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Abstract

The problems with the implementation and use of RP technology is choosing the best system from the fifteen or more RP systems commercially available and more than 20 other systems under development throughout the world (Wohlers, 1993). The problem of this study was to evaluate each of six preselected RP systems based on key characteristics. This study provides pertinent data so that those teams and individuals involved in the implementation and the use of a RP process can make sound decisions.

COMPARISON OF RAPID PROTOTYPING SYSTEMS FOR IMPLEMENTATION INTO THE PRODUCT DEVELOPMENT CYCLE

A Research Project for Presentation
to the Graduate Faculty
of the Department of Industrial
Technology
University of Northern Iowa

Submitted in Partial Fulfillment
of the Requirements of 330:270
Research Project in Industrial Technology

Daniel S. Koenig

14 April 1995

Approved by:	
______________________	______________________
Advisor	Date
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Graduate Faculty Member	Date

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Chapter 1

Introduction

"RP (rapid prototyping) is a term that refers to a group of technologies which can be used to create model parts directly from a CAD model without tooling and machining" (Mueller, 1992, p.1). Rapid prototyping converts computer aided design (CAD) data directly into physical models by selectively hardening, bonding, or cutting layers of material to shape. Models are built of soft low strength materials that are either molded, polymerized, or bonded together. More conventional methods of building prototypes would use a forming process or a material removal process. Rapid prototyping is a new concept of manufacturing. It is a new tool that can shorten the product development cycle and assist in manufacturing the product to specification. Robert A. Lutz, President of Chrysler Corp. says rapid prototyping and manufacturing can be used to increase a company's competitiveness (Jacobs, 1992).

Statement Of The Problem

The problems with the implementation and use of RP technology is choosing the best system from the fifteen or more RP systems commercially available and more than 20 other systems under development throughout the world (Wohlers, 1993). The problem of this study was to evaluate each of six preselected RP systems based on key characteristics. This study provides pertinent data so that those teams and individuals involved in the implementation and the use of a RP process can make sound decisions.

Statement Of The Purpose

The intent of this analytical descriptive study was to provide data for the defined key characteristics for each of the selected major

RP systems. This data will be useful for design teams to determine which system best suits their needs. Each system has its own strengths and limitations. In order for a design team to maximize their efforts in RP they need to know and compare the strengths of these systems before choosing the one to be used. The team must understand their applications' requirements, understand the potentials and limitations of each of the RP systems, understand the technology, and understand what to look for in a RP system.

Statement Of The Need

The complete development, manufacturing, and marketing process of a product has become very competitive. Not only are manufacturers competing against companies headquartered in the United States, they now have to contend with international rivals. For many years American companies have been feeling the pressure from international sources like Japan and Germany. Increasing competition is now coming from other parts of the world as once underdeveloped countries spawn their own new industries with lower labor costs. A second respect of global competition is that American companies are competing in international markets as they find their domestic markets growing smaller. These crowded markets mean that new products are facing an ever-shrinking window of uniqueness as businesses strive to gain an advantage over each other. In some cases niche markets are being sought to boost profits. As new international trade agreements are ratified, competition will increase for our lucrative domestic markets. On the other hand- foreign markets will present new opportunities.

Competition is not the only factor driving markets. Customer needs and demands are changing more rapidly than they have in the past. As new technology develops, it propagates even more technological developments. Technology has a snowball effect on future developments. Customers are demanding products that have the latest innovations. There is pressure to keep ahead of consumer demands. The manner in which a product is brought to market can be critical to the future profitability and market share. Delays result in lost sales. Successful introduction of new products will permit companies to develop a reputation of leadership and create barriers for competitors (Peterson, 1993; Manji 1992; Yovoich, 1994).

Diverse competition, products with multiple options to satisfy multiple markets, and quicker product turn over have made product development more important. Doing it faster is only one demand on the product development cycle. Another demand is that the products must be functional and reliable. Today's products are much more complicated than they have ever been. Also, many capabilities and features are now being packed into today's new products. The manufacturer must design all of these features in such a way that the product meets the customer's expectations while keeping the product cost effective. The sum of these effects puts increasing pressure on the efficient use of materials, manufacturing processes, and resources to manufacture the best product a company can produce. In other words, the product must be done right.

All of these factors are affecting Deere and Company too. John Deere is competing in a global market. According to the Deere & Company 1994 Annual Report net sales for the company are up 29% from 1992 to 1994 while export sales are up 47% for the same period. There is greater growth in the export market. The GATT and NAFTA agreements will provide increased opportunities as they gradually lower tariffs on equipment exports, thus making the export markets even more attractive. Through its product development Deere & Company is attempting to introduce technological advances and products that meet customers' needs in new geographic and niche markets. These are markets where they have not participated in the past. In 1994 Deere & Company introduced 40 new products and product improvements. In the past three years the Waterloo operations has replaced the John Deere agricultural line of tractors with eleven all new models. Three of the seven activities that will provide profitable growth for the company are (Deere & Company, 1994):

> - expanding into new world markets
> - matching our products and services to customers' exact needs
> - extending our product line into new markets and new applications (p. 9)

Shortening the development process is not without risk. In order to shorten the development cycle, steps either have to be omitted or done more quickly and smarter (Voegtlen, 1974). Today there are many tools that are targeted at shortening and improving the product development and manufacturing processes. Leading manufacturers are learning to use these tools such as concurrent engineering, computer-integrated manufacturing, CAD/CAM, finite element analysis, and rapid prototyping.

Many companies design, manufacture, and purchase a wide variety of products. They range from small plastic components to large highly stressed iron castings. It is important to keep all of these potential applications in mind while evaluating RP systems. One system may not satisfy all applications. A strategic plan should be developed that evaluates the future applications of RP within any company. This study is a resource for that strategic plan. According to Aronson (1993):

> Given that RP is an important technology that may both improve product quality and get it to market faster, the question is, should you apply it to your situation? Unfortunately, no list of RP system's features gives that answer. You need an in depth analysis of your own design and manufacturing operations. (p. 38)

This study aids the individual design engineer. In many cases, design engineers develop an urgent need for a rapidly produced prototype. At this point in the design process the engineer may not have the luxury of time to identify and investigate all of the relevant processes available to produce prototype models. The data from this study helps guide the engineer in selecting a suitable process.

It is also very important that corporate managers are aware of today's emerging technologies. It is these technologies that will provide business opportunities and help companies remain competitive. Leading manufacturers are taking advantage of a variety of recent technologies to bring products to market quicker, thus reducing the costs of product development. Most Japanese electronic companies and auto makers now use some kind of RP. (McGee, 1992) This study will help inform management of this developing technology.

Delimitations

The most fully documented RP systems are direct shell production casting (DSPC) by Soligen Technologies Inc., fused deposition molding (FDM) by Stratasys Inc., laminated object manufacturing (LOM) by Helisys Inc., solid ground curing (SGC) by Cubital, Ltd, stereo lithography apparatus (SLA) by 3D Systems, and selective laser sintering (SLS) by DTM Corp. (Aronson, 1993; Mueller, 1992; Sprow, 1992). Although there are other RP systems, this study was be delimited to the six listed above because they are the most commercially available. The immaturity of the remaining systems would present risks to those who choose to use them at this time. Those risks are the lack of information, the lack of application experience, and the unknown reliability. Although all of these systems are new, the six chosen systems have some application experience. They also cover a wide range of the technology which presented different characteristics.

There are many characteristics of rapid prototyping. This study only focused on eight characteristics of RP systems. Those characteristics were model size, processing time, materials, accuracy, machine costs, model costs, secondary costs, and model surface finish (Aronson, 1993; D. J. Backens, personal communication, December 9, 1994; C. Klages, personal communication, Sprow, 1992; Stevens, 1993; Stundt, 1994). These characteristics and the type of data that was collected is listed in Table 1 and they represent the operational definitions for this study.

Table 1
Key Characteristics and Description

Characteristic	Data
Model Size	The height, width and depth in inches of the largest model that can be built by the machine
Processing Time	The time in minutes it takes to build a R95850 transmission oil filter housing, a R96911 transmission output planetary carrier, and a R121548 reduction gear box housing at 0.005 inch per layer
Material	The type of material and the tensile and flexural strengths in pound per square inch of the materials that can be used to build models
Accuracy	The dimensional correctness in inches for each of the three models
Machine Costs	The capital expenditure in dollars for the machine and all necessary supportive hardware and software
Model Cost-	The costs in dollars to produce a R95850 housing, a R96911 carrier, and a R121548 housing
Secondary Costs	The incidental costs in dollars to cover such items as maintenance and facility preparation
Model Surface Finish	The surface texture in micro-inch

Limitations

One of the limitations of this study is that the data collected is very general and not precise. Specific machine requirements were not provided to rapid prototyping equipment manufacturers. So, they could only provide the maximum and minimum machine costs, which does not permit direct costs comparisons between the six systems. No models were produced for this study. This only allows estimates to be made for the manufacturing costs and accuracies of the models. Five of the six manufacturers responded to the request for estimates. One of those five responses was not a formal response so it was not included in this study. RP users within Deere and Company were surveyed to determine the applications of RP technology. The extent to which these findings can be universally applied was not determined. The sample of people interviewed and surveyed, outside those representing the manufacturers, only covered the LOM, SGC, SLA, and SLS processes. There were no recent users of DSPC and FDM within John Deere.

Research Questions

There were three research questions to be answered by this study.

1. How do the six selected RP systems compare on the eight key characteristics?
2. How do the users of rapid prototyping within John Deere rank these eight characteristics?
3. What is the perception of John Deere rapid prototyping users regarding the desirability of purchasing rapid prototyping equipment by Deere and Company?

