 4.4 illustrates the sample geometry divided into 3 zones. The blue indicates zone 1, the area between the red and blue indicates zone 2 and the area between the outside edge and the red indicates zone 3. These zones will be represented as levels in the array.

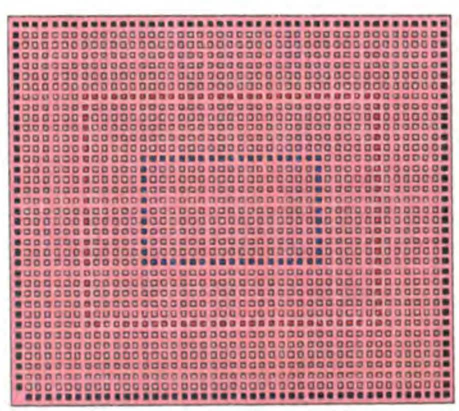

Figure 4.4. Dimensional Accuracy Test Specimen

The Z sample part characterizes the dimensions expressed within the Z direction. These Z sample parts will be placed within the zones described above to reflect the 3 levels of the orthogonal array. Pictured below in Figure 4.5 is a Z sample part.

Figure 4.5. Z-Axis Test Specimen

The angled specimen characterizes the dimensions expressed as a part that is orientated at 0°, 45°, and 90° relative to the X-Y plane. These angle sample parts will be placed within the zones described above to reflect the 3 levels of the orthogonal array. See Figure 4.6 below for the angle samples.

Figure 4.6. Angled Specimen

Figure 4.7 illustrates a sample build setup prior to processing in the SLS machine. Note the strategic placement of the Z-axis and angled test pieces in the top of the build. The build envelope Z orientation of these parts captures the thermal performance of the cylinder heater, which only is banded in the upper portion of the build chamber. The individual zoned plates are placed directly on top of one another to represent eighteen individual parts within a build volume. Each plate is to be measured with respect to dimensional variation from each individual peg on each plate.

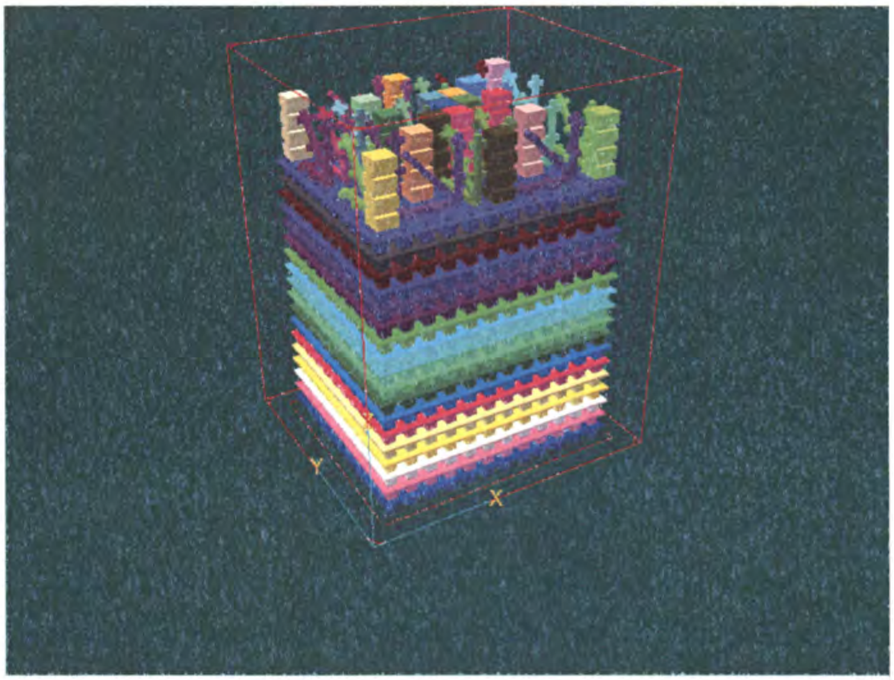

Figure 4.7. Screenshot of SLS Batch Setup

The control factors listed in § 4.2.3 are represented in the L18 orthogonal array. The 1,2,3 levels are zoned areas of the X-Y build area, shown in Figure 4.4. The X,Y,Z paremeters represent measurements in each direction and the angle control parameters are also measured in the same zoned levels. For example, part number 1 will be measured in zone 3 in the X direction, zone 1 in the Y direction and zone 1 in the Z direction. In addition, part number 1 will also be measured in zone 1 with respect to each axis of the geometry shown in Figure 4.5 and 4.6. See Table 4.1 for an example of the orthogonal array.

Table 4.1. L18 Orthogonal Array

Part #	Control Factors					
	X	Y	Z	Angle - 0	Angle -45	Angle-90
1	3	1	1	1	1	1
2	3	1	2	2	2	2
3	3	1	3	3	3	3
4	1	2	3	1	2	2
5	1	2	1	2	3	3
6	1	2	2	3	1	1
7	2	3	3	2	1	3
8	2	3	1	3	2	1
9	2	3	2	3	3	2
10	3	1	1	1	1	3
11	3	1	2	2	2	1
12	3	1	3	2	3	1
13	1	2	1	3	1	2
14	1	2	2	3	1	2
15	1	2	3	1	2	3
16	2	3	1	3	2	3
17	2	3	2	1	3	1
18	2	3	3	2	1	2

4.2.6.1. Noise Factor Simulation. The first noise is premature evacuation of the build cake. Indicated by a 'High' and a 'Low', two levels of noise will be reflected in the L4 inner array. In the 'Low' designation the part cake will be allowed to cool an additional 24hrs past the build time. This is a common practice in industry to negate the effects of premature evacuation of parts. In the 'High' designated test, the part cake will be evacuated as soon as the machine allows – this should result in oxidization of the parts within the nylon powder.

Concerning the second noise, heat load adjacency, the spacing between samples is adjusted to represent a high and a low noise designation. At the 'High' level, the spacing will be .250" between the parts. The 'Low' setting will represent part spacing at .300".

The third noise, uneven heating of the part bed, will be simulated by adjusting the inner/outer heat ratio of the heaters during the build. In the 'High' level, the heaters will have a ratio of .5. In the 'Low' level, the heaters will have a ratio of .6- a typical default setting. Pictured in Table 4.2 is the noise factor outer array of the orthogonal array.

Table 4.2. Noise Factor Outer Array

Noise Factor Conditions				
Uneven Bed Temps	L	H	H	L
Heat load adjacency	L	H	L	H
Time to Cool	L	L	H	H
Run #	1	2	3	4

The target value for the quality characteristic is ±.015" in the static experiment. As shown in Equation (24), the Type I Nominal-the-Best form of the signal-to-noise (S/N) ratio was used.

In summary, six 3-level control factors were used, and three 2-level noise factors were used in the static experiment. Therefore, a L18 inner array and L4 outer array was used, which required the collection of 72 data points. If a full-factorial experiment were run, it would requires 1,152 data points. The orthogonal arrays are much more efficient. The completed experiment data is reflected in Appendix A.8.

4.2.6.2. Scaling and Two-Step Optimization. Like most rapid prototyping technologies, Selective Laser Sintered parts shrink when cooled to ambient temperatures. In order to compensate for this unwanted effect, the SLS software is equipped with the ability to scale solid models up past their nominal sizes. The amount of scaling is determined within the software during a screening test and is largely based upon the amount of x-sectional mass within the part. Once identified, the scaling factor is applied to the solid model in the X,Y, and Z dimension. For the purpose of this test, the software scaling feature was used to place the mean on target after the variation is reduced, thus resulting in two-step optimization. The screen-shot of the software in Figure 4.8 illustrates the scaling input.

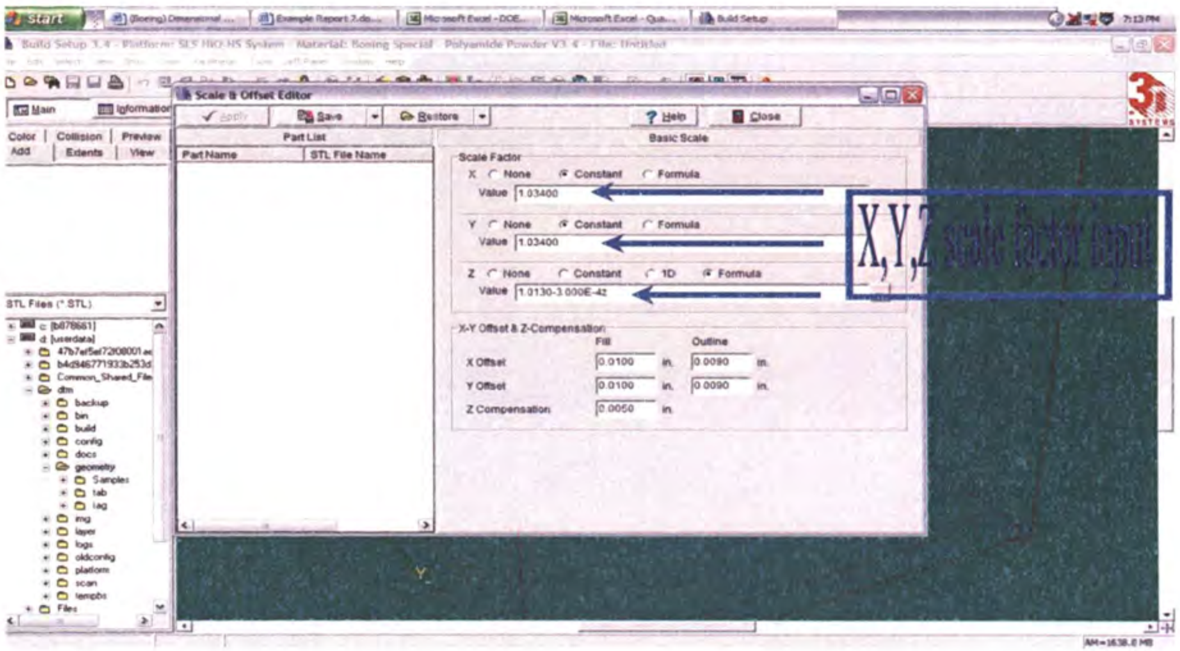

Figure 4.8. Screenshot of Geometry Scaling Software

4.3. THE DYNAMIC EXPERIMENT

Much like injection molding the SLS process is subjected to variability in the process without knowing geometric scaling relative to part mass. Currently, the process specifies ±.015". However, dimensional variation will occur due to changing X-sections of parts within the build envelope. As a result, varying thermal characteristics of parts will be illustrated as parts are built from thick, to thin, to thick cross sections.

In order to simulate thermal variance within this experiment, laser fill wattage was selected as the M in the equation, y = βM. See Figure 4.9 below. Specifically, M1 through M3 will represent laser fill wattages that range in 5W increments between 45W to 55W. These fill wattages were chosen based upon previous screening experiments established.

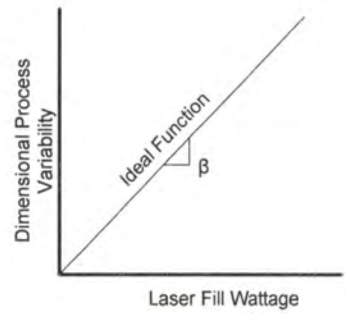

Figure 4.9. Dynamic Ideal Function

The p-diagram for the dynamic experiment is developed and shown in Figure 4.10.

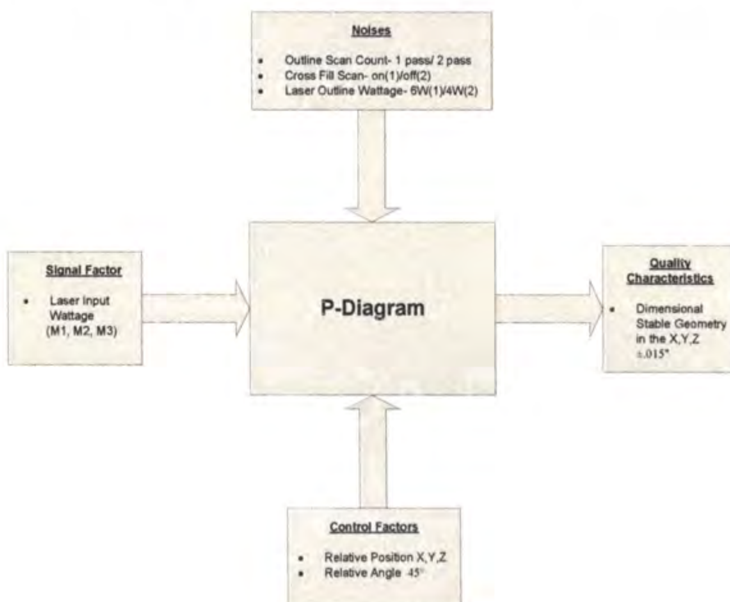

Figure 4.10. Dynamic Experiment P-Diagram

4.3.1. Experimental Plan. Many settings may be changed within the SLS process. The freedom of changing settings allows for more robust optimization, however, changes must be bridled to prevent variation chaos. The noise factors selected in Table 4.3 are during the build setup stage of the process.

Table 4.3. Noise Factor Selection – Dynamic Test

	Outline Scan Count- 1 pass/ 2 pass	Cross Fill Scan- on(1)/off(2)	Laser Outline Wattage- 6W(1)/4W (2)
Noise Factors	D	E	F
N_1	2	1	2
N_2	1	2	1

Outline Scan Count is the number of times the outline laser scans the perimeter or circumference of geometry. As an unknown effect on dimensional performance, the outline scan count will be set to two scans and one scan for N_1 and N_2 respectively.

Cross Fill scan is a feature that allows for a perpendicular scan direction at each indexing layer. As a noise factor, current knowledge bases are unknown for how much the setting cross fill scan impacts dimensional integrity of geometry. At default, the cross fill scan is set to on, with the high noise (2) set to off.

The Laser Outline Wattage sets the amount of wattage the laser is set to as it scans the outline laser. 6 Watts is typically the default. The unknown is what the dimensional impact is on parts when the wattage is decreased to 4 Watts.

These compound noise factors will interact with varying ranges of laser fill wattages acting as signals M1, M2, and M3. The target wattage shall be 55W and be represented by M2. However, due to laser degradation, the actual wattage input used during the test is 57.5W as M2. By using compound noise factors, the dynamic experiment should be completed more efficiently. See Appendix A.10 for Orthogonal Array Setup of the Dynamic Experiment.

4.3.2. Test Specimens. The test consisted of six boxes placed within the build chamber, shown in Figure 4.11. The purpose of the box design is to offer a method that easily segregate parts with different process parameters applied. The boxes are designed with holes in them for easier powder evacuation once the parts are completed. A bead blaster evacuates the powder with ease, just leaving the parts inside remaining. The box was then band sawed opened, pouring the parts out.

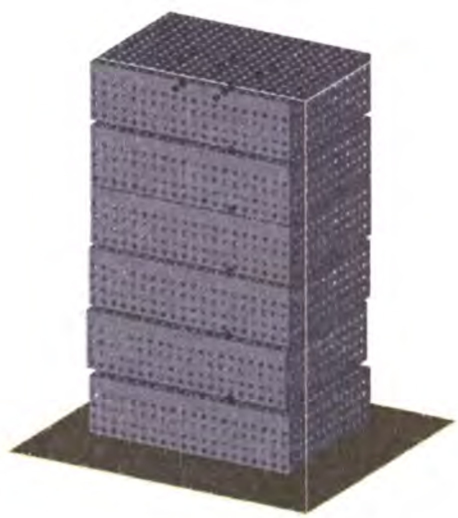

Figure 4.11. Batched Build Setup of SLS

Each individual box contains parts oriented per the specified control factors, (X,Y,Z, and angled). For an example of the nesting of parts in the box, see Figure 4.12. Each box is labeled M1-N1, M1-N2, M2-N1, etc. This allows each noise factor to be applied to all of the parts and the box without mixing of the tested parts.

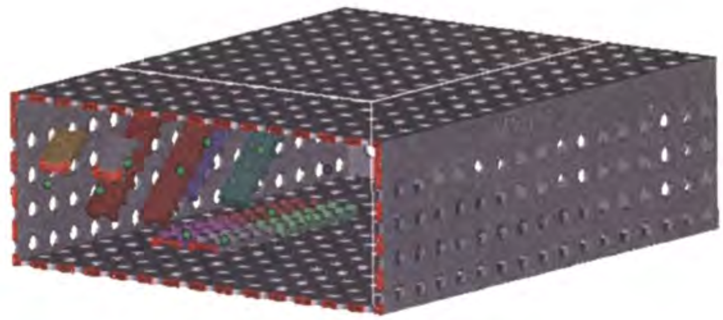

Figure 4.12. Cross Section View of Parts within Box

4.4. ROBUST DESIGN FOR FDM

A need for characterization arises from a desire to move RP to rapid AM. FDM is a relatively simple process of extruding an amorphous polymer filament that has been wound on a spool. The extrudate path is then numerically controlled and the filament deposited layer by layer to achieve a 3D part. Because of FDM's relatively simple process, a certain amount of processing robustness is inherently built into the system. However, in order to transition into AM, a need has risen to define the known variables within the process to produce more quality parts with less variation. However, when a problem is noticed in the extrudate, it is difficult to determine the source and location of the problem without control instrumentation (Rauwendaal, 2001).

A critical element of emerging technology development, the main goal associated with this study involves a thorough characterization of FDM. Under the overall arching goal of characterization, several objectives are associated with this study. Objective (1) is to identify signal factor and quality characteristic associated with the FDM process. Objective (2) is to identify the known control and noise factors associated with the process. Objective (3) would quantify the amount each identified control factor plays in the robustness of the FDM process. By understanding the percentage of contribution that each control factor plays in the system robustness, this will help advance the field of knowledge regarding process improvements and demonstrate a methodology for emerging technology deployment into a supply chain. Objective (4) is to understand the amount of void density inherently generated within the FDM process. Objective (5) covers a throughput study that mathematically discovers which material, (ABS, PC, PPSF) processes the fastest and by exactly how much. In addition, objective five will also investigate tip clogging issues as tip change also adds to the build time. Ultimately, by thoroughly understanding throughput restrictions, economic decisions may influence material selection. The final objective, (6), covers identifying processing restrictions within the system as suggested areas of improvement. These areas of processing improvement shall then be submitted to Stratasys for future machine enhancements. These future machine enhancement recommendations will assist an effort to transition Rapid Prototyping to Rapid Manufacturing. However, due to research brevity, objectives five and six are omitted from this research.

4.4.1. Experiment Methodology. To fully understand the FDM process variability relative to material systems, a methodology shall be developed to organize a plan for the development effort. This methodology is specific to FDM but also acts as an example for all emerging technologies by highlighting how individual control elements are investigated to determine process characterization. Figure 4.13 illustrates the methodology used for this testing. In Figure 4.13, the goals addressed above are highlighted as boxes and the vehicle used to achieve each goal are hexagons.

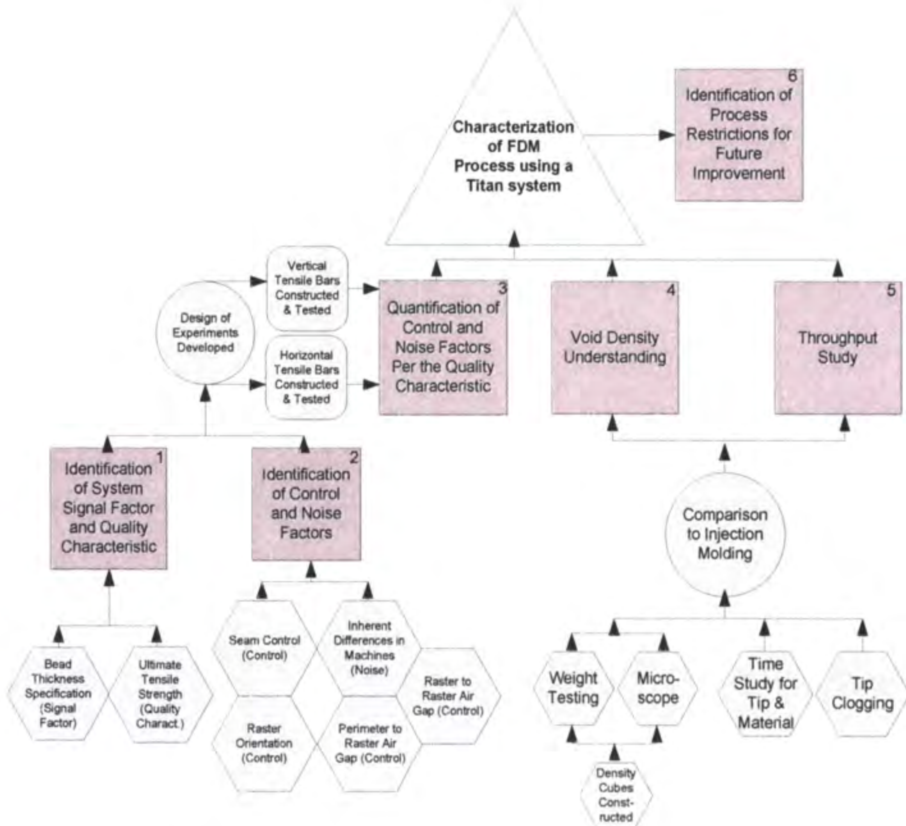

Figure 4.13. Characterization Road Map Design

4.4.2. FDM Process Variability. Many variables exist within the Fused Deposition Modeling process. FDM is one of the most plug-and-play rapid manufacturing systems offered. Unlike other rapid manufacturing processes such as Laser Sintering and Stereolithography, Stratasys, has taken the strategic position with FDM to allow the end user to manipulate few critical features needed to construct a 3D solid. This type of approach is both good and bad for an end-user of the equipment. From a positive standpoint, the lack of user controls leads to an overall more robust system; conversely, the machine is somewhat restrictive for research and development of process improvement.

This section will focus on only the variables that are allowed to be controlled by the end user. The understanding of performance variables represents a critical element of technology development and will fabricate a designed experiment to quantify the amount of interaction and percentage of contribution each variable plays in the robustness of the quality characteristic. Despite "user-only" control, Agarwala et al. (1996) have defined many variables, Table 4.4 lists variables by different functions within the process.

Table 4.4. FDM Variables by Function

Operation specific	Machine specific	Materials specific	Geometry specific
Slice thickness	Nozzle diameter	Powder characteristics	Fill vector length
Road width	Filament feed rate	Binder characteristics	Support structure
Head speed	Roller speed	Viscosity	
Extrusion temperature	Flow rate	Stiffness (column strength)	
Envelope temperature	Filament diameter	Flexibility	
Fill pattern		Thermal conductivity	

Some of these variables may be manipulated by the end user of the machine and others may only be manipulated by the machine manufacturer, Stratasys. The parameters available to be manipulated only by the user include:

- Road Width (Raster and Contours)
- Raster Angle (Fill Pattern)
- Seam Control
- Perimeter to Raster AirGap (Road Width Placement)
- Raster to Raster AirGap (Road Width Placement)

The goal of the experiment was to determine how test specimen tensile strength is affected by changing selected design and process variables for the FDM. The variables selected for this experiment were chosen from a larger set based on the experience of The Boeing Company and knowledge of the researchers such as Comb et al. (1994); Rodriguez et al. (2000).

The next step in setting up the DOE is to determine the resolution for the experiment and the number of levels for each variable. It is expected that a linear relationship exists between the response, tensile strength, and road width (bead) variables, see Figure 4.14.

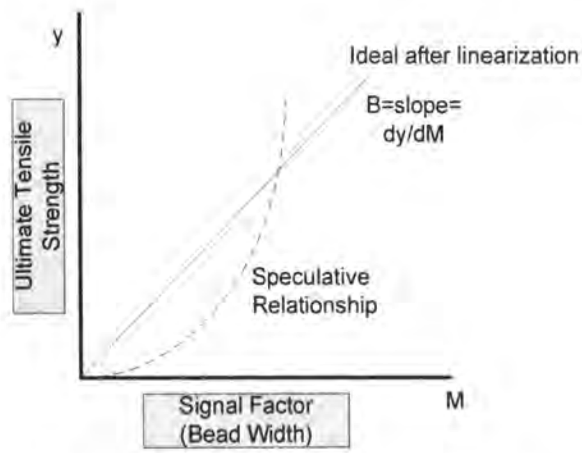

Figure 4.14. UTS with respect to Bead Thickness

Three signal levels are set high (M1), and one set low (M3) and one set to medium (M2). In order to set the appropriate levels, preliminary tests were conducted for each variable to define its range. Each variable was adjusted independently, and the tensile strength was measured. The results of these preliminary tests provided the settings for the levels of each parameter. The p-diagram is shown in Figure 4.15.

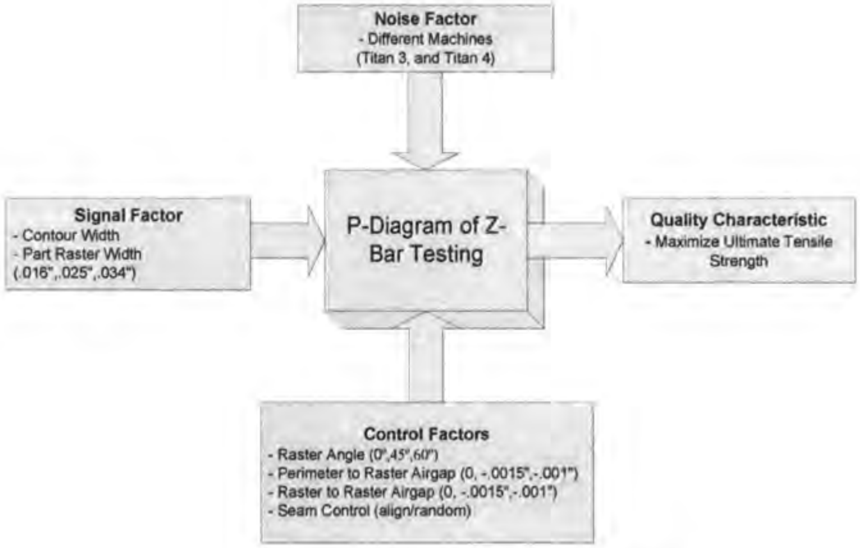

Figure 4.15. P-Diagram for FDM

4.4.3. Signal Factor Selection. A signal factor is an input factor that adjusts a system based upon engineering analysis of a system. Previous research conducted in the field of FDM strength optimization by Comb et al. (1994); Agarwala et al. (1996); and Rodriguez et al. (2003) indicate that two of the most significant inputs to FDM processing are the Contour Width and Raster Width settings. For the purpose of this study, these two separate variables are grouped together to form a single signal factor known as "Bead Width". By grouping these two variables into one signal factor, the DOE will become less complicated as opposed to two signal factors. In addition, from a structural standpoint, the contour and raster pattern would mostly like be changed in tandem (Pandey et al. 2002; Ahn et al. 2003).

The native software program, Insight, which accompanies the FDM process, allows a spread of .018" thickness differences. Three different widths, .016", .025", .034" will be regarded as signals to encompass the full range of width selection choices.

4.4.4. Control Factor Selection. Control Factors were chosen based on the availability of user controlled parameters. These controlled parameters include, raster angle, seam control, perimeter to raster air gap, and raster to raster air gap. Other known variables are inherent in the systems, however, these variables are locked out by the Stratasys for both diagnostics repairs and research by their support staff.

4.4.5. Raster Angle. The first selected control factor is known as raster angle. Raster angle is defined as the relative angle placement of contours in the Z direction. It is widely known that the raster angle may contribute to positive mechanical properties of FDM (Kulkarni and Dutta, 1999; Ahn et al. 2003; Rodriguez et al. 2003), however, it is not known by what percentage it is affected per each material system. Figure 4.16 indicates different raster angle configurations and differences between inter and intra layer bonding.

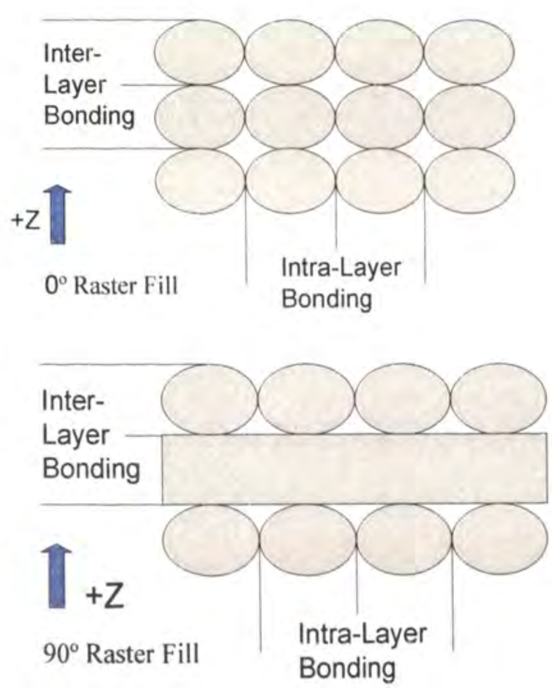

Figure 4.16. Raster Angle Definitions

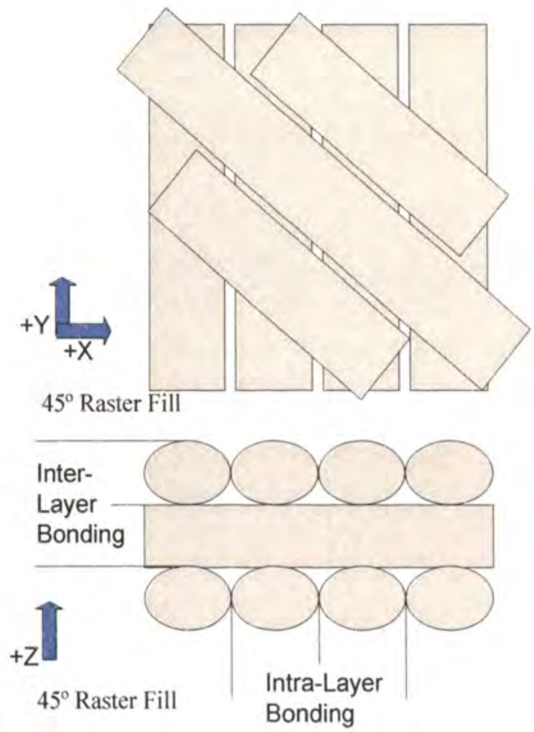

Figure 4.16. (Continued) Raster Angle Definitions

4.4.6. Perimeter to Raster Gap. The next control factor allowed for adjustment is perimeter to raster air gap. This feature is defined as the amount of bead overlap between the interior fill material and the outside contour of a planar cross section. By lowering the airgap value, theoretically, the user is creating more overlap and reducing the voids between the raster pattern and the outside contour.

4.4.7. Raster to Raster Gap. Another control factor would include raster to raster air gap. This factor is defined as the amount of interstitial bonding among horizontal fill rasters. By reducing the raster to raster airgap, more overlap should create fewer voids in the process. If the airgap is reduced, then too much backpressure may occur in the deposition process and result in clogged deposition tips. Figure 4.17 illustrates raster to raster airgap.

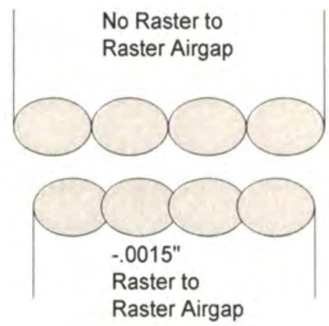

Figure 4.17. Raster to Raster Gap

4.4.8. Seam Control. The final control factor is known as seam control. When a part file is analyzed in Stratasys' Insight software, toolpaths for deposition is created. If seam control is set to random these toolpaths start and finish at different relative z axis locations during a part build. This randomization effect is shown as the white arrows in Figure 4.18.

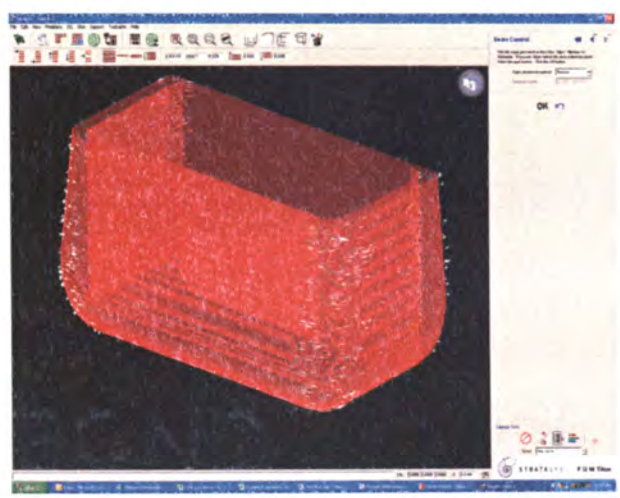

Figure 4.18. Random Seam Control Illustration

If the seam control is set to aligned, which is always the default, the toolpath starts and stops at the same relative Z axis locations. The aligned software feature is shown in Figure 4.19.

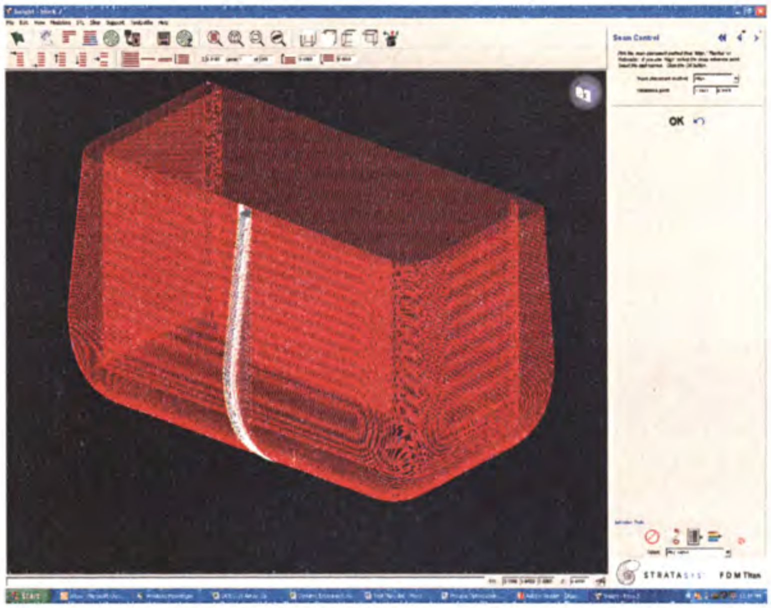

Figure 4.19. Aligned Seam Control

Very similar to a knit line in injection molding, from a mechanics standpoint, aligning the seam in the same relative Z-axis location may leave an inconsistent structurally weak seam within the part. It is postulated that randomizing the seam location in the Z-axis may yield stronger z axis tensile properties.

4.4.9. Noise Factor Selection. For this experiment, the noise factor will be the inherent variable difference in building between two separate FDM Titans. Each machine manufactured date is more than one year apart and each machine has very subtle design changes between the same model machine. Some of these design changes include different wiper gasket designs, firmware software versions and other factors only known by Stratasys. These subtle design differences will be the basis the noise in the parameter optimization experiments.

4.4.10. Density Study. Tensile strength of FDM is directly related to the amount of voids present in the geometry. As a result, a void density study was conducted to understand how much porosity exists within the FDM process. In order to determine void differences among bead thicknesses, a high accuracy scale was utilized that has the capability of weighing parts in grams to .XXX.

The first part of the study was weighing the remaining unbroken Y tensile bars that were constructed for the tensile tests. The photo below in Figure 4.20 illustrates a tensile bar being weighed in the sensitive scale.

Figure 4.20. Tensile Bar Being Weighed

The second part of the study included the construction of density cubes to a nominal volume and a nominal density. However, in order to capture maximum void density, the density cubes should be as large as possible. Once the part geometry was maximized, density measurements yielded a 6% void density in the measured geometry.

5. ECONOMIC ANALYSIS

5.1. COST MODEL DEVELOPMENT OF SLS

In order to establish an emerging technology into a supply chain it is helpful for shareholders to understand the technologies' costs that are associated with the process. According to the Joint Defense Manufacturing Technology Panel (2009), this step of cost modeling generally occurs around an MRL of 5 within the technology maturation step. By understanding the costs associated with the emerging technology, the OEM may provide a general template of costs to supplier partners who are eager to start producing parts from the emerging technology. This generalized cost template acts as a common language for the technology and ultimately offers a sense of pricing consistency when multiple suppliers are developed to compete to produce the same geometry.

One of the first steps in establishing a cost model for an emerging technology involves the practice of process breakdown analysis. The author recommends two formats in mapping process costs for a technology, which includes value stream mapping and process flow diagrams. Each format may be used individually or coupled together; depending upon the breadth of coverage the cost model should encompass.

5.1.1. Value Stream Mapping. Traditionally used as a tool for lean manufacturing, Value Stream Mapping (VSM) is a tool that offers a bird's eye viewpoint of a factory and/or process that focuses on the lean concepts of kanban[23] systems, and the reduction of muda[24] to affect takt[25] time. Though generally useful for lean process

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[23] Defined as an act of signaling to trigger action on a production floor for inventory control.

[24] Term for an activity that is wasteful and doesn't add value or is unproductive.

optimization, the author recommends VSM to generate a high level supply chain illustration of a process being emerged into the supply chain.

Originally focused on the analysis and improvement of disconnected flow lines in manufacturing (Serrano et al., 2008) VSM is a simple tool that fosters concurrent engineering principles through cross functional teaming between supplier managers, design engineers, system engineers and manufacturing engineers; all of which will need to be involved to develop an emerging technology into an aerospace supply chain. In addition, the VSM should also be developed with the supplier partners that will produce parts for the OEM so that everyone understands how the entire supply chain is laid out and how one supplier's actions may affect another supplier and the OEM when it comes to costs, schedule or inventory. Courtesy of Tucker and Cudney (2009) an example of VSM applied to SLS is located in A.6.

After laying out the VSM of the process being evaluated, the next objective is to develop a high level cost model map, similar to the SLS cost model map found in Figure 5.2. A good recommendation includes starting with the emerging technology to establish costs from the ground up. Each cost developed for each process then rolls into a sub-process cost which rolls into another sub-process cost until a high level cost model map is established for the entire emerging technology as shown in Figure 5.2. In order to start at the basement level of cost assignments, it is recommended that a process flow diagram(PFD) be developed for the emerging process.

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[25] Defined as the maximum time per unit allowed producing a product in order to meet demand. Generally believed to set the pace for industrial manufacturing lines.

5.1.2. Process Flow Diagram. A process flow diagram[26] of the SLS process is shown in A.2. The development of a PFD should be a team effort to establish costs and lead times at the base level (Kiemele et al., 1999). In addition to the general format, the author recommends developing themes around the decision points of the PFD to understand in what business process element does each decision concern. For example, the first decision in the A.2 PFD challenges whether a machine is available or not within the company. This particular decision of machine availability may be tied to a theme of machine capacity within the company; the more machines within the company, the higher the probability a machine is free to be used for processing. The next two decision points within the process flow diagram are related to split work orders and the question of whether more parts are needed to be added to the batch prior to processing. For a batched process like SLS, these two questions are related to the theme of machine flexibility, specifically, size flexibility p[A]. After the parts are produced in the SLS process, the next decision point in the SLS process concerns the theme relating to the technical performance of the SLS process relative to the inspection of the parts. After the technical performance decision, the final four decision points in the SLS production PFD are related to documentation and work order inspection to ensure that all of the parts are accounted. These aspects of the PFD are related to the theme of workforce personnel quality within the process.

Although each decision point within the SLS- PFD must work in order for parts to be produced at the supplier, by grouping the decision points around business process

[26] A visual representation of all the major steps and decision points in a process (Kiemele et al, 1999)

themes, a supplier of SLS may then be encouraged to proactively focus continuous improvement strategies on theme areas. For example, as more of the decisions within the SLS process focus on quality personnel of the workforce, continuous improvement resources may be focused on training and documentation at the supplier level prior to technology deployment.

5.1.3. Cost Model Spreadsheet Development. After the appropriate costs are accounted for by using the VSM and PSD, the next step in cost development for an emerging technology is the development of a spreadsheet model that generates theoretical costs based on input variables. The spreadsheet must focus on satisfying the cross-functional team requirements for the cost model and offer both flexibility of inputs and offer modularity for potential improvements in the future. For SLS, a standard input/output diagram works well to map the structure of the spreadsheet, shown in Figure 5.1.

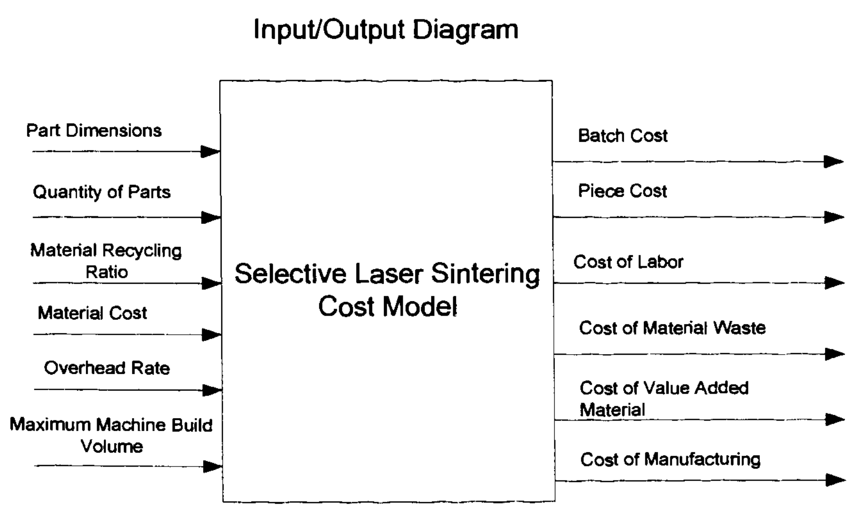


Figure 5.1. Input/Output Diagram for SLS Cost Model Development

Once the spreadsheet is developed using the functional relationships established the Input/Output Diagram may be used for analysis. In the case of SLS, a dual cost model was developed (Tucker, 2009) to understand the batching relationships between the small frame SLS machine and the large frame SLS machines. Specifically, the cost model encompasses the P730 SLS machine and the 3D Systems Vanguard machine. The two machines build volumes are shown in Table 1.1.

The model developed assesses the bounding box condition of parts to be placed within the build volume, in other words, the physical extents of the part geometry in the X,Y, and Z directions. However, the model does not take into account the nesting aspect of parts. A potential exists for the model to be refined to take into account the 'nestibility' of part geometry, though, research must be conducted to determine what makes a specific piece of geometry more nestible than another piece of geometry. These part nesting attributes would then need to be translated into quantifiable values that would seamlessly work within a SLS cost model.

5.1.3.1. Equations Developed for the SLS Cost Model. Ruffo (2006) laid the foundation for basic equations relative to costing the SLS process. According to Ruffo, the costs of a build *($Cost_B$)* is the sum of the indirect cost associated with the time of building *(t_B)* and the direct cost associated with the material used during manufacturing *(m_B)*:

$$Cost_B = Cost(t_B) + Cost(m_B) \tag{26}$$

Where:

$$Cost(m_B) = \frac{direct\_Cost}{mass\_unit} * m_B \tag{27}$$

$$Cost(t_B) = \frac{\sum indirect\_Costs}{working\_time} * t_B \tag{28}$$

The time and material used during the build (t_B and m_B respectively) are the main variables of Ruffo (2006) costing model for SLS. Time refers to how long the machine works for the build: part mass (or volume) is an index of the raw material used.

The author proposes a SLS cost structure that is made up of direct and indirect costs developed using ABC techniques for each process listed on the PFD. In contrast to the Ruffo (2006) model the author offers the following equations based off of the proposed model:

$$SLS\ Cost_{Total} = C_i + C_d \tag{29}$$

$$C_i = M_r * t_b \tag{30}$$

$$M_r = f\left(\frac{C_m, O_p, O_a}{t_p}\right) \tag{31}$$

$$C_d = C_{mat} + (L_T * t_b) + (L_Q * n_p) \tag{32}$$

$$C_{mat} = f(C_p, C_{rec}, C_{wst}) \tag{33}$$

Where;

C_i = Cost of indirect labor ($)

C_d = Cost of direct labor ($)

M_r = Overhead Machine Rate ($/hr)

t_b = Time of Build (hr)

C_m = Cost of the Machine ($)

O_p = Cost of Production Overhead ($)

O_a = Cost of Administrative Overhead ($)

t_p = Period of time for specific accounting cycle (Months, Quarters, Annual)

C_{mat} = Direct Cost of the Material in a Batched Build ($)

L_T = Labor Rate of the Technical Staff ($/hr)

L_Q = Labor Rate of the Inspection Quality Staff ($/hr)

n_p = Number of Parts in the Batched Build (integer)

C_p = Cost of Sintered Material ($)

C_{rec} = Cost of Recycled Material ($)

C_{wst} = Cost of Wasted Material ($)

Mapping each individual function of the process allows for an easier way to understand how the process interacts from a costing perspective. Graphically, the author offers the proposed structure shown in Figure 5.2.

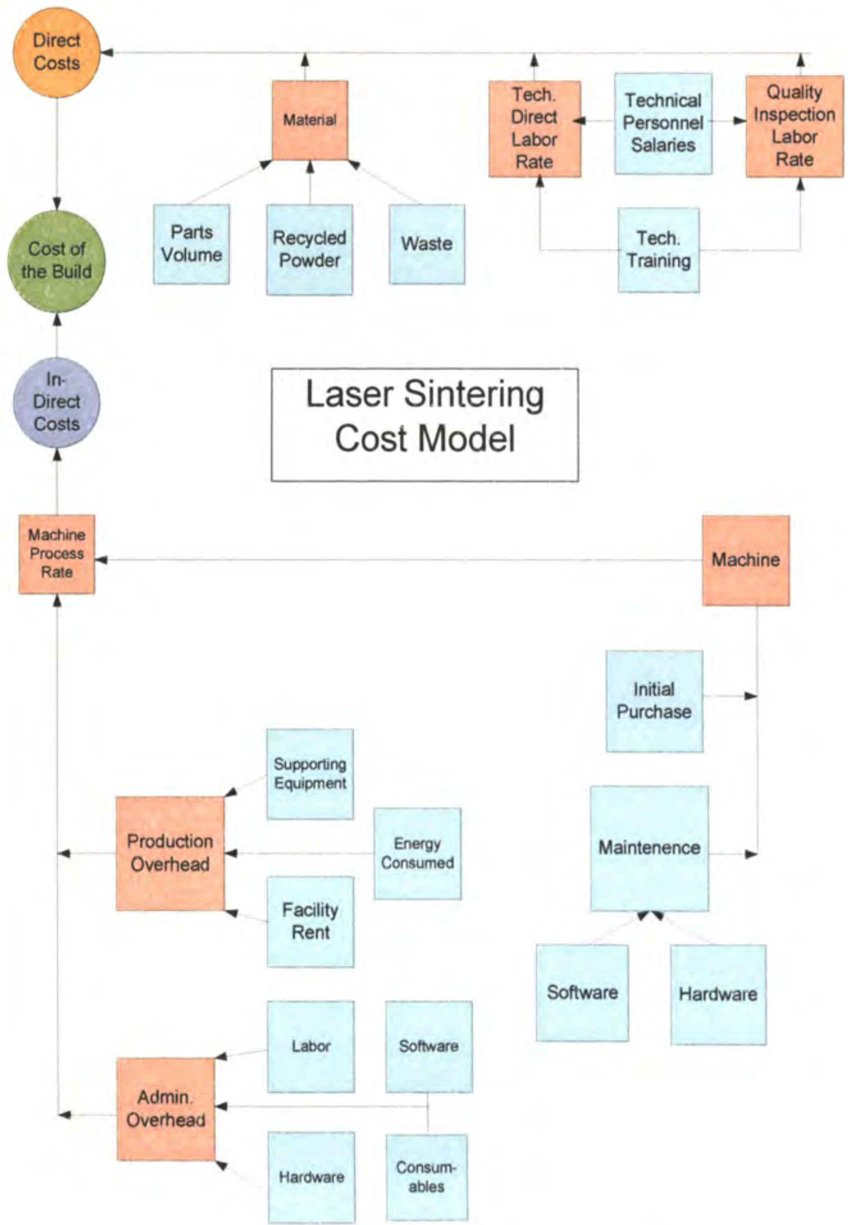


Figure 5.2. Structure of Costs for SLS

5.1.3.2. Laser Sintering Small and Large Frame Machine. Understanding the relationship between the costing of the large and small frame machine is critical in understanding what strategies SLS suppliers should take in expanding production capacity. For example, a supplier reaching capacity challenges must be able to understand how the SLS part costs are impacted due to the machine differences. One fallacy of the

Ruffo (2006) model is the lack of comparative research between large and small SLS machines. Using the spreadsheet cost model that bounds the build envelope for available build volumes, an unlimited amount of SLS machine sizes may be used in the cost model. A list of fundamental system differences is made to compare the two machines, an EOS P730 large frame machine and a 3D Systems Sinterstation HiQ machine, shown in Table 5.1.

Table 5.1. Large and Small Frame SLS Cost Model Differences

	3D Systems Sinterstation HiQ	EOS P730	How Does it Impact the Cost Model?
# of Lasers	1	2	Speed of Laser Scanning over X-Sectional Area
Build Volume	13" X 15" X 18"	28" X 15" X 23"	Total Material Consumed, Cooldown Required, Size of Parts, # of Parts
Automated Material Delivery System	N	Y	# of Hours of Direct Labor
Cleaning Required Between Runs	45 minutes	1.5 Hours	# of Hours of Direct Labor
Removable Build Frame	N	Y	The frame cooldown time is amoritized into the machine rate
Thermal Delivery System	Carbon Fiber Heaters	Quartz Rod IR Heaters	Different Material Recycling/Waste Ratio, Energy Consumption
Cost of Capital	$350,000	720,000 €	Depreciation of Equipment, Upfront Initial Investment, Directly Affects Machine Process Rate

The system differences between the two machines are noted and integrated within the cost model to accurately reflect a SLS supplier running the two different SLS machines. Now that the differences are noted, geometries are simulated within the model to explore the relationship between the size of parts and the quantity of parts between the two SLS systems in terms of unit cost. It is also appropriate to note that only costs are developed in the model, no profit margin is accounted for so the costs of parts are listed, not the price of parts. Therefore, when comparing quotes from existing suppliers for the same geometry processing within the cost model, error within the cost model must be understood to lie among the variables of profit margin differences among suppliers, differences in accounting structures, different material acquisition rates, and different labor rates depending upon the geographic area where the supplier is located.

Based on the SLS cost model, a series of case examples are used to illustrate the economic differences between the large and small frame machine with respect to part scale and quantity. Within the examples provided, an attempt will be made to convey the message that comparisons cannot simply be made for whether a large or a small SLS machine is most economical, that in reality, it depends on the geometry being evaluated. In addition, as with any AM technology, it should be illustrated that part integration is the key to effective SLS justification

Consider the following case study to provide an example of how AM technology may be evaluated to highlight an economic analysis of the emerging technology. Recall in Figure 3.1 the plastic spacer support piece shown in Figure 5.3.

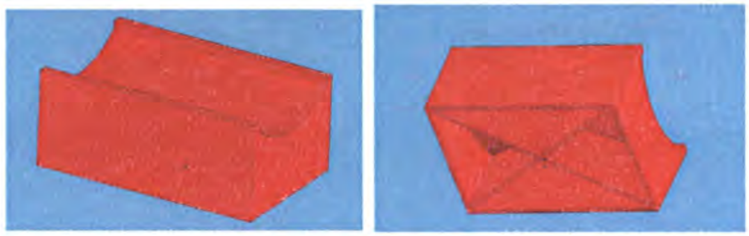


Figure 5.3. Images of the Spacer Part

The spacer is traditionally injection molded to perform the function of supporting a steel pipe that carries water to subsystems onboard the aircraft. Each plane consists of thirty six identical spacers per aircraft with a total production scheduled for 30 aircraft annually. Thus, the annual buy is 1,080 spacers. The injection mold tooling has already been paid for and the part is in production, although a design revision is expected in the coming year.

Without the consultation of system engineers or suppliers, the OEM design engineers responsible for the spacer component conducts an economic review to compare a direct replacement of the part using SLS using the direct replacement economic analysis suggested by Ruffo (2006). The dimensions of the spacer part are located in Figure 5.4.

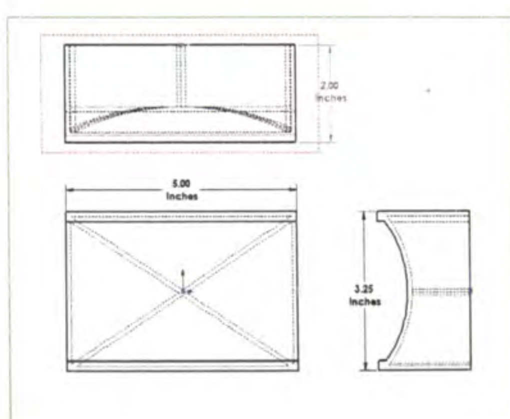


Figure 5.4. Dimensions of Spacer

The dimensions listed in Figure 5.4 are input into the SLS cost analysis spreadsheet model described in §5.1.3. Once the dimensions are entered into the model and quantities are increased to the annual production quantity of 1,080 pieces for a small frame machine only, an economic analysis may be determined as in Figure 5.5.

It may be noted that the saw tooth pattern, described by Ruffo (2006) is reflected in Figure 5.5 and is a function of the batched style of production of a maximum capacity of 69 pieces per batch. The peaks are reflective of a batch at capacity and the next part requires another machine run, but does not have enough parts to amortize the cost of the next run; therefore the part cost is relatively high, producing a spike. The author coins the term, 'batch cap +1' to describe this effect. Counting the number of peaks in the model, approximately 16 individual batches would be necessary to accommodate a quantity of 1,080 pieces. Each batch is estimated to take approximately one week to prepare, produce, inspect and ship parts. Therefore, if a supplier had a single small frame SLS machine, a delivery schedule of 16 weeks at full capacity would match the estimate.

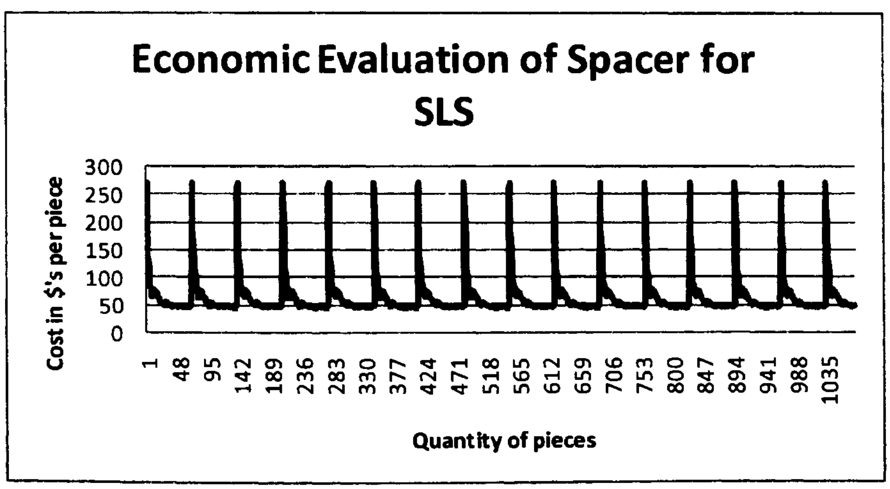


Figure 5.5. Economic Evaluation of Spacer

Next, consider the same part, shown if Figure 5.3, compared to a large frame SLS machine illustrated in Figure 5.6.

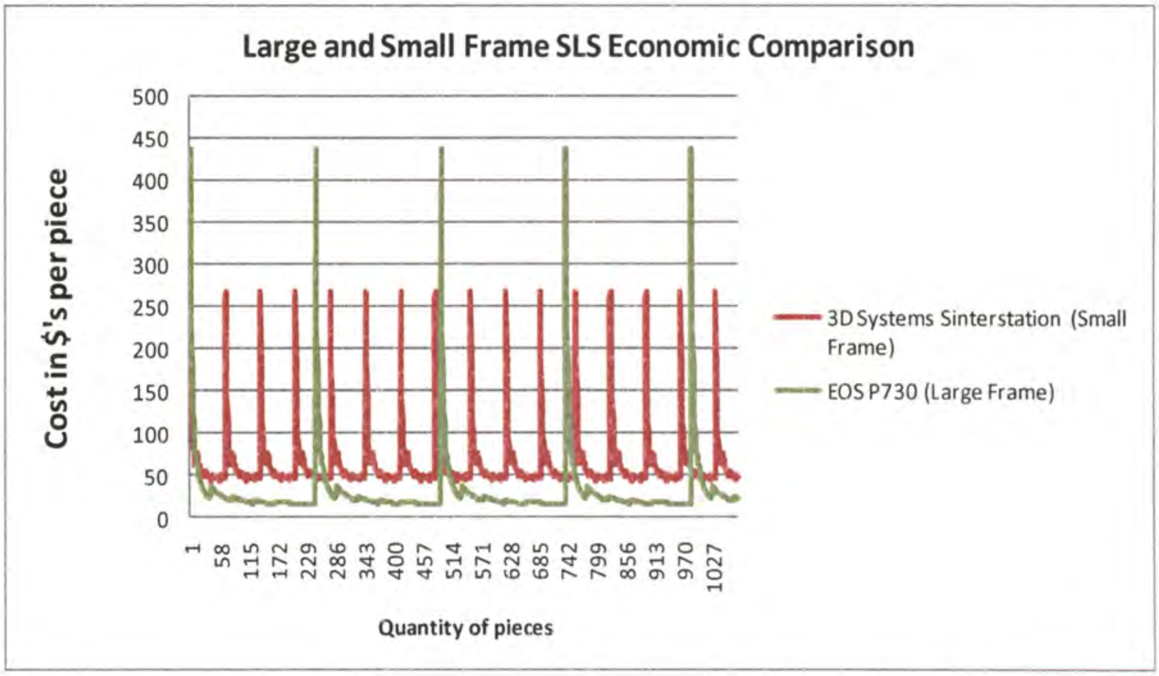


Figure 5.6. Comparison of Large and Small Frame SLS

According to Figure 5.6, more parts may be packed inside the large machine during each batched build. Table 5.2 indicates the difference in data between the large frame machine and the small frame machine for the geometry specified. This effect of greater batch capacity produces three main conclusions. (1) Over the entire production quantity of 1,080 pieces, parts built in a large frame SLS machine generally cost roughly half per build compared to the small machine, see Table 5.2. (2) Due to the larger size machine, the 'batch cap +1' effect is more drastic than the small frame machine as illustrated by 19% standard deviation increase from the small machine to the large. (3) By counting the number of spikes, it may be determined that only 5 machines are required to build the parts for the year, as opposed to the 16 required by the small frame machine.

Table 5.2. Summary of SLS Machine Size Data

	3D Systems Sinterstation (Small Frame)	EOS P730 (Large Frame)
Average Cost Per Part ($'s)	65.15	32.09
Standard Dev.	42	50
# of Parts Until Capacity	69	247
Ratio of Small Frame to Large Frame for Specified Geometry	0.28	

In addition, the large frame machine takes an average of 1.5 weeks of time for processing parts at full capacity. Thus, it would take a time period of 7.5 weeks at full capacity if a supplier had a single large machine. It is important to note that this economic analysis is reflective of single case study part geometry. For the specific geometry listed, 69 parts reaches the capacity of the small frame machine. The large machine requires 247 parts to reach capacity. Using a simple ratio of $\frac{69}{247}$ produces a value of .28. This ratio accurately reflects the capacity differences between the two size SLS machines for the specific geometry packs in the case.

To exemplify how little the small to large frame ratio can be changed depending on the geometry being evaluated; a second part is introduced to the case study for evaluation. An air transfer manifold is pictured in Figure 5.7.

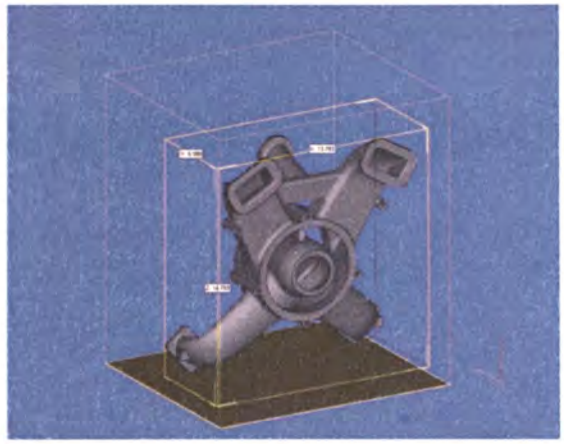


Figure 5.7. Second Evaluation Geometry for SLS

The manifold reaches the maximum capacity of the small frame SLS machine in only one piece. Only 5 pieces may be placed in the large frame machine, thus changing the small to large frame ratio to $\frac{1}{5}$ or, .20.

Due to the size of the manifold, only one piece may be placed within the small frame SLS chamber. Because of the volumetric constraint of the machine, the batch +1 effect is eliminated and a constant cost line is established for the small frame machine while the batch +1 effect remains for the large frame machine. The effect is illustrated in graphical form in Figure 5.8.

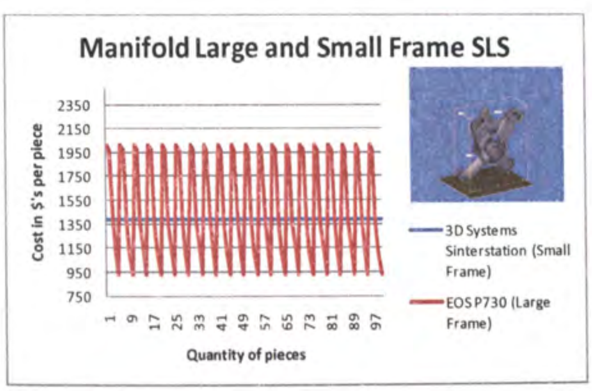


Figure 5.8. Manifold Evaluation between SLS Size Machines

Diving deeper into the analysis, a power fit curve equation may be established for each machine relative to the case study part per batch. Figure 5.9 illustrates the small frame SLS machine batch equation derived from data output of the cost model, where y = cost in $'s per piece and x = production quantity.

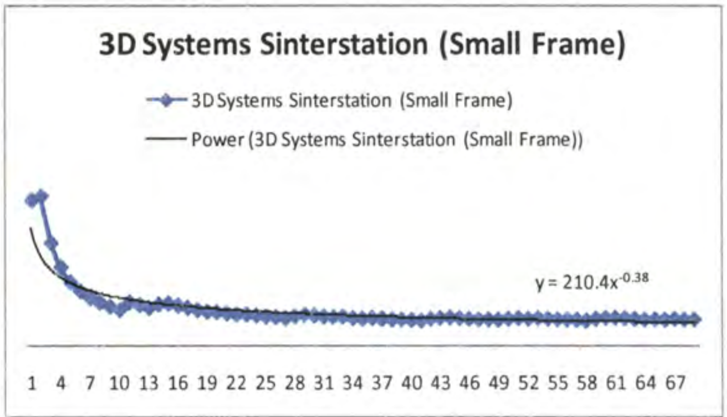


Figure 5.9. Power Fit Equation of Small Frame Batch

Contrasting the power fit equation associated with the small frame machine to the large frame machine, Figure 5.10 illustrates the large frame SLS machine.

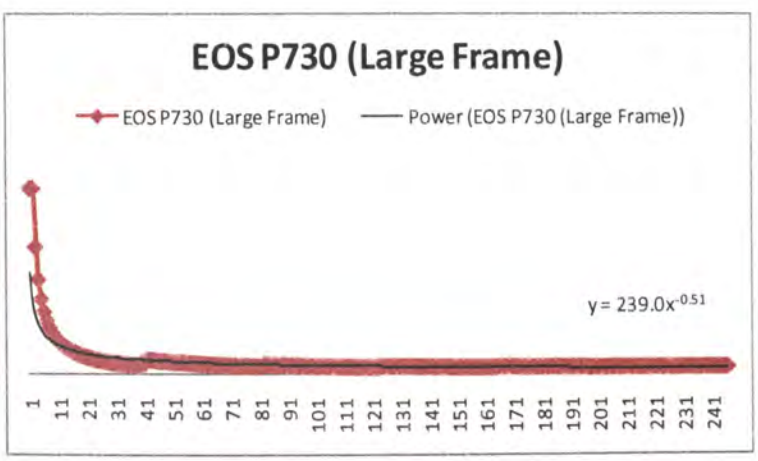


Figure 5.10. Power Fit Equation of Large Frame Batch

5.2. ECONOMIC COMPARISON TO INJECTION MOLDING

Next, consider how injection molding compares to the large frame and small frame SLS machines. Bouaziz et al. (2004) offer a procedure for evaluating machining costs of dies produced on a CNC machine. Coupling this technique with Poli's (2001) injection molding estimating techniques, a comparative curve may be generated and graphed. Recall from the case study, that the part being evaluated is currently fabricated using injection molding, therefore, an assumption is made that the tooling cost has already been paid for upfront prior to production; therefore, negating tooling costs within the model. This initial sunk cost of tooling is common in industry, however, tooling costs may also be amortized across quantities.

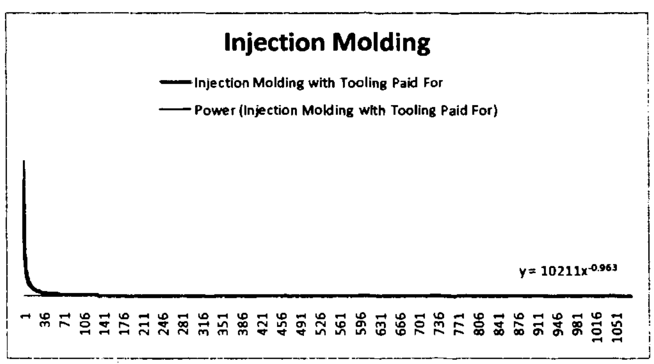


Figure 5.11. Comparison of SLS to Injection Molding

Figure 5.11 illustrates the entire curve for the geometry specified in Figure 5.3 with respect to injection molding until the specified 1,080 annual quantity. Again, the equation $y = 10211x^{-.963}$ was derived using the power fit function within Excel to depict the economic cost profile of injection molding, where y = $'s/unit. Due to the lack of batch style processing, injection molding does not offer 'batch +1' effects of spikes within the model, therefore, the entire production quantity of 1,080 parts is constant without batched interruption in data.

Once the injection molding model is established, the next step places the large frame SLS machine, the small frame SLS machine and injection molding on the same chart to determine specific economic cross-over points for technology. The results are shown in Figure 5.12.

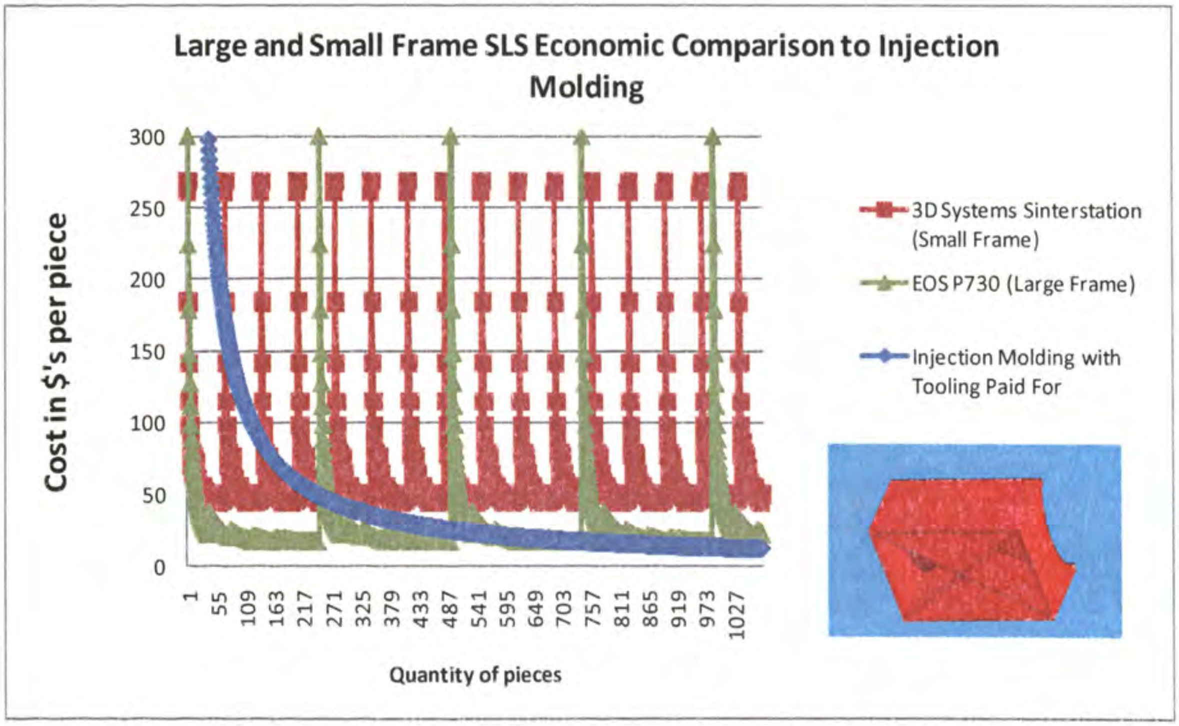


Figure 5.12. Comparison of SLS to Injection Molding

Figure 5.12 elicits a number of observations regarding the analyzed geometry. The first observation includes the break point of roughly 276 pieces before the small frame becomes economically unattractive compared to injection molding. Continuing down the slope of the injection molding curve, injection molding starts to offer more savings at the 741 part range over the large frame SLS machine and ultimately, offer a $12 per part savings at the targeted quantity of 1,080 pieces per year.

This case illustrates that for the geometry specified; injection molding appears more attractive than SLS large or small machine at 1,080 pieces a year. To review, the following assumptions are made for this case. First, the injection mold tooling has already been paid for and that upfront cost was not included in the case study. Second, this case is only for the geometry specified and does not take into account part design integration as a subassembly.

Next, let us consider a case that involves SLS part design integration within the economic analysis to understand the impact design integration has in the economic analysis. Reconsider the original case study let us pretend that the design engineer who picked the candidate part listed in Figure 5.3 expanded his communication chain and discussed his/her preliminary economic analysis, that showed SLS unfavorable compared to injection molding, with other aerospace systems engineers. The systems engineers investigated how the spacer connected to the support brackets and involved a manufacturing engineer into the discussion to establish a cross-functional design team. The manufacturing engineer suggests touch labor savings if fasteners were eliminated from the design. The systems engineer suggests integrating all of the parts of the spacer subassembly into a single unit to reduce weight as a functional objective. The cross functional team contracts a SLS supplier and brings a supplier manager from the OEM onboard to offer input. The supplier manager offers schedule requirements of the part design and the SLS supplier offers build volume restrictions and machine capacity scheduling to the team for an initial prototype run. A preliminary design is sketched up by the cross-functional team members as shown in Figure 5.13.

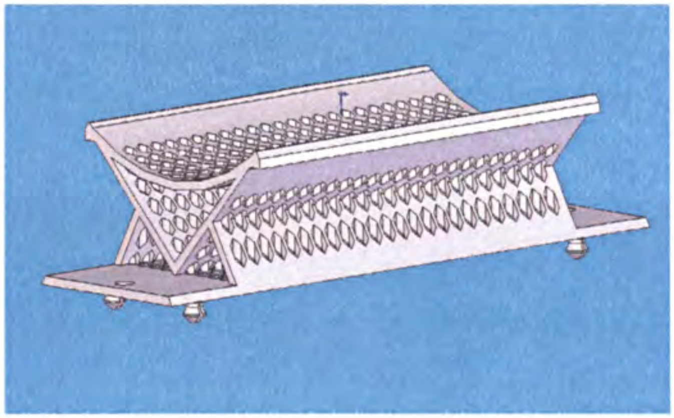


Figure 5.13. Proposed Integrated Design

Using the proposed integrated design reduces the fastener count from 12 screws to 2 screws; the support brackets are also eliminated. Annually, due to the integrated design, 10,800 screws are saved and 2,160 brackets are saved. The proposed designs' dimensions are found in Figure 5.14.