Chapter 2

Review Of Literature

Changing markets, marketing strategies, and customer demands are forcing design teams to become more efficient, faster, and more accurate at product development. Product development is that portion of the product life cycle that includes concept and feasibility, detail design, prototype, pre-production demonstration, production, design change and customer use (Voegtlen, 1974). Throughout this whole process there is often a need to build models of the product for evaluation.

These models can and have been made many different ways. Two dimensional models are hand sketches, orthographic drawings, and isometric drawings. Electronic models can be generated on CAD systems. These electronic models can be two dimensional or three dimensional models. Three dimensional electronic models are wire frame, surface, solid, holograms, and virtual reality models. These electronic models contain an abundance of information such as mass, section views, coloring, and shading (Sprow, 1992). Finally, there are physical models. Physical models are very desirable. They can be held and observed from any angle and they do not require any visualization. Physical models can be hand-made quickly from wood, clay, or fabricated from other materials. They can also be machined using computer numerical control (CNC) machine tools.

One of the other processes used to make three dimensional physical models is rapid prototyping. RP is very similar to but has an advantage over CNC. CNC requires extra set-ups and additional programming to produce a part from six sides. RP requires only a single set up and minor program modification to produce a part (Sprow, 1992). CNC can produce a metallic part. But, with secondary processes such as casting and molding more complex RP parts can be built from a variety of materials including metals for application testing and even low volume production. Once the soft RP model is made more durable, casting, and molding tools can then be made from the model by a number of secondary processes.

When asked what technologies will have a major impact on manufacturing during the next ten years, Kevin Hardings Ph. D., of the Industrial Technology Institute in Ann Arbor, stated that rapid prototyping is one of the technologies that has the "potential to produce revolutionary effects for companies willing to take a chance to be among those who determine the future of manufacturing." ("Future Views: Tomorrow's Manufacturing Technologies," 1992, p. 84) LaRoux K. Gillespie, senior project engineer of the Allied-Signal Aerospace Company of Kansas City chose RP processes as technologies that will save millions as RP material properties improve ("Future Views: Tomorrow's Manufacturing Technologies," 1992).

Jacobs (1992) lists five practical applications of RP parts. They are (1) visualization, (2) verification, (3) iteration, (4) optimization, and (5) fabrication. First of all, a three-dimensional part helps the design and manufacturing engineers visualize the part in its true form and proportions. They can also touch the part. Many of those who have worked with RP feel that visualization is the real benefit of the process. Today's engineers need the physical model. The next generation of engineers, who have grown up with video games and computers, may not need the physical model. They may be able to accurately visualize the part through electronic modeling such as CAD, holograms and virtual reality (Aronson, 1993). Secondly, it allows for verification of fit and in some cases function. This prevents mistakes that would not have been found until later in the development process when they are likely to be much more costly to correct. Thirdly, since RP parts can be built and modified quickly more iterations can be made. These iterations lead to optimization of the design. Finally, fabrication of parts by secondary processes such as investment casting, sand casting, and other processes allows more durable and functional parts to be made.

Leading companies in the automotive, aerospace, and consumer electronics fields are already using RP techniques to realize 50% - 95% savings in time and costs to design and engineer new products (Stevens, 1993). The Sandia National Laboratory, in Albuquerque has reduced the precision investment casting time from 52 weeks to three weeks. This is possible because RP eliminates the need to fabricate additional tooling. It is the direct transfer of a CAD model to a prototype part (Stundt, 1994).

Chrysler has used RP extensively. They have used SLA models for bench testing engine head models to flow test various port designs. They have used tooling made from SLA models to produce parts using secondary processes like resin transfer molding, squeeze molding and silicone molding. A SLA model was used to make gray iron sand casings for the exhaust manifold of the V-10 viper engine. They were able to build the complex curves of the tuned manifold in the CAD model. Conventional pattern making processes would have shown a limited number of cross sections and relied on the pattern maker to interpolate between the cross sections. The SLA model saved Chrysler $6,000.00 on the prototype pattern. With the 0.0025 inch accuracies of the SLA master, it was used to produce 5,200 parts for the production run. This saved an additional $50,000.00 and 18 weeks lead time (Jacobs, 1992).

The Texas Instrument Defense Systems and Electronics Group compared the cost and time to produce an investment casting using three processes. One method was to use a SLA model to produce an investment casting mold. The other two were to cut the mold out of a block of steel and to use a conventional wax investment casting. Their results of the cost and time study are shown in the Table 2. As can be seen there were substantial savings in money and time (Jacobs, 1992).

Table 2

Texas Instrument Process Evaluation

	Costs	Time (months)
SLA To Investment Casting	$215,000.00	5
Cut Investment Casting Mold From Steel	$549,700.00	7
Wax Investment Casting	$328,700.00	8

Many different forms of models have always been used in the product development cycle. Over the years these models have been used for the same reasons. Those five reasons are visualization, verification, iteration, optimization and fabrication. Now rapid prototyping has changed the way prototype models can be built. This new technology can lead to significant savings in time and money which improves competitiveness.

History Of Rapid Prototyping

Jacobs and Metelnick (Jacobs 1992; Metelnick, 1994b) point out that rapid prototyping technology started in the 70's with the development of photopolymers and the commercial application of laser technologies. Commercialization of RP became possible with the creation of hi-tech software that slices CAD models and is also capable of being run on PC's. The first RP system developed was SLA in 1986. Other systems were not far behind.

Rapid Prototyping Processes

Steps common to all of the rapid prototyping processes are to create the CAD model, conversion of that model to a computer file that is readable by the RP machine, setting the parameters that are used to build the model, and finally slicing the model into layers. See

Figure 1. Some processes and model geometries may require the addition of supports. These supports are needed to provide structural integrity to the model while the model is being constructed. During the construction phase some of these processes and their materials do not have sufficient strength to support themselves. Once the building process is completed and the model is completely cured the strength is present and the supports are removed.

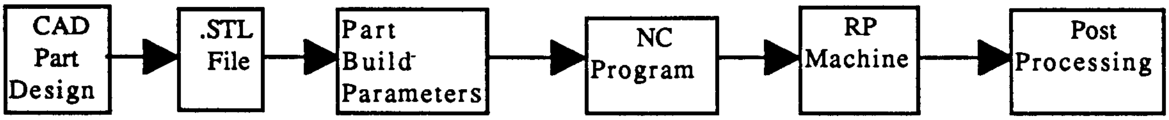

Figure 1. Rapid Prototyping Process

Proper CAD data is essential to a good, accurate detailed model. RP models can only be produced when they are generated from three dimensional CAD models. Solid models produce the best results. Surface and wire frame models can leave gaps in the geometry which are open for interpolation by the operator and the computer software (Jacobs, 1992; Sprow, 1992). During the development of the CAD model the designer must choose the accuracy of the CAD model. This chosen accuracy will affect the ultimate accuracy of the rapid prototype model. If the designer selects a wide CAD model tolerance the eventual RP model will reflect the accuracy of the CAD model. The designer must anticipate the eventual use of the CAD file. Once the CAD file is complete it is converted to a .STL file. This .STL file is a neutral data base and it is the defacto standard for the RP industry. It is the equivalent of the IGES files that are used to translate two dimensional CAD data (Clark G. personal communication February 15, 1995). .STL was specifically designed to handle three dimensional solid models (Rohrbeck T. personal communication February 1995). It was developed for the stereolithography process; hence its name. After the .STL file is loaded into the computer system of the RP equipment the operator then selects the build parameters for the model. The common variables that the operator has to choose from are build layer thickness, speed, laser power, build sequence, raster spacing, layer orientation, and build style.

Build layer thickness refers to the thickness of the individual layers that the CAD model is sliced into. Thicker slices up to 0.030" provide less accurate models more quickly. Slices as thin as 0.002" are used to create the most accurate models with a much smoother finish. These more precise models take proportionally more time to generate. On some systems the build speed can be modified for the various geometries within the model. Slower speeds in certain sections will build a more dense model which creates more strength. In some systems laser power in combination with build speed affects the degree of cure and bonding that occurs. When specifying the build sequence the operator determines how he wants to construct the model. He can choose to build the perimeter of each layer first and then fill in the internal portions last. The systems that use the point to point construction method allow the operator to choose the spacing between adjoining paths of the construction tool. They also allow the operator to choose a change in raster orientation from one layer to the next. Larry Soucy the technical sales representative for 3D Systems says that they have developed several build styles which have different characteristics depending on the eventual use of the model (personal communication February 1995; Jacobs, 1992). On all RP systems the construction parameters can be selected by the use of pull down menus. As the operator gains experience he can build models to his liking based on his experience. He will eventually become a craftsman. The final common step is for the computer to electronically slice the model into the prescribed layers. There is a schematic representing each of the six processes in Appendix E.

Stereolithography (SLA). The stereolithography process developed by 3D Systems is one of the layer-additive laser point-by-point fabrication methods. The model is generated one layer at a time, starting from the bottom using a UV laser to draw each layer on the surface of a photocurable resin. The photocurable or photopolymer resin solidifies in the presence of UV light of a certain wavelength. Photopolymers can only be used with specific lasers that generate a beam with the correct wave length (Soucy L. personal communication February 1995). Each layer is drawn in a sequence where the outside boundary is created first and then the internal patterns are drawn (Belfiore, 1991). In the vicinity of the focal point of the laser the resin polymerizes and cures. The state of cure varies indirectly as the distance from the focal point increases (Jacobs, 1992). The internal pattern used is based on the laser power, drawing speed, and resin used. The pattern spacing, and drawing sequence is built into the .STL file. This pattern is offset horizontally from the pattern in the previous layer. The offset is determined by the amount of cure obtained. Without this offset, drawing subsequent patterns on top of one another will result in areas of over cure and areas of undercure. After each layer is drawn the construction platform is lowered into the liquid resin bath by the amount of the predetermined slice thickness. These steps are repeated over and over until the model is completed. After the top layer is drawn the model is complete and ready for post processing (Jacobs, 1992).

Post processing consists of additional UV curing, cleaning, and model finishing. As the model is removed from the build station it possesses 40%-60% of its final cure strength (Jacobs, 1992). The final state of cure is achieved by placing the model under UV lights for a prescribed minimum amount of time. The final curing process is from the outside in. Operators have to be certain the model is completely cured. The phase change from a liquid to a solid is an exothermic reaction. This plus the heat from the UV lights can cause a heat build up in the part depending on the mass to surface area ratio. Heat then causes the uncured resin to expand and pressurize the model's honey comb construction. Expansion due to heat and pressurization combined with the shrinkage due to cooling and solidification can lead to distortion (Belfiore, 1991; Jacobs, 1992). Cleaning is accomplished by wiping with water, alcohol, or a solvent. The cleaning process and the cleaning medium is dependent on the resin used. Alcohol, when used as a solvent, can cause the polymer to swell resulting in lost accuracy. Other solvents present explosion hazards. They are volatile and present a disposal situation that has to be handled properly. The resin in its uncured state can cause skin irritation. Depending on the model's final application, additional hand finishing may be required. Operations such as bead blasting, tap water washing, sanding, buffing, and polishing may be used. Each of these secondary operations may result in a loss of accuracy.

Depending on the geometry of the model, supports may be required. Stereolithography models are not strong enough to support bridges and cantilevers in the green state. Supports may be needed to reinforce certain geometrical shapes until the model is completely cured. These prevent sag and curl. Once cured the processing supports are removed. Table 3 lists the strengths and limitations of the SLA process.

As a result of the on going development 3D Systems has developed four build styles. The first style is Weave which is used for fast and less accurate models. Another style is Star Weave which is used for more accurate models but requires longer build times. The third build style is Aces. This is used when smooth surface finishes are required for tooling. The final build style is QuickCast^{TM} which was specifically developed for the investment casting process.

A recent development by 3D Systems for stereolithography is the QuickCast^{TM} process. This new process was specifically developed so the SLA models can be conveniently adapted to the

Table 3
Stereolithography (SLA)

Strengths	Limitations
• most popular process	• requires mastered technologies
• high accuracy	• resin is toxic
• produces detailed models	• requires supports for overhangs
• produces thin walls (0.011")	• massive sections curl
• good surface finish	• limited materials
	• laser to material match
	• shrinkage

shell investment casting process. Prior to rapid prototyping shell investment castings were made by dipping a wax model into a slurry. Once dipped, the slurry covered model is then coated with a ceramic powder. The dipping process is repeated until a suitable mold is built. After sufficient layers of the shell are built up the mold is fired and the wax melted out. This would leave a mold suitable for casting of a metal part. With conventional SLA models the process was the same. But, the thermal expansion of the SLA model is so much greater than the ceramic shell that the shell molds would crack during the firing process. Since the photopolymers are thermoplastics the models will not melt like the wax predecessors. These SLA models have to be burnt out leaving an ash residue. To eliminate these problems 3D Systems developed QuickCast^{TM}. This new process builds a "quasi hollow model". These honey combed models have less mass and when heated the structure collapses from within instead of expanding and cracking the shell mold. It also leaves less ash from the firing operation (Baumgardner, 1994).

Chuck Hall the founder of 3D systems, the prominent manufacturer of SLA equipment, patented the stereolithography process in 1984 and founded his company in 1986. In the following year they started beta testing their equipment. In 1988 they sold their first machine, a SLA-250. By the end of 1994 they sold a total of 480 machines world wide.

Selective Laser Sintering (SLS). Another layer-additive laser point-by-point fabrication method is the selective laser sintering (SLS) process manufactured by the DTM Corporation, a BF Goodrich company. The difference between stereolithography and selective laser sintering is the resin used. SLS uses a powdered-thermoplastic resin. In this process the particles of powder bond or fuse together when heated by the infrared laser beam. A thin layer of the powder is spread over the build region. Then the details of that layer are drawn into the powder by the laser. After each layer is completed the model is lowered and a new layer of resin is distributed by a roller. The build chamber is purged with the inert gas nitrogen at an elevated temperature close to the fusion temperature of the resin. This minimizes the heat required by the laser which increases drawing speed and minimizes heat distortion. Nitrogen eliminates the remote chance of an explosion due to the dust of the resin and the presence of the laser. Uncured resin surrounds the model and supports it during the build process. This eliminates the need for secondary supports. Unattached geometry can be built during initial layers and subsequently attached at a higher layer (Nutt, K. personal communication February 1995).

Once the model is built it is removed from the unit and allowed to cool. The model is cleaned using mechanical methods such as brushes, dental tools, and light air. No postcuring is required. The unbonded powder is fed back into the machine and reused. Table 4 lists the strengths and limitations of the SLS process.

One criticism of SLS is its surface finish. One cause of the rough surface finish is that the models are built from powders. These powders are not liquefied during the bonding process. Particle size range from Ø0.003 - Ø0.005. A second reason for the rough surface finish is the raster scanning laser drawing technique. DTM rotates

Table 4
Selective Laser Sintering (SLS)

Strengths	Limitations
• uses investment casting wax	• rough surface finish
• low distortions	• porosity
• wide range of materials	
• strong models	
• does not need supports	

the orientation of the raster scan 90° between alternating layers. This reduces the negative effect of the raster build process on the model's surface finish (Nutt K. personal communication February 1995). Surface finish could be further improved by drawing the perimeter of the layer prior to drawing the internal raster. Since these models are built from powders that are only bonded together, porosity may become a problem. Because there is no phase change in the building process there is less concern about shrinkage and distortion (Jacobs, 1992).

The SLS process currently has the largest assortment of model building materials; ABS, PVC, polycarbonate, investment casting wax, and nylon. The nature of this process allows for an easier switch from one material to another. It does require a machine configuration change to make the switch. The ability to use investment-wax lends this process to be very compatible with investment casting (Jacobs, 1992; Kimble, 1991).

A recent development of the SLS process is called Rapid Tooling TM. For this process an iron based powder is coated with a thermoplastic binder. The laser bonded model called the "green" part is post cured in an oven where the binder is burned off. This is a traditional sintering process resulting in a "brown" part. Then a second metal is infiltrated into the porous part via capillary action. The end result is a durable metal tool which can be used in many subsequent processes. Metal tooling such as this allows a real injection molded part to be tested. Injection molding of plastics may produce internal residual stresses during the molding process that may lead to failure. These stresses can not be simulated by conventional prototype molding processes.

The SLS process was invented at the University of Texas in 1986. In 1987 DTM was formed to commercialize the process. In 1990 DTM was purchased by BF Goodrich and two years later they began shipping their first machines. Now in 1995, they have sold 66 systems.

Fused Deposition Modeling (FDM). One of the two layer-additive nonlaser point-by-point processes discussed in this study is fused deposition modeling (FDM) by Stratasys, Incorporated. FDM is an example of the potential for desk top manufacturing. It is small, clean, and relatively simple to use. The process uses a precision controlled head that extrudes a thermoplastic filament at a temperature just above its melting point. The hot fresh extrusion bonds to the previous layer of the model. This layer additive process is susceptible to seams and delamination if the speeds, extrusion rate and temperatures are not matched properly. At the end of each layer the extrusion head stops momentarily while the platform lowers. This cycle leaves a small bump in the model.

The nature of this process does not produce much wasted material but the filament material is expensive. There are three materials available for this process; nylon, machinable wax, and investment casting wax. Normally there are no secondary processes required to clean the model after it is removed from the machine. Polishing can be done to improve the surface finish. Because hot thermal plastics are extruded at their melting point, cantilevers and bridges may need supports (Crump, 1991; Jacobs, 1992; Sprow, 1992). Table 5 lists the strengths and limitations of the FDM process.

Table 5
Fused Deposition Modeling (FDM)

Strengths	Limitations
• portable unit	• small build volume
• uses investment casting wax	• delamination
• low distortion	• requires supports for overhangs
• little post processing	
• low material waste	
• ease of use	
• wall thickness as low as 0.012"	

Stratasys, the maker of FDM equipment, was founded in 1988. It received a patent for this process in 1991 and began selling equipment that same year. Thus far they have sold 100 systems. Recently Stratasys acquired the rights to the RP technologies that were being developed by IBM. These technologies are very similar.

Direct Shell Production Casting (DSPC). DSPC which is also known as Three-Dimensional Printing (3DP) is the second layer-additive nonlaser point-by-point process. 3DP was developed by Massachusetts Institute of Technology. This process is currently licensed to Soligen Technologies Incorporated. They call the process Direct Shell Production Castings (DSPC). DSPC is unique from all of the other process covered by this study. It does not produce a model of the part. It produces a mold like those used in shell investment casting. A thin layer of refractory powder is spread across a piston. Then an ink-jet like nozzle distributes a binder which bonds the powder particles together. The nozzle sprays a continuous stream of electrically charged drops of binder. The spray mechanism moves across the build area in a raster motion dispensing the binder. The unwanted drops are deflected by applying a voltage to electrodes located below the nozzle. Once the molds are built they are placed in a furnace to cure the binder. After curing and strengthening the mold it is ready for use. DSPC is the most direct process for using RP to produce a casting. It can produce more accurate parts since the intermediate step of making a mold from a model has been eliminated. With this process the mold and its cores can be fabricated as one unit providing better registration between the two components. The one draw back for this process is again the surface finish (Bredt, 1991: Jacobs, 1992). Table 6 lists the strengths and limitations of the DSPC process

Table 6
Direct Shell Production Casting (DSPC)

Strengths	Limitations
• produces a casting mold	• does not produce a model
• fabricates molds & cores as a single unit	• very new process

Soligen Technologies was founded in 1991 and became the licensed manufacturer of 3D printing in 1992. Right now they are in the midst of Beta testing their process with Johnson and Johnson, Ashland Chemical, and Pratt and Whitney.