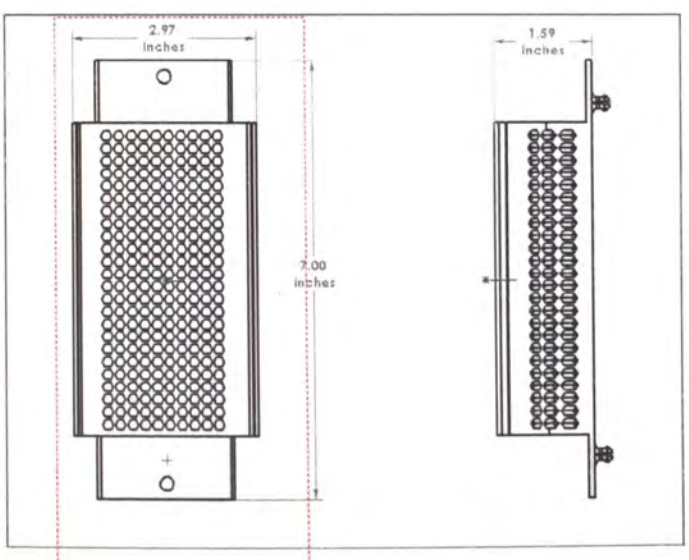


Figure 5.14. Integrated Design Part Dimensions

Next, an economic model for the integrated design is conducted to assess how the SLS integrated design compares to the conventionally manufactured subassembly. First, following a similar approach to the spacer support, a large and small frame economic breakeven analysis chart is generated to reflect the integrated SLS design as a single piece as shown in Figure 5.15.

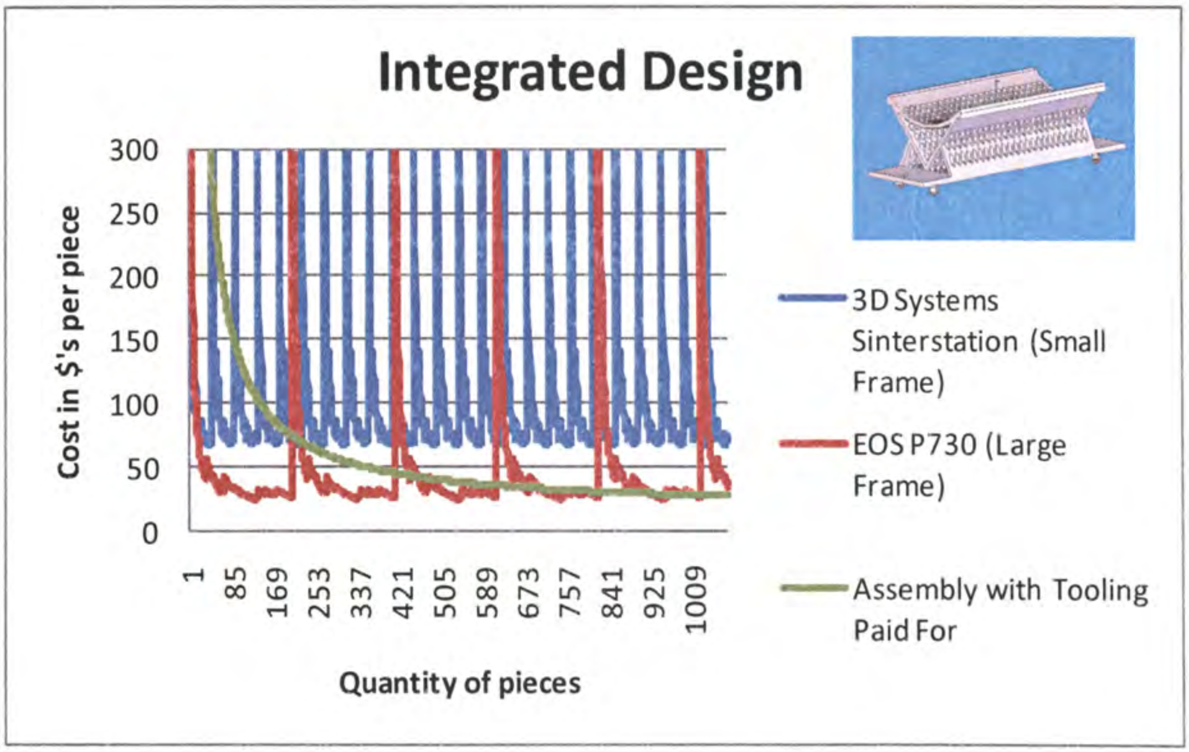


Figure 5.15. Integrated Design Crossover Point Analysis

For reference, the assembly cost line was calculated by adding $15 to the previous spacer costing. This $15 adder is justified for the cost of the 2 brackets plus the 12 fasteners. The $15 additional cost does not represents a marginal increase in part cost of the integrated design, thus, substantiating the need to look for more expensive components that move the integrated assembly curve up the Y axis.

Analyzing the breakeven analysis, shown in Figure 5.15, a number of key points are observed. On average, the cost distance between the large and small frame cost structure has increased to an average of $50 compared to $33 for the previous geometry. This cost discrepancy effect is directly attributed to the size difference of the integrated part being evaluated. Comparing the assembly to the small frame SLS machine, the cost for the conventional assembly becomes consistently cost attractive around 180 parts. For the large frame, SLS machine the cost seems roughly the same as the conventional assembly at the targeted quantity of 1,080.

In terms of the number of batches required the small frame SLS machine requires approximately 24 batches to produce the 1,080 targeted parts, whereas, the large frame SLS machine requires only 6 batches. This point illustrates the cost sensitivity and lead-time effect of the small frame SLS machine to part size changes relative to the geometry by comparing dimensional changes presented in Figure 5.4 and Figure 5.14. Of note, the large frame SLS machine seems to be relatively unaffected by the geometry change, initially requiring 4 batches with the geometry specified in Figure 5.4 and only 5 batches required with the geometry specified in Figure 5.14.

This model assumes the replication of the same part to justify the batch process. It may be mentioned that in practice, SLS suppliers may manufacture several different parts in the same batch in order to reduce the part costs. Further research on multiple geometry packing is needed to account for multiple geometry types processed in the SLS process simultaneously. For example, Gogate and Pande (2007) have developed a genetic algorithm that helps define an optimum pack layout for a defined set of parts.

5.3. COST MODEL DEVELOPMENT OF FDM

The costing structure for FDM is slightly altered from the SLS model. When a single part is processed within an FDM machine, a copy of the same piece is simply added to the build platform. The material required and time required to construct the FDM parts exhibits a linear relationship. Upon placement of a second part, the FDM process doubles the material required and time required to construct the parts. Part quantity is constrained by the X and Y limits of the build volume within the machine evaluated. Since material choices are more abundant in the FDM process, than SLS, the specific material chosen becomes a major cost driver. Coupled with the material choice, part orientation plays a much more significant role in processing cost, as opposed to SLS. This is due to the support material requirement of the FDM process. In addition, the supplier assigned machine-processing rate, which is generally based on depreciation of the equipment, also drives the costs for the FDM process. This is especially true for larger geometry constructed in 900MC machines, which encompasses long build times.

As with SLS, FDM part files are processed via digital definition files offline from the FDM machine. Therefore, processing labor rates should account for the time it takes for an engineer to process the file in CAD software prior to downloading to the machine. This time is known as pre-build processing. Because the FDM process requires the generation of support material, depending on the part complexity, the time required for pre-build processing may vary greatly. It may also recognized that highly complex geometry may require more post-processing labor associated with support material removal.

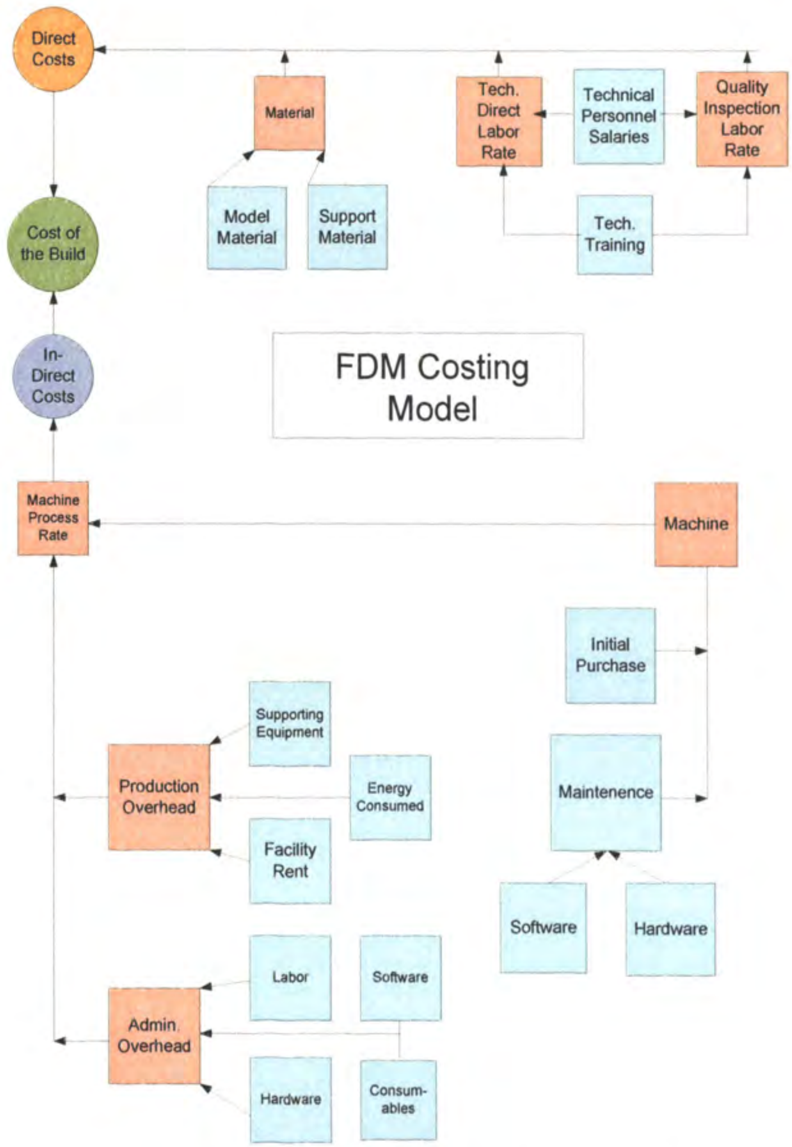


Figure 5.16. FDM Costing Structure

5.3.1. FDM Costing Structure. Using the same costing development methodology for SLS, a costing structure model was built to estimate the cost of components for the FDM process with significant focus placed on material cost and part orientation which represents a large emphasis on costs. The processing cost formulas developed are as follows:

$$FDM\ Cost_{Total} = C_i + C_d \tag{34}$$

$$C_i = M_r * t_b \tag{35}$$

$$M_r = f\left(\frac{C_m, O_p, O_a}{t_p}\right) \tag{36}$$

$$C_d = C_{mat} + (L_T * t_b) + (L_Q * n_p) \tag{37}$$

$$C_{mat} = (v_p * C_{mod}) + (v_s * C_{sup}) \tag{38}$$

$$v_s = f(A_{face\_down}, \sum_{i=0}^{n} A_{overhang} * Z_{overhang}) \tag{39}$$

C_i = Cost of indirect labor ($)

C_d = Cost of direct labor ($)

M_r = Overhead Machine Rate ($/hr)

t_b = Time of Build (hr)

C_m = Cost of the Machine ($)

O_p = Cost of Production Overhead ($)

O_a = Cost of Administrative Overhead ($)

t_p = Period of time for specific accounting cycle (Months, Quarters, Annual)

L_T = Labor Rate of the Technical Staff ($/hr)

L_Q = Labor Rate of the Inspection Quality Staff (\$/hr)

n_p = Number of Parts in the Batched Build (integer)

C_{mod} = Cost of Model Material (\$)

C_{mat} = Direct Cost of the Material in a Batched Build (\$)

C_{sup} = Cost of Support Material (\$/in^3)

v_p = Volume of the Part Produced (in^3)

v_s = Volume of Support Material Consumed (in^3)

A_{face_down} = Area of the Downward Facing Surface of the Part Produced

$A_{overhang}$ = Area of features that overhang the part produced

$Z_{overhang}$ = The Z height of the overhanging features

As the build volume estimator and time estimator within the Insight software package is accurate, v_p, v_s, and t_b are known during file setup for FDM processing. Having this information prior to part building makes cost estimation much easier than SLS.

An element of AM comparison involves the aspect of how part complexity affects economic comparison to injection molding. As injection molding part cost is a function of tooling complexity. The objective of the FDM economic comparison is to highlight how part complexity affects the breakeven analysis relative to injection molding.
Like the SLS approach, using Poli's (2001) method of determining relative tooling and fabrication of injection molding relative part costs, and comparing to the simple FDM costing equation derived, a simple economic comparison may be established. As it is suspected that the cross over point will change based upon the complexity of geometry,

two geometries were evaluated. The next step required for FDM cost modeling is the construction of a spreadsheet for FDM economic analysis.

Geometry 1, illustrated in Figure 5.17, is a simple L-Bracket shape that could easily be manufactured via injection molding with relatively simple tooling. This geometry provides the most fundamental baseline for economic performance between the two processes.

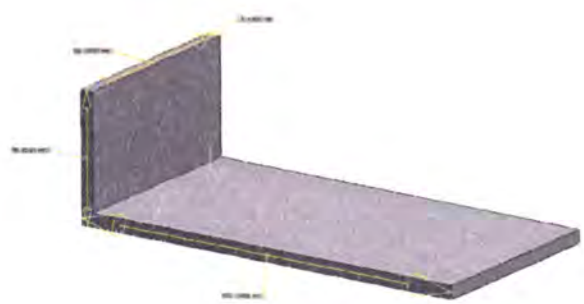


Figure 5.17. Costing Sample Geometry 1

Using injection molding relative part costing formulas developed by Corrado Poli (2001) the cross over point at which injection molding becomes lower cost than FDM for Sample Geometry 1, comes at a quantity of 445 pieces - shown in Figure 5.18. At that point, the injection molding tooling costs have been amortized over enough parts. With this analysis comes the disclaimer of the following: Part processing labor was not figured into the analysis, in addition, no universal method of FDM part costing has been developed, it was assumed that one constant price would be offered regardless of quantity, this assumption follows the Hopkinson and Dickens (2003) model for SLS. The author prefers using a straight line model for FDM for two main reasons. (1) FDM time and material is strictly a function of the number of parts evaluated, thus, generating a linear relationship between cost and quantity. (2) There exists no powder to self-support parts in the FDM process. Unlike SLS, a customer will not be paying for additional material used to construct FDM parts, therefore, only model material and support material consumed will make up the direct material costs. Most likely, a batch+1 phenomenon will only occur to produce a relatively small saw-tooth pattern with FDM. This small–toothed pattern delta between the highest and lowest point in the saw tooth pattern is constrained by the X-Y, bounding platform. The small-toothed pattern may grow from a small frame 400MC, to a large frame 900MC, but most likely still remain smaller than SLS, due to the absent ability to stack parts in the third Z-axis dimension.

Using the part described in 5.17, the small frame 400MC FDM machine will produce a cross over effect similar to 5.18. The cross-over point for this particular geometry is around 435 pieces. This straight-line effect will most likely encompass a vast majority of parts constructed on a smaller 400MC machine.

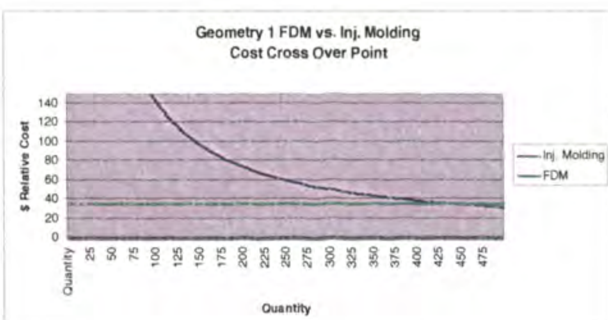


Figure 5.18. Geometry 1 Costing Cross Over Point

Figure 5.19 shows the geometric extreme from Geometry 1. This sample geometry was designed to test how much additional complex geometry featuring many undercuts would affect the cross-over point in the analysis.

Figure 5.19. Costing Sample Geometry 2

The objective of this geometry is to illustrate how design complexity assists FDM to illustrate the break-even point of 1,807 pieces, as shown in Figure 5.20.

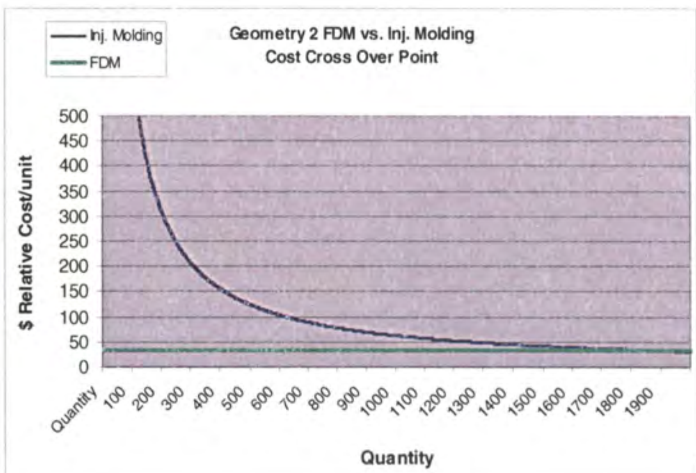


Figure 5.20. Geometry 2 Costing Cross Over Point

The preceding simple case study quantitatively illustrates how complex geometry impacts overall FDM feasibility and how geometry and quantity of pieces contributes to a significant impact in costing. By understanding how part geometry complexity shifts the business case to and from Fused Deposition Modeling, one may be able to understand the business economic aspect of the technology.

6. PROPOSED SUPPLY CHAIN MODEL AND VALIDATION

6.1. PROPOSED SUPPLY CHAIN MODEL

The implementation of emerging manufacturing technology not only affects manufacturing, but also affects whole business operations, giving new challenges for an enterprise to manage both manufacturing operations and information technology (Dangayach and Deshmukh, 2005). Tay et al. (2001) describe a future where digital CAD files transmit globally via the internet directly to AM technology for part construction. One day this ability to build and design anywhere in the world may come to fruition, however, Creveling et al. (2003) states that long term variation of a process in a manufacturing environment is generally substantially larger than the short-term variation defined in research and development. Specifically, the deployment of AM into a global aerospace manufacturing enterprise is challenging. This effort will consist of several phases of deployment with a series of gates that act as technology development checks.

Often, emerging technologies are developed solely internally, outsourced exclusively, developed as a partnership with an outside company as a hybrid type of technology development, or, simply a refinement of a commercially available technology. The specific implementation strategy of an emerging technology would depend on the maturity of the technology and which strategy by the company adopting the technology. The resulting strategy must be evaluated from an intellectual property and deployment speed aspect, with each aspect inversely related. For example, see Figure 6.1.

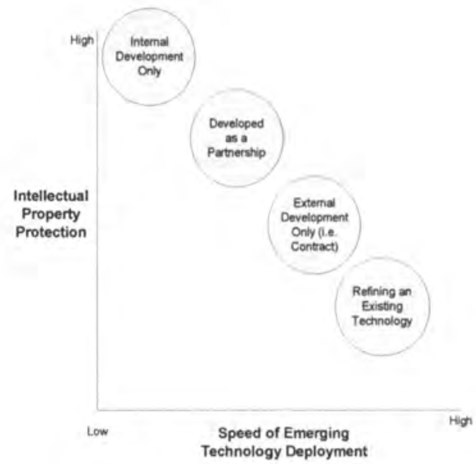


Figure 6.1. Technology Deployment Strategy

With AM, the technology has already been commercialized for a rapid prototyping market, therefore, most companies looking to invest in AM deployment may simply be refining the existing technology which will result in relatively rapid system deployment versus creating the technology from scratch. This rapid system deployment is dangerous to production manufacturing without a bridled effect of parameter optimization.

Thus far, much has been discussed regarding individual tools used for the development of AM systems; however, a clear supplier deployment and implementation roadmap has not been discussed.

6.1.1. Emerging Technology Implementation Roadmap. Creveling et al. (2003) discuss a methodology of technology development using design for six sigma approaches. They discuss that the company deploying and/or developing the technology must prove that the new technology is both robust and tunable before it can be used to make a new product for the company. By robust, Creveling et al. (2003) describes mean capable short-term performance as measured by C_p indices, even in the presence of noise factors. By tunable, they mean capable of long term performance, measured by C_{pk} indices.

In order to achieve this goal of performance measurement of an emerging technology a thorough technical and economic analysis must be conducted on the emerging technology's current state. When conducting an emerging technologies current state for eventual implementation the team conducting the analysis should be advised that change that affects the company will been seen as controversial. According to Robinson, 2006) rumors concerning strategic plans are particularly disruptive to any manufacturing organization. To quell this potential uprising, the management approach with the organizational culture will influence the relative success of deploying the technology (Componation et al., 2008). Shown in Figure 6.2, this effort shall be known as Phase 1- Current State Evaluation within the technology implementation cycle.

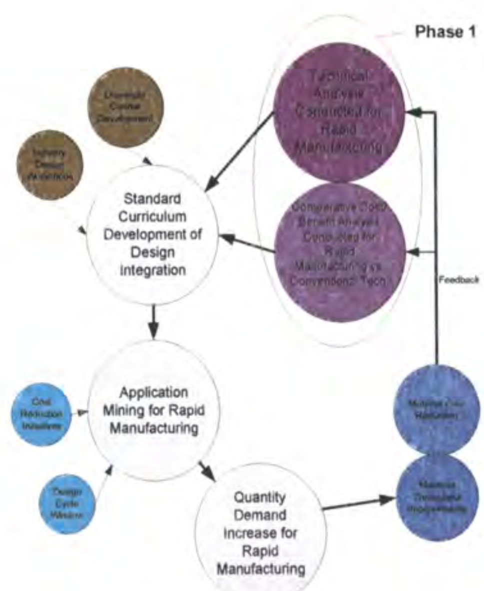


Figure 6.2. AM Technology Implementation Cycle – P1

6.1.1.1. Phase 1 – Current State Evaluation. This phase is meant to act as a catalyst to investigate the emerging technology's technical and economic feasibility prior to significant amounts of funding being committed to the technology and will require Gate 1-A and Gate 1-B to be passed in order to move to Phase 2. During this phase, the first step to take place involves a comprehensive technical evaluation that describes, in more detail, where the technology lies relative to a customer defined performance metric.

The customer-defined performance metric is discovered using quality function deployment (QFD) analysis. The QFD methodology efficiently translates customer wants into quantitatively driven metrics capable of translation into technology development. For example, industry experts agree that the technical mechanical property performance is where AM lacks compared to more robust manufacturing technologies (Bourell et al., 2009). This technical gap then translates into an area of improvement in the house of quality (HOQ) matrix. An AM customer may ask for stronger and more ductile parts, using the HOQ matrix, this qualitative requirement then translates into a maximum tensile strength, maximum percentage of elongation requirement, see Appendix A.20 for more information. It is recommended that the performance requirements be generated by potential users of the emerging technology and subject matter experts versed in the technical capability of the technology. Upon amassing data, technical design manuals are created and initial process specifications are created to control the process and document the process capability.

Phase 1 also requires a deep investigation into the maturity of the technology using the technology readiness level and manufacturing readiness level techniques referenced in §1.6.1. This assessment exercise will provide a cursory analysis for the technical and economic evaluation steps and will act as a template for answering the following gates for a Phase 1 gate review. The first gate passed during this phase shall be known as 'Gate 1-A' and include the following:

1. Market Opportunity of the Technology
    - Customer Lists
    - Customer Needs/Wants
2. Corporate Strategy for the Emerging Technology
    - Competitive Situation Regarding the Technology
    - Internal and External Market Need of the Technology
    - Intellectual Property Strategy
3. Technology Viability
    - Expected Cost Savings
    - Total Internal Investment
    - Total Supplier Investment
    - Return on Investment of the Technology
4. Risks of the Technology
    - External Competition to the Technology
    - Internal Resources
    - System Design Instability of the Technology
5. Testing Plan Definition
    - Testing Budget Defined
    - Testing Timeline Defined

If Gate 1-A is passed, a deeper technical evaluation is then conducted that requires an extensive use of parameter optimization for the emerging technology prior to technology deployment into the supply chain. The idea behind a thorough technical analysis is justified as developing process quality early within the technology deployment cycle. The parameter optimization plan shall be linked to the performance metrics identified within the HOQ exercise. The objective of the parameter optimization plan would focus on maximizing technical performance criteria of the emerging technology prior supply chain deployment. Examples of technical performance may include elements such as; process throughput, mechanical properties of parts produced, machine-to-machine variation. Individual technical performance criterion is developed from the VOC exercises listed in Phase 1. After performing the parameter optimization section of Phase 1, a final gate is then required to pass Phase 1. This gate is known as Gate 1-B, and is defined as:

1. Performance Requirement (PR) Definition
    - Hypothesis Testing of PRs
    - Regression Analysis of PRs if applicable
2. Static Design of Experiment
    - Establishment of 'Tunable Performance'
    - ANOM
    - Control Factor Effects
3. Dynamic Design of Experiment if applicable
    - ANOVA
    - System Robustness

4. Risks of the Technology

    - Control Factor Interaction
    - Budget and Timeline Update

6.1.1.2. Phase 2 – Developing the Demand. Once incubated, the emerging technology will mature only if there is enough demand for its use to necessitate its existence within the company. Phase 2 is illustrated in Figure 6.3.

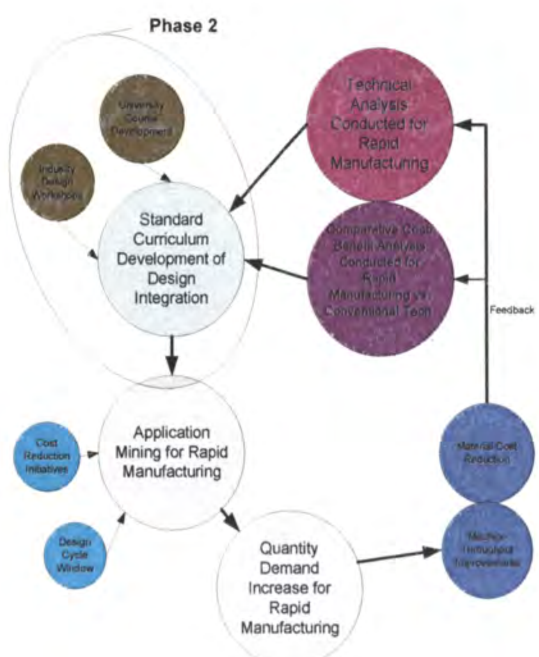


Figure 6.3. AM Technology Implementation Cycle – P2

Demand for emerging technology may be generated through a variety of communication strategies. One way to spawn adoption of an emerging technology is to generate demand for the emerging technology through technical training seminars. Taking the technical design manuals created in Phase 1, workshops are held to educate emerging technology shareholders on the benefits and challenges of the technology to prevent misuse and potential negative marketing of the technology. The target demographic of the workshops includes existing employees within the company and potential suppliers of the emerging technology. The customers within the workshops are surveyed and the voice of the customer is recorded using a QFD approach and matched with specific performance requirements spawned by the customers for the emergent technology.

In a parallel effort, the design manuals created in Phase 1 may also be integrated into strategic universities that look to hire incoming engineering professionals that will eventually assist in developing the technology within corporations. This type of proactive approach to demand push marketing allows incoming professionals to become change agents for the adoption of the emerging technology. For example, the Georgia Institute of Technology, University of Texas – Austin, Missouri University of Science and Technology, and Loughborough University all have entire undergraduate and/or graduate courses dedicated to AM technology.

In order to have enough workforce to operate the emerging technology, community colleges and vocational training centers should be explored to develop technology training for the emerging technology. For example, Saddleback College and York Technical College each have entire technician training programs specifically designed for AM technology. Developing the workforce while concurrently creating the demand for the technology will ensure a proper balance for the technology's development path. After completion of Phase 2, a Gate 2 is required and is described as:

1. Education of Industry
    - Cross-Functional Training Seminar
    - Specialized Training Seminars for Each Function
2. University Training
    - Establishment of Curriculum
    - Curriculum Deployment
    - Funding Avenues Explored
3. Technical College Training
    - Emerging Technology OEM Agreements
    - Funding Avenues Explored
4. Risks of Technology Training
    - Teaching Resources Available
    - Funding Resources Available
    - Budget and Timeline Update

6.1.1.3. Phase 3 – Sparking the Catalyst. Once design engineers, manufacturing engineers, procurement specialists, technicians, system designers and potential suppliers are all trained in the benefits of the technology, a catalyst is needed to deploy the technology into mainstream production use. Within the aerospace industry, this catalyst comes in the form of a scheduled or forced cost reduction initiative for an existing aerospace platform, a design window for an upcoming and newly designed platform, or a niche specific application, such as, a spares and modification environment that would be willing to adopt a technology readily. Shown in Figure 6.4, this catalyst is known as Phase 3 of the AM technology implementation cycle.

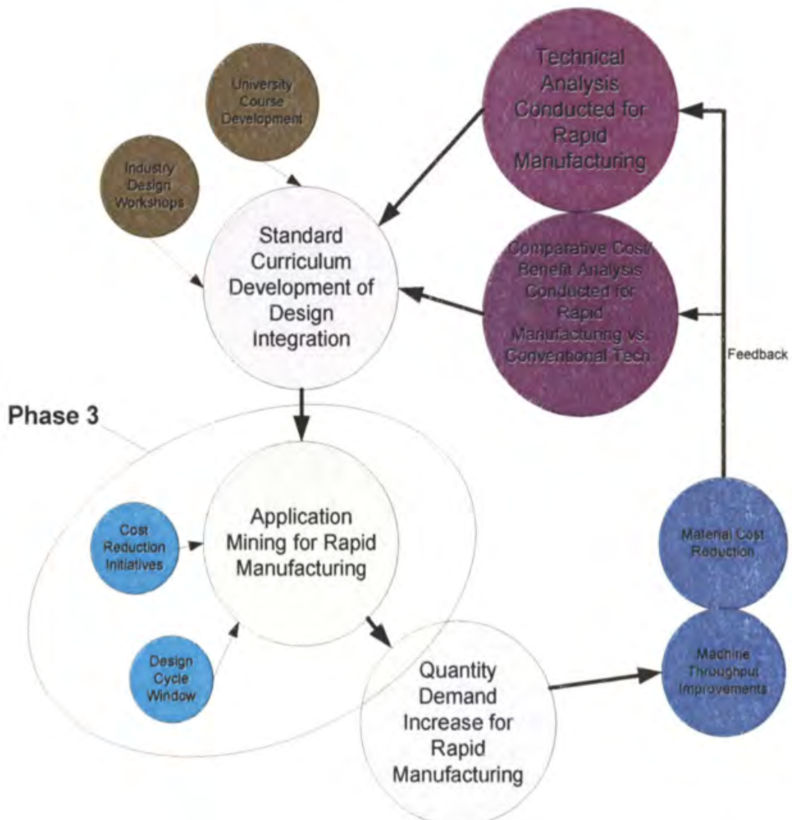


Figure 6.4. AM Technology Implementation Cycle – P3

During the third phase a part candidate, screening mechanism is put into place to evaluate candidates for the emerging technology. This screening mechanism must coincide with cost reduction initiative imposed by the OEM for specific platforms, or a design cycle window of opportunity, or quick response spares and modifications teams. Figure 6.5 illustrates the proposed methodology for aerospace part screening for AM that is broken down into two Phases.

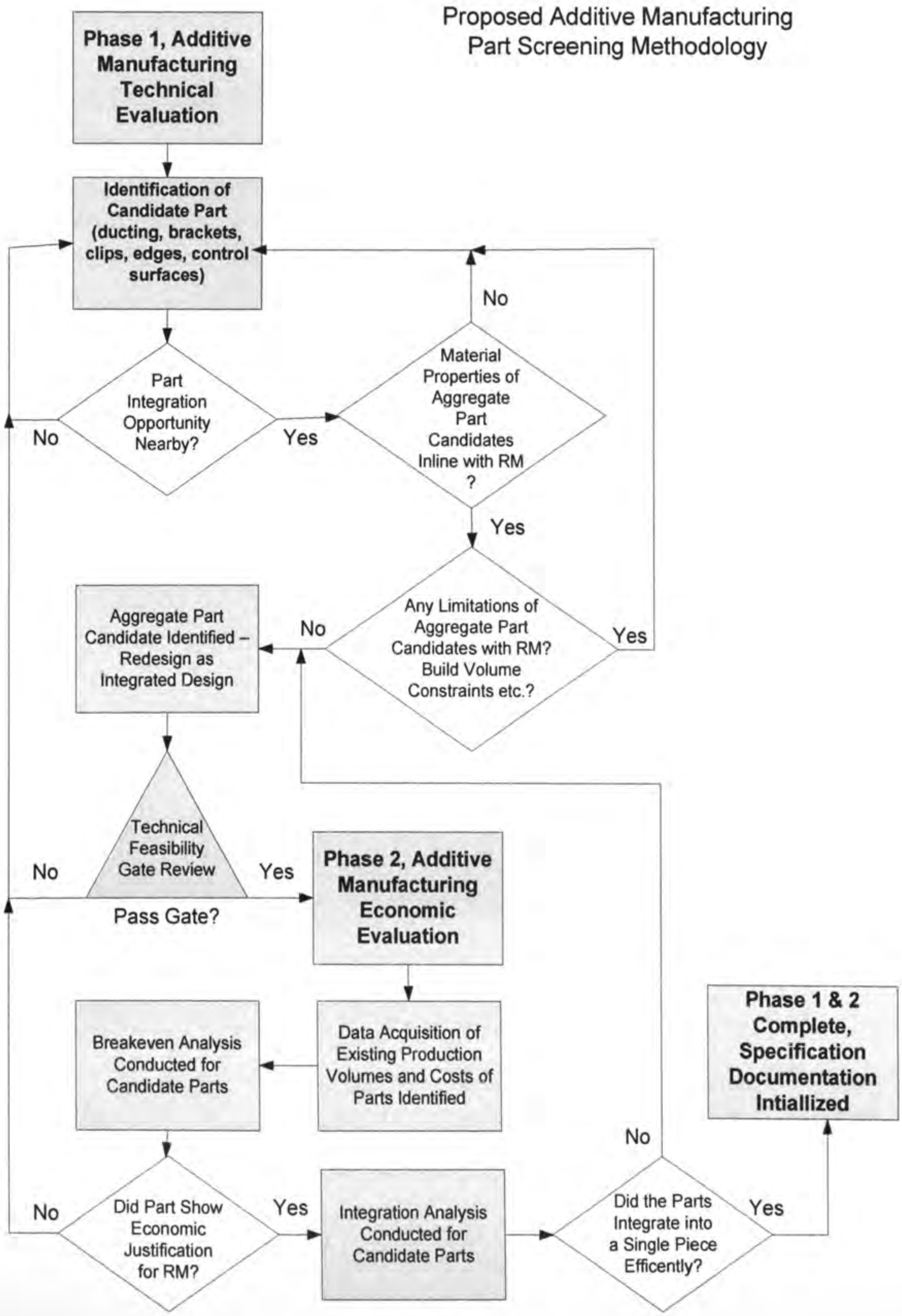


Figure 6.5. Part Candidate Screening Methodology

Phase 1 of the candidate screening process focuses on technical evaluation of part candidates that exist on current aircraft. A key element of this technical evaluation is the focus on AM's critical element of design integration. A departure from most AM literature, this research proposes that for low volume aerospace components, part integration opportunities must exist for the candidate design before proceeding to compare the part candidate to conventional manufacturing technology. This need for part integration comes from economic analysis research data located in § 5.0.