Laminated Object Manufacturing (LOM). A layer-subtractive laser fabrication method of RP is the laminated object manufacturing (LOM) process of Helisys Incorporated. It is a subtractive process because the model is built within a block and the excess material is removed. The current process uses an adhesive coated paper as the construction material. The paper is fed across a platform that moves downward as the model is built. After a new section of paper is stationed above the platform a heated roller traverses the platform applying heat and pressure. This heat and pressure bonds the new section of paper to the previous layer. A laser then draws the contour of the layer that is to be built. The waste section of the build is then cut into squares or tiles by the laser. This tiling process aids in the removal of the waste portion of the build. This process is repeated until the model is complete. With this process the model is imbedded inside the block. Now the waste tiles have to be removed to produce the model, hence the name layer-subtractive process.

Removing the tiles can be difficult since they are bound together into cubes. They become more difficult to remove from internal cavities and horizontal surfaces. Internal tiles have to be cut small enough to be removed through the smallest opening. Consequently LOM cannot be used to build hollow models. During the heating and pressing cycle horizontal surfaces are bonded together. To aid in the removal of tiles on a horizontal surface the waste tiles are cut into tiny squares through a process called "burnout". This reduces the surface area of the bond and the tiles are easier to remove. Removal of the waste tiles from a complicated model can be difficult. Many of the finishing process applied to wood patterns can also be applied to LOM models.

Since the model is built within a block the model is very stable during the building process and it requires no supports. Without phase changes and extreme heating of the building material there are no shrinkage problems as with other processes. Also, islands can be easily built until bridges are added in subsequent layers. The Helisys system uses a laser mounted on an XY translator. This is more accurate than pivoting a mirror as the other laser applications do. There is no need to compensate for changes in focal distance as the laser beam moves to the extreme edges of the build platform.

(Arronson, 1993; Jacobs, 1992). Table 7 lists the strengths and limitations of the LOM process.

Table 7

Laminated Object Manufacturing (LOM)

Strengths	Limitations
• stable build process	• tiles can be difficult to remove
• large build volume	• not practical for tiny models
• low cost material	• anisotropic material properties
• low shrink	• minimum wall is 0.040"
• good accuracy	

Helisys was organized in 1987. They sold their first commercial unit in 1991 and have a total of 120 units in service.

Solid Ground Curing (SGC). The final process to be presented is the solid ground curing (SGC) process by Cubital Ltd., an Israeli company. This is a layer-additive nonlaser fabrication process. SGC, like stereolithography, uses a photocurable liquid resin. The process for curing the resin is dramatically different. Like SLA, a thin layer of resin is spread over the model platform. That layer is then exposed to UV light through a mask which has a transparent area that corresponds to the part geometry. The mask is produced using ionography technology. Ionography applies electrostatic charges to a plate of glass in the form of parallel raster lines. A toner is then applied to the plate of glass producing a mask where the toner is attracted by the static charge. Once the layer is exposed the mask is erased and the mask for the next layer is developed. After the layer is exposed the uncured resin is removed by an air knife wiper. This uncured resin can be recycled through the Cubital organization saving on disposal costs and the cost of new resin. To support the model during building the vacant areas are filled with wax. After the wax is applied a cooling plate solidifies the wax prior to a milling operation. A mill makes a flat cut across the whole width of the platform in preparation for the next layer. Throughout this whole four station process a carriage moves the construction platform from station to station within the machine. This carriage also lowers the platform in the Z direction.

There are a number of advantages to the SGC process. One is that the wax helps support and stabilize the model as it is being built resulting in better accuracy. Another is that for high volume model production, several models, even different models can be built at one time. The model is fully cured when it is removed form the machine. There is no need for post cure. The uniform total curing of the model layer by layer provides for uniformity. Exposing each layer to a four kilowatt lamp provides a faster curing cycle than the point to point process of SLA. Milling each layer provides a flat substrate for subsequent layers. Draw backs are that the mask does not provide for sharp images. Light can reflect and give out of focus results around the edges of the model. This along with the raster process creates a rough surface texture. Cubital has made improvements in the raster process in attempts to overcome the surface finish problems associated with the earliest machines. Table 8 lists the strength and limitations of the SGC process.

Cubital was formed in 1987 and they began selling equipment in 1992. They have 23 units in operation throughout the world.

Table 8

Solid Ground Curing (SGC)

Strengths	Limitations
• stable build process	• post processing to remove wax
• high accuracy	• requires a man-monitor 10%-15% of the time
• high volume output	
• Flexi-Volume	
• Erase Layer	

Market Share

Based on the information supplied by the sales representatives SLA machines have 60% of the market. As shown in Figure 2, LOM is second with approximately 20%. Stereo lithography is the most fully developed product and it is the oldest.

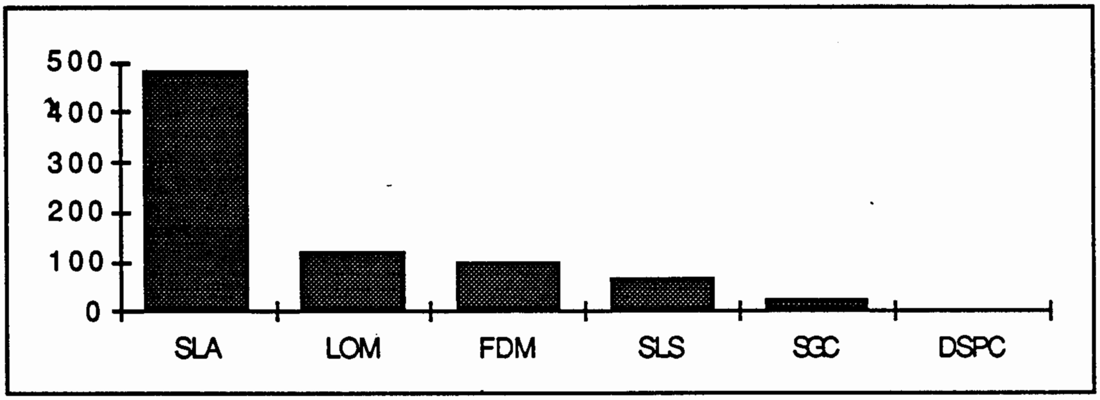

Figure 2. Rapid Prototyping System Sales

Comparison Of SLA, SLS, and CNC

All three (SLA, SLS, CNC) of these systems are very comparable in the technology, application, and function. It is very difficult to find distinguishing characteristics without first hand knowledge of each of the systems. Frost (1993) of the Plynetics Corporation made a comparison between the SLA, SLS, and CNC process. Plynetics is a custom prototyping and pattern manufacturer located in San Leandro, California. They use each of these three systems and can provide a valid comparison between them when they are used to make plastic prototypes. Strengths of SLA are its ability to generate complex geometry that is difficult to machine and its ability to produce features in great detail. SLS, the other RP process can also produce complex geometry but not to the detail of SLA. SLS offers the widest variety of material with properties of higher toughness and heat resistance. These are important when models are used for functional testing. CNC requires several set ups when manufacturing models of complex geometry. CNC machines are capable of producing large accurate models from an unlimited source of materials.

Application Of Rapid Prototyping

Paul Jacobs (1992) identified five applications of rapid prototyping. Those are visualization, verification, iteration, optimization and fabrication. Chrysler has been applying stereolithography since 1990 (Schmidt, 1994). Over that period they have gained insight to the usage of RP. During the last 18 months Lavern Schmidt, Manager of Special Projects and Operations for the Chrysler Corporation Jeep and Truck Engineering has been accumulating data on their usage of RP. See Table 9. They are conducting a survey on each model that they produce. Chrysler has issued 450 surveys and have received 202 responses (Schmidt, 1994). Key data obtained from these surveys is that 55% of their models are built within six days. Designers are using 94% of the models for design aids and reference models and 96% of the models are not measured. Model users report that 74% of their models had no problems and 80% say that they would like to have a machine that could produce larger models. They are currently using a SLA-250. The operators who build the models have problems with the solid CAD model 23% of the time.

Schmidt's survey did not clearly state its accuracy question. It was not explained as to weather they were looking for a +\- value or a total span of that accuracy. The user did respond to the question but the interpretation of that data is open to questions. The results of that accuracy question are listed in Table 9.

Table 9

Chrysler Survey Results

Turn Around Time

- 41% of the models are built within 5 days
- 55% of the models are built within 6 days

Use

- 94% used their SLA models a design aid and/or a reference model
- 13% used their SLA models for functional testing
- 10% used their SLA models for master patterns
- 96% of the users did not measure their model

Problems

- 74% had no problems with the model
- 13% stated that warpage was a problem
- 10% stated that surface finish was a problem
- 80% stated that they could use a larger machine
- 23% of the CAD models had problems

Accuracies

- 46% asked for accuracies between 0.015" and 0.020"
- 33% asked for accuracies of 0.010"
- 9% asked for accuracies between 0.002" and 0.005"

Processing Time

The benchmarking study by Chrysler JTE presented by Jacobs (1992) showed a wide variation in total processing time to build a speedometer adapter. See Table 10. For that study the total processing time ranged from 5:15 to 11:21. The Sinterstation 2000 was the fastest while the Solider 5600 was the slowest. The study also shows that the processing time for a SLA-250 with a 286 MPU was almost twice that of a SLA-250 with a 386 MPU. The 286 MPU took 10 hours to build the model while the 386 MPU took only five

SMALL SPEEDOMETER ADAPTOR							
	3D SYSYTEM	3D SYSYTEM	3D SYSYTEM	CUBITAL	DTM	STRATASYS	HELISYS
	SLA-250	SLA-250	SLA-500	SOLIDER 5600	SINTER STATION	3D MODELER	LOM 1015
	286MPU	386MPU			2000		
COST OF EQUIPMENT	$195,000.00	$195,000.00	$395,000.00	$490,000.00	$397,000.00	$182,000.00	$95,000.00
MACHINE BUILD TIME	10:00	5:06	4:44	10:00	3:00	8:00	9:51
TOTAL PROCESSING TIME	14:04	7:25	7:03	11:21	5:15	12:39	11:02
MATERIAL COSTS/PART	$4.00	$4.00	$4.00	$5.96	$5.89	$4.00	$3.82
OPERATOR COST	$0.00	$0.00	$0.00	$220.00	$66.00	$0.00	$0.00
TOTAL PART COSTS	$298.60	$111.80	$145.80	$378.09	$198.16	$319.81	$93.25
LARGE ENGINE BLOCK							
			3D SYSYTEM	CUBITAL			HELISYS
			SLA-500	SOLIDER 5600			LOM 2030
COST OF EQUIPMENT	-	-	$420,000.00	$550,000.00	-	-	$180,000.00
MACHINE BUILD TIME	-	-	50:30	36:00	-	-	68:48
TOTAL PROCESSING TIME	-	-	64:42	71:46	-	-	76:28
MATERIAL COSTS/PART	-	-	$665.55	$3,000.00	-	-	$370.00
OPERATOR COST	-	-	$0.00	$104.83	-	-	$31.45
TOTAL PART COSTS	-	-	$1,640.23	$3,766.48	-	-	$843.45
TOTAL PROCESSING TIME = PREPROCESSING + MACHINE BUILD + POST PROCESSING							
OPERATOR COSTS = MACHINE BUILD TIME X $22.00/HOUR							
Reprinted with permission of the Society of Manufacturing Engineers, from Rapid Prototyping & Manufacturing: Fundamentals of StereoLithography							

Table 10. Chrysler Cost Study

hours and six minutes. Computer speed is a significant factor. With the on going development of computer technologies the processing time will continue to decrease and should be reevaluated frequently. Computer system capabilities should be specified in any future studies. Hicks' study (Hicks, 1994) also showed the Sinterstation 2000 to be the fastest while the SLA-250 was the slowest.

Costs

Jacobs (1992) references a study conducted by Chrysler JTE (Schmidt, 1993) on a small speedometer adapter. This study compares the cost to build a particular model using a SLA-250 by 3D Systems with 286 micro processing unit, a SLA-250 using a 386 micro processing unit, a SLA-500 by 3D Systems, a Cubital Solider 5600, a Sinterstation 2000 by DTM, a Stratasys 3D Modeler, and a LOM 1015 by Helisys. The results of that study are listed in Table 10. This study combined the equipment costs and the costs associated with the building of the model to calculate the cost of manufacturing this one model. The equipment cost was depreciated over an eleven year period and was used to figure the cost per hour of use. By using standard labor rates and making certain assumptions based on their operations they were able to calculate the total costs to build this model. The total cost was the summation of costs as listed below:

preprocessing costs
post processing costs
build costs (machine + attendant)
material costs (part + incidental)
\+ maintenance costs
Total Model Cost

The least expensive part was produced on the LOM 1015 because of it had the lowest equipment costs. The most expensive model was produced on the Solider 5600 because almost 60% of the model's costs was due to the labor costs of the attendant. For this process they allotted one full time person for the entire build cycle. Cubital recommends 10% - 15% of operator's time is needed to monitor the machine. The remainder of his time can be used for other activities. The Sinterstation 2000 had a much smaller attendant cost but it too was adversely affected by that factor. All other models were built unattended. The assumption of no labor may not be realistic. The most expensive machine was the Solider 5600. Relative to the overall cost of the model the maximum material costs was less than 4% of the actual part cost.

Schmidt (1993) conducted an identical study on a large engine block. In that study he compared the SLA-500, Solider 5600, and LOM 2030. Again the lowest price model was the one produced on the LOM machine. It is approximately one half the cost of the SLA model and less than 25% the cost of the SLS model. Material cost is the factor that negatively impacted the Solider 5600. Also, for the engine block study an operator was assigned to the Solider 5600 10% of the time. This is not consistent with the speedometer adapter study where the cost included a full time operator. There were no explanations given for these differences.

Hicks (1994) did a comparable cost analysis for rapid prototyping equipment. He compared a SLA-250, Sinterstation 2000, Solider 5600, LOM-1015, and a 3D Modeler. Again, as shown in Table 11, the LOM 1015 was the least expensive and the Solider 5600 was the most expensive. Based on a predetermined annual usage rate Hicks was able to compare the annual expenses of operating each of these systems. After a five year depreciation the annual cost differences become less. As expected the LOM-1015 had the lowest annual expenses and the Solider 5600 had the highest. Hicks also did a part cost analysis for a tibia prostheses. The study was very similar to the one noted by Jacobs. The results are again the same. The least expensive model was produced on the LOM-

	3D SYSYTEM			CUBITAL	DTM	STRATASYS	HELISYS
	SLA-250			SOLIDER 5600	SINTER STATION	3D MODELER	LOM 1015
					2000		
TOTAL SYSTEM COSTS	$264,523.00			$621,300.00	$434,345.00	$218,036.00	$114,407.00
TOTAL ANNUAL EXPENSE	$152,974.00			$277,830.00	$222,009.00	$121,047.00	$105,951.00
MACHINE BUILD TIME	10:12			5:48	4:42	7:00	9:12
TOTAL PROCESSING TIME	15:48			8:18	6:24	8:18	9:48
TOTAL PART BUILD COSTS	$574.78			$634.63	$399.56	$265.94	$205.29
QUOTED PRICE OF PART	$1,081.73			$250.00	$709.33	NOT AVAILABLE	$650.00
DIFFERENCE	$506.95			($384.63)	$309.77		$444.71
TOTAL SYSTEM COST = EQUPMENT + COMPUTER + POST PROCESSING EQUIPMENT + INSTALLATION +TRAINING + SHIPPING + TAX							
TOTAL ANNUAL EXPENSE = DEPRECIATION + SERVICE CONTRACT + LABOR + ESTAMATE MATERIAL COST							
TOTAL PROCESSING TIME = PREPROCESSING + MACHINE BUILD + POST PROCESSING							
DIFFERENCE = TOTAL PART BUILD COSTS - QUOTED PRICE OF PART							
Reprinted from Rapid Prototyping & Manufacturing '94							

Table 11. Hicks Cost Study

1015 and the most expensive was produced on the Solider 5600. Hicks also added the price of the model if it was purchased. The least difference between the purchased price and the manufacturing costs was approximately $310.00. Based on the difference between the quoted purchased price of the model and the manufactured cost of the model, it would take 521 models to pay off the equipment costs of the SLA-250. Likewise it would take 1,100 models to pay off the Sinterstation 2000 and 257 models to pay back the LOM-1015.

Both of these studies show that equipment costs are the significant factor that influences the cost of producing a model. The other costs are less significant but they do influence the operating costs. The results of these studies would surely be influenced by the size of the models being built. Figure 3 shows the costs of the models produced for both Chrysler's and Hick's study. Figure 4 is the ranking of those costs for each of the projects. In both cases LOM produced the lowest cost models while SGC was the most expensive.