Once performance requirements are met for the part candidate, a formalized gate review process is initiated that ensures technical feasibility is demonstrated. Technical feasibility is achieved through technical performance metrics established for the particular zone of the aircraft where the candidate parts are located. These performance requirements may come in the form of tensile strength, burst pressure, electrical requirements, surface finish requirements, and other technical performance metrics.

Upon passing the technical feasibility gate of the part screening methodology, Phase 2 is initialized to ensure economic feasibility of part candidate screening. Again, departing from the normal RP/AM screening methodologies (Pande and Kumar, 2008; Mahesh et al, 2004; Mansour and Hague, 2003; Munguia et al, 2008), economic justification must also be met prior to part candidate deployment. Data are gathered for the candidate parts' existing manufacturing process in terms of production volume, lead time, costs and flexibility. Next, a breakeven analysis is conducted for the candidate part integrated design. Finally, to concentrate on integrated design even more, a final step of integrated design efficiency is conducted to ensure the design was integrated as much as possible prior to moving to the final phase, known as specification and documentation.

The identification of part candidates coupled with the increased demand for the technology sparks a quantity demand increase of the emerging technology. Once the part screening methodology, such as the example in Figure 6.5, has been setup for the emerging technology a Gate is required to move to Phase 4.

After completion of Phase 3-Sparking the Catalyst, a Gate 3 is required before moving to Phase 4 and is described as:

1. Application Opportunities
    - Cost Reduction Initiatives on Existing Products
    - Design Cycles for New Products
2. Part Candidate Screening Process Flow Diagram Developed
    - Technical Comparison
    - Economic Comparison
    - Mapping of Candidate Parts
3. Risks of Application Mining
    - Too Few Candidate Part Available
    - Budget and Timeline Update

6.1.1.4. Phase 4 – Quantity Demand Increase. As more part candidates are submitted to suppliers for production, suppliers must be able to react to the demand through the use of accurate forecasting and cost models. This phase manages the quantity demanded by concurrently providing a picture of the emerging technology's demand and production, as shown in Figure 6.5.

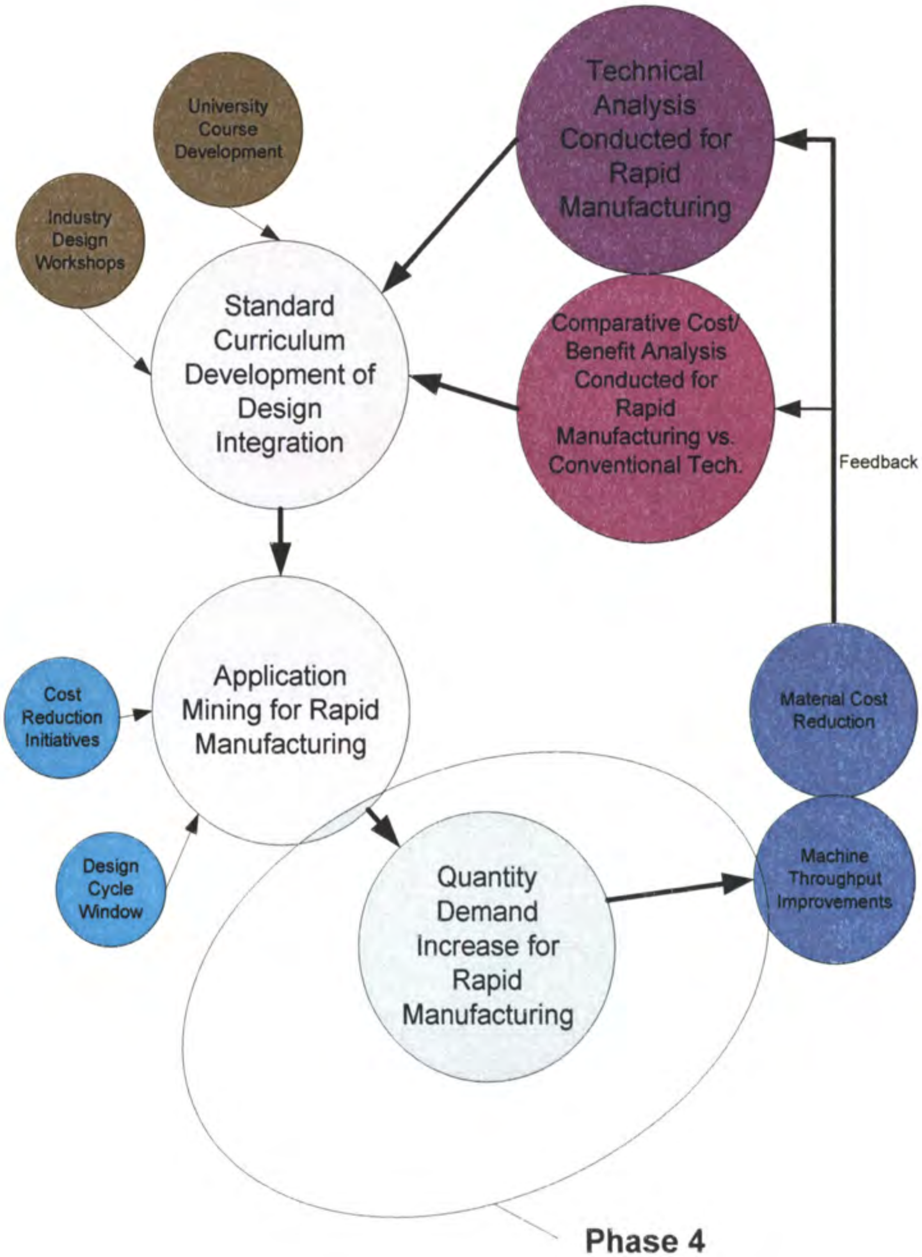


Figure 6.5. AM Technology Implementation Cycle – P4

During Phase 4, care must be taken by the company deploying the emerging technology to balance the development of the supplier base, the rising demand of the technology, and the subsequent quality maturation of the emerging technology. This balanced relationship is shown in Figure 6.6.

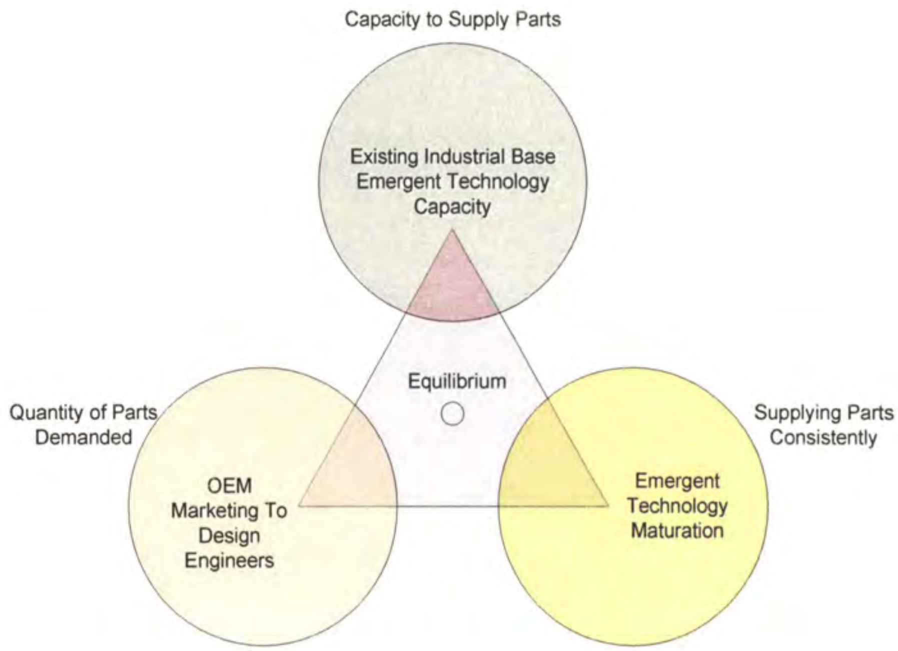


Figure 6.6. Balance of Technology Development

In order to keep this balanced equilibrium, robust cost models must be put in place that accurately describe the technology's true cost of manufacture. The emergent technology's suppliers and OEM stakeholders must deem the cost model for the technology accurate and account for changes in production volume as quantity of parts demanded increases. This is prepared by coupling the manufacturing flexibility assessment techniques described in §3.1.2 with the cost modeling development described in §5.1.3. A Gate 4 is required to move the next phase and is described as:

1. Cross-Functional Cost Model Development
    - Supplier Input
    - Supplier Manager Input
2. Manufacturing Process Flexibility Assessment

- Manufacturing Engineer Input
- Design Engineer Input
- Supplier Manager Input

3. Risks of Demand Increase
   - Too Much Demand Increase for Supply
   - Too Little Demand Increase to Justify Supply
   - Too Little System Robustness
   - Budget and Timeline Update

6.1.1.5. Phase 5 – Cost of Manufacturing Decreases. Given that in a competitive market, price equalizes the quantity demanded by customers and the quantity supplied by suppliers, which results in economic equilibrium. Therefore, it may be postulated that as quantity demand increases in Phase 4, an initial resulting price increase may be expected for the emerging technology itself in the short term due to a demand curve shift to the right. However, in the long term, machine manufacturers will react to the increased demand through competition and drive the price of material and machines downward by shifting the supply curve to the right. This price decrease may be manifested in the cost of raw material consumed in the AM process. In addition, with increased demand, AM machine manufactures will be forced, through competition, to offer faster throughput of their systems as they compete against each other for the sale of machines. With a decrease in material cost, increase in throughput and potential decrease in machine price, more machines will be sold to the market of upcoming AM suppliers. Figure 6.7 illustrates Phase 5.

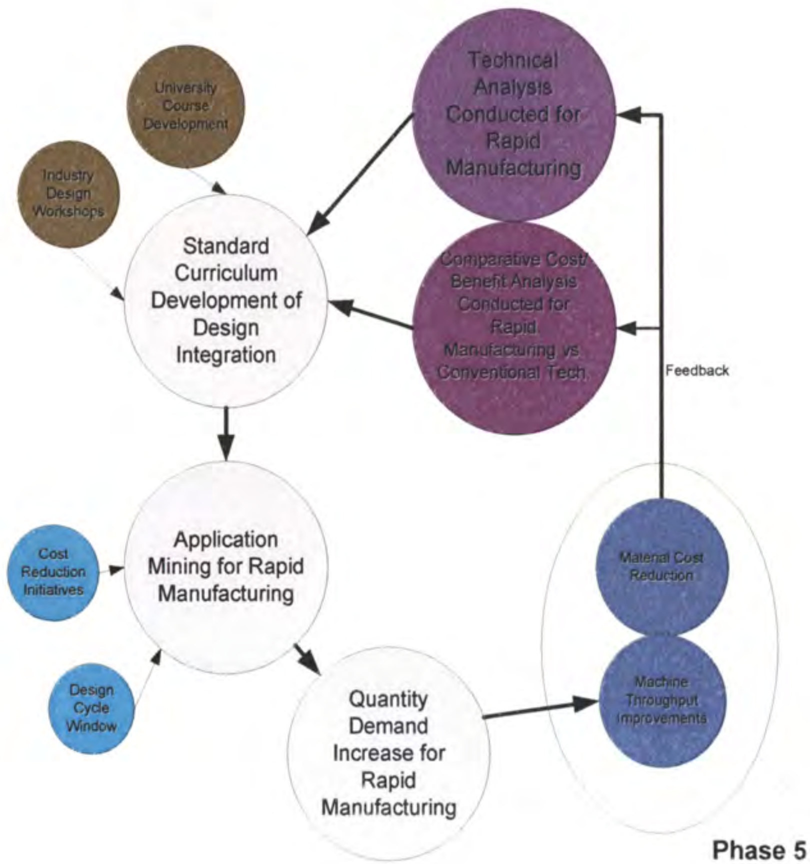


Figure 6.7. AM Technology Implementation Cycle – P5

As the cost of manufacturing of AM decreases and the technical capacity and efficiency of the machines increase, these changes must be recorded and fed back into the economic and technical design guidelines to provide updated information for training and workforce development. It is theorized that the actions of Phase 5 would provide information flow back to Phase 1 and start another cycle of analysis due to newly acquired machine throughput and cost information.

6.1.2. Project Management. It is expected that the implementation of Phases 1-5 shall take as long as funding and scope allow. Therefore, an approach to emerging technology deployment implementation similar to a strategy offered by project management best practices may be considered.

6.1.2.1. Phase Estimating. Using a phase estimating process allows for accurate budget forecasting with regard to the technology deployment. The main idea of phase estimating is the macro estimating of the entire project crosschecked by detailed estimates prior to each phase start. This hybrid type of phase estimating allows for flexible estimating and affords the company the opportunity to adjust scope, re-evaluation or cancellation prior to funding between phases. This type of flexibility allows for effective project management during annual budget adjustments within the corporate environment. Table 6.1 illustrates a phased estimate approach, defined by Gray and Larson (2006) and applied to the AM technology implementation cycle.

Table 6.1. Estimating Sequence for AM maturation

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Current State Evaluation – P1	→	Macro estimate →	→	→	→
Developing the Demand - P2		Detailed estimate →	→	Macro estimate →	→
Sparking the Catalyst – P3			Detailed estimate →	Macro estimate →	→
Quantity Demand Increase – P4				Detailed estimate →	Macro estimate →
Cost of Manufacturing Decreas – P5					Detailed estimate →

6.1.2.2. Work Breakdown Structure. Each phase shall be broken down into a work breakdown structure (WBS) format to allow for appropriate rollup of costs, Gantt charting, earned value tracking and forecasting. For example, a sample of a WBS breakout for Phase 1 may look like Figure 6.8.

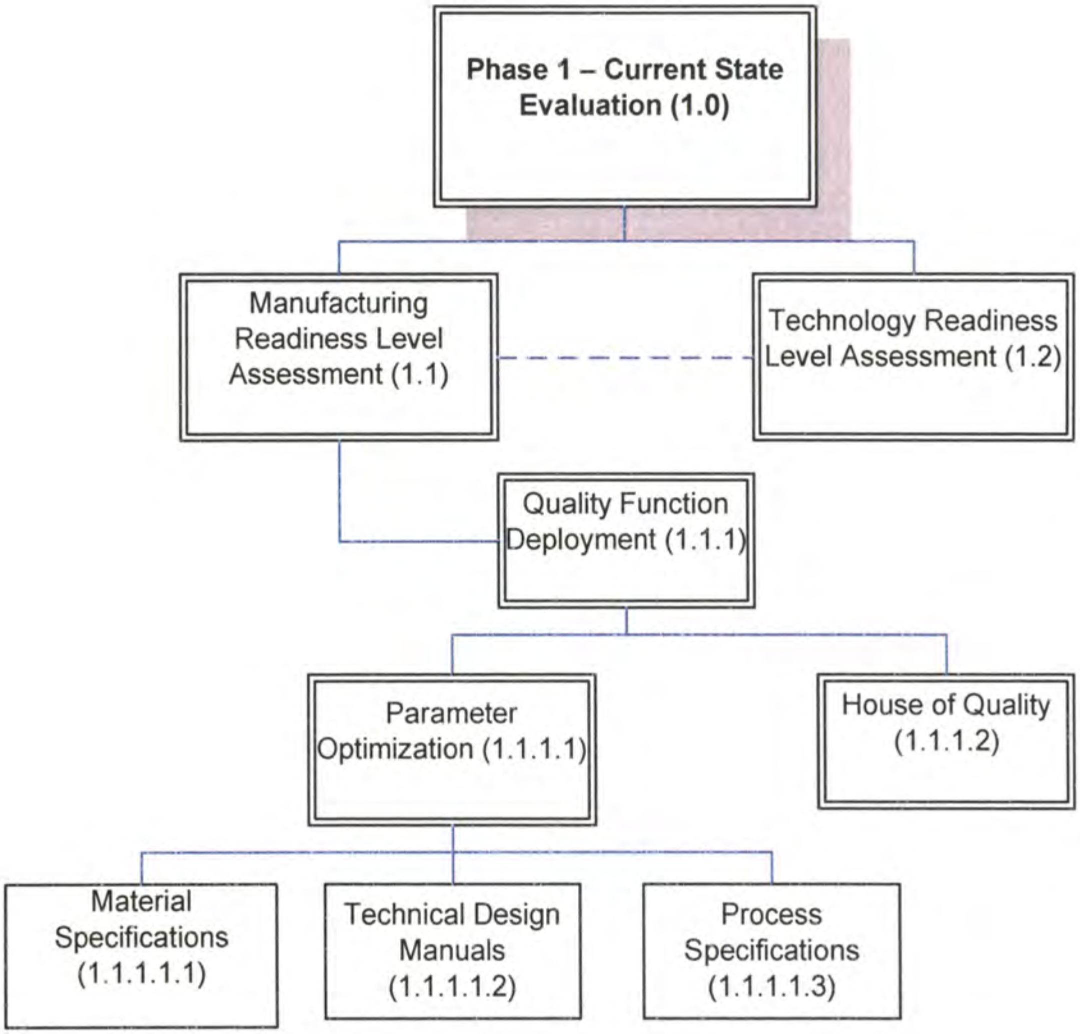


Figure 6.8. Work Breakdown Structure Sample

6.1.2.3. Budget and Schedule Tracking. Using the WBS format, methods of variance analysis may be conducted to evaluate the effectiveness of the phased implementation activity. Measuring this effectiveness may be facilitated by either comparing earned value with the expected schedule value and comparing earned vale with actual costs accrued. The following metrics should be used to determine the effectiveness of the phased implementation activity:

- PV = planned cost of the work scheduled
- EV = budgeted cost of work completed
- AC = actual cost of work completed
- SV = schedule variance
- CV = cost variance

By using metrics to track schedule and budget, a certain amount of control and documentation exists to implement the emerging technology using a phased approach.

6.1.2.4. Human Resource Development. Highly skilled technicians and engineers are needed to develop any emerging technology. When hiring these highly skilled individuals, Maurer (2006) highlights a need to assess the highly skilled employees via situational interviews.

Of utmost importance is the strategic placement of supplier selection based on access to these highly skilled individuals. For example, a despite a propensity of rural areas to develop advanced manufacturing technology using government stimulus funding and low cost labor as attractions, highly skilled individuals still need to reside in the area to supplement the equipment. However, the propensity of the younger generation to adopt new technology may assist in technology transfer in rural areas. According to Wagner et al. (2008), the younger, computer-literate generation perceives this type of new technology as attractive.

6.2. MODEL VALIDATION

The overall arching model of emerging technology development may be validated through the verification of individual sub-modules; such as, the economic analysis, lead time analysis, designed experiments, quality loss function gains through integrated design, and manufacturing readiness maturity risk.

6.2.1. Economic Analysis Validation. First, the economic analysis model of the research encompasses a breadth of knowledge. In order to verify the economic analysis model, several methods may be used. The first method would involve empirical verification through supplier quote mechanisms. Several sample geometries are proposed for fabrication and submitted to additive manufacturing (AM) suppliers for quotes. All geometry submitted represents different scales and complexity to test the scope capability of the model. In addition, multiple quantities of the geometries are requested in order to test the quantity depth of the model.

Quotes are received and compared to the model. The quotes received are not expected to match the economic model perfectly and quoting inconsistency among suppliers is expected, which in turn, justifies the need for the model. Plotting quoted price versus quantity for a specified geometry, a regression analysis is then conducted to plot supplier quotes to the model in order to derive a coefficient of determination (R^2).

However, the model does not always represent a simple regression pattern. As noted previously, for SLS, the saw-toothed pattern generated by the model may pose a challenge of accuracy of a single line. Individual teeth may need to be broken down as separate lines within the model. The objective of deriving a R^2 value is to illustrate the amount of disparity of quoting among suppliers and illustrate how a common model may be used to normalize quoting inconsistencies and provide rationale for future research.

6.2.2. Lead Time Analysis Validation. The objective of the lead-time analysis is to illustrate that AM technologies will most likely always be faster than conventional manufacturing technologies. A model was established, based on supplier input, for AM technology relative to composite manufacturing. In order to explicitly verify this model, parts must be processed using both composite manufacturing and AM. At each step within each process individual times must be recorded. In order to achieve this verification, it may be necessary to produce a sample part, from a different supplier than where the input was given for the model, using both processes and record process step times. This verification step may be conducted pending budget approvals.

An alternative approach that qualitatively verifies the lead-time model would be a simple lead-time analysis of supplier lead-time performance of previous parts that have been built using composite manufacturing or injection molding. A handful of candidate parts may be evaluated based on the time required to build them. These data would then be compared to lead time quotes from both the AM suppliers and the lead-time model to correlate the three pieces of lead-time information together.

6.2.3. Validation of Designed Experiments. P-Diagrams offer a concise way to view the experiment from a systems point of view. By mapping out the experiment in a p-diagram format, the experiment designer is forced to think of the experiment in terms of a complete system to be analyzed. Although the specimens produced for the testing may not be the same for each technology, the specimen should reflect the quality characteristic defined for the experiment. As an example of appropriate test design, examples have been provided that highlights two different quality characteristics for two technologies. The quality characteristic dimensional stability of peg board geometry was constructed for the SLS p-diagram in Figure 6.9. Tensile test bars were constructed and tested for the FDM p-diagram shown in Figure 6.10.

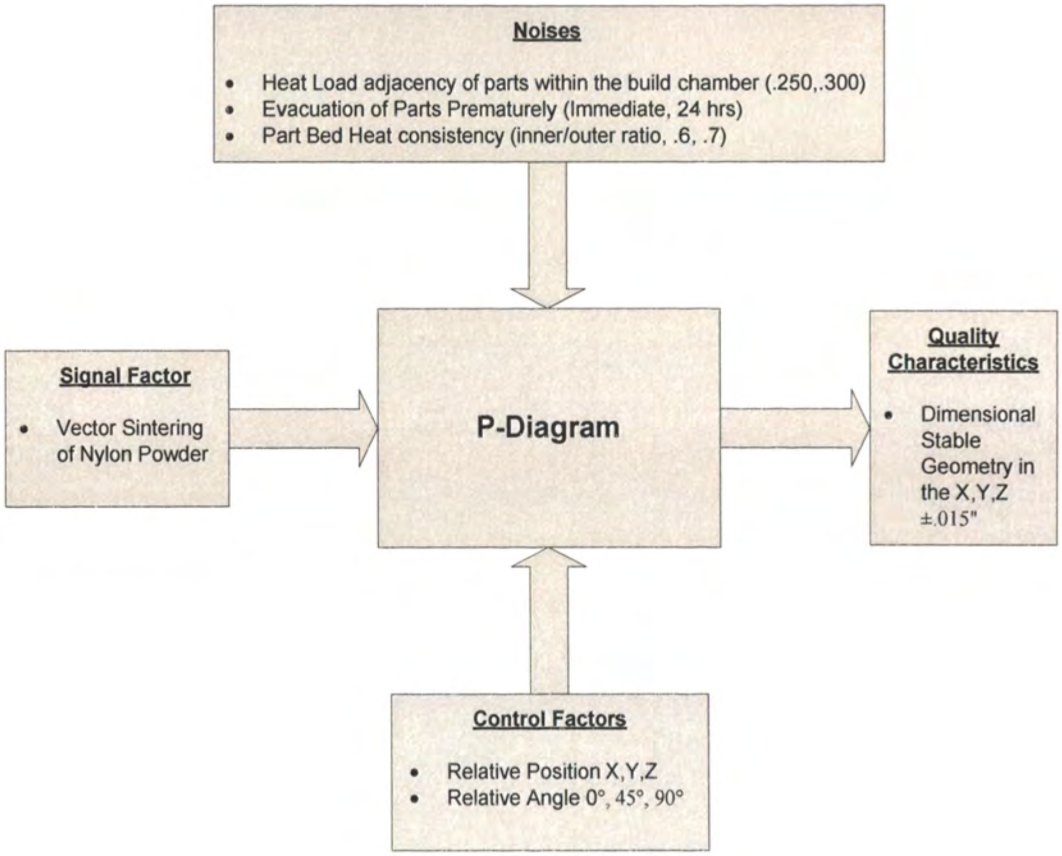


Figure 6.9. SLS p-diagram

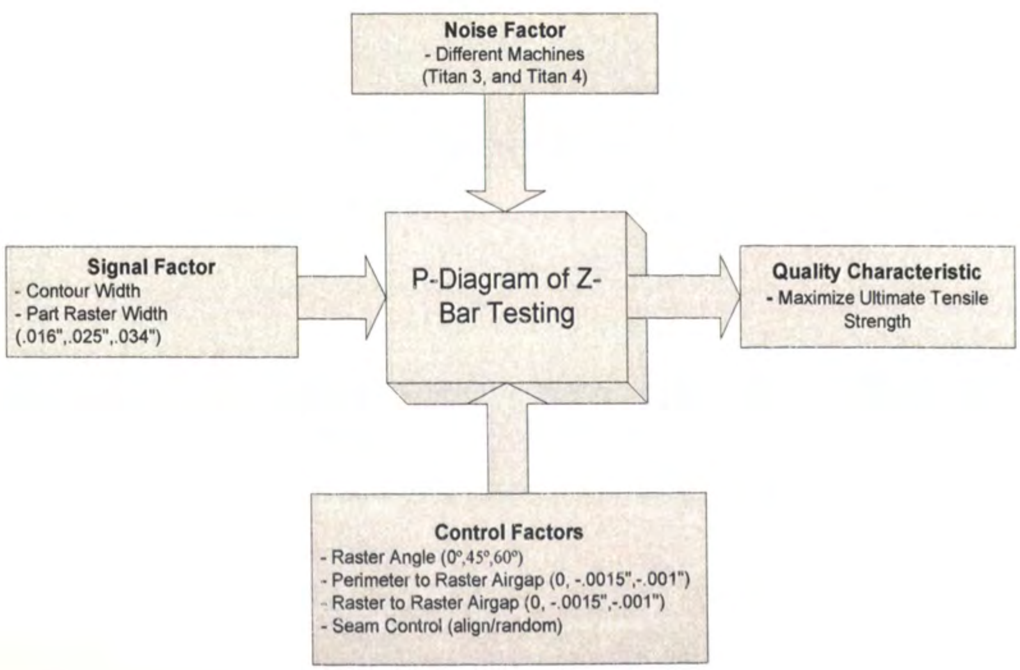


Figure 6.10. FDM p-diagram

Significant data were captured from the tensile specimens during the design experimentation. In addition, verification of the design experiment methodology was obtained through documented optimization of the processes that enhanced the quality characteristics of ultimate tensile strength in FDM and dimensional stability of SLS.

Quality loss function gains through integrated design may be verified by collecting subassemblies of parts conventionally manufactured and conducting a thorough dimensional inspection on the subassembly using a coordinate measuring machine (CMM) or three-dimensional white light scanning techniques. Several parts may be used in the subassembly in order to capture true manufacturing tolerance deviation. A second integrated design AM part is then produced that is a direct representation of the conventionally manufactured subassembly. The AM part is then dimensionally verified using CMM or, and then compared to the original conventionally manufactured subassembly and then a dimensional deviation analysis would then be conducted between the two methods. With respect to comparisons among AM technology only, research has been conducted in the field by Munguia et al., (2009) and Kotlinski et al., (2009) where they compare different AM technologies dimensionally to one another using CMM and white light scanning equipment.

6.2.4. Validation of Manufacturing Maturity Risk. Manufacturing readiness maturity risk may only be verified at an organizational enterprise level. Technology readiness levels (TRLs) and manufacturing readiness levels (MRLs) are used on a daily basis by the Department of Defense and various industries globally. Therefore, the aspect of MRL and TRL applied to the model are without need of verification. However, using the modified MRL risk approach needs time for use at an enterprise level in order to see verification. Recording the true MRL risk values of emerging technologies currently may yield results in the future as the emerging technologies continue to develop under organizational control. In addition, the model may be verified by others through publishing, however, for now it may remain conjecture.

In conclusion, verification of models is extremely important for an establishment of research credibility and future research. By verifying the models in the context of AM and emerging technologies, strong data will support the continuation of AM maturity through both scholarly and industrial endeavors.

7. RESULTS OBTAINED

7.1. DESIGNED EXPERIMENTS – SLS.

As described in § 4.2 a design experiment was conducted on dimensional stability for SLS. The objective of the test was to discover what parameters optimized the process and how those same parameters affected dimensional stability of the process. Each objective is crucial in understanding the process prior to deployment into a supply chain.

7.1.1. Static Test Analysis of Means. An analysis of means (ANOM) was performed in the static experiment to pick optimum control factor levels, to identify a scaling factor for two-step optimization, and to identify compound noises for the dynamic experiment.

Four batches of parts were run to capture the different levels of noise. Of the four, build 1 illustrated the highest S/N ratio. Maximizing the S/N for each factor identified optimum control factor levels. Values obtained in the ANOM for the control factors are pictured below the optimum level for each factor is indicated in red in Table 7.1. The control factor effect plots are located in Appendix A.9.

Table 7.1. Optimum Levels for Each Factor

		S/N Ratio						
		X	Y	Z	A-0	A-45	A-90	Average
Level	1	51.9	52.15	45.39	71.68	67.21	62.73	58.51
	2	48.57	49.6	46.74	63.04	60.29	64.64	55.48
	3	44.52	46.82	47.62	62.56	63.83	63.95	54.88

Predictive Analysis	
S/N_{exp}	56.29
S/N_{opt}	73.74

Two compound noise factors (N_1 and N_2) were identified so that the dynamic experiment could be conducted more efficiently. N_1 and N_2 are the extreme noise conditions. Values obtained in the ANOM for the noise factors are presented below. As illustrated in Table 7.2, the levels of the noises compounded into N_1 resulted in the highest S/N ($D_1E_1F_1$); N_2 resulted in the lowest S/N ($D_2E_2F_2$).

Table 7.2. Noise Factor Effect

		Noise Factor Effect Plots		
		S/N (dB)		
		Uneven Bed Temps (D)	Heat Load Adjacency	Time to Cool (F)
Level	1	32.39	32.69	33.83
	2	30.49	30.19	29.05

7.1.2. Static Confirmation Experiment. A confirmation experiment verified the results predicted by the additive model using the optimal control factor combinations. The following formulas were used to predict the optimal mean and S/N,

$$\widetilde{S/N}_{opt} = \overline{S/N} + \sum_{i=1}^{n_{cf}} \left(\widetilde{S/N}_i - \overline{S/N}\right) \tag{40}$$

$$\tilde{y}_{opt} = \bar{y} + \sum_{i=1}^{n_{cf}} (\tilde{y}_i - \bar{y}) \tag{41}$$

As shown in Table 7.3, the existing test that included all control factors yielded an S/N ratio of 56.29 dB and a mean of .005 in. With the optimized design using the applied software scaling confirmation test, S/N was increased to 59.33 dB and target deviation from mean decreased to .004 in. This was not as good as predicted, but within range to determine that there is a confirmation. Further experimentation may be needed to isolate other undiscovered factors.

Table 7.3. Predicted vs. Confirmed

	Predicted		Confirmed	
	S/N (dB)	Mean (in)	S/N (dB)	Mean (in)
Existing Design	n/a	n/a	56.29	0.005
Optimal Design	73.74	0.002	59.33	0.004

7.1.3. Industry Application. The overall goal is to assess the dimensional stability of the build volume while subjected to various noise conditions. Build #1 of 4 proved to be the most robust, see calculations in Appendix A.14. In build #2, a great deal of information indicated how the robustness of the X and Y was affected by the applied noise of "Uneven Bed Temps". Relative to the X and Y zone, in the "high" setting, note the robustness of zone 3 dropping off significantly compared to run 1 with the noise set to "low". This trend was confirmed in build #4 when the uneven bed temperatures noise was set back to 'low". Also, the heat load adjacency setting was increased in run 2 – this moved the parts closer together from .300" to .250". This is represented by a consistent robustness drop with all Angled and Z axis parts relative to the first run with spacing of .300".

Because the X and Y planes tended to be the most sensitive to part placement within zones, Table 7.4 attempts to translate only the X-Y S/N data into actual dimensional tolerance ranges for each noise condition.

Table 7.4. Dimensional Variation to Tolerance

Build 1 (D_1,E_1,F_1)	S/N	**Build 2 (D_2,E_2,F_1)**	S/N
Zone 1 Robustness	51.39	Zone 1 Robustness	48.50
Zone 2 Robustness	48.98	Zone 2 Robustness	46.58
Zone 3 Robustness	46.82	Zone 3 Robustness	40.67
Dimensional Variation in % Inside to outside edge	8.89%	Dimensional Variation in % Inside to outside edge	16.14%
Translated to	± .015"	Translated to	± .030"
Build 3 (D_2,E_1,F_2)	S/N	**Build 4 (D_1,E_2,F_2)**	S/N
Zone 1 Robustness	50.1035	Zone 1 Robustness	50.33009
Zone 2 Robustness	46.46093	Zone 2 Robustness	47.5155
Zone 3 Robustness	40.33007	Zone 3 Robustness	45.51695
Dimensional Variation in % Inside to outside edge	19.51%	Dimensional Variation in % Inside to outside edge	9.56%
Translated to	± .036"	Translated to	± .018"

By using Table 7.4 and Dr. Taguchi's quality loss model in Appendix A.10, dollar amounts may be assigned to each noise condition prior to two-step optimization. Given a

\$1200 scrap material cost incurred per batch of parts that exceed the tolerance limit of ± .030", this will be A_0 and Δ_0 respectively. Prior to optimization, if the noises D,E,F, are set to 1, according to the quality loss calculation, the quality loss would only be \$313 with ± .015"accuracy. Build #4 parameters would result in \$450 loss at ± .018". See appendix A.13 for the calculations. After the optimized confirmation build, the S/N ratio for Zone 1 is now 59.33. The mean shifted to ± .008". Using this optimized configuration of building primarily in zone 1 coupled with the software scaling applied, parts will now only incur \$88.90 of loss. A net savings of \$450 (@±.018") - \$88.90 (@±.008") = \$361 per build.

The techniques utilized during the static experiment highlighted the amount of dimensional robustness variation throughout the entire build envelope. AM experts have known of thermal variation within the process, but none has mathematically mapped the amount of thermal variation using the static experiment.

Primarily, the static experiment "lessons learned" through ANOVA quantified this knowledge to determine a 8.8% dimensional variation from the center of the X-Y part bed to the edge of the part bed throughout the entire build envelope. The center of the build envelope proved to be more dimensionally robust. By using the crossed orthogonal array, the peg-board geometry reached the optimum thermal stability approximately 1/3 of the build height.

By using two-step optimization through software scaling, the mean from target was reduced to .004" decreasing the old specified tolerance from ±.015" to ±.008". This dimensional tolerance reduction will help the SLS process to become more of a "production" system.

7.1.4. Dynamic Analysis of Means (ANOM). An ANOM was performed on the data collected in the dynamic experiment to identify optimum control factor levels. The goal of the ANOM is to maximizing the S/N for each factor identified optimum control factor levels and identify the smallest delta from target. For this specific experiment, the target distance measured was 1.25"; the delta from target represents how close the mean was to the 1.25" target. Values obtained in the ANOM for the control factors are presented in Table 7.5. The optimum level for each factor is indicated in red.

Table 7.5. Analyis of Means - Dynamic

Dynamic ANOM Results		
Factor	S/N	Δ from Target
X1	-15.33	0.0093
X2	-13.7	0.0098
X3	-12.84	0.0047
Y1	-15.28	0.0089
Y2	-15.11	0.0084
Y3	-11.48	0.0087
Z1	-10.61	0.0118
Z2	-14.63	0.0119
Z3	-16.63	0.012
A1	-15.6	0.0093
A2	-14.29	0.0115
A3	-11.97	0.0088

7.1.5. Dynamic Confirmation Experiment. A confirmation test was completed for the dynamic experiment to determine the appropriate level settings to be used. The results are found in Table 7.6, which indicates the optimization of the dynamic signal to noise ratio.