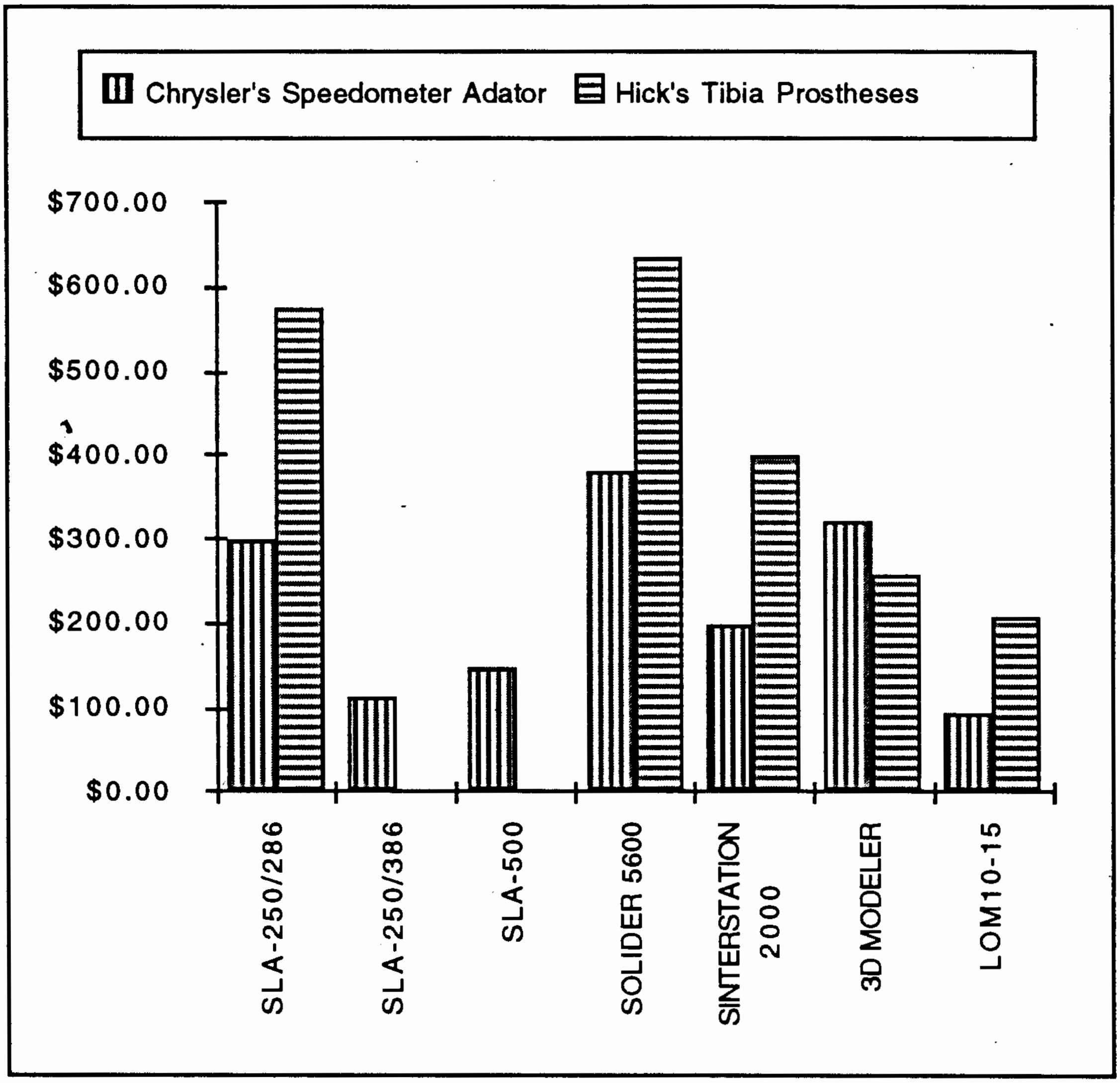

Figure 3. Benchmark Studies Of Model Costs

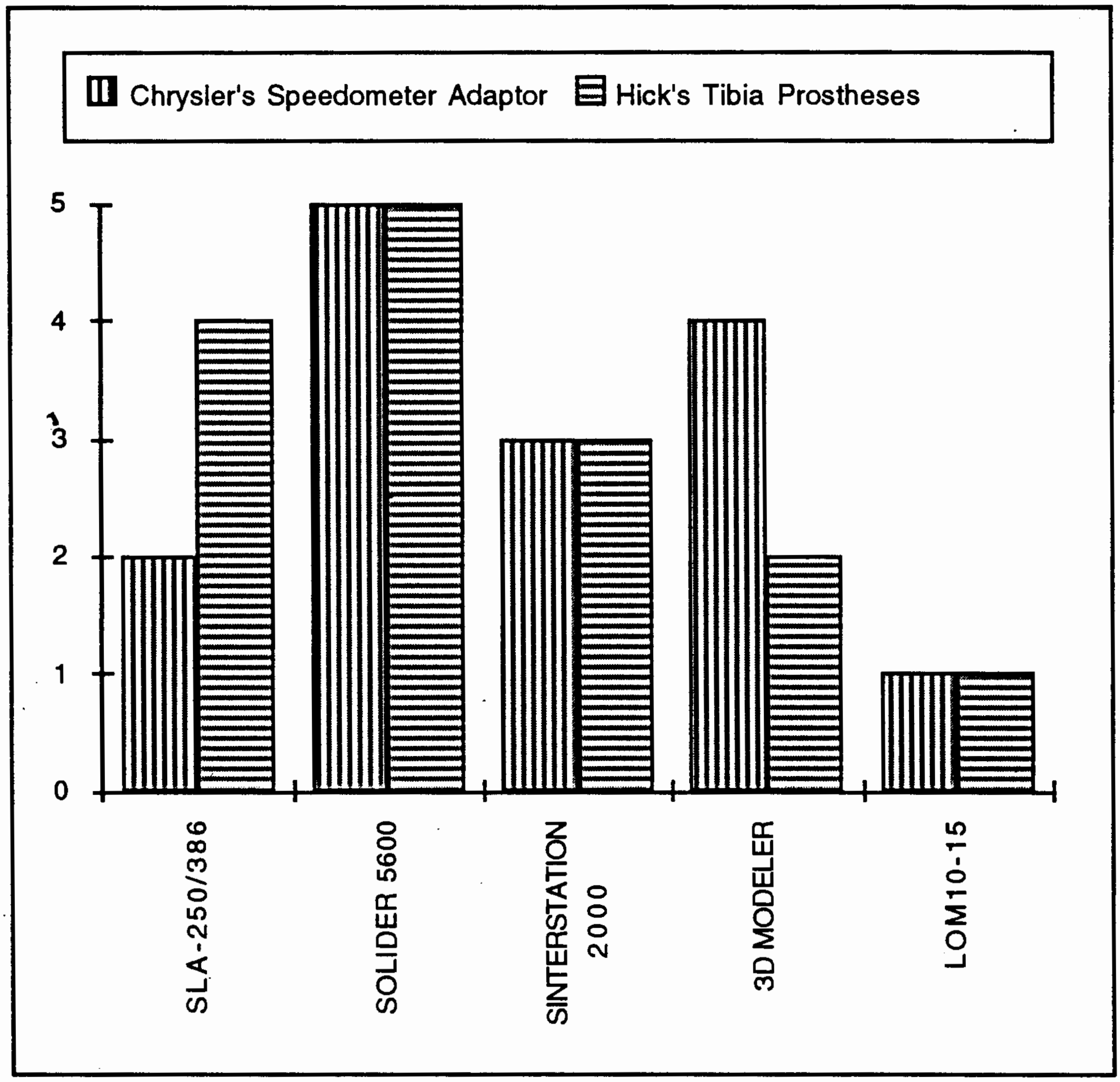

Figure 4. Benchmark Studies Model Costs Ranking

Material

There is uncertainty to the presentation of material properties in sales literature. Kimble of the DTM Corporation conducted a study of the various properties of materials produced by the rapid prototyping processes of SGC, SLA, and SLS. See Table 12. In his study he found discrepancies between results that he obtained and the values presented by the other manufacturers. Kimble (1993) tested 24 specimen of each material in tensile per ASTM D638. He also tested 20 samples of each material for flexural properties per standard ASTM 790. These are the test procedures typically used for plastic materials. Kimble cites variations in test procedures, the method used to build the test specimen, and the method of cure. One should also be aware that these materials, due to their manufacturing processes, are anisotropic. Their physical properties are dependent on the build pattern and the direction that the properties are evaluated.

Table 12
Kimble's Material Comparison

PROCESS	TENSILE STRENGTH ASTM D638 (psi)	TENSILE MODULUS ASTM D638 (psi)	FLEXURAL STRENGTH ASTM D790 (psi)	FLEXURAL MODULUS ASTM D790 (psi)
SGC				
G5601	2,395	91,005	2,093	51,198
G5601 As Advertised	5,100	127,500		
SLA				
SL 5149	2,445	133,125	4,320	100,455
SL 5149 As Advertised	5,000	160,000		
SLS				
LN-4000	5,168	202,133	5,699	126,267
LN-4000 As Advertised	5,722	177,000		

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Accuracy

E. P. Gargiulo from E. I. Du Pont de Nemours and Company of Wilmington, Delaware and D. A. Belfiore (1991) conducted a statistical accuracy study of the SLA-250 by 3D Systems. They designed a low profile model with numerous features in the X-Y plane. The model was only 38mm tall in the Z direction so this study did not evaluate accuracy in the Z direction. Nor did it evaluate the affects higher Z heights have on the accuracy due to sag and curl. Jacobs (1992) summarized the results of that study by drawing four conclusions.

> 1. The standard deviations of the machine accuracy are proportional to the length of the dimension .
> 2. The machine accuracy is about an order of magnitude better than the overall RP&M accuracy.
> 3. It is essential that all variables are under control during the build sequence.
> 4. Stereolithography is approaching having 90% of all measurements within 0.005". (p. 312)

When referring to RP&M accuracy Jacobs is saying that the overall accuracy of the model which includes the machine and the process. This takes into consideration shrink, warpage, and the like. He states that the mechanical and laser equipment is very accurate.

In 1990 the 150 member stereolithography users group developed a "User-Part" (Jacobs, 1992). The model was large enough to test the total capability of the machine. It had a range of long to short dimensions both inside and out. The part is relatively short in the Z direction and there are no massive sections. These two factors if found in a typical model may adversely affect accuracy due to sag and curl effects. The study used that model to complete an accuracy study of the SLA process. For each of 15 models they took 170 measurements. From that study they concluded that 73% of all dimensions are within +\- 0.005 of an inch. They also demonstrated that the error is not directly proportional to the length of the dimension. It is more nearly equal to the square-root of the length. For example a nine inch dimension will have three times the error of a one inch dimension. This is contrary to the simplified claims made by other manufacturers that error is linearly proportional to the length of the distance being measured.

Chris Hicks' study (1994) had mixed results when trying to compare the accuracies of various RP processes. He had 26 models made with varying quantities from the FDM, LOM, SGC, SLA, and SLS processes. There was also one model fabricated on a CNC machine. He measured 53 different features on each one of these models. Every process had it strengths and limitations depending on the feature being measured and the orientation of the model during the build process. Hicks selected the perpendicularity of a stem to face -A-, the flatness of face -A-, the curvature of a surface, and the combined accuracy of all 53 features as the most distinguishing features. From this study one can conclude that modeling and measuring a single part from each of the processes will not give a very accurate picture of the performance of the systems. The accuracies of these systems are so very close that there will be overlaps in the distribution of the measurements. The fabricated model was the most accurate closely followed by SGC. FDM, SLA, and LOM were a distance third through fifth. SLS was a weak sixth. Table 13 is a summary of Hicks' study. This table shows the rankings of the 24 models presented in that report. For example the LOM sample ranked 12th on perpendicularity. The two FDM samples ranked 11th and 19th which gave them an average ranking of 15th for perpendicularity. Each feature and process has an average ranking for that combination. Then for each process there is a grand average that combines the average rankings of all four features.