Table 7.6. Confirmation Experiment

Confirmation Test					
	S/N (dB)				
Level	X	Y	Z	A-0	Average
1	-15.33	-15.28	-10.61	-15.6	-14.21
2	-13.7	-15.11	-14.63	-14.29	-14.43
3	-12.84	-11.48	-16.63	-11.97	-13.23
				S/N_{exp}	-13.96
Predictive Analysis				S/N_{opt}	-5.03
Confirmation Software Scaling				Optimized Value	
					-11.15

According to the predictive analysis equation, the theoretical optimized S/N ratio should be -5.03. By picking the best control factor levels (X3,Y3,Z1,A3) and applying the scaling software as illustrated in Figure 4.8 of the static experiment, the test was re-ran and the new S/N optimized value is -11.15. This was a 20% improvement in S/N ratio. A weak interaction between control factors may exist.

Figure 7.1 illustrates the linear ideal function of the relationship between Wattage range and dimensional stability. The trend line reflects the data achieved in the dynamic test.

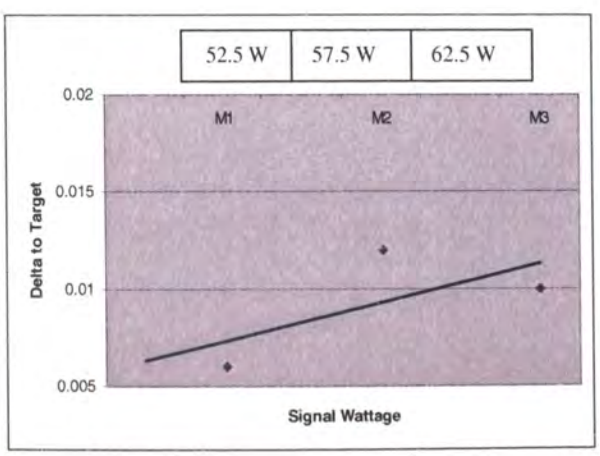


Figure 7.1. Ideal Function

7.1.6. Analysis of Variance. Table 7.7 reflects the percentage of contributions of each control factor. Experimental Error was determined by pooling the sum of squares of up to half of the control factors that contribute the least. An "F- ratio" of > 4.32 is considered to represent statistically significant control factors. For this simulation, the highest F-ratio is 3.13 for the Angle control factor. As a result, the control factors have a low to moderate effect on system control. Because pooling is the most conservative estimate for error variance, experimental error plays less of a part.

Table 7.7. Analysis of Variance Results

avg s/n (X1)	-15.3313	SS(X)	12.787	Percent Cont. X	11.22%
avg s/n (X2)	-13.7038	SS(Y)	12.235	Percent Cont. Y	10.74%
avg s/n (X3)	-12.8417	SS(Z)	17.283	Percent Cont. Z	15.17%
avg s/n (Y1)	-15.2801	SS(A)	36.755	Percent Cont. A	32.26%
avg s/n (Y2)	-15.1109				
avg s/n (Y3)	-11.4858				
avg s/n (Z1)	-10.6106				
avg s/n (Z2)	-14.6336				
avg s/n (Z3)	-16.6326				
avg s/n (A1)	-15.6096				
avg s/n (A2)	-14.294				
avg s/n (A3)	-11.9732				

The final percentage of contribution of each relative effect on the measured response listed in the Table 7.7. Upon a summation of the percentages, 69% of the system robustness are controlled by the orientation with respect to the laser wattage input. The remaining 31% totaled may be attributed to experimental error and unforeseen control factor interactions.

Pending continued funding and SLS machine availability, a thorough control factor interaction study may have to be completed to establish more significant data. Other approaches would include error variance using replication, and unassigned columns as other techniques for experimental error.

One major room for improvement would be the expansion of the control factor zones to extend to the outer limits of the build chamber, thus, exposing the variation to a larger X-section of the build. Based upon the outcome of the static experiment, the zone pattern was tightened to capture a finer detail of variability. In the dynamic experiment, this X-section may have been too small and thus, reduced the control factor zoned variability too much. Another area of improvement would be more measurement points on the test parts. Hopefully, with more data points measured, the variability would become more accurate and expansive.

7.1.7. Industry Application. Understanding the relationship between how a part is placed within the build chamber and its relative dimensional robustness is a large improvement in the SLS process. Although further work is necessary to understand interactions, funding and machine availability will govern future development. Although the dynamic experiment was not definitive with the control factors, the methodology of discovering the percent contribution is reliable. Although too much error is assigned, using the additive model equation developed below, a SLS operator will be trained that an angled part lends itself to more dimensional variation than a part placed in the X and Y. This concept will ultimately assist operators make decisions of specific part placement for dimensional stability. Once understood, the CAD part placement will now be able to have a major impact on how SLS is matured into large scale production. See Appendix 4A for a revised FAST diagram reflecting the percentages of contribution

7.1.8. Conclusion of SLS Designed Experiments. The Selective Laser Sintering Process is a relatively immature manufacturing system. As companies rely on the SLS process to directly manufacture parts, the industry will shift from Rapid Prototyping into Rapid Manufacturing. Along with this transformation, the process will need to become more robust. By using Dr. Taguchi's method of offline quality engineering, the process may become mathematically analyzed in structured approach.

7.2. DESIGNED EXPERIMENTS – FDM.

The results of FDM designed experiment testing are shown below. The testing included the Polycarbonate material system on the FDM Titan platform. The quality characteristic includes tensile testing of the ASTM D638 Type I specimens, shown in Figure 1.6.

7.2.1. Y-Direction Quantitative Results. Table 7.8 is a capture of the orthogonal array and input data for Ultimate Tensile Strength (UTS) listed in pounds per square inch (psi). The signal factor is bead width in inches. More information on bead width may be found in § 1.2.4.2. The noise factors identified are two separate machines. The inner array consists of four separate control factors, seam control, raster angle, perimeter to raster air gap and raster to raster air gap. Each run number corresponds to the level changes of each control factor as discussed above. A note of interest is that Titan 4 consistently yields a higher UTS mean than Titan 3, thus, introducing variation among machines.

Table 7.8. Y Direction Tensile Testing of FDM

					Bead Thickness (inches)							
					0.016		0.026		0.034			
Seam Control	Raster Angle	Perimeter to Raster Air Gap	Raster to Raster Air Gap		Titan 3 (N1)	Titan 4 (N2)	Titan 3 (N1)	Titan 4 (N2)	Titan 3 (N1)	Titan 4 (N2)	Mean	Standard Deviation
1	1	1	1		6720	7550	7680	7950	5820	6320	7007	849
1	2	2	2		8600	9020	7720	8710	7910	8800	8460	522
1	3	3	3		9300	9050	8200	8650	7750	7940	8482	621
1	1	2	2		8730	8960	6710	6950	7410	7710	7745	923
1	2	3	3		8660	8630	7360	7410	6640	7600	7717	790
1	3	1	1		6920	7460	6540	7230	6800	7490	7073	382
1	2	1	3		9320	9550	7850	8540	5890	8320	8245	1316
1	3	2	1		7430	7870	6680	7210	7270	7560	7337	399
2	3	3	2		8760	8070	8060	8460	7830	8900	8347	428
2	1	1	3		8120	8210	7410	7010	7000	6990	7457	572
2	2	2	1		7860	7990	7130	7410	7530	8120	7673	379
2	2	3	1		7560	7530	6590	6660	7040	7190	7095	415
2	3	1	2		9050	9440	8100	8920	7170	8200	8480	822
2	3	1	2		8690	8730	8010	8310	7620	7730	8182	474
2	1	2	3		8420	8540	7440	7520	7120	7170	7702	623
2	3	2	3		8560	8630	7820	7750	7530	7600	7982	487
2	1	3	1		7350	8050	7750	8030	6290	6840	7385	706
2	2	1	2		8420	8540	7500	7730	7460	7710	7893	469
				Mean	8248	8434	7475	7803	7116	7677		
				Std. Dev.	777	634	542	679	622	655		

The levels highlighted in Table 7.9 yield the highest levels of tensile strength. Therefore, if one were to optimize for tensile properties for parts built in the Y orientation out of Polycarbonate, then setting seam control to randomized (2) and raster angle to 60 deg. (3), the perimeter to raster air gap to -.0015" (2) and raster to raster air gap to -.0015" (2). Combining this with the Table 7.8, using a .016" bead thickness for contour and raster, the part will be optimized for ultimate tensile strength.

Table 7.9. Ultimate Tensile Strength Values per Level

Average U.T.S. Values Regardless of Machine or Contour Thickness (psi)					
		Seam Control	Raster Angle	Perimeter to Raster Air Gap	Raster to Raster Air Gap
Level	1	7758.1	7459	7715	7262
	2	7819.5	7847	7816	8184
	3	n/a	7983	7805	7931

After the signal to noise ratio calculation, the following average S/N's for each control factor is developed; the higher the S/N value, the more robust the control level. Given this information, a conclusion can be drawn in regard to robustness. The highest-level values are highlighted in Table 7.10. Random Seam control, Raster Angle set to 60 deg., Perimeter to raster gap @ -.0015" and Raster to raster gap @ 0 degree produce the least amount of variation in the system for geometry produced in the Y direction on a FDM Titan using Polycarbonate.

Shown as percentages in Table 7.10, the % of contribution each control factor plays in system stability. When totaled, the %'s equal ~30%. Given the control factors identified are the extent of variability allowed by the process user, this draws the conclusion that for geometry produced in the Y direction on a FDM Titan using Polycarbonate, only 30% of system variability is able to be manipulated. Only the machine manufacturer may alter the remaining 70% of system robustness. Of the 30% able to be manipulated in the system, Raster to Raster air gap makes up 17.69% of contribution, Raster Angle 8.96% etc.

Table 7.10. S/N Ratios for the Control Factors

Average S/N			
(Seam Control-Aligned)	39.66893	Percent Cont. Seam Control	0.66%
(Seam Control-Random)	39.9688	Percent Cont. Raster Angle	8.96%
(Raster Angle -0)	39.31904	Percent Cont. P to R Gap	3.42%
(Raster Angle-45)	39.82349	Percent Cont. R to R Gap	17.69%
(Raster Angle-60))	40.21475		
(P to R Gap -0)	39.55085		
(P to R Gap -.0015")	40.09793		
(P to R Gap -.001")	39.91919		
(R to R Gap -0)	40.40145		
(R to R Gap -.0015")	39.95892		
(R to R Gap -.001")	39.14619		

7.2.2. Conclusions Drawn from Y Direction Results. As there is only 30% contribution from the user controlled factors, opening up the software architecture to allow for more user-defined variables could lead to more system robustness improvements. Knowing that .016" bead thickness results in higher tensile properties in geometry for Y direction geometry, efforts should be made when setting up builds to minimize the bead thickness profile as much as possible to optimize part strength characteristics. Overall system robustness can vary between machines as little as .4% However, tensile strength can vary between machines as much as 7.3% using .034" bead thickness and as little as .2% using .016" bead thickness. Therefore, when running the same part or mating parts on different machines with the majority of critical geometry in the Y direction, use a smaller bead thickness to minimize the amount of tensile strength variation among machines.

In addition, to maximize tensile strength for a geometry that remains critical in the Y direction, the following settings yield the highest UTS values: Setting seam control to randomized (2) and raster angle to 60 deg. (3), the perimeter to raster air gap to -.0015" (2) and raster to raster air gap to -.0015" (2).

7.2.3. Z-Direction Results. Using the Y results as a baseline, a number of Z direction orientation tensile bars were produced to evaluate how build orientation plays a role in tensile strength. Using lessons learned examples from the Y direction testing, machine resource restrictions, and in an effort to reduce testing costs, the Z direction tensile testing bars were only produced on Titan 3. On the grounds of resource availability, Titan 4 was omitted from the Z Direction tensile bar construction.

The Y direction control factors of raster to raster gap, perimeter to raster gap, raster angle and seam control were also used for the Z direction build. As mentioned above, the only difference in the experiment was the two separate machines as noise, N1 and N2 became just N1. Table 7.11 depicts the experiment array.

Table 7.11. Z-Direction Tensile Test Results

						0.016	0.025	0.034				
Part #	Seam Control	Raster Angle	Perimeter to Raster Air Gap	Raster to Raster Air Gap		Titan 3	Titan 3	Titan 3	mean	SD	n	S/N
1	1	1	1	1		3510	3440	4230	3726.67	437.3	72.6	18.6108
2	1	2	2	2		5420	5290	6140	5616.67	457.9	150	21.775
3	1	3	3	3		6250	6170	5270	5896.67	544.2	117	20.6973
4	1	1	2	2		7010	7200	5610	6606.67	868.4	57.9	17.6257
5	1	2	3	3		3560	3740	3140	3480.00	307.9	128	21.0635
6	1	3	1	1		4050	3980	4150	4060.00	85.44	2258	33.5373
7	1	2	1	3		3540	3300	3770	3536.67	235	226	23.5499
8	1	3	2	1		5170	4940	5030	5046.67	115.9	1896	32.7783
9	2	3	3	2		4290	4750	3880	4306.67	435.2	97.9	19.9083
10	2	1	1	3		3610	3410	3780	3600.00	185.2	378	25.7731
11	2	2	2	1		4560	3320	5320	4400.00	1010	19	12.7865
12	2	2	3	1		5410	5280	4960	5216.67	231.6	507	27.0535
13	2	3	1	2		6060	5820	4890	5590.00	618	81.8	19.1287
14	2	3	1	2		4560	3100	4800	4153.33	920.1	20.4	13.0915
15	2	1	2	3		3890	3310	4300	3833.33	497.4	59.4	17.7369
16	2	3	2	3		3910	4270	4000	4060.00	187.3	470	26.7174
17	2	1	3	1		3740	3520	3120	3460.00	314.3	121	20.834
18	2	2	1	2		2650	2550	2460	2553.33	95.04	722	28.5837
					mean	4510.56	4299.44	4380.56				
					SD	1149.657	1254.87	954.9097			mean	22.2917
					n	15.39301	11.73889	21.04426				
					S/n	11.87323	10.69627	13.23134				

The results from this experiment shows that despite a change in the signal factor of contour thickness, any drastic change in ultimate tensile strength remains insignificant. Another interesting point is that the average ultimate tensile strength value for the Z direction is approximately 55% of the Y direction. The third point is the amount of robustness based in the experiment indicates very little UTS variability in the system when the selected control factors are changed.

7.2.4. Conclusions Drawn from Z Direction Results. One simple conclusion drawn from the Z Direction Result is that perhaps the tensile bar test geometry cross-sectional neck area may be too small to highlight the contour thickness variation when tested. Due to the nature of the process, contours are laid around a raster pattern, it is possible that this raster pattern were so small that it had a negligent impact on tensile strength results. This topic of discussion is much different for the Y direction bars where the raster pattern has significant cross sectional area to deposit material.

In order to prove this theory, ten D638-Type 3 tensile bars of Z orientation were constructed. These tensile bars were much thicker and longer than the type 4 bars previously constructed. The idea is test the larger and thicker tensile bars in order to determine if tensile bar cross sectional thickness plays a role in the correlation between contour thickness and ultimate tensile strength.

Of the larger tensile bars, six tensile bars from each signal factor group of contour thickness were tensile tested. Very little tensile strength deviation observed indicates that regardless of scale, tensile strength relative to contour thickness remains relatively unchanged.

7.2.5. Mass Evaluation. It was determined that for Y bars, at bead width grows from .016" to .034", the difference between the actual weight of the Y bars and the computed nominal mass grows. Figure 7.2 indicates the relative relationship between nominal to actual weight differences versus bead width.

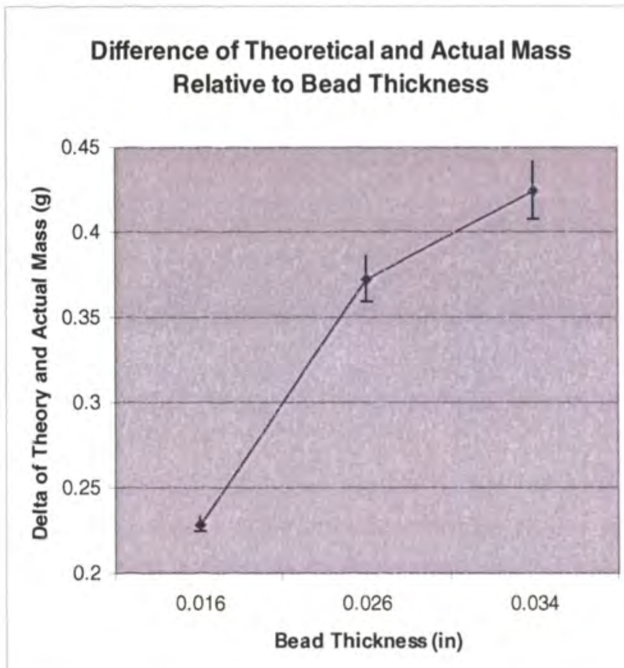


Figure 7.2. Plot of Tensile Bar Mass Study

In addition to the Y bars, large density cubes of solid material were constructed to capture the maximum amount of density in the process. The density cubes results illustrated a similar trend to the Y axis bars. The density cube example helps to determine that, independent of scale, a relationship of delta mass versus bead width is held constant. Figure 7.3 pictures a density cube being weighed and Figure 7.4 shows the density cube delta mass data.

Figure 7.3. Density Cubes Being Weighed

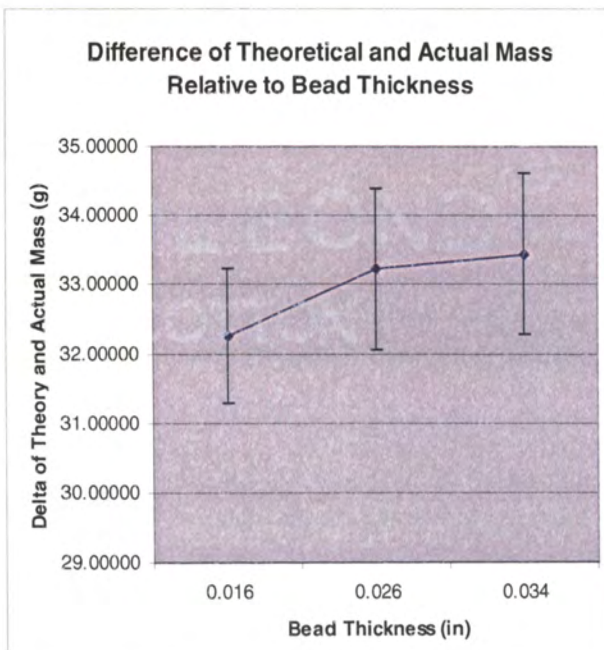


Figure 7.4. Plot of Density Cube Mass Study

The X-Y raster to raster bonding seems to be much more inconsistent that Z-axis bonding. The bead thicknesses shown in Figure 7.5 are .034" the largest contour setting.

It was established that by increasing bead profile width, raster to raster X-Y adhesion becomes more unstable, at worse condition .009" gaping was noticed. Figure 7.6 illustrates the gaping condition.

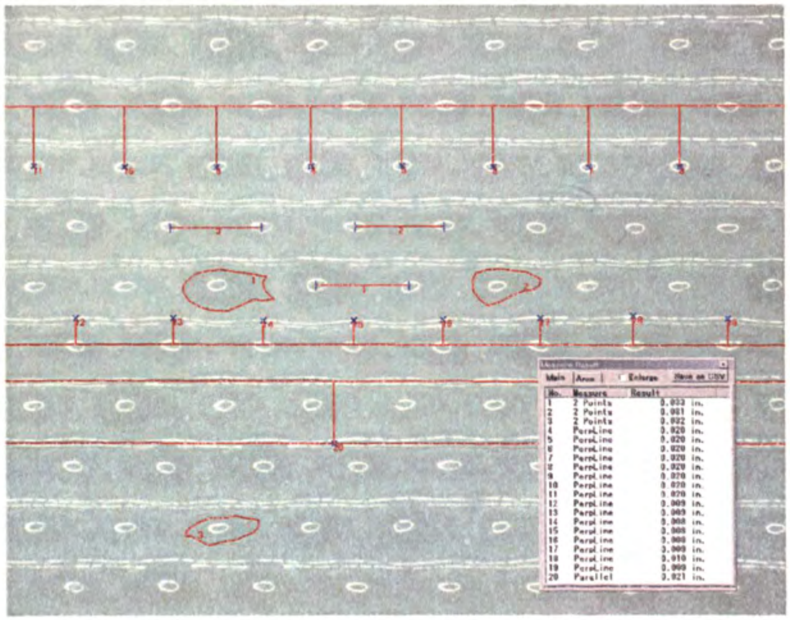


Figure 7.5. Z-axis Interlay Bonding at 50X's Magnification

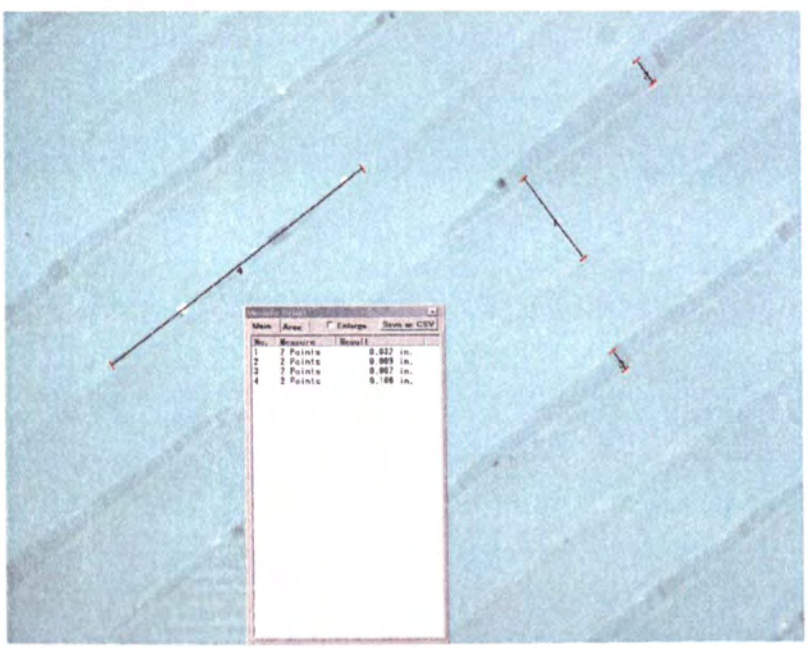


Figure 7.6. X-Y Raster Pattern Layer Variability

7.2.6. Tensile Testing Analysis. As the objective function of FDM process optimization is the enhancement of laminar adhesion, ultimate tensile strength became the primary metric to correlate bonding strength to robust product performance. Within this area of testing, two separate elements were address based upon orientation of the tensile test sample. By testing each orientation, a percentage knockdown could be established for the Z direction bars relative to the Y direction. Given the average UTS values for each orientation, Z direction bars exhibited roughly 56% of the tensile properties associated with Y direction builds.

Y direction testing provided evidence of structural integrity within the system. With each control factor adjusted in the design of experiment, a user may be able to contribute to 30% of the tensile robustness by adjusting main controls within the software. The remaining 70% of the factors remain to be non-user defined parameters. Of the most important user controlled parameters in the system, raster to raster gap remained the most sensitive to variation. With this in mind, when critical design features require significant structural integrity, it should be advantageous to reduce the raster to raster air gap to -.0015" to achieve a slightly higher level of structural integrity. Another product of the Y direction testing indicated that a small amount of variability does exist between two machines of exactly the same model. With this in mind, caution should be exercised when establishing routine process robustness parameters. In the study two separate machines (N1 and N2) each produced the exact same geometry and each machine was updated to the manufacturer's preventative maintenance schedule, each running the exact firmware version, produced different tensile test results. Given the previous example, a realistic case for consistent mass production, or what is known as

Rapid Manufacturing, becomes a much more distant objective when machine-to-machine variability is clearly exhibited.

Z direction testing provided evidence of structural weakness within the tensile test specimen. In the Z direction, despite each control factor adjusted in the design of experiment, a user may be able to contribute to only 12% of the tensile robustness by adjusting main controls within the software.

Like the Y direction orientation, raster to raster gap remained the most sensitive to variation. With this in mind, when critical design features require significant structural integrity, it would be advantageous to reduce the raster to raster air gap to -.0015" to achieve a slightly higher level of structural integrity.

The test density data concludes that, regardless of density scale, a relationship exists between the contour bead width specified in the construction of geometry and the amount of void density. Given the data above reflecting the mass change a general heuristic may be developed that states, the smaller bead width the less void density exists within the geometry.

Ultimately, the a main goal of FDM should be to reduce as much void density as possible. This objective would allow the technology to mechanically mature to a point of injection molding comparability and assist in transitioning to more mainstream AM.

7.2.7. Comparison to Injection Molding. As engineers constantly weigh technical and business trade-offs for using any type of deposition modeling process for low-volume applications, many engineers wonder if FDM would stand up to the functional loadings associated with their specific geometric designs. When directly comparing the situation to the relatively mature injection molding industry one may certainly express some apprehension in adopting FDM immediately.

Table 7.12 illustrates a comparison of Z axial tensile strength, Y axial tensile strength and typical injection molding tensile strength all for polycarbonate. Note that the FDM values are averages of testing data completed during this study.

Table 7.12. Comparison of Injection Molding to FDM

Polycarbonate Material System	Tensile Strength (psi)	Bulk Density (lb/in^3)	Post-Process Density %
Avg. Z - Axis FDM	4397	0.04335	94%
Avg. Y - Axis FDM	8230		
*Injection Molding	9014		100%
*Inj. Molding Source - CES EduPack Software			

As a reminder, data generated from the FDM machine were taken from FDM Titan modeler machines processing polycarbonate material. In 2008, Stratasys released a new modeling machine known as the 400MC with promotes more accurate cross-linking of Z-axis layers. This more consistent cross-linking will create higher Z-axis tensile properties. In addition, other material systems that offer more processing stability and higher mechanical properties will continue to be offered by Stratasys in the future.

7.3. ECONOMIC ANALYSIS

The first objective of the economic analysis portion of this body of knowledge is highlight how the establishment of a cost structure of an emerging technology may be obtained through process flow diagramming or value stream mapping. Once a cost structure is in place, and an appropriate model defined for the emerging technology, the model needs validated. Although the number of existing SLS suppliers is few, with relatively immature costing definition, quotes were received from suppliers and compared to the established model. Examples are provided that highlight cost structures for two common AM technologies, SLS and FDM.

7.3.1. Economic Analysis for SLS. For SLS, two machine sizes are evaluated to highlight changing economic profiles for geometry built in a smaller and a larger SLS machine. However, very few SLS service bureaus have the large frame EOS P730 machine, must less the build volume defined as an established cost model, therefore, the ability to verify the large frame cost model to actual supplier quotes was limited to only a 3D Systems Sinterstation Pro for Supplier 2. Table 7.13 depicts the analysis.

Table 7.13. Camera Bracket SLS Cost and Price Evaluation

	Quantity	AM - SLS Model cost per batch	Supplier 1 price per batch	Supplier 2 price per batch	% Difference to Supplier 1	% Difference to Supplier 1 with 35% profit margin added to AM cost model	% Difference to Supplier 2	% Difference to Supplier 2 with 35% profit margin added to AM cost model
Small Frame	1	$ 271	$ 882	$ 225	-225%	-141%	17%	38%
	5	$ 591	$ 1,121	$ 1,025	-90%	-41%	-73%	-28%
	10	$ 975	$ 1,514	$ 1,950	-55%	-15%	-100%	-48%
	40	$ 2,308	$ 6,418	$ 7,520	-178%	-106%	-226%	-141%
Large Frame	1	$ 458	Does not	$ 110	n/a	n/a	76%	82%
	5	$ 932	have a	$ 500	n/a	n/a	46%	60%
	10	$ 927	Large	$ 950	n/a	n/a	-2%	24%
	40	$ 1,781	Frame	$ 3,680	n/a	n/a	-107%	-53%

As referenced in §5.1.3, the AM –SLS model accounts for only cost but not price, therefore; a certain amount of difference is expected between the AM – SLS cost model and the prices offered by suppliers. In Table 7.13, a profit margin of 35% was added to the cost model to attempt to align the pricing offered by suppliers to a simulate pricing derived from the cost model. This simulation of a 35% profit margin brought the difference to a more realistic representation. However, a deeper understanding was required to compare the reported difference in supplier's quotes compared to the cost model. Ignoring any aspect of profit margin, Figure 7.7 shows the difference.

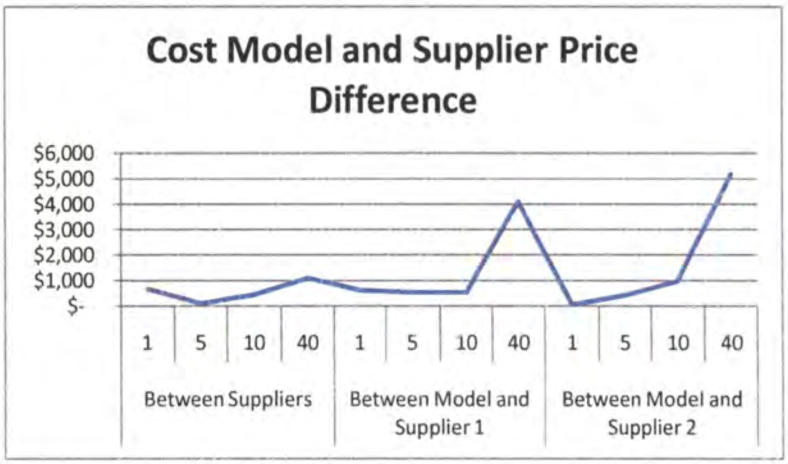


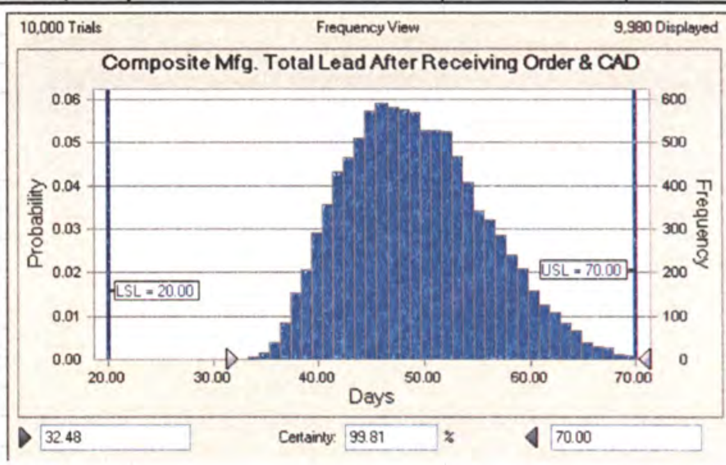
Figure 7.7. Cost Model versus Supplier Price

The prices offered by both suppliers are within $1,000 per batch of each other. The cost model also offers a consistent flat trend until higher quantities are observed. Therefore, the erratic trending of the cost model at higher quantities relative to the price pattern offered by the suppliers suggests that an adjustment may be needed to the cost model algorithm at higher quantities.

7.3.2. Lead-Time Analysis Results. Fabrication lead-time analysis of specific composite part geometry was studied over a multi-year period and compared to the composite manufacturing Monte-Carlo simulation model established in § 3.1.3. The Boeing Company held specific images of geometry shapes proprietary. After the evaluation period, Table 7.14 shows that of the surveyed geometry constructed at two separate composite suppliers, all actual lead times fall within the predicted Monte Carlo probability distribution.

Table 7.14. Composite Lead-Time to Monte Carlo Simulation

		Composite Manufacturing Lead Time		
		Days From Order to First Article Inspection (First Order)	Days From Order to First Article Inspection (Second Order)	Days From Order to First Article Inspection (Third Order)
Supplier A	**Geometry 1**	64	58	56
Supplier B	**Geometry 2**	55	55	49
Supplier B	**Geometry 3**	45	45	39



8. CONTRIBUTION TO THE FIELD

8.1. INDUSTRY AWARENESS

As mentioned in § 1.1, AM has traditionally been thought of as nothing more than a process to prototype designs. Thoughts have been given to deploying AM technology as a mainstream manufacturing technology (Rajagopalan et al., 1998; Pande and Kumar, 2008; Yang et al., 2009; Benard et al., 2009; Munguia et al., 2008; Raquet, 2005; Mansour and Hague, 2003; Mongol et al., 2006; Drizo and Pegna, 2006; Ruffo et al., 2006; Hopkinson and Dickens, 2003; Hague et al., 2003; Tuck et al., 2007; Walter et al., 2004) but no outline has been presented that provides a deployment path for the technology into a significant supply chain. This research provides a clear path forward for the development of AM technology by providing a step-by-step methodology verified through sub modules.

According to Wu and Blackhurst (2009), evaluating and selecting suppliers is an important aspect of managing today's dynamic global supply chains. Offering a methodology to deploy AM provides justification for technology investment by industry and provides a path to evaluate supplier effectiveness. Using the research provided, industry executives may populate AM systems within their own supply chains, thus, sparking an increase in the system and material sales. As highlighted in § 8.1, a surge of systems sold will spawn further improvements in the AM process and reduce material costs.

Furthermore, the part candidate screening methodology highlights both the technical and economic requirements for part transition to AM. This screening methodology highlights the importance of using integrated designs for AM part screening. The literature reviewed does not focus the importance of integrated design for AM part candidates, using the information from the cost model, integrated design should be a primary reason for part candidate screening.

8.2. ACADEMIC IMPACT

The research offered provides significant breakthroughs specific to academic research related to the field of emerging technology development. Specifically, the academic contributions presented in this research affect AM economic analysis for batched production, risk assignment to readiness levels, the assessment of AM flexibility, and design optimization for additive manufacturing technologies. In addition, how integrated part design affects the cost of quality is also discussed. Based on the comprehensive literature review provided, these individual tools have not been applied to AM technology or offered as a methodical approach to supply chain development of an emerging technology.

8.2.1. Additive Manufacturing Economic Analysis. All literature review regarding AM cost modeling has centered on SLS technology and only small frame machines. The research provided evaluates both large and small frame SLS machines and draws conclusions on how part geometry scaling and build envelope scaling affect the cost per unit. In addition, the economic impact of part design integration is illustrated via a case study.

In addition, the literature review of FDM costing analysis is sparse. This body of knowledge offers a basic building block of FDM cost analysis, § 5.3.1., with conclusions drawn regarding part geometry scaling within AM technology compared to injection molding. Moreover, the use of process flow diagramming and value stream mapping to generate the costs for thte AM model offers a novel approach to cost analysis generation not mentioned in literature reviews. Finally, the concept of establishing 'themes' centered on PFD decision points and grouping the themes, much like an affinity diagram, is a new contribution to the field of engineering management.

8.2.2. The Risk of Technology and Manufacturing Maturation. It has been noted that boilerplate Department of Defense/NASA technology readiness level and manufacturing readiness level assessment techniques lack the ability to understand the amount of risk associated with advancing the candidate technology from one column to the next with respect to each category, or rows, listed within the matrices. As a result, another contribution to this body of knowledge is the derivation of the MRL and TRL true risk score. Shown in §3.2.2, by coupling the risk cube definition to the standard MRL and TRL format, a new approach to emerging technology management is brought to light. This methodology has been documented and accepted to be published by the International Journal of Production Research.

8.2.3. Integrated Design for Quality Improvement. The body of knowledge generated from this research effort illustrates how part design integration, facilitated by AM technologies, allow for part count reduction, material savings, lead-time reduction, and no tooling requirements. However, a unique aspect of design integration is the ability to reduce the amount of loss to society due to poor quality, which is measured in dollars. Using the Taguchi quality loss function model, a case example is provided that breaks ground in the field of dimensional tolerance stackup by illustrating that part design integration leads to less tolerance deviation, which in turn, leads to a reduction in the amount of loss due to poor quality. In addition, comparisons to tolerance stackup equations highlighted by Lin and Zhang (2001) and future opportunities exist to exploit AM technologies affect on quality due to the ability of AM technologies to construct integrated designs.

8.2.4. Manufacturing Flexibility Assessment. Within the global economy, manufacturing performance is evaluated by time, cost and performance. Manufacturing flexibility should also be considered as supply chains fluctuate, creating a bullwhip effect on inventory. Using an adaptation of the Stockton and Bateman (1995) model, AM is evaluated in terms of manufacturing flexibility by looking at how the process accommodates different scaled geometry, different materials, different shapes and the ability to change materials quickly. Each aspect is scored and weighted to determine an overall total manufacturing flexibility score. This contributes to the body of knowledge by providing a case example of how to assess AM technology in terms of flexibility. The knowledge gained from this assessment contributes to an overall understanding of how the emerging technology may react to a flexible production environment.

8.2.5. Parameter Optimization. The application of parameter optimization techniques to AM technology offers a significant body of knowledge contribution. Other researchers have concentrated on optimization of SLS and FDM to achieve supreme part finish, orientation (Singhal et al., 2009; Thompson and Crawford, 1997) geometric accuracy, and reduction of void density (Agarwala et al., 1996, Ahn et al., 2003; Rodriquez et al., 2000; Bueth and Narayan, 1996). This body of knowledge places an emphasis on dimensional stability of the SLS process itself as the quality characteristic in the designed experiment. Instead of focusing on dimensional stability of individual pieces of geometry (Mahesh et al., 2006), this body of knowledge transforms the attention from rapid prototyping to direct manufacturing AM technologies by investigating the variation caused by the AM process itself.

8.3. IMPACT TO ADDITIVE MANUFACTURING

The field of additive manufacturing is on the cusp of developing into a significant manufacturing process for responsive low volume, high mix applications. This body of knowledge specifically focuses on both the technical and economic aspects of AM technology deployment and provides a methodology of technology deployment for AM and provides a clear, scientific path for the development of the AM supply chain based on designed experiments, cost models, supply chain research with a focus on quality engineering. Largely industry driven, the AM community is in need of an academic effort that offers a non-biased third party outlook on an appropriate manufacturing maturity path to act as a guideline for large-scale commercialization of the technology. One example includes suppliers within the AM community benefiting from the provided research by following the economic analysis section. That same supplier may be trying to understand if they should purchase a small frame SLS machine or a large frame SLS machine. The research provided hopes to assist the supplier during their own procurement of machine mix by illustrating how part scale and quantity demanded influences the unit cost of the part.

The AM community has not fully understood the power of design integration for the technology. Through case study examples, it is hoped that this body of knowledge illuminates the benefits of part design integration for AM by showing how part design integration positively affects quality, leverages economic gains, and reduces lead-time.

Another contribution to the AM community involves the development of the tensile bar ring pattern for FDM tensile testing the Z-Axis direction. Using the ring grouping of tensile bar pattern, stable Z-axis tensile bars may be produced using the FDM process without the need for support material.

8.4. IMPACT TO MANUFACTURING

According to Kathawala and Wilgen (2005), as more industries transition from a seller to a buyer market, the importance of build-to-order manufacturing increases. Due to its inherent quick turnaround processing, as shown in §3.1.3, AM technology is positioned to supplement the demand of build-to-order manufacturing. Using the body of knowledge provided, the manufacturing community should receive a thorough understanding of AM technology through an extensive literature review, provided economic analysis and detailed introduction to AM technology. In addition, tools may be used by the manufacturing community that enhances the likelihood of developing not only AM technology, but also many types of emerging technologies into production.

9. SUMMARY

9.1. EMERGING TECHNOLOGY MANAGEMENT

Currently, polymer rapid prototyping technology, such as SLS, FDM and Stereolithography exist as a staple element for prototyping industry. Many machine manufactures understand that the majority of their customers fall into the realm of rapid prototyping. As a result, the majority of research and development effort expended by the machine manufactures is tied to characteristics such as surface finish improvements, smaller and more affordable desktop system development, and ease of use for the customer. In an effort to not exclude the companies interested in producing parts for production, these same machine manufacturers have claimed to address true manufacturing needs by developing 'rapid manufacturing' systems. Despite the claims by machine manufacturers that their product represents manufacturing quality production, a clearer picture needs established to achieve the claims. Industry must work hand in hand with machine manufacturers to convey customer specified design requirements of end use parts. By treating machine and material manufacturers as partners, rather than suppliers, industry may be able to expedite the maturation of AM technology.

Expanding this thought, companies implementing emerging technology must be willing to truly partner with suppliers to ensure an expedient progression of the technology. This concept is rich with case study effectiveness, however, falls short in general implementation. Some of the very basic examples are linked to differing corporate cultures, unwillingness to collaborate, a lack of competence fitness, and negative affectivity/empathy or distrust (Rosas and Camarinha – Matos, 2009). In addition, companies are financially motivated to keep information clandestine in order to keep competitive advantages over competitors. Karim et al. (2008) and Fraser et al. (2003) highlight the fact that transparency of information is key to building trust between emerging technology suppliers and customers of the technology, short term financial pressure forces a conflict within companies. If multiple companies are courting an emerging technology supplier concurrently, the likelihood of complete transparency is not encouraging. Therefore, when selecting an emerging technology partner, it is critical that the technology adopting company contract exclusivity agreements with the emerging technology partner that prohibits the emerging technology from sharing information outside the adopting company. Breaking exclusivity agreements disrupts technology maturation and exposes companies to legal risk. For this reason, the emerging technology company must give a great deal of thought toward with which company poses the strongest financial backing and potential quantity demand for the technology.

Deploying the emerging technology, as shown in §6.1, through systematically structuring a deployment plan offers a great deal of competitive advantage for companies looking to adopt emerging technologies. Hirtz et al. (2007) describes that executive leadership is critical in the development of quality-based manufacturing. Executive leadership is also critical in deploying emerging technologies. Within these companies, it is the responsibility of management teams to properly managing end-use customer expectations, emerging supplier development, and quantity demand of the end-use application. It cannot be stressed enough that strategic business management is as equally important to the development of emerging technologies as technical development of the technology and economic evaluation of the technology.

9.2. ENGINEERING EMERGING TECHNOLOGIES

Emerging technologies must be developed using sound engineering science principles and guidance. Technical testing analysis inputted from customer requirements is needed to baseline a technology. Particular advantages specific to the emerging technology, such as AM part design integration, must be exploited to highlight technical and economic savings. An in depth costing analysis of the technology must be performed prior to technology implementation. A thorough part candidate screening process flow diagram must be developed that integrates the advantages of the emerging technology with the technical and economic limitations of the emerging technology. Once customer perceptions are fixed, they are difficult to sway, thus, the most detrimental case of emerging technology deployment would come from too much haste in the technical maturation of the technology. To measure the amount of risk associated with this development, a risk based TRL-MRL matrix methodology has been provided in this research.

As an example of emerging technology development, there is an enormous opportunity for AM technology to become a leader in low-volume production of parts in a variety of industries. Given the current technology maturity, it may be applied to low risk applications such as direct tooling, fixturing, etc. Opportunities for deployment of directly manufactured parts exist, albeit in niche applications where technical and economic feasibility is favorable. If technical machine enhancements were placed into action, economic evaluations may then be conducted based on the technical machine enhancements, and perhaps one day rapid manufactured parts will be a staple consideration for production environments in low-volume industries. If larger systems with smart nesting software were then implemented, perhaps, higher volume markets of insertion would exist. Alternatively, if the machines were re-formatted to not batch process parts, such as palletized systems, even lower inventory accumulations would occur.

In summary, if AM systems took on a goal of technology insertion, it would be to achieve the level of economic evaluation maturity of the injection molding industry, the level of technical detail of the composite manufacturing industry, and the system reliability of the NC machining industry. If achieved, then very complex parts could be produced very quickly, without tooling, to be used as end-use items.

10. FUTURE RESEARCH

10.1. TRANSFERRING RESEARCH TO OTHER TECHNOLOGIES

An upcoming technology that relates to FDM and SLS is laser beam welding (LBW). Tran (2009) discusses laser drilling as an extension to LBW. Mendez and Eagar (2001) offer detailed discussion on welding processes specifically for aerospace. This dissertation calls for several tools to be used when deploying an emerging technology, such as AM, into an aerospace supply chain. Some of these common tools include:

- Planned and controlled designed experiments for the emerging technology for system optimization
- Value stream mapping (VSM) and/or process flow diagramming (PFD)
- Cost modeling of the emerging technology based on VSM and/or PFD
- Assessment of manufacturing flexibility
- Assessment of technology maturation with respect to development risk

The objective of this section is to summarize how these tools may apply to LBW. An extension to the objective includes how these tools may apply to LENS and LAMP.

10.1.1. Designed Experiments. Compared to polymer based additive manufacturing technologies, such as FDM and SLS, LBW shares many common technical similarities. These similarities include similar quality performance characteristics. For example, Anawa and Olabi (2008) state that weld bead geometry plays an important role in determining the mechanical properties of the welded joints. Therefore, the selection of the welding process parameters is very essential for obtaining optimal weld bead geometry. Similarly, the parameters adjusted for laser process input, and the resultant energy density, establishes an appropriate melt pool of layer-to-layer bonding within the SLS, LAMP and LENS process. Like LBW, these laser adjustment parameters are critical to establishing appropriate structural integrity of parts processed using SLS (Nelson, 1993). Rodriguez et al, (2003) state that FDM also requires parameter optimization based on user input to result in effective layer-to-layer bonding.

Therefore, it may be noted that SLS, FDM, LBW, LENS and LAMP share a similar quality characteristic of structural integrity based on the fundamental element of layered fusion. In addition, the technologies share common constraints. LBW is constrained to a maximum amount of material joining thickness of .100" (Degarmo, et al., 2003), whereas, SLS, FDM, LENS and LAMP are constrained by a maximum build volume based on limited travel of gantries, like LAMP, LENS, and FDM, or the area of scan for the SLS. Comparing commonality in quality characteristics and constraints, justification may be made for using similar design of experiment methodology for system optimization among the technologies.

10.1.2. Value Stream Mapping. Another suggested tool that may be applied to among FDM, SLS, LBW, LAMP and LENS includes the use of value stream mapping and process flow diagrams to underscore process breakdown for cost modeling analysis. By analyzing each process step of the LBW process in a mapped format, costs may become more apparent for each step. Edwards (2009) suggests that LBW involves a large amount of hand touch labor due to large amounts of pre and post process steps. These process steps became apparent after Edwards mapped out a value stream map of the LBW process. In a similar manner, both LENS and LAMP requires a fundamental of pre and post processing steps such as the setup of fixtures, programming, de-burring and cleaning of parts in the process. Discussed in the dissertation, using tools such as value stream mapping and process flow diagramming to capture the complete manufacturing process assists in not only capturing cost development of an entire system (Tucker and Cudney, 2009), but also offers a concurrent engineering approach to system development by offering stakeholder input from supplier managers, customers, manufacturing engineering and design engineering prior to deployment in the supply chain.

10.1.3. Economic Evaluation through Cost Modeling. Once VSM and/or PFD are conducted, one may gain an understanding of associative costs within the system. These costs are assigned as value added individual steps as in activity based cost accounting. LBW, LENS and LAMP may also be setup in a similar costing fashion. However, distinction must be made between the batch based processing of SLS and the single piece costing approach to FDM, LBW, LENS, and LAMP. SLS parts may be constructed to the extents of all three axis of X, Y, and Z due to the self-supporting nature of the powder. Therefore, in order to reduce powder waste and machine costs, often SLS machines are stacked atop of each other in the Z direction to reach economic justification to build parts, resulting in a batched cost account system.

On the other hand, FDM, LENS and LAMP will not allow parts to be stacked atop of each other spatially within the X, Y, and Z build volume, thus fewer parts may be processed at a time and the cost is a function of the size of the candidate part. Much like FDM, it is assumed that both LENS and LAMP candidate parts may provide a straight line, or a slight saw-tooth pattern based on the size of the candidate parts and the X, Y constraints of both the LENS and LAMP process. For example, if the candidate part reaches the X, and Y dimensional limits of the process, a single part may be produced per run in the FDM, LENS or LAMP process, thus resulting in the straight line shown in Figure 10.1. This straight-line costing model is known as single piece, or one-off costing.

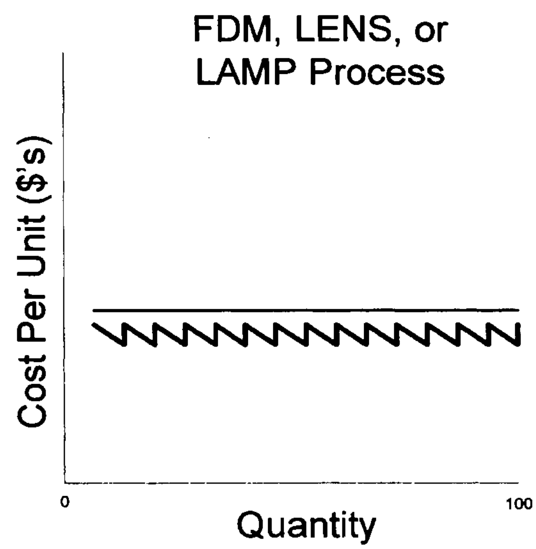


Figure 10.1. Single Piece and Semi-Batched Costing

However, if size of the part allows multiple pieces to fit within the X, Y boundary plane, a small-scale saw-tooth pattern may be depicted for the process, as shown in Figure 10.1. The slope of the line is a function of both the X, Y boundary plane dimensional constraints and the size of the candidate part being evaluated.

Due to the ability to stack parts atop of each other, SLS utilizes the Z-axis for multiple part fabrication, this allows for more parts to be packed together into a single batch. This justification to construct a batch of parts causes a higher initial batch cost but more parts may be placed within the build volume. This effect results in a larger saw-tooth pattern as shown in Figure 10.2.

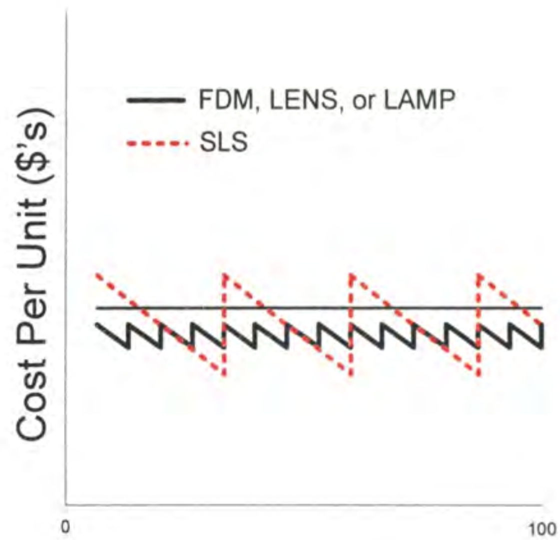


Figure 10.2. Comparison of Batched, Semi-Batched and Single Piece Costing

LBW may be used in both high volume circuit production and low production volume single piece repairs. According to Edwards (2009), for aerospace, LBW is generally limited to low production volume and high mix applications, thus resulting in a single piece, straight lined cost model for each part produced. Each piece processed must be set in a fixture customized for that specific geometry and each part may take a different path within the value stream depending on the geometry type.

SLS, LAMP, and LENS share an element of the cost model known as material recycling. According to Slaughter (2009), much like the SLS process, the materials used in both the LAMP and LENS process may be recycled to limited extent. This aspect of material recycling is in contrast to FDM, which does not include material recycling within its cost model.

10.1.4. Manufacturing Flexibility Assessment. In a global environment, lead time, cost and performance are essential elements of production. Often overlooked, manufacturing flexibility is also a critical component of manufacturing that should be analyzed for emerging technologies. Used in the dissertation to compare FDM, SLS and injection molding, the Stockton and Bateman (1995) model for flexibility assessment of flexible manufacturing systems may be applied to LBW, LAMP, and LENS easily. The model addresses the following aspects of manufacturing flexibility: Size, Shape, Materials, Machine, Material Handling, Process, Routing, and Production Range. Each aspect of manufacturing flexibility may be applied to LBW, LAMP and LENS with the goal to quantitatively asses the level of manufacturing flexibility each process offers.

10.1.5. Manufacturing Maturity Model. The main objective of the maturity assessment model is to map an emerging technology in terms of technology readiness and manufacturing readiness. Like the flexibility assessment model, the manufacturing maturity model is generic enough to accommodate many different types of manufacturing technologies. Considered another contribution to the dissertation, the concept of altering the standard manufacturing readiness level model to include elements of risk would accommodate evaluation of LBW, LAMP and LENS.

10.1.6. Integrated Part Design. Integrated part design offers a wealth of opportunities for additive manufacturing. However, some AM technologies may not be able to offer the level of part design complexity as other AM technologies. Therefore, the amount of integrated design opportunity is different among many AM technologies. For example, SLS offers one of the largest design complexity opportunities with the self-supporting nature of the powdered process. As a result, encapsulated geometry may be constructed to highlight highly complex shapes. The only constraint necessary for SLS geometry complexity involves the ability to evacuate the powder from parts during post processing.

However, FDM is limited on the amount of design complexity. Due to the processing requirement for FDM to produce support material during part construction, only water-soluble support material allows for highly complex encapsulated design complexity. Water-soluble support material is only available for ABS model material. Because FDM offers many types of non-soluble support material choices, in order to achieve higher levels of design complexity, material flexibility must be sacrificed for FDM.

As LBW is simply joining separate pieces together as a single piece the amount of design integration opportunity is restricted to the type of gantry system that is attached to the laser head (Watkins, 2003). For example, a laser head attached to a three-axis mill would offer very little opportunity for part design integration, whereas, a multi-axis robotic arm welding system, often used in the automotive industry, would allow for joining of geometric features in multiple planes, thereby, allowing for substantial design integration opportunities. Aerospace LBW joining is generally of the three-axis mill variety, thus, for the purpose of this research, LBW will express very little design integration opportunity.

According to Slaughter (2009) LENS is also restricted to a three axis system. Without the ability to offer multi-axis capability, part integration opportunities are limited. However, according to Missouri University of Science and Technology's LAMP website (2009), LAMP allows the deposition head to be placed relative to a five axis controlled table allowing multiple features to be constructed on a single piece. This freedom to place several features on a single part without the need for support material coupled with the rotational control of the fixture allows for more opportunities for design integration compared to the LENS process.

10.2. SUMMARY OF EMERGING TECHNOLOGIES TOOLS

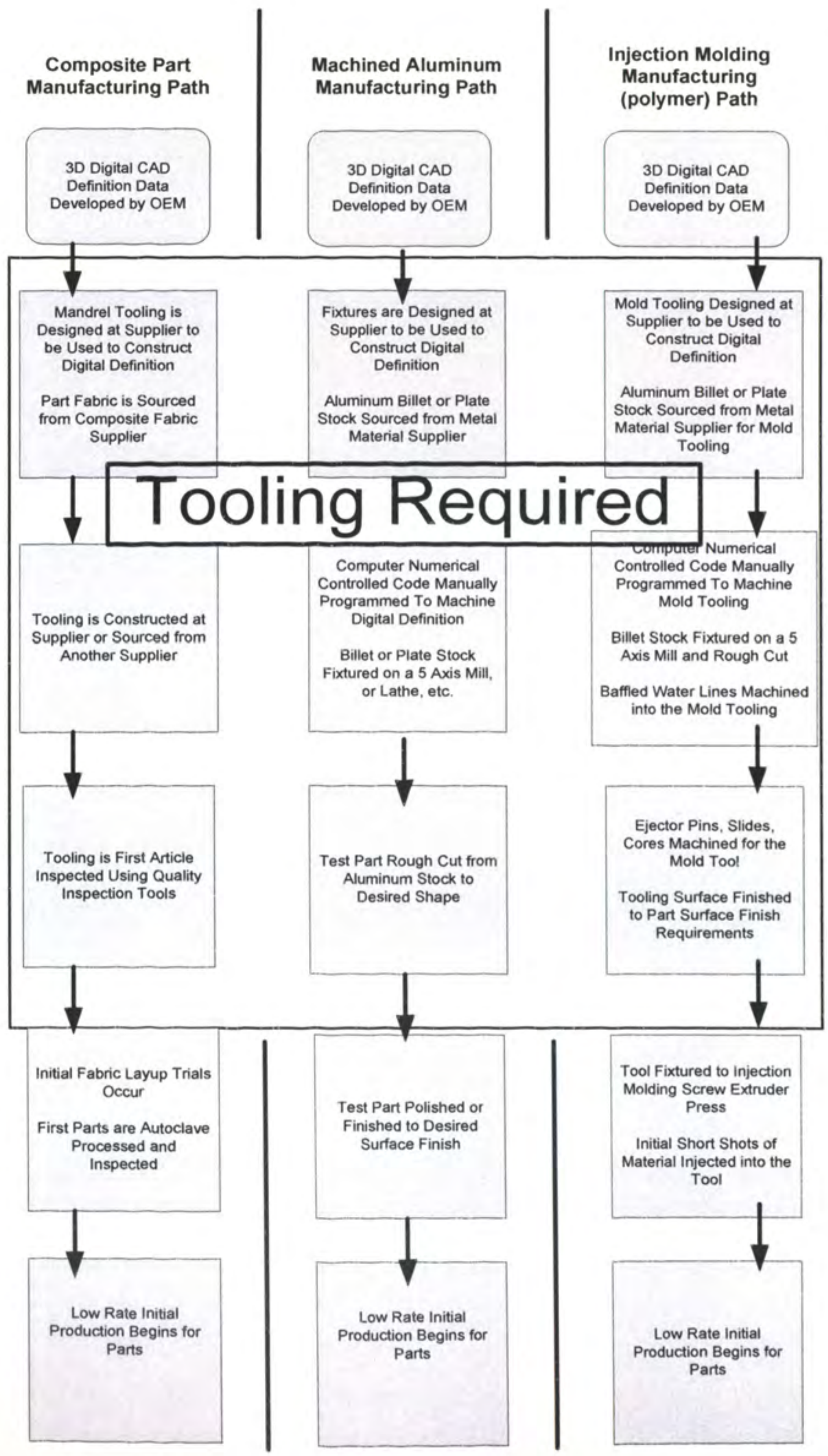
In conclusion, several approaches of the dissertation research may be applied to LBW, LENS and LAMP processes. Specifically, a set of tools were chosen that has potential for application for many emerging technologies. Though not all tools may be applied to all technologies, a Table 10.1 has been constructed to summarize the opportunity to apply several tools developed for dissertation research to each process.

Table 10.1. Summary of Emerging Technologies

	Technology Type				
Tool for Emerging Technology	SLS	FDM	LBW	LENS	LAMP
Design of Experiment Methodology for Process Improvement	Y	Y	Y	Y	Y
Use of Value Stream Mapping and Process Flow Diagramming to Generate Costs	Y	Y	Y	Y	Y
Batched Cost Model	Y	N	N	N	N
Single Piece Cost Model	N	Y	Y	Y	Y
Material Recycling Integrated in Cost Model	Y	N	N	Y	Y
Manufacturing Flexibility Assessment	Y	Y	Y	Y	Y
Manufacturing Maturity Model	Y	Y	Y	Y	Y
Integrated Part Design	Y	Y	N	N	Y

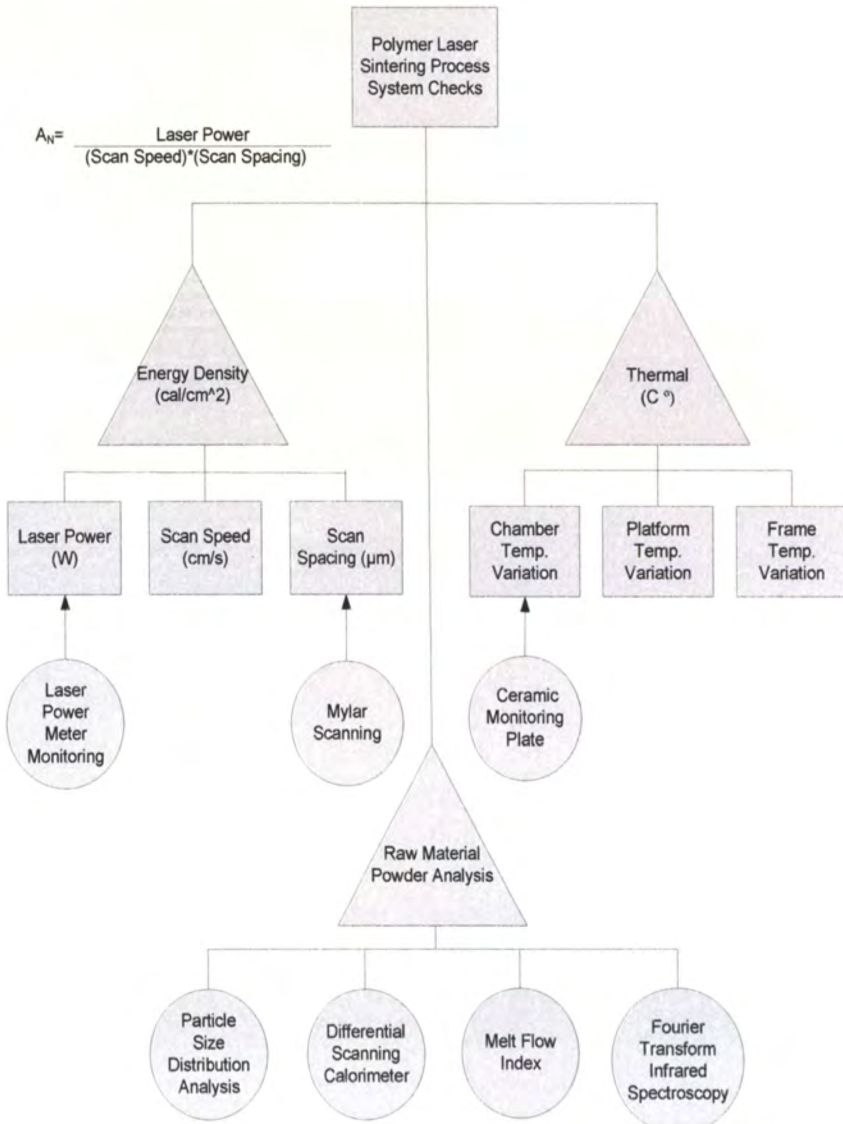
APPENDIX

A.1. Conventional Manufacturing Paths

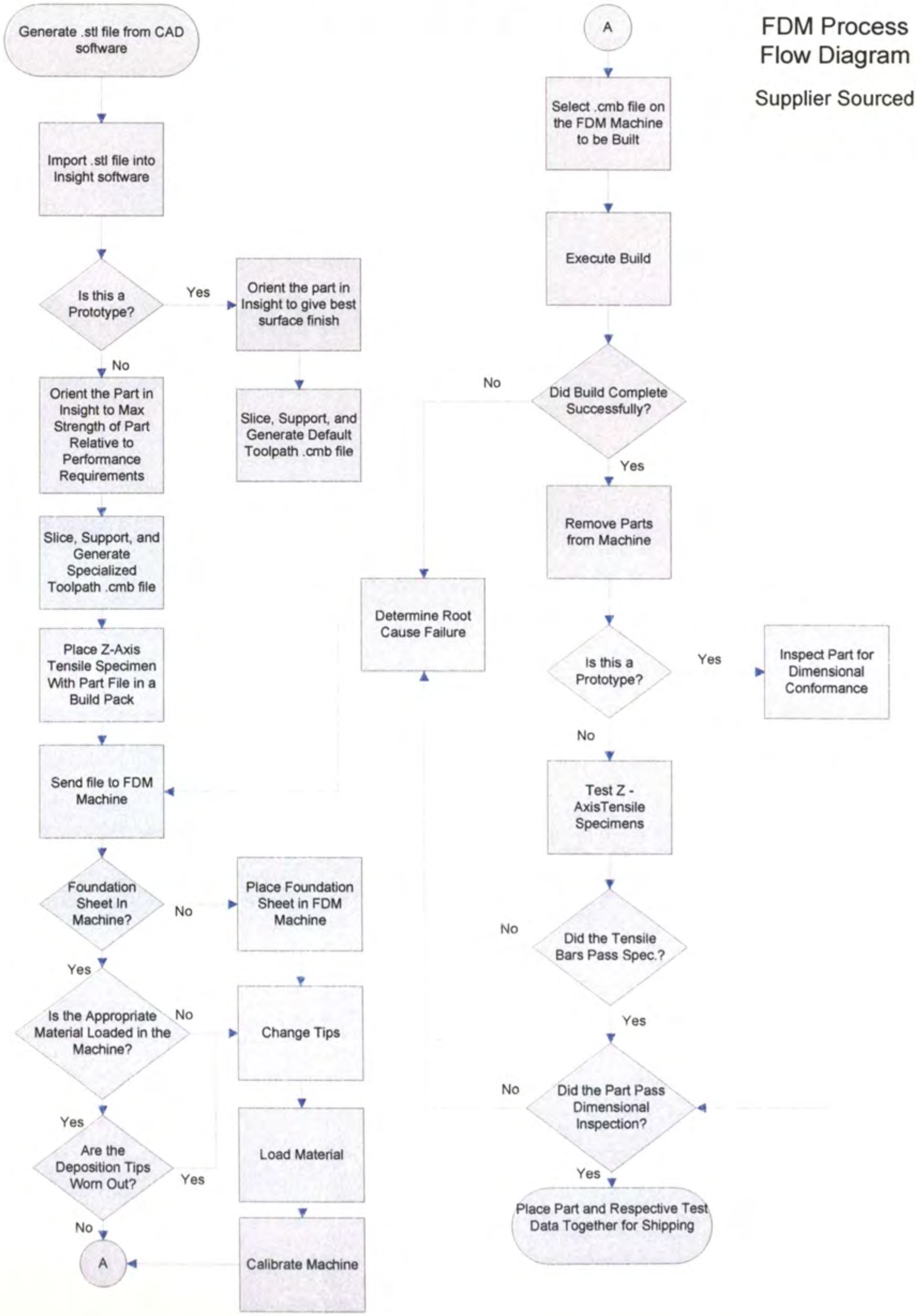


A.2. Laser Sintering Process Flow Diagram

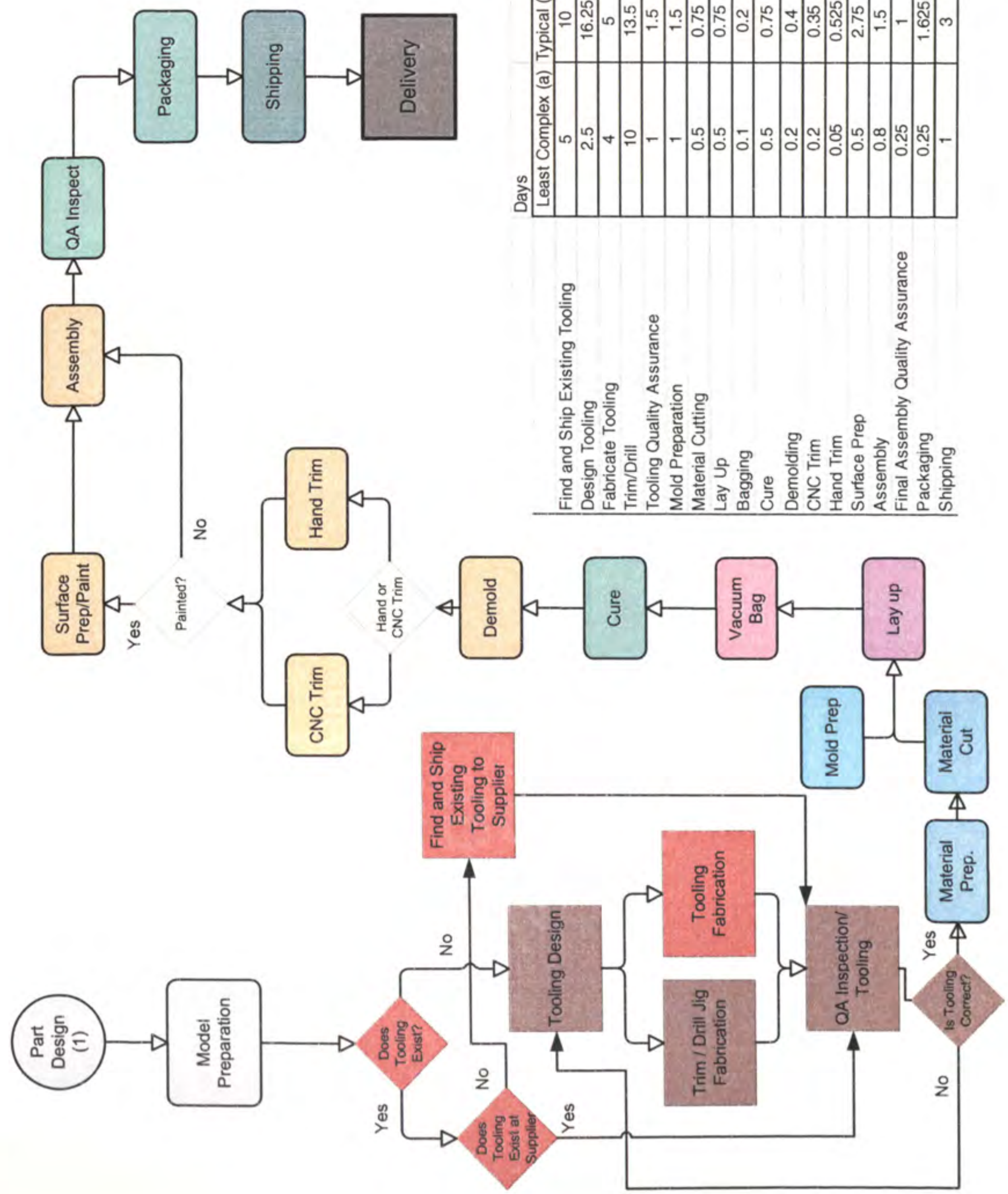
A.3. Laser Sintering Process Influence Chart and Check Mechanisms