Professor J. P. Kruth (1991) of the University of Leuven in Belgium also conducted a study that compared the accuracies of various RP systems. He designed a fictional part that had a variety of features of varying size and orientation. His results were not conclusive. Again each process excelled in certain facets of the geometry. Kruth remarked that the SLA-250 was the most accurate.

ACCURACIES	STRATASYS	HELISYS	CUBITAL	3D SYSTEMS	DTM	FABRICATED
	FDM	LOM	SGC	SLA	SLS	
PERPENDICULARITY						
RANK	11, 19	12	3, 10	1, 4, 6, 7, 14	15, 20, 22	2
AVERAGE	15.0	12.0	6.5	6.4	19.0	2.0
FLATNESS						
RANK	11, 17	13	6, 7	2, 3, 4, 5, 10	9, 15, 24	1
AVERAGE	14.0	13.0	6.5	4.8	16.0	1.0
CURVED SURFACE						
RANK	1, 6	9	2, 4	12, 17, 18, 19, 20	3, 8, 9	11
AVERAGE	3.5	9.0	3.0	17.2	6.6	11.0
OVERALL						
RANK	4, 5	9	2, 3	7, 10, 11, 14, 15	12, 19, 22	1
AVERAGE	4.5	9.0	2.5	11.4	18.6	1.0
GRAND AVERAGE	9.3	10.8	4.6	10.0	15.1	3.8

Table 13. Hicks Accuracy Study

Model Surface Finish

Hicks (1994) had the design engineers rate the as manufactured surface finish of each of the models as either good or poor. Models were not polished to preserve accuracy. The LOM-1015, Solider 5600, and the SLA-250 all received a good rating, with layer thicknesses were 0.037", 0.006", and 0.003" respectively. The 3D Modeler and the Sinterstation 2000 received poor ratings, with layer thicknesses of 0.010" and 0.005" respectively. The fabricated part was rated excellent. Hicks' study shows that there is a direct correlation between the measured surface finish and the perceived appearance of the models. He noted that the finish on all of the models can be improved by post processing except for the Sinterstation 2000's model. Its grainy finish cannot be significantly improved.

Secondary Operations

The fifth usage of RP according to Jacobs (1992) is fabrication. This involves fabrication usable parts from the RP model. these parts can be used for functional testing and production. Secondary operations continue the process from model to functional parts. A list of secondary operations is given in Table 14.

Table 14
Secondary Operations

- plaster molds
- epoxy molds
- sand casting
- vacuum forming
- electrodes for EDM
- silicone rubber molds
- spray metal molds
- investment casting
- trace model for CNC tool path
- forging dies from investment castings

Future Developments

According to Robert Aronson (1993) and Paul Jacobs (1992) significant improvements will come in the development of new materials that improve accuracy, model detail and reduces distortion. As computer technology continues to improve their speed, equal reductions in build times will also be obtained.

Chapter 3

Methodology

Systems Studied

Based on library research the RP systems that were studied are:

DSPC - direct shell production casting
FDM - fused deposition molding
LOM - layer object manufacturing
SGC - solid ground curing
SLA - stereolithography
SLS - selective laser sintering

These are the most mature, fully documented systems, and they cover the widest variety of the new technology.

Key Characteristics

The problem with the implementation of rapid prototyping technology is choosing the best system that fits a particular need. This study provided data that described key characteristics for each of the major RP systems. Literature and conversations with RP users were used to determine the key characteristics of RP systems and to identify the six most applicable RP systems. These characteristics and systems were chosen based on the experiences of authors and users who are familiar with the various systems. The key characteristics are those that describe system performance and are listed in Table 1.

Part size is the height, width, and depth in inches of the largest part that can be built by the machine in one set up. Larger models can be built by bonding several components together.

The total processing time will be the itemized total time required to build a model (Pre-processing + Machine build time + Post-processing). Pre-processing time includes the time it takes for the conversion of the CAD file from CATIA and Pro/Engineer to a machine language and the time needed to add in secondary supports that may be required to supply the necessary stability to the part. Machine build time is the time it takes for the machine to build the part. Post-processing time is the amount of time required to fully cure the part plus the time it takes to clean the part. These times were compiled for three parts currently manufactured at the John Deere Waterloo Works. These three parts were selected by the writer.

The materials used by the various processes were listed along with their tensile and flexural strengths. Accuracy is an estimated measure of how well the physical model duplicates the CAD model. It was partially based on sales literature. Also, each system manufacturer was asked to estimate the accuracy of their system relative to reproducing critical features on each of the three parts to be estimated.

Machine costs is the total of all capital expenditures for hardware and software. Support equipment like curing ovens, ultrasonic cleaners, and protective equipment were included in the hardware expenditures. Part costs were limited to material costs. Since labor rates vary from one company to another and for each phase of the manufacturing process the part costs does not include labor. Specific labor costs can be calculated from the component times listed earlier using the appropriate labor rates for each of the individual components. Secondary costs include facility preparation, training, and equipment maintenance costs.

Part finish was evaluated by recording the surface finish on sample parts. Each manufacturer was requested to supply a small sample part for evaluation.

Manufacturer's Data

Sales literature from the system manufacturers and telephone interviews of technical sales representatives of Soligen Technologies Inc., Stratasys Inc., Helisys Inc., Cubital America Inc., 3D Systems, and DTM Corp. was used to quantify most of the characteristics for their major systems. Specific questions that relate to each individual system were also be asked. In addition each of the manufacturers was requested to provide an estimate of the time, the accuracy, and the costs of producing each of the three selected parts listed in Table 1. Detailed model build guidelines are posted in Appendix A. These guidelines were specified to promote comparable estimates between manufacturers. Everyone of the six RP systems comes with a variety of hardware and software options. Since detailed machine specifications could not be provided by this study each manufacturer was requested to provide a maximum and a minimum equipment cost for each of their systems.

Part Selection

The parts selected for this study were chosen because they represent the range of products that are designed at the John Deere Product Engineering Center. They also contain a variety of geometrical shapes that presented a challenge to the six chosen systems. The R95850 transmission oil filter housing is a small die cast aluminum housing that has several cored passages. The R96911 transmission output planetary carrier is a large complex cast iron part. It has several layers that are supported by posts. The carrier was chosen for its complexity and its size. It fills the part envelope of the smallest RP machine being evaluated. The third part, R121548, is a very large simple casting that will show the advantages of using a process with a very large working area. Photos of the selected parts are in Appendix C.

Review Of Literature

Technical literature from the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), and the Society of Manufacturing Engineers (SME) that discusses the six selected RP systems, their application and implementation into automotive and off-highway manufacturing systems was reviewed. The Dissertation Abstract and The Engineering Index Annual were examined for any related literature. This literature was used to validate the claims made by the system manufacturers. It also provided insights in the implementation of RP systems.

Interviews

Interviews with people who have used various RP systems were also used to support the information provided by the manufacturers. The people interviewed started with those within the John Deere organization and branched out as more contacts were found. Don Backens of the John Deere Waterloo Foundry has used stereolithography and solid ground curing to produce various sand casting molds. Larry Burkholder of the John Deere Technical Center in Moline is the corporate coordinator of rapid prototyping. Corwin Klages of the John Deere Product Engineering Center has used laminated object manufacturing, solid ground curing, and stereolithography to produce various cab parts which were eventually molded out of plastic or cast out of aluminum for production. Backens, Burkholder, and Klages were contacted early in the project to provide input to the types of questions that need to be included in the survey instrument.

Survey

A survey modeled after the one used by L. D. Schmidt (Schmidt, 1994) of the Chrysler Corporation was sent to those technicians within the Deere organization who have been active in the rapid prototyping process. The population was limited to the

John Deere organization and the sample was the 17 active users of RP. It provided feedback as to what the users perceive to be the important characteristics of RP, how John Deere is using RP, what their objectives as users of RP are, and what they think should be the direction of RP within John Deere. Larry Burkholder, of the John Deere Technical center, provided the list of all known individuals within the Deere organization, who have recent experiences with rapid prototyping. Those individuals surveyed were:

Dave Colgan	Engineering Procurement	Des Moines
Mike Baker	Loader Engineering	Dubuque
Matt Boge	Loader Engineering	Dubuque
Greg Kedley	CAD Services	Dubuque
Mike Kieffer	CAD Services	Dubuque
Vern Bandelow	Combine	Harvester
Rick Clark	Planters	Harvester
Dan Deering	Castings	Harvester
Larry Green	Seeding	Harvester
Dean Yoder	Planters	Harvester
Jim Hartwig	Engineering	Horicon
Larry Burkholder	RP Coordinator	Moline
Don Backens	Foundry	Waterloo
Dave Easton	Operator Station	Waterloo
Corwin Klages	Operator Station	Waterloo
Howard Uehle	Operator Station	Waterloo
Don Sabin	Engineering Procurement	Waterloo

There were five objectives for the survey. One was to determine what the users of RP within John Deere consider to by the most important uses of RP. The second objective was to identify those RP process used by John Deere. Thirdly the users were asked to specify the accuracy that they were looking for in their last RP model. The fourth item on the survey asked each user of RP to rank the six characteristics of RP and to add any other characteristics that they consider to be important. The numerical average of the responses were be used to provide the ranking. Finally the users were asked if they think John Deere should purchase RP equipment and explain their opinion. A copy of the instrument is provided in Appendix B. It was a goal of this study to survey at least one user for each of the six systems being studied.