A.4. Fused Deposition Modeling Process Flow Diagram

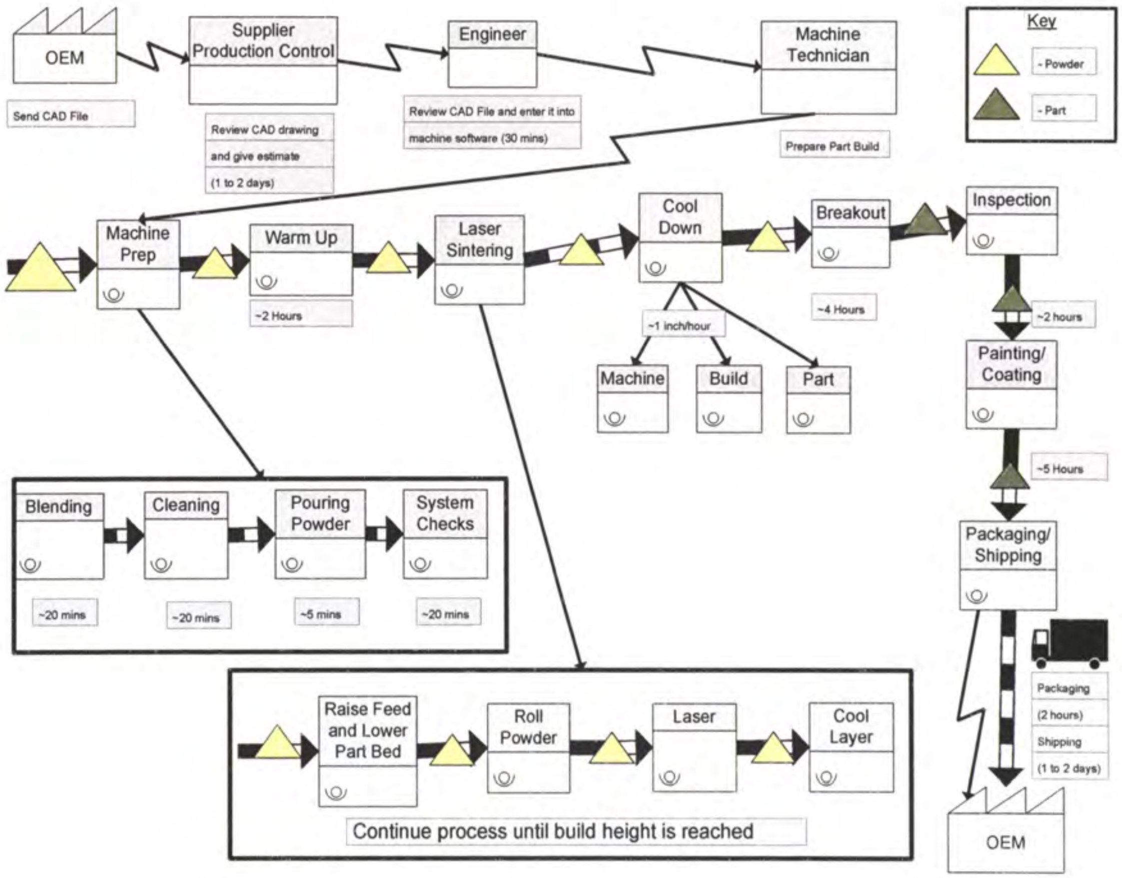


A.5. Composite Manufacturing Process Flow Diagram with Lead Time Analysis

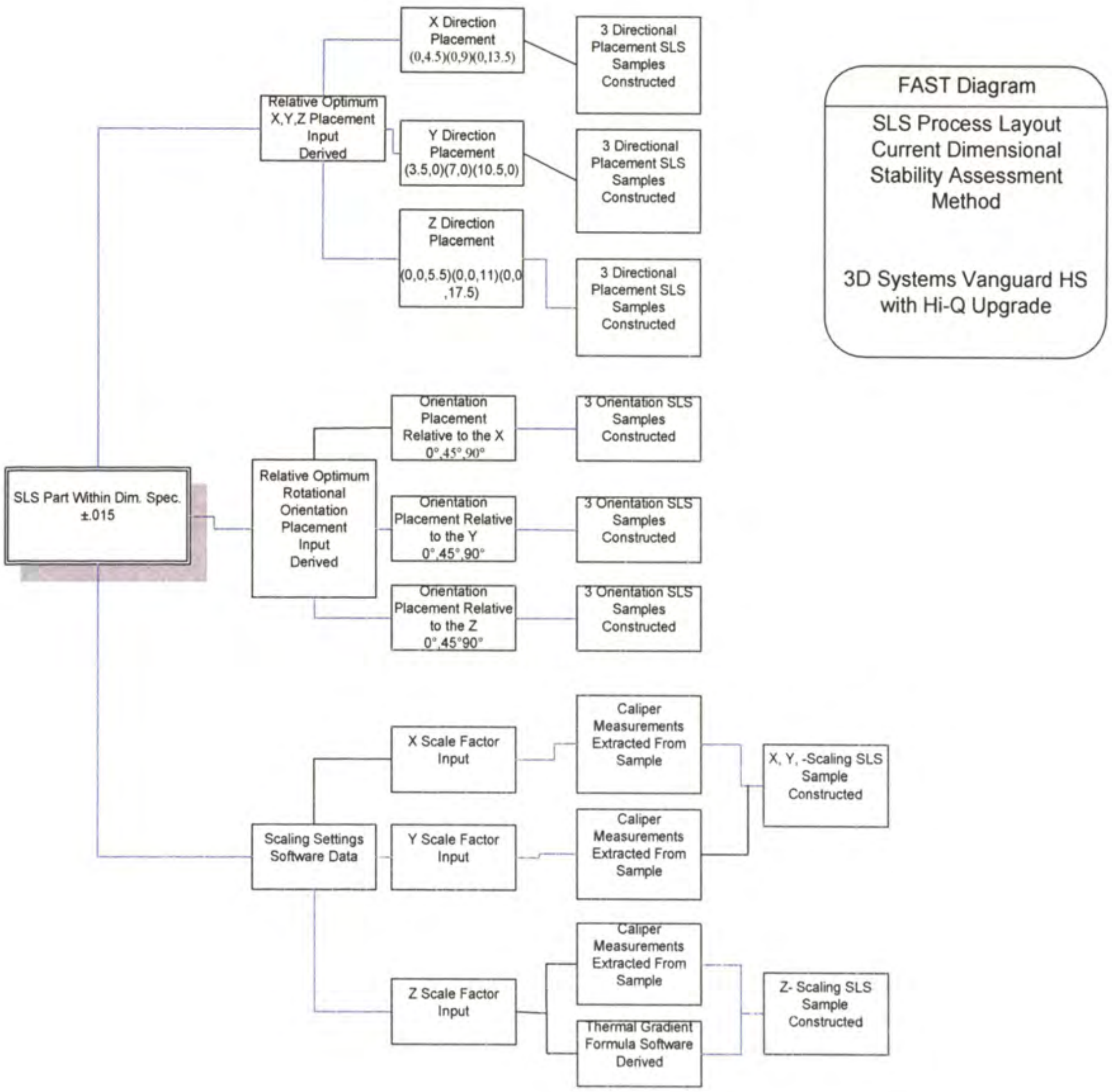


	Days		
	Least Complex (a)	Typical (m)	Complex (b)
Find and Ship Existing Tooling	5	10	30
Design Tooling	2.5	16.25	30
Fabricate Tooling	4	5	6
Trim/Drill	10	13.5	25
Tooling Quality Assurance	1	1.5	2
Mold Preparation	1	1.5	2
Material Cutting	0.5	0.75	1
Lay Up	0.5	0.75	1
Bagging	0.1	0.2	0.5
Cure	0.5	0.75	1
Demolding	0.2	0.4	1
CNC Trim	0.2	0.35	0.5
Hand Trim	0.05	0.525	1
Surface Prep	0.5	2.75	5
Assembly	0.8	1.5	3
Final Assembly Quality Assurance	0.25	1	3
Packaging	0.25	1.625	3
Shipping	1	3	5

A.6. Value Stream Mapping of the SLS Process

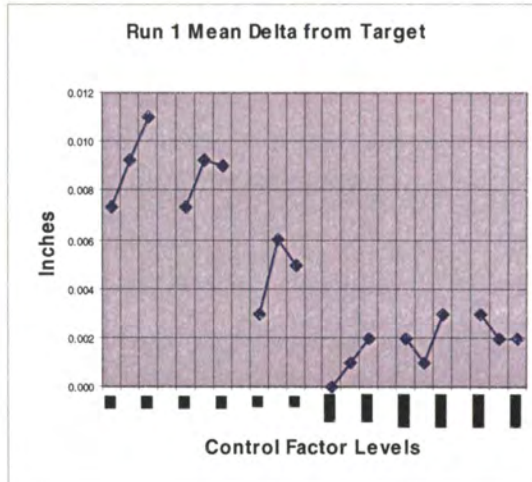


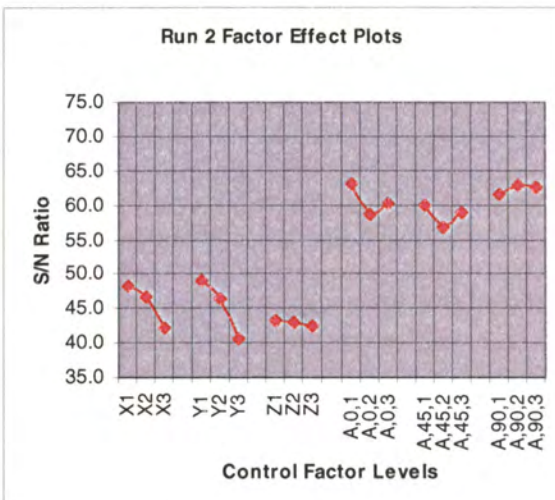
A.7. FAST Diagram – SLS

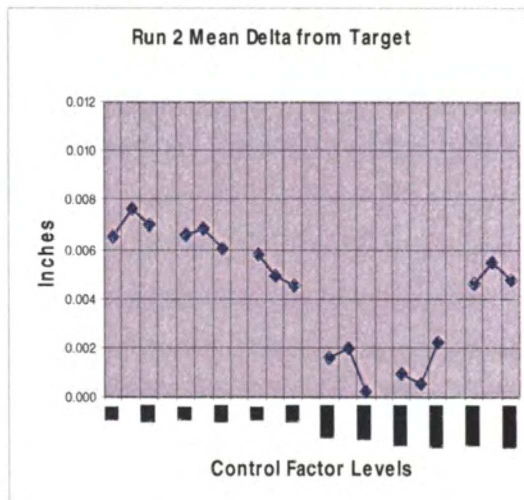


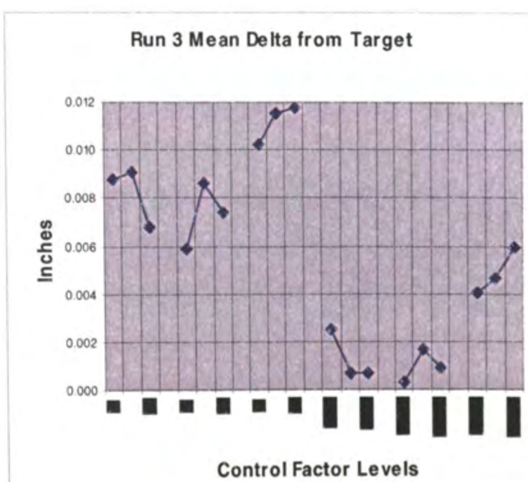
								Noise Factor Conditions							
						D	Uneven Bed Temps	1	2	2	1				
						E	Heat load adjacency	1	2	1	2				
						F	Time to Cool	1	1	2	2				
	Control Factors						Build #	1	2	3	4				
Part #	X	Y	Z	Angle 0	Angle 45	Angle-90						mean	SD	n	S/N
1	3	1	1	1	1	1		55.54	56.07	50.80	53.11	53.88	2.43	493	26.9
2	3	1	2	2	2	2		53.08	52.49	50.83	52.50	52.23	0.97	2892	34.6
3	3	1	3	3	3	3		54.26	53.81	48.56	48.05	51.17	3.32	237	23.7
4	1	2	3	1	2	2		53.71	52.72	51.40	52.06	52.47	0.98	2844	34.5
5	1	2	1	2	3	3		53.11	50.58	51.08	50.97	51.44	1.14	2048	33.1
6	1	2	2	3	1	1		54.68	52.01	52.67	52.38	52.93	1.2	1961	32.9
7	2	3	3	2	1	3		53.00	50.86	47.77	48.16	49.95	2.46	414	26.2
8	2	3	1	3	2	1		53.00	51.29	46.88	48.36	49.88	2.77	324	25.1
9	2	3	2	3	3	2		54.13	51.59	49.78	50.29	51.45	1.94	703	28.5
10	3	1	1	1	1	3		53.69	53.31	50.03	52.87	52.47	1.66	994	30
11	3	1	2	2	2	1		52.84	52.51	48.92	49.35	50.91	2.06	613	27.9
12	3	1	3	2	3	1		55.42	54.29	51.72	53.37	53.70	1.56	1179	30.7
13	1	2	1	3	1	2		53.32	52.45	53.77	53.77	53.33	0.62	7338	38.7
14	1	2	2	3	1	2		54.20	54.21	49.22	49.30	51.73	2.86	328	25.2
15	1	2	3	1	2	3		54.04	53.01	51.93	52.19	52.79	0.95	3083	34.9
16	2	3	1	3	2	3		53.48	51.85	50.66	50.80	51.70	1.3	1580	32
17	2	3	2	1	3	1		55.05	54.24	51.19	51.19	52.92	2.02	683	28.3
18	2	3	3	2	1	2		53.19	52.95	51.08	52.47	52.42	0.94	3095	34.9
							mean	53.87	52.79	50.46	51.18				
							SD	0.85	1.38	1.72	1.87				
							n	4005	1454	861	749				
							S/n	36	31.6	29.4	28.7				

A.9. Static Experiment Data and Calculations

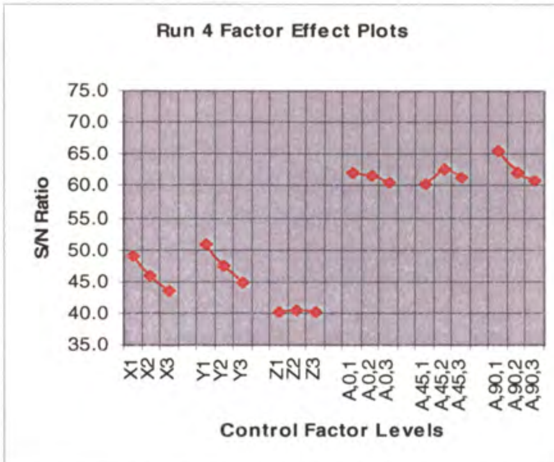


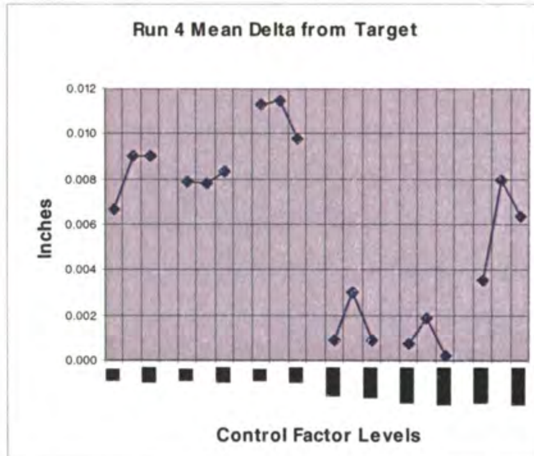






A.9. Static Experiment Data and Calculations (cont.)



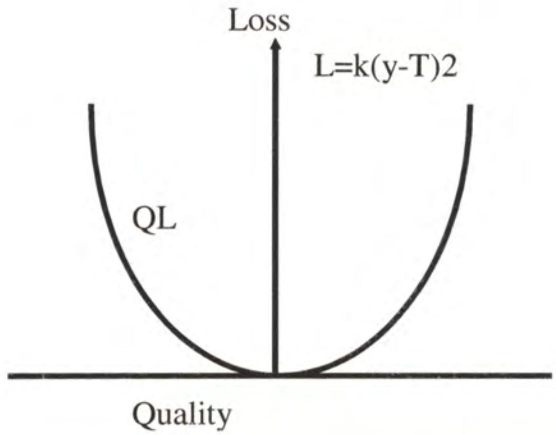


A.10. Static Confirmation Experiment Data & Calculations

		S/N (dB)					
		X	Y	Z	A-0	A-45	A-90	Average
Level	1	51.9	52.15	45.39	71.68	67.21	62.73	58.51
	2	48.57	49.6	46.74	63.04	60.29	64.64	55.48
	3	44.52	46.82	47.62	62.56	63.83	63.95	54.88
							S/N_{exp}	56.29
				Predictive Analysis			S/N_{opt}	73.74
Applied Software Scaling Confirmation Test		61	51	46	68	64	66	59.33

		Mean (in) (normalized to Δ from target)						
		X	Y	Z	A-0	A-45	A-90	Average
Level	1	0.007	0.007	0.003	0	0.002	0.003	0.003667
	2	0.009	0.009	0.006	0.001	0.001	0.002	0.004667
	3	0.011	0.009	0.005	0.002	0.003	0.002	0.005333
							$mean_{exp}$	0.00456
				Predictive Analysis			$mean_{opt}$	-0.00278
Applied Software Scaling Confirmation Test		0.006	0.008	0.002	0.001	0.001	0.003	0.004

A.10. Quality Loss Calculations for Static Experiment (cont.)



Taguchi Quadratic Loss Function Calculator		Taguchi Quadratic Loss Function Calculator		Taguchi Quadratic Loss Function Calculator	
A_0 =	$1,250.00	A_0 =	$1,250.00	A_0 =	$1,250.00
Δ_0 =	0.015	Δ_0 =	0.015	Δ_0 =	0.015
y =	0.004	y =	0.0075	y =	0.009
m =	0	m =	0	m =	0
k =	5555555.556	k =	5555555.56	k =	5555555.56
$ Loss	**$88.89**	**$ Loss**	**$312.50**	**$ Loss**	**$450.00**

Dynamic Experiment

			level	
	Signal Factor	M1	M2	M3
M	Fill Wattage	52.5	57.5	62.5

					Outline Scan Count- 1 pass/ 2 pass		Cross Fill Scan- on(1)/off(2)		Laser Outline Wattage- 6W(1)/4W(2)	
			Noise Factors		E		F		G	
			N_1		2		1		2	
			N_2		1		2		1	
					Vertical Zone 1 (M1)		Vertical Zone 2 (M2)		Vertical Zone 3 (M3)	
		Control Factors		Watts	52.5		57.5		62.5	
Part #	X	Y	Z	Angle	N_1	N_2	N_1	N_2	N_1	N_2
1	1	1	1	1	50.31	54.18	47.31	48.52	53.52	50.28
2	1	2	2	2	53.28	57.01	49.78	46.67	61.46	49.13
3	1	3	3	3	41.52	49.13	45.69	47.92	47.09	46.87
4	2	1	2	3	48.35	54.19	54.47	49.37	53.85	51.10
5	2	2	3	1	57.55	58.36	56.70	50.56	50.44	47.80
6	2	3	1	2	46.21	46.64	51.80	47.77	52.03	50.53
7	3	1	3	2	46.45	54.30	45.47	44.29	48.34	46.96
8	3	2	1	3	43.16	45.59	45.47	50.45	51.24	48.98
9	3	3	2	1	51.56	50.31	50.98	47.86	52.69	51.37

L_1	L_2	r	S_β	S_T	$S_{N.\beta}$	S_e	V_e	V_N	β	η	S/N	(S/N-avgS/N)^2
8706.7638	8776.463738	19937.5	15331.07	15451.16	0.243666	119.8431	29.96077	24.01735	0.876902	0.031954	-14.9547	0.991643806
9500.77624	8747.828992	19937.5	16702.78	16937.22	28.43534	206.0111	51.50278	46.88929	0.915291	0.017812	-17.493	12.48954489
7750.39788	8264.212436	19937.5	12863.59	12936.49	13.24165	59.66487	14.91622	14.5813	0.803241	0.044197	-13.5461	0.170424669
9035.88275	8877.415115	19937.5	16094.61	16189.39	1.259536	93.52466	23.38116	18.95684	0.898473	0.042522	-13.7139	0.060043703
9434.06165	8958.293297	19937.5	16966.96	17317.5	11.35326	339.1913	84.79781	70.1089	0.922501	0.012078	-19.1802	27.26139306
8656.6624	8353.596932	19937.5	14512.8	14536.93	4.60683	19.52813	4.882033	4.826992	0.853179	0.15075	-8.21742	32.96472613
8074.21787	8332.508193	19937.5	13501.22	13677.19	3.346151	172.6233	43.15582	35.19389	0.822908	0.01918	-17.1716	10.32104122
8082.33828	8355.702345	19937.5	13552.81	13577.76	3.748108	21.20428	5.30107	4.990477	0.824479	0.136159	-8.65953	28.08344073
8931.84349	8603.622267	19937.5	15422.82	15494.67	5.403344	66.43979	16.60995	14.36863	0.879522	0.053779	-12.6939	1.600260682
												total SS
										mean	-13.9589	113.9425189

avg s/n (X1)	-15.3313
avg s/n (X2)	-13.7038
avg s/n (X3)	-12.8417
avg s/n (Y1)	-15.2801
avg s/n (Y2)	-15.1109
avg s/n (Y3)	-11.4858
avg s/n (Z1)	-10.6106
avg s/n (Z2)	-14.6336
avg s/n (Z3)	-16.6326
avg s/n (A1)	-15.6096
avg s/n (A2)	-14.294
avg s/n (A3)	-11.9732

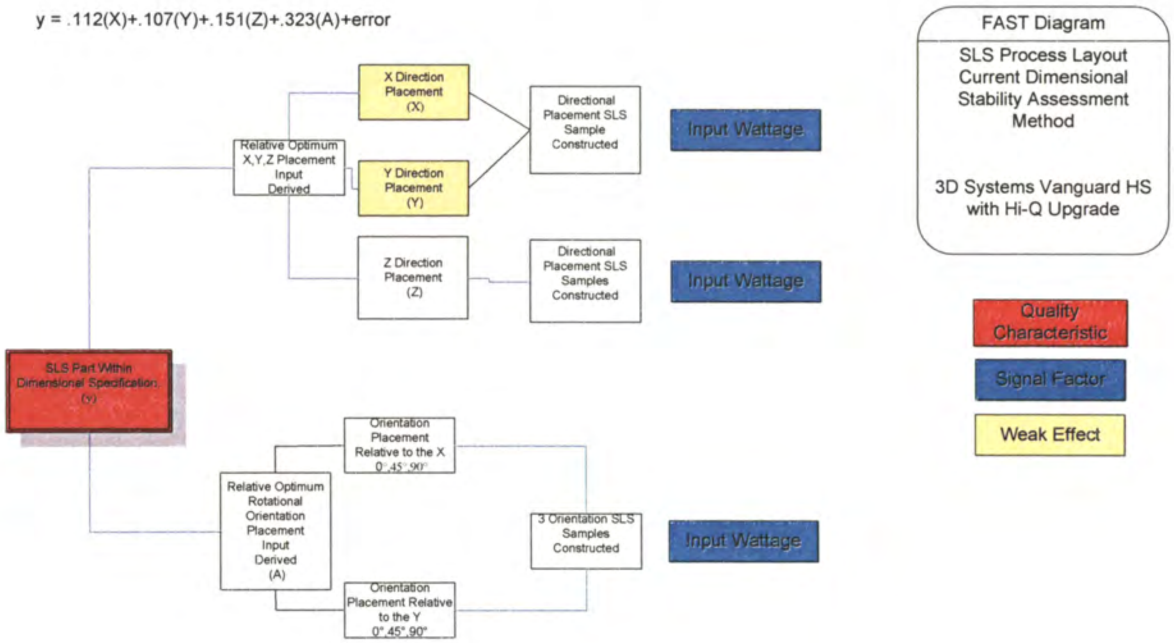
A.13. Dynamic Experiment Data & Calculations

Error Variance (Pooling)			
	factor effect sum of sq.		factor deg. Freedom
	1962.808		8
	MS	245.351	
	error sum of Sq.(X&Y)		error deg. Freedom
	313.192		4
	S_e^2	78.29801	
	Angled		
	F-ratio	3.133554	

A.14. Dynamic Experiment Data & Calculations

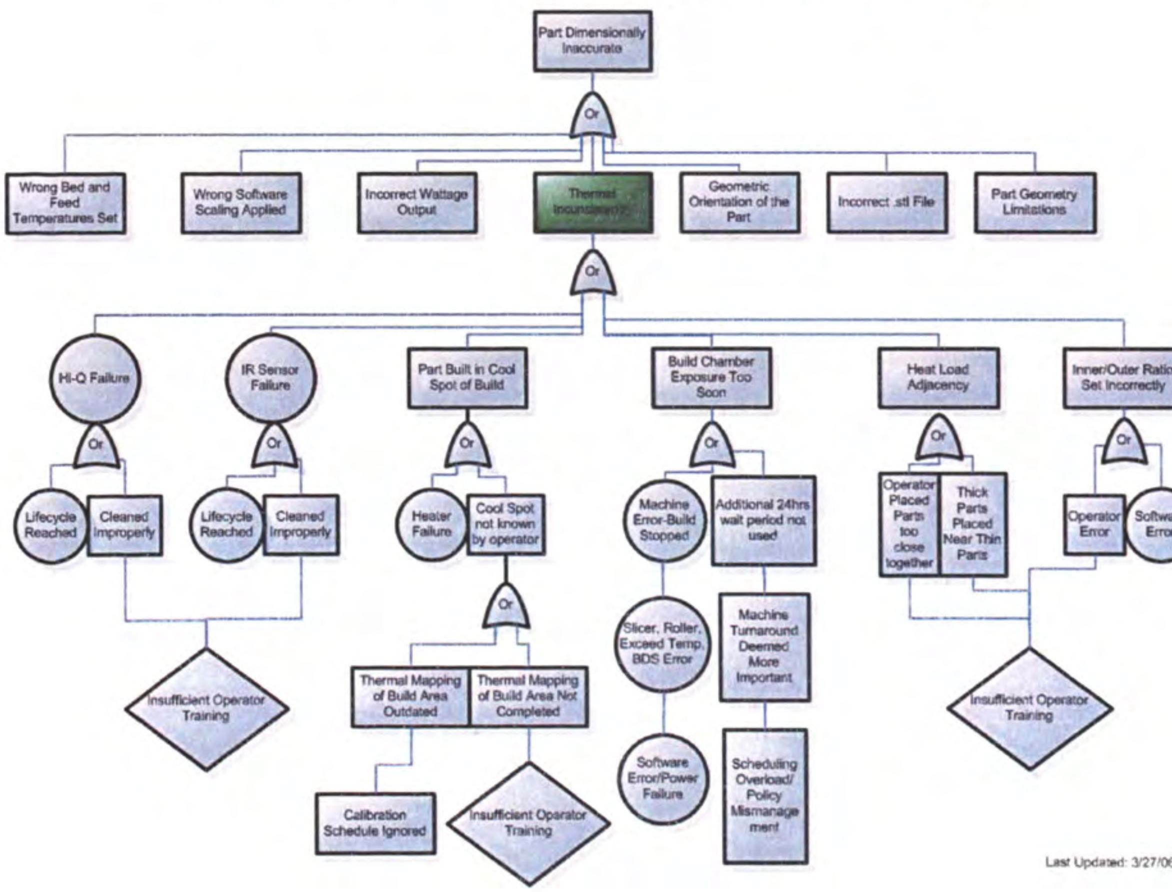
		Mean	SD	Δ from Target
x	zone 1	1.259306	0.002121	0.009305556
x	zone 2	1.259806	0.003582	0.009805556
x	zone 3	1.254722	0.001554	0.004722222
y	zone 1	1.258861	0.003359	0.008861111
y	zone 2	1.258444	0.004056	0.008444444
y	zone 3	1.258722	0.001615	0.008722222
z	zone 1	1.261778	0.003456	0.011777778
z	zone 2	1.261889	0.003649	0.011888889
z	zone 3	1.261972	0.003377	0.011972222
a	zone 1	1.259278	0.003465	0.009277778
a	zone 2	1.261528	0.007011	0.011527778
a	zone 3	1.258847	0.002549	0.008847222
		1.259596		0.009596065

A.15. Revised FAST Diagram



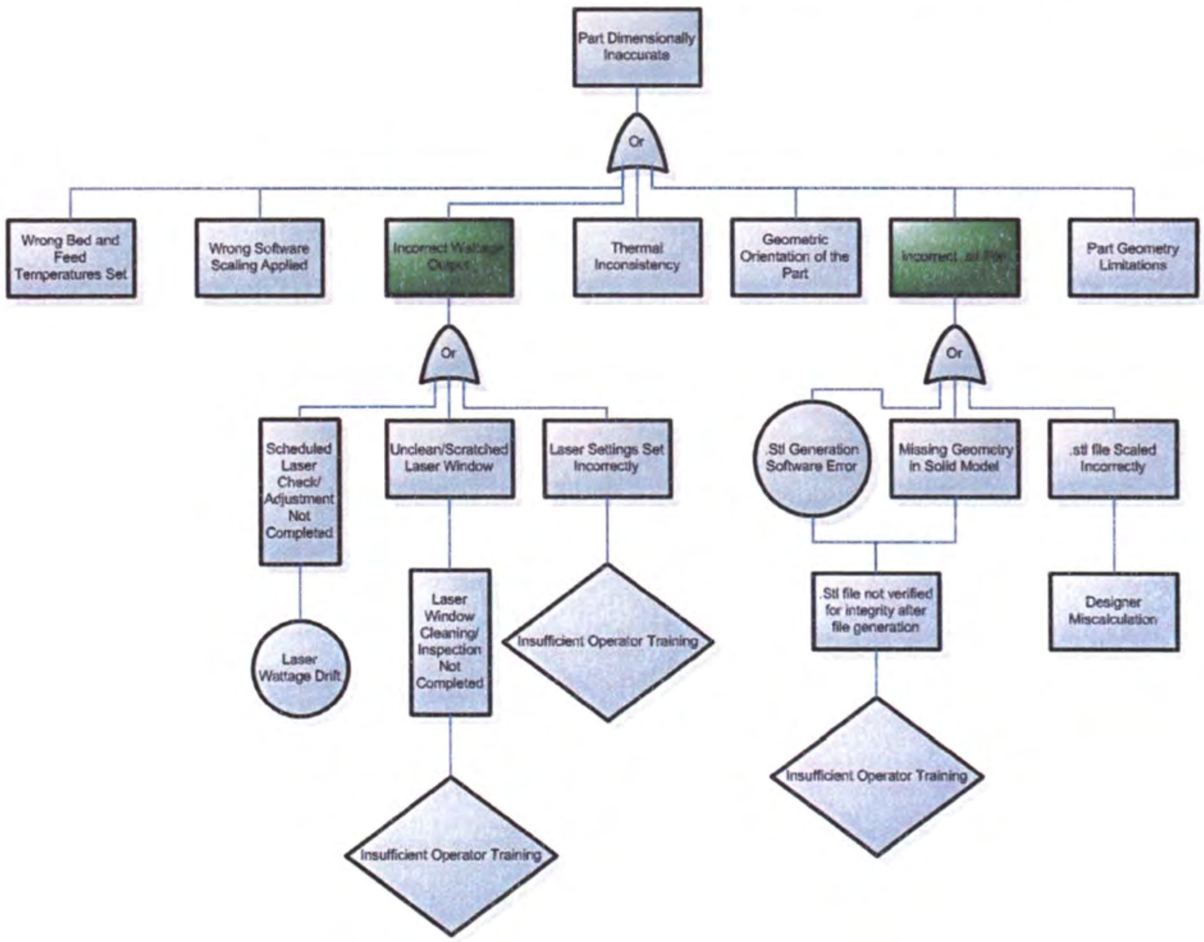
A.16. Fault Tree Analysis Diagram 1

Selective Laser Sintering 3D Systems Vanguard HS-HQ Fault Tree Analysis



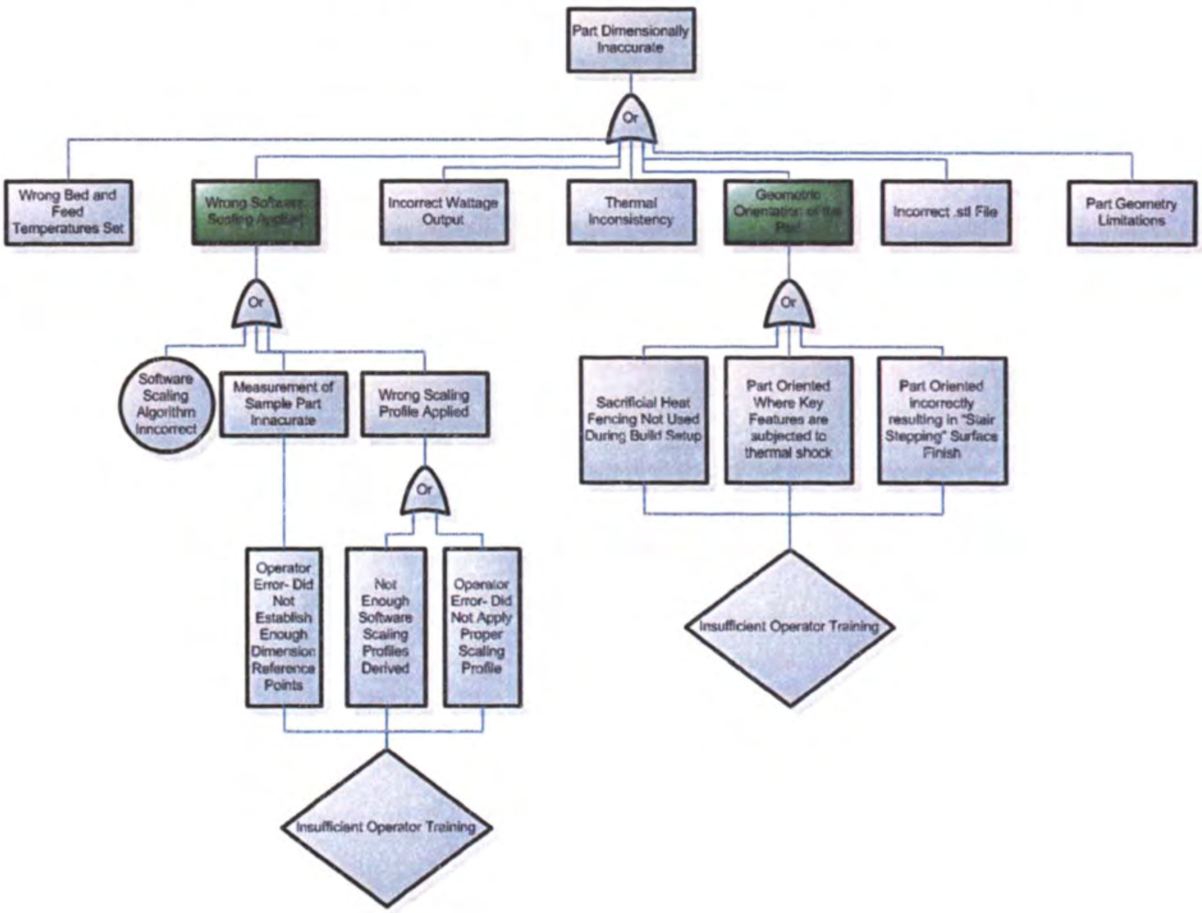
A.17. Fault Tree Analysis Diagram 2

Selective Laser Sintering 3D Systems Vanguard HS-HQ Fault Tree Analysis

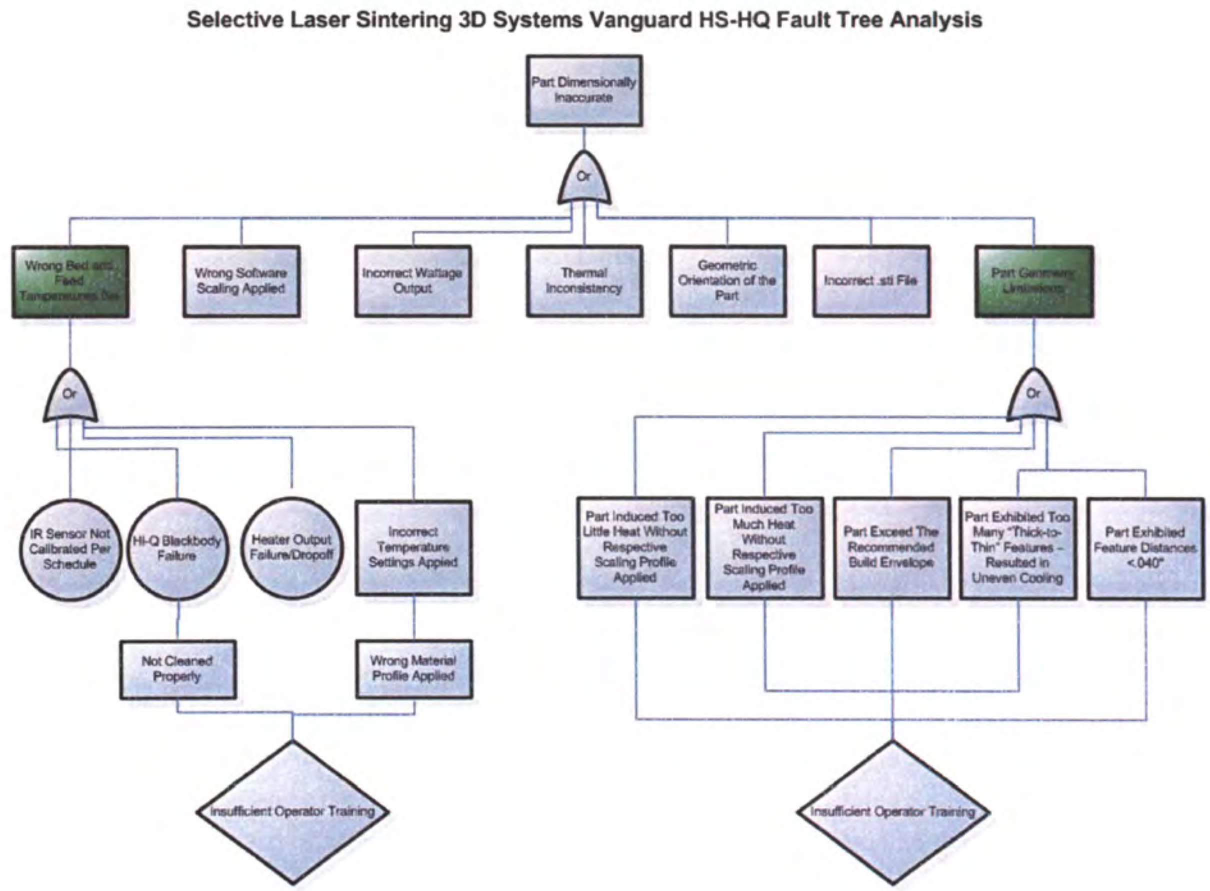


A.18. Fault Tree Analysis Diagram 3

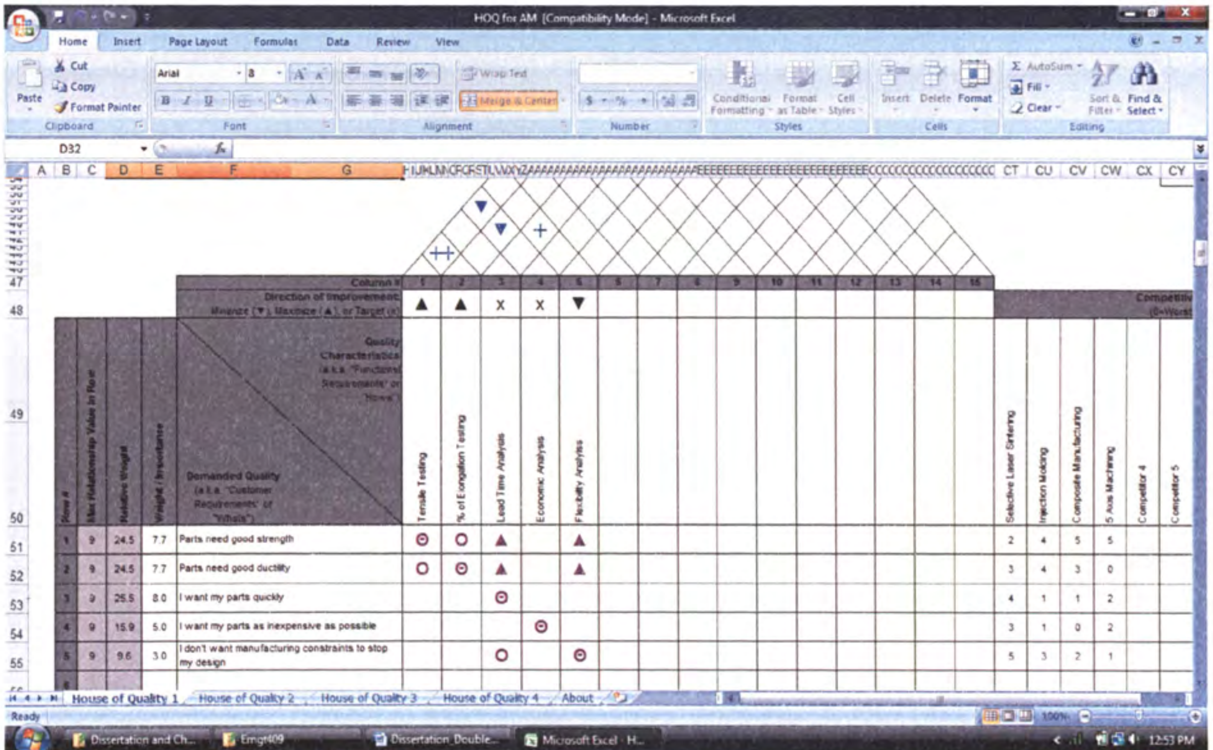
Selective Laser Sintering 3D Systems Vanguard HS-HQ Fault Tree Analysis

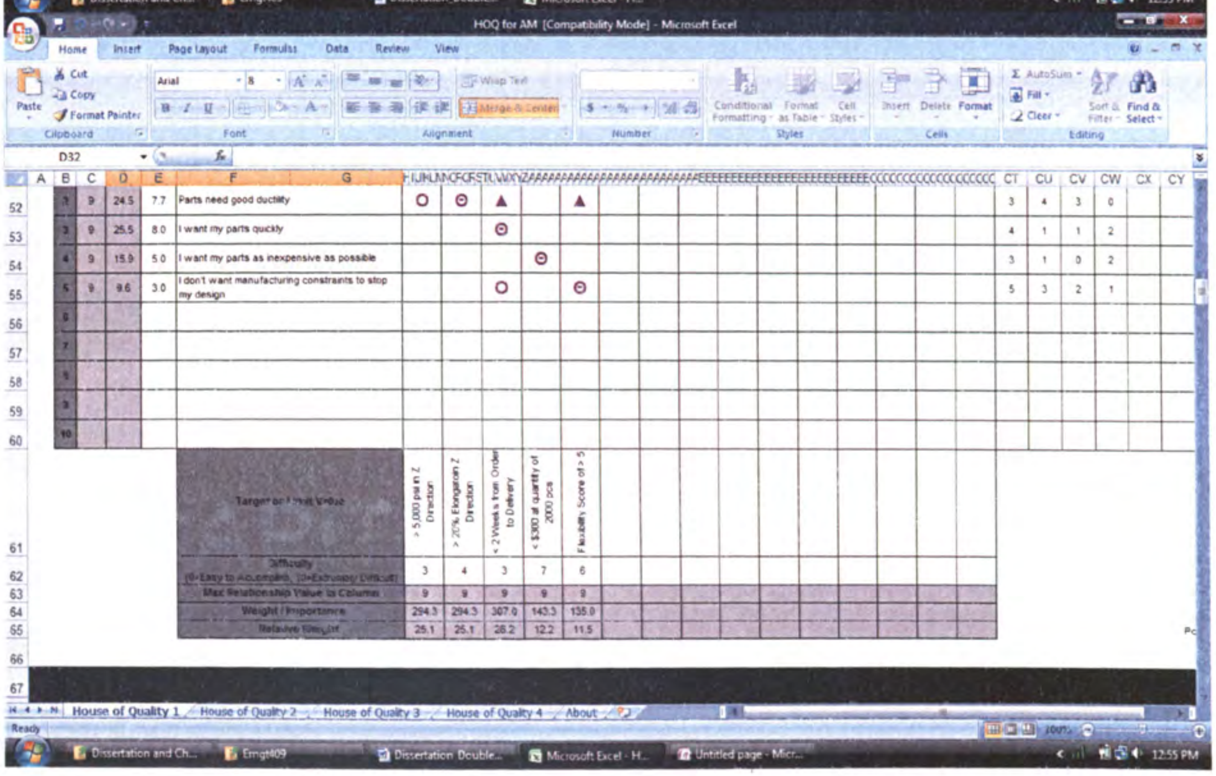


A.19. Fault Tree Analysis Diagram 4



A.20. House of Quality Example





BIBLIOGRAPHY

European Patent Specification, Application No. 04013326.6 Title: Optimal Dimensional and Mechanical Properties of Laser Sintered Hardware by Thermal Analysis and Parameter Optimization, Date of Filing, 05.06.2004

Agarwala, M., Jamalabad, V., Langrana, N., Safari, A., Whalen, P., Danforth, S., "Structural Quality of Parts Processed by Fused Deposition" *Rapid Prototyping Journal*, Vo.2, No.4, pp.4-19, 1996.

Agrawal, S., Dhande, S., "Analysis of Mechanical Error in a Fused Deposition Process Using a Stochastic Approach," *International Journal of Production Research*, Vo.45, No.17, pp.3991-4012, 2007.

Ahn, S., Baek, C., Lee, S., Ahn, I. "Anisotropic Tensile Failure Model of Rapid Prototyping Parts – Fused Deposition Modeling," *International Journal of Modern Physics B*, Vo.17, No. 8, pp. 1510-1516, 2003.

Anawa, E., Olabi, A., "Using Taguchi Method to Optimize Welding Pool of Dissimilar Laser-Welded Components," *Optics & Laser Technology*, Vo.40, pp.379-388, 2008.

Arieh, D., Qian, L., "Activity Based Cost Management for Design and Development Stage," *International Journal of Production Economics*, Vo.83, pp.169-183, 2003.

Aurand, S., Roberts, C., Shunk, D., "An Improved Methodology for Evaluating the Producibility of Partially Specified Part Designs," *International Journal of Computer Integrated Manufacturing*, Vo.11, No.2, pp.153-172., 1998.

Barker, R.C., "Value Chain Development an Account of Some Implementation Problems," *International Journal of Operations & Production Management*, Vo.16, No. 10, pp.23-32, 1996.

Beamon, B., "Measuring Supply Chain Performance," *International Journal of Operations & Production Management*, Vo.19, No.3, pp.275-292, 1999.

Benard, A., Taillandier, G., Karunakaran, K., "Evolutions of Rapid Product Development with Rapid Manufacturing: Concepts and Applications," *International Journal of Rapid Manufacturing*, Vo. 1, No. 1, pp.3-17, 2009.

Berginc, B., Kampus, Z., Sustarsic, B., "The Use of the Taguchi Approach to Determine the Influence of Injection-Moulding Parameters on the Properties of Green Parts," *Journal of Achievements in Materials and Manufacturing Engineering*, Vo. 15, No. 1-2, pp. 63-70, 2006.

Beuth, J., Narayan, S., "Residual Stress-Driven Delamination in Deposited Multi-Layers," *International Journal Solids Structures*, Vo.33, No. 1, pp.65-78. 1996.

Bullingston S., Easley, J., Greenwood, A. Bullington, K., "Success Factors in Initiating Versus Maintaining a Quality Improvement Process," *Engineering Management Journal*, Vo. 14, No. 3, pp.8-14, 2002.

Bouaziz, Z., Younes, J., Zghal A., "Methodology of Machining Costs Evaluation for Die and Mould Manufacturing," *Journal of Materials Processing Technology*, Vo. 152, pp.237-245, 2004.

Bourell, D., Leu, M., Rosen, D., "Roadmap for Additive Manufacturing – Identifying the Future of Freeform Processing, " *Roadmap for Additive Manufacturing Workshop: Identifying the Future of Freeform Processing*, University of Texas at Austin, pp.1-92, 2009.

Chen, I., Small, M., "Implementation Advanced Manufacturing Technology: An Integrated Planning Model," *OMEGA*, Vo.22, No.1, pp.91-103, 1994.

Chen, J., "Implementing Six Sigma Via TQM Improvement: An Empirical Study in Taiwan," *The TQM Journal*, Vo.20, No.3, pp.182-195, 2008.

Childerhouse, P., Towill, D., "Engineering Supply Chains to Match Customer Requirements," Logistics Information Management, Vo. 13, No. 6., pp. 337-345, 2000.

Choi, S., Chan, A., "A Virtual Prototyping System for Rapid Product Development," *Computer-Aided Design*, Vo. 36, pp.401-412, 2004.

Choi, S. Samavedam, S., "Modelling and Optimisation of Rapid Prototyping," *Computers in Industry*, Vol. 47, pp.39-53, 2002.

Coleman R. et al., Northrop Grumman Corporation Making Risk Management Tools More Credible: Calibrating the Risk Cube, SCEA 2006, Washington D.C.

Comb, J., Priedeman, W., Turley, P., "Layered Manufacturing Control Parameters and Material Selection Criteria" *Manufacturing Science and Engineering*, Vol. 2, ASME 1994, p.547-556.

Componation, P., Youngblood, A., Utley, D., Farrington, P. "A Preliminary Assessment of the Relationships Between Project Success, System Engineering, and Team Organization," *Engineering Management Journal*, Vo. 20, No. 4, pp.40-46, 2008.

Cooper, K., "Rapid Prototyping Technology: Selection and Application," Marcel Dekker, New York, NY., 2001. ISBN 0824702611

Creveling, C., Slutsky, J., Antis, D., "Design for Six Sigma in Technology and Product Development" Prentice Hall, NJ. ISBN0130092231. 2003, pp.22

Cudney, E., Drain, D. "Effective Use of Process Capability Indices for Supplier Management," *Proceedings from Industrial Engineering Research Conference*, 2007.

Dangayach, G., Deshmukh, S., "Advanced Manufacturing Technology Implementation," *Journal of Manufacturing Technology*, Vo.16, No.5, pp.483-496, 2005.

De Toni, A., Tonchia, S., "Manufacturing Flexibility: A Literature Review," *International Journal of Production Research*, Vo. 36, No. 6, pp.1587-1617, 1998.

De Trevelle, S. Bendahan, S., Vanderhaeghe, A., "Manufacturing Flexibility and Performance: Bridging the Gap Between Theory and Practice," *International Journal of Flexible Manufacturing Systems*, Vo 19, pp.334-357, 2007.

Degarmo, P. "Materials and Processes in Manufacturing," 9th edition, John Wiley and Sons, Hoboken, NJ, pp. 317, 2003. ISBN 0471656534.

Dietrich, D., Hayes, M., Liou, F. "Additive Manufacturing Mechanical Property Assessment and Part Candidate Screening," Submitted to the *International Journal of Rapid Manufacturing* on May 10th, 2010.

Department of Defense, "MIL-HDBK-17-1E, Composite Materials Handbook," Vo.1,pp.83, 2002.

Dimitrov, D., Schreve, K., Taylor, A., Vincent, B., "Rapid Prototyping Driven Design and Realisation of Large Components," *Rapid Prototyping Journal*, Vo. 13, No. 2 pp.85-91, 2007.

Dong, L., Makradi, A., Ahzi, S., Remond, Y., "Three-Dimensional Transient Finite Element Analysis of the Selective Laser Sintering Process," *Journal of Materials Processing Technology*, Vo. 209, pp. 700-706, 2009.

Drizo, A, Pegna, J. "Environmental Impacts of Rapid Prototyping: An Overview of Research to Date," *Rapid Prototyping Journal*, Vo. 12, No. 2 pp.64-71, 2006.

Edwards, P., A Subject Matter Expert in LBW at Boeing. A phone conversation discussing LBW cost modeling, 12-21-2009.

El Maraghy, H., "Enabling Change in Manufacturing Systems," *International Journal of Flexible Manufacturing Systems*, Vo. 19, pp.125-127, 2007.

Federal Aviation Administration (FAA), "Acceptance Guidance on Material Procurement and Process Specifications for Polymer Matrix Composite Systems," Advisory Circular, No 20-107A, pp.1-25, 1984.

Foster, S., Ogden, J., "On Differences in How Operations and Supply Chain Managers Approach Quality Management," *International Journal of Production Research*, Vo.46, No. 24, pp.6945-6961.

Fowlkes, W. Creveling, C. *Engineering Methods for Robust Product Design: Using Taguchi Methods in Technology and Product Development*; Addison-Wesley, Reading MA, 1995.

Fraser, P., Farrukh, C., Gregory, M., "Managing Product Development Collaborations – a Process Maturity Approach," *Institution of Mechanical Engineers*, Vo. 217 Part B. Journal of Engineering Manufacture, pp. 25-30, 2003.

Fung, R., Tang, J., Tu, P., Chen Y., "Modelling of Quality Function Deployment Planning with Resource Allocation," *Research in Engineering Design*, Vo.14, No.1, pp. 247-255, 2003.

Gindy, N. , Cerit, B., Hodgson, A., "Technology Roadmapping for the Next Generation Manufacturing Enterprise," Journal of Manufacturing Technology Management, Vo.17, No.4, pp.404-416, 2006.

Gogate, A., Pande, S., "Intelligent Layout Planning for Rapid Prototyping," *International Journal of Production Research*, Vo.46, No.20, pp.5607-5631, 2008.

Gray, C., Larson, E., "Project Management: The Managerial Process" McGraw-Hill, 3rd ed. ISBN 072978635, pp.136, 2006.

Griffin, A., Hauser, J., "The Voice of the Customer,", *Marketing Science*, Vo.12, No.1, pp.1-27, 1993.

Gunasekaran, A., Tirtiroglu, E., Wolstencroft, V., An Investigation into the Application of Agile Manufacturing in an Aerospace Company," *Technovation*, Vo.22, pp.405-415, 2002.

Hague, R., Cambell, I., Dickens P., "Implications on Design of Rapid Manufacturing," *Institution of Mechanical Engineers*, Vo. 217 Part C. pp. 25-30, 2003.

Hanumaiah, N. Ravi, B., "Rapid Tooling Form Accuracy Estimation Using Region Elimination Adaptive Search Based Sampling Technique," *Rapid Prototyping Journal*, Vo. 13, No. 3 pp.182-190, 2007.

Hastings, B., "The Transition from Rapid Prototyping to Direct Manufacturing," *Proceedings from Society of Manufacturing Engineers – RAPID Conference*, Detroit, MI, 2007.

Hirtz, P., Murray, S., Riordan, C., "Effects of Leadership on Quality," *Engineering Management Journal*, Vo. 19, No. 1, pp.22-27, 2007.

Hopkinson, N., Dickens, P. "Analysis of Rapid Manufacturing – Using Layer Manufacturing Processes for Production," *Journal of Engineering Science*, Vo. 217, pp.31-9, 2003.

Hopkinson, N., et al., "Rapid Manufacturing: An Industrial Revolution for a Digital Age", John Wiley and Sons Ltd, Chichester (UK), November 2005, ISBN: 0470016132

Hon, K., "Performance and Evaluation of Manufacturing Systems," *CIRP Annals - Manufacturing Technology*, Vo.54, No.2, pp.139-154, 2005.

Huang, M., Tai, C., "The Effective Factors in the Warpage Problem of an Injection-Molded Part with a Thin Shell Feature," *Journal of Materials Processing Technology*, Vo. 110, pp. 1-9, 2001.

Huang, M., Zhong, Y., Xu, Z., "Concurrent Process Tolerance Design Based on Minimum Product Manufacturing Cost and Quality Loss," International Journal of Advanced Manufacturing Technology, Vo.25, No. 7, pp.714-722, 2005.

Hurd, A., "Implementation of Lean Processes at a High-Mix Low-Volume Aerospace Manufacturing Facility in France," MBA, MS. Electrical Engineering Thesis, Massachusetts Institute of Technology, 2004.

Jacobs P. F., "Stereolithography and other RP&M Techniques - From Rapid Prototyping to Rapid Tooling", Dearborn, Michigan: Society of Manufacturing Engineers; New York: American Society of Mechanical Engineers, 1996, ISBN 0-87263-467-1.

Jiang, J., Shiu, M., Tu M., "DFX and DFSS: How QFD Integrates Them," *Quality Progress*, Vo.40, No.10, pp. 45-51, 2007.

Joint Defense Manufacturing Technology Panel (JDMTP), 2009. *U.S. Department of Defense Manufacturing Readiness Assessment Deskbook*, ver. 7.1. Available from: *https://acc.dau.mil/CommunityBrowser.aspx?id=182129 - 42k* [Accessed 28 May 2009]

Juran, J., "Juran on Quality by Design: The New Steps for Planning Quality into Goods and Services," Free Press, New York, NY, pp.15, 1992. ISBN 0029166837

Juran, J., "Juran on Leadership for Quality," Free Press, New York, NY, pp. 37. 1989. ISBN 0743255771.

Kannan, S., Jeevanantham, A., Jayabalan, V., "Modelling and Analysis of Selective Assembly Using Taguchi's Loss Function," *International Journal of Production Research*, Vo.46, No.15, pp.4309-4330, 2008.

Karim, M., Smith, A., Halgamuge, S., "Empirical Relationships Between Some Manufacturing Practices and Performance," *International Journal of Production Research*, No.46, No.13, pp.3583-3613, 2008.

Kathawala, Y., Wilgen, A., "The evolution of build-to-order supply chain and its implications with selected case studies," *International Journal of Services Operations Management*, Vo. 1, No. 3, 2005.

Kiemele, M., Schmidt, S., Berdine, R. "Basic Statistics – Tools for Continuous Improvement," Air Academy Press, 4th Edition, Colorado Springs, CO, pp.12-7, 1999. ISBN 1880156067

Kotlinski, J., Kesy, Z., Kesy, A., "Dimensional Deviations of Machine Parts Produced in Laser Sintering Technology," *International Journal of Rapid Manufacturing*, Vol.1, No.1, pp. 88-98, 2009.

Kulkarni, P., Dutta, D. "Deposition Strategies and Resulting Part Stiffnesses in Fused Deposition Modeling" *Journal of Manufacturing Science and Engineering*, vol. 121, ASME 1999, p.93-121.

Levy, G., Schindel, R., "Overview of Layer Manufacturing Technologies, Opportunities, Options, and Applications for Rapid Tooling," *Institute of Mechanical Engineers,* Vo. 216 Part B: J Engineering Manufacture pp. 1621-1634, 2002.

Liou, F, Rapid Prototyping and Engineering Applications: A Toolbox for Prototype Development (Dekker Mechanical Engineering). CRC Press, Sep. 2007.

MacDonnell, M., Clegg, B., "Designing a Support System for Aerospace Maintenance Supply Chains," *Journal of Manufacturing Technology Management*, Vo.18, No.2, pp. 139-152, 2007.

Mahesh, M., Wong, Y., Fuh, J., Loh, H., "Benchmarking for Comparative Evaluation of RP Systems and Processes," *Rapid Prototyping Journal*, Vo. 10, No. 2, pp.123-135, 2004.

Mansour, S., Hague, R. "Impact of Rapid Manufacturing on Design for Manufacture for Injection Molding," *Proceedings of the Institution of Mechanical Engineers*, Vol. 217, Part B, pp.453-60, 2000.

Maritan, D., Panizzolo, R., "Identifying Business Priorities through Quality Function Deployment," *Marketing Intelligence and Planning*, Vo.27, No.5, pp.714-728, 2009.

Maskell, B., "The Age of Agile Manufacturing," *Supply Chain Management: An International Journal*, Vo.6, No.1, pp.5-11, 2001.

Maurer, S., "Using Situational Interviews to Assess Engineering Applicant Fit to Work Group, Job, and Organizational Requirements," *Engineering Management Journal*, Vo. 18, No. 3, pp.27-35, 2006.

Meade, B., Farrington, P., "Faster, Better, Cheaper in the Context of Systems Engineering," *Engineering Management Journal*, Vo. 20, No. 3, pp.29-35, 2008.

Mendez, P., Eagar, T., "Welding Processes for Aeronautics," *Advanced Materials & Processes*, May 2001.

Miguel, P., Carnevalli, J., "Benchmarking Practices of Quality Function Deployment: Results from a Field Study," *Benchmarking: An International Journal*, Vo.15, No.6, pp.657-676, 2008.

Miltenburg, J., "Setting Manufacturing Strategy for a Company's International Manufacturing Network," *International Journal of Production Research*, Vo. 47 No. 22, pp. 6179-6203, 2009.

Mognol, P., Lepicart D., Perry, N., "Rapid Prototyping: Energy and Environment in the Spotlight," *Rapid Prototyping Journal*, Vo. 12, No. 1 pp. 26-34, 2006.

Muchuri, P., Pintelon, L, "Performance Measurement Using Overall Equipment Effectiveness (OEE): Literature Review and Practical Application Discussion," *International Journal of Production Research*, Vo.46, No.13, pp. 3517–3535, 2008.

Munguia, J., Ciurana, J., Riba, C., "Pursuing Successful Rapid Manufacturing: A Users' Best Practices Approach," *Rapid Prototyping Journal*, Vo. 14, No. 3, pp. 173-179. 2008.

Musa, R., Huang, S., Rong, Y., "Simulation based tolerance stackup analysis in machining," *Transactions of NAMRI/SME*, Vo. 32, pp. 533-540, 2004.

Naylor, Ben J., Naim, M, Berry, D., "Leagility: Integrating the Lean and Agile Manufacturing Paradigms in the Total Supply Chain," *International Journal of Production Economics*, Vol. 62, pp.107-118, 1999.

Nelson, J. "Selective Laser Sintering: A Definition of the Process and an Empirical Sintering Model," Dissertation for University of Texas - Austin, pp. 1-223, 1993.

Oktem, H., Erzurumlu, T., Uzman, I., "Application of Taguchi Optimization Technique in Determining Plastic Injection Molding Process Parameters for a Thin-Shell Part," *Materials and Design*, Vo. 28, pp. 1271-1278, 2007.

Pande, S., Kumar, S., "A Generative Process Planning System for Parts Production by Rapid Prototyping," *International Journal of Production Research*, No.46, No.22, pp.6431-6460, 2008.

Pandey, P., Reddy, N., Dhande, S., "Improvement of surface finish by staircase machining in fused deposition modeling" *Journal of Materials Processing Technology*, vol. 132, 2002, p.323-331.

Performance Testing of Plastics Products, *SPI Plastics Engineering Handbook,* Chapter 27, pp.801-818. ISBN: 0442317999, 1991.

Pham, D.T., Wang, X. "Prediction and Reduction of Build Times for the Selective Laser Sintering Process," *Proceedings of the Institution of Mechanical Engineers*, Vol. 214, Part B, pp.425-30, 2000.

Pham, D.T., Dimov, S. S. "Rapid Prototyping and Rapid Tooling – The Key Enablers for Rapid Manufacturing," *Journal of Mechanical Engineering Science*, Vol. 217, pp.1-23, 2003.

Poli, C. *Design for Manufacturing, A Structured Approach;* Butterworth-Heinemann, Boston, MA 2001.

Rajagopalan, S., Pinilla, J., Losleben P., Tian, Q., Satyandra G., "Integrated Design and Rapid Manufacturing Over the Internet," *Proceedings from DETC98, ASME Design Engineering Technical Conference*, Sept. 13-16, 1998.

Raquet, J. "An investigation into the material properties and precision of rapid prototyping technology", Dissertation for the University of North Carolina at Charlotte, 2005.

Rauwendaal, C. *Polymer Extrusion, 4th edition;* Hanser Gardner, Cincinnati, OH, 2001. pg.237-238

Rezaie, K., Ostadi, B., Torabi, S., "Activity-Based Costing in Flexible Manufacturing Systems with a Case Study in a Forging Industry," *International Journal of Production Research,* Vo. 46. No. 4, pp. 1047-1069, 2008.

Robinson, T. "Cost Modeling in the Integrated Supply Chain Strategic Decision Process," M.B.A. and M.S. Mechanical Engineering Thesis, Massachusetts Institute of Technology, Submitted May 6, 2006.

Rodriguez, J., Thomas, J., Renaud, J., "Design of Fused-Deposition ABS Components for Stiffness and Strength" *Journal of Mechanical Design,* vol. 125, ASME 2003, p.545-551.

Rodriguez, J., Thomas, J., Renaud, J., "Characterization of the Mesostructure of Fused-Deposition Acrylonitrile-Butadiene-Stryrene Materials" *Rapid Prototyping Journal,* Vo 6, No.3, p.545-551, 2000.

Rosas, J., Camarinha-Matos, L., "An Approach to Assess Collaboration Readiness," *International Journal of Production Research,* Vo. 47, No.17, pp. 4711–4735, 2009.

Rosen, D., Chen, Y., Sambu S., Allen J., Mistree, F., "The Rapid Tooling Testbed: A Distributed Design for Manufacturing System," *Rapid Prototyping Journal,* Vo. 9, No. 3, pp.122-132, 2003

Roy, R., Souchoroukov, P., Griggs, T., "Function-Based Cost Estimating," *International Journal of Production Research,* Vo. 46, No. 10, pp. 2621-2650, 2008.

Ruffo, M. "The Impact of Rapid Manufacturing on Business Management," Dissertation for Loughborough University, pp. 65, 2006.

Ruffo, M., Tuck, C., Hague, R., "Make or Buy Analysis for Rapid Manufacturing," *Rapid Prototyping Journal,* Vo. 13, No. 1 pp.23-29, 2007.

Ruffo, M., Tuck, C., Hague, R., "Cost Estimation for Rapid Manufacturing – Laser Sintering Production for Low to Medium Volumes," *Proceedings of the Institution of Mechanical Engineers -- Part B -- Engineering Manufacture,* Vo.220, Part B., pp.1585-1591, 2006.

Ruffo, M., Hague, R., "Cost Estimation for Rapid Manufacturing – Simultaneous Production of Mixed Components Using Laser Sintering," *Proceedings of the Institution of Mechanical Engineers -- Part B -- Engineering Manufacture,* Vo.221, Part B., pp.1585-1591, 2007.

Sambu, S., Chen, Y., Rosen, D., "Geometric Tailoring: A Design for Manufacturing Method for Rapid Prototyping and Rapid Tooling," *Journal of Mechanical Design*, Vo. 126, pp. 571-579, 2004.

Schroder, R., Sohal, S., "Organizational Characteristics Associated with AMT Adoption; Towards a Contingency Framework," International Journal of Operations & Production Management, Vo.19, No.12, pp.1271-91, 1999.

Sethi, A.K. and Sethi, S.P. "Flexibility in manufacturing: a survey," *International Journal of Flexible Manufacturing Systems*, Vo.2, No.4, pp.289-328, 1990.

Serrano, I., Ochoa, C., De Castro, R., "Evaluation of Value Stream Mapping in Manufacturing System Redesign," *International Journal of Production Research,* Vo.46, No.16, pp.4409-4430, 2008.

Sharifi, H., Zhang, Z., "A Methodology for Achieving Agility in Manufacturing Organizations: An Introduction," *International Journal of Production Economics,* Vo. 62, pp.7-22, 1999.

Shen, X, et al, "The Implementation of Quality Function Deployment Based On Linguistic Data," *Journal of Intelligent Manufacturing*, Vo.12, No.1. pp.65-75, 2001.

Singhal, S., Jain, P., Pandey P., Nagpal, A. "Optimum Part Deposition Orientation for Multiple Objectives in SL and SLS Prototyping," *International Journal of Production Research*, Vo. 47, No. 22, pp.6375-6396, 2009.

Sinha, P., Whitman, L., Malzahm, D., "Methodology to Mitigate Supplier Risk in an Aerospace Supply Chain," *Supply Chain Management*, Vo.9, No. 2, pp.154-168, 2004

Slack, N., "Flexibility as a Manufacturing Objective," *International Journal of Operations & Production Management*, Vo. 3, No.3, pp. 4-13, 1991.

Slaughter, B., A Subject Matter Expert in Additive Metals Fabrication at Boeing. A phone conversation discussing LENS and LAMP cost modeling, 12-27-2009.

Small, M., Yasin, M., "Developing a Framework for the Effective Planning and Implementation of Advanced Manufacturing Technology," *International Journal of Operations & Production Management,* Vo.17, No.5, pp.468-73, 1997.

Stockton, D., Bateman, N., "Measuring the Production Range Flexibility of a FMS," *Integrated Manufacturing Systems*, Vo.6, No.2, pp.27-34, 1995.

Stratton, R., Warburton, R., "The Strategic Integration of Agile and Lean Supply," *International Journal of Production Economics*, Vo. 85, pp. 183-198, 2003.

Suh, N., "Designing-in of Quality through Axiomatic Design," *IEEE Transactions on Relieability*, Vo.44, No.2, pp.256-264, 1995.

Taguchi, G., Clausing, D., "Robust Quality," *Harvard Business Review*, Jan-Feb. pp.65-75, 1990.

Talluri, S., Baker, R.C., Sarkis, J.,"A Framework for Designing Efficient Value Chain Networks,"*International Journal of Production Economics*, Vol. 62, pp.133-144, 1999.

Tang, S., Tan, Y., Sapuan, S, Sulaiman, S., Ismail, N., Samin, R., "The Use of Taguchi Method in the Design of Plastic Injection Mold for Reducing Warpage," *Journal of Materials Processing Technology*, vo. 182, pp. 418-426, 2007.

Tay, F., Khanal, Y., Kwong K., Tan K., "Distributed Rapid Prototyping – A Framework for Internet Prototyping and Manufacturing," *Integrated Manufacturing Systems*, Vo.12, No.6, pp.409-415, 2001.

Thomas, A., Barton, R., Okafor, C., "Applying Lean Six Sigma in a Small Engineering Company – A Model," *Journal of Manufacturing Technology Management*, Vo.20, No.1, pp. 113-129, 2009.

Thompson, D., Crawford, R., "Computational Quality Measures for Evaluation of Part Orientation in Freeform Fabrication," *Journal of Manufacturing Systems*, Vo.16, No. 4, pp. 273-289, 1997.

Tran, Q., "Laser Drilling Techniques in Aircraft Engine Refurbishing," *Advanced Manufacturing Technology*, Vo.30, No.10, pp.1-2, 2009.

Tuck, C. et. al., "Rapid manufacturing: impact on supply chain methodologies and practice," *International Journal Services and Operations Management*, Vo.3, No.1, pp.1-22, 2007.

Tucker, E., Cudney, E. "Using Value Stream Mapping for Financial Analysis," Proceedings from the American Society of Engineering Management Conference, Springfield, MO. Oct. 17, 2009.

Violante, M., Iuliano, L., Minetola, P., "Design and Production of Fixtures for Free-Form Components Using Selective Laser Sintering," *Rapid Prototyping Journal*, Vo. 13, No. 1 pp.30-37, 2007.

Wagner, H., Dainty, A., Hague, R., Tuck, C., Ong, M. "The Effects of New Technology Adoption on Employee Skills in the Prosthetics Profession," *International Journal of Production Research*, Vo.46, No.22, pp.6461-6478, 2008.

Walter, M., Holmstrom, J., Yrjola, H., "Rapid Manufacturing and its Impact on Supply Chain Management," *Proceedings of the Logistics Research Network Annual Conference,* Dublin, Ireland, Sept. 9-10, 2004.

Wang T., Xi, J., Jin, Y., "A Model Research for Prototype Warp Deformation in the FDM Process," *International Journal of Advanced Manufacturing Technology,* Vo. 33, pp.1087-1096, 2007.

Watkins, K., "Laser Welding of Magnesium Alloys," *Magnesium Technology*, pp. 153-156, 2003.

Wikner, J., Towill D., Naim, M., "Smoothing Supply Chain Dynamics," *International Journal of Production Economics*, Vo. 22, No. 3, pp. 231-248. 1991.

Williams, T., Maull, R., Ellis, B., "Demand chain management theory: constraints and development from global aerospace supply webs," *Journal of Operations Management*, Vo. 20, pp.691-706, 2002.

Womack, J., "Raising the Game," Manufacturing Magazine, pp. 44-45, 2007.

Wu, C., Shu, M., Pearn, W., Liu, K., "Bootstrap Approach for Supplier Selection Based on Production Yield," *International Journal of Production Research*, Vo. 46, No. 18, pp. 5211-5230, 2008.

Wu, T., Blackhurst, J., "Supplier Evaluation and Selection: An Augmented DEA Approach," *International Journal of Production Research*, Vo.47, No.16, pp.4593-4608, 2009.

Yang, Z., Wysk, R., Joshi, S., "Conventional Machining Methods for Rapid Prototyping and Direct Manufacturing," *International Journal of Rapid Manufacturing*, Vo.1, No.1, pp.41-62, 2009.

Zhang, Q., Tseng, M., "Modelling and Integration of Customer Flexibility in the Order Commitment Process for High Mix Low Volume Production," *International Journal of Production Research*, Vo.47, No.22, pp.6397-6416, 2009.

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