Analysis and Conclusions

The data was studied to see if there were any differences between the processes. Conclusions were drawn and recommendations made based on the data collected.

A weighting system was not provided by this study since every design application has different needs and priorities. The survey did provide input to what others considered important in their applications. The characteristics can be weighted during a decision process which would include representatives from many facets of the manufacturing operation.

Schedule

A flow chart and a Gantt chart of the research project is presented in Figures 5 and 6.

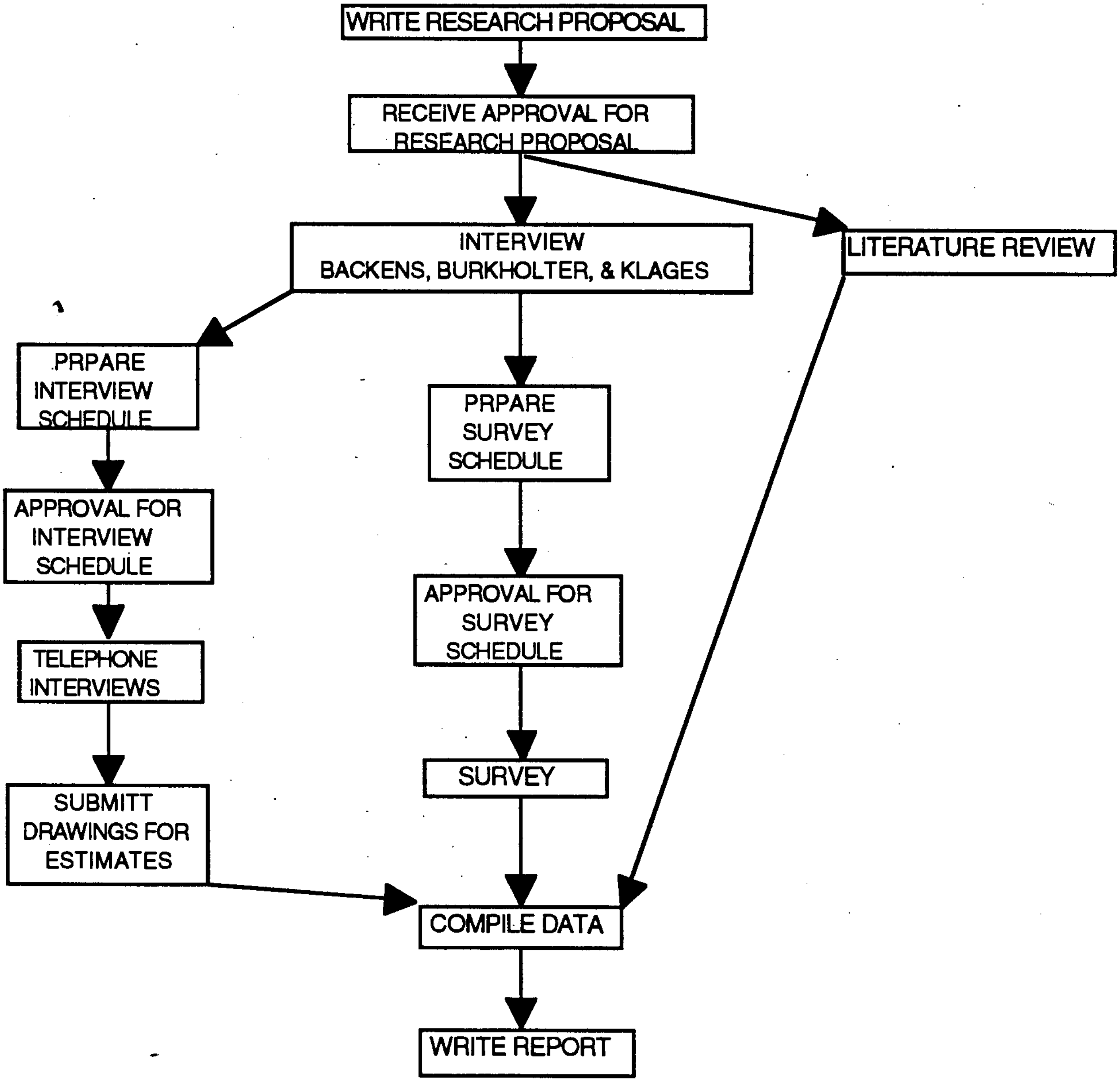

Figure 5. Rapid Prototyping Research Project Flow Chart

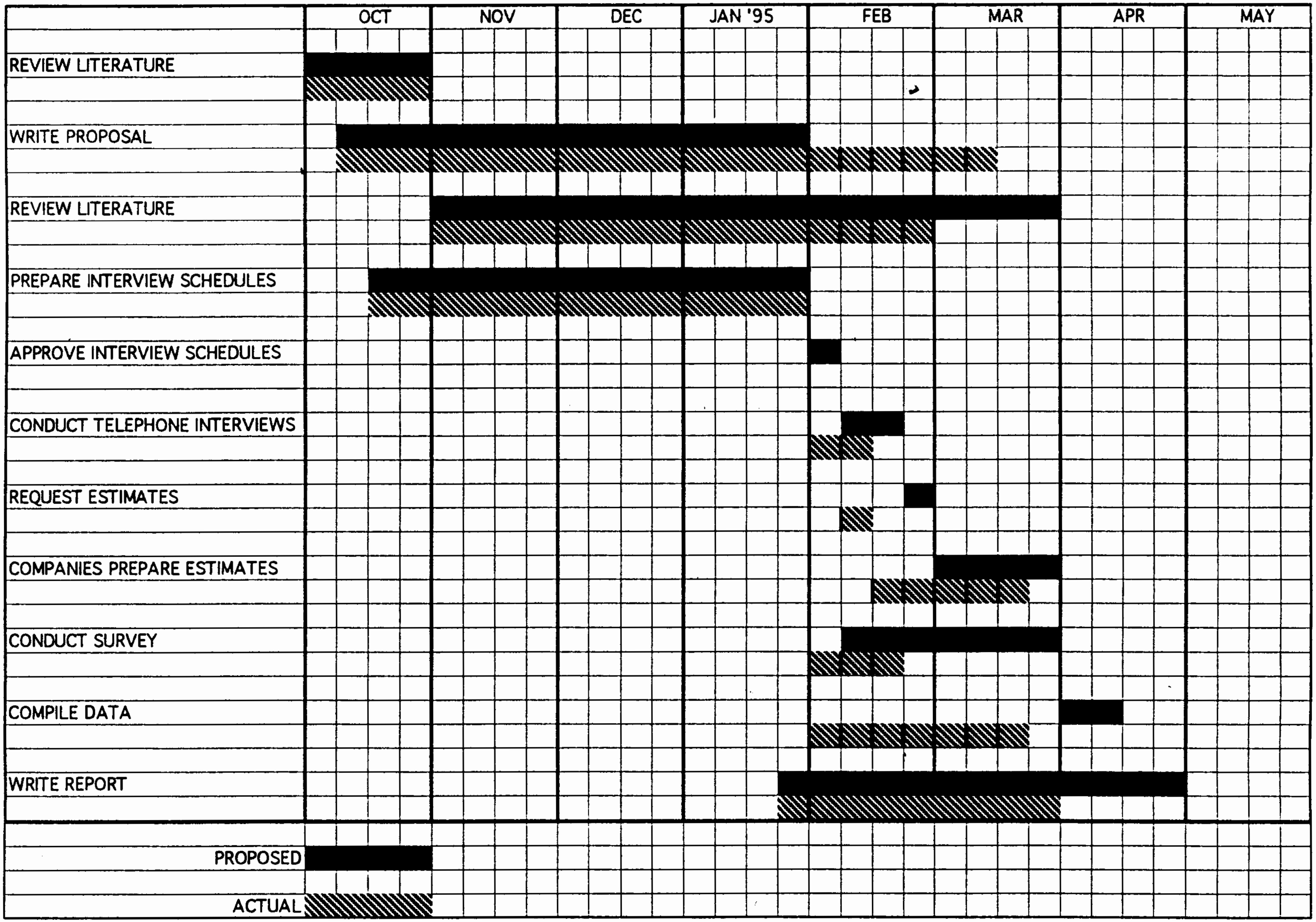

Figure 6. Rapid Prototyping Research Project Gantt Chart

Chapter 4

Findings

John Deere Rapid Prototyping Users Survey

Recent users of rapid prototyping were surveyed to determine the usage of RP within Deere and Company. Sixteen of seventeen instruments were returned. The 17th survey was not returned because the user is now in the process of ordering his first model and he did not feel qualified to answer all of the questions. The primary objective of the survey was to find out how John Deere users ranked each of the eight key characteristics of the RP systems. Every user was asked to rank each characteristic. Figure 7 shows the results of that survey question. The most important characteristic was accuracy, and followed closely by processing time. Accuracy was ranked as the highest priority by three of the respondents while processing time ranked as the highest priority by eight of the respondents. There is very little difference between any of the characteristics that apply to the physical model. Similar to the study conducted by Chrysler (Schmidt, 1994) only three of the 22 models made were accurately measured. Several of the models were measured with a calipers. This technique can only measure size, not form and position.

A second objective was to obtain the users' opinions as to what direction Deere and Company should proceed with purchasing RP equipment. Fifteen of the sixteen respondents felt that RP equipment should not be purchased. They cited a variety of reasons for not making the purchase. They felt that the company would be better served by using the expertise of the service bureaus. Plus, these bureaus could take the process further using their experience with the secondary processes. Respondents also felt that the variety of the models that would be built within the company could not be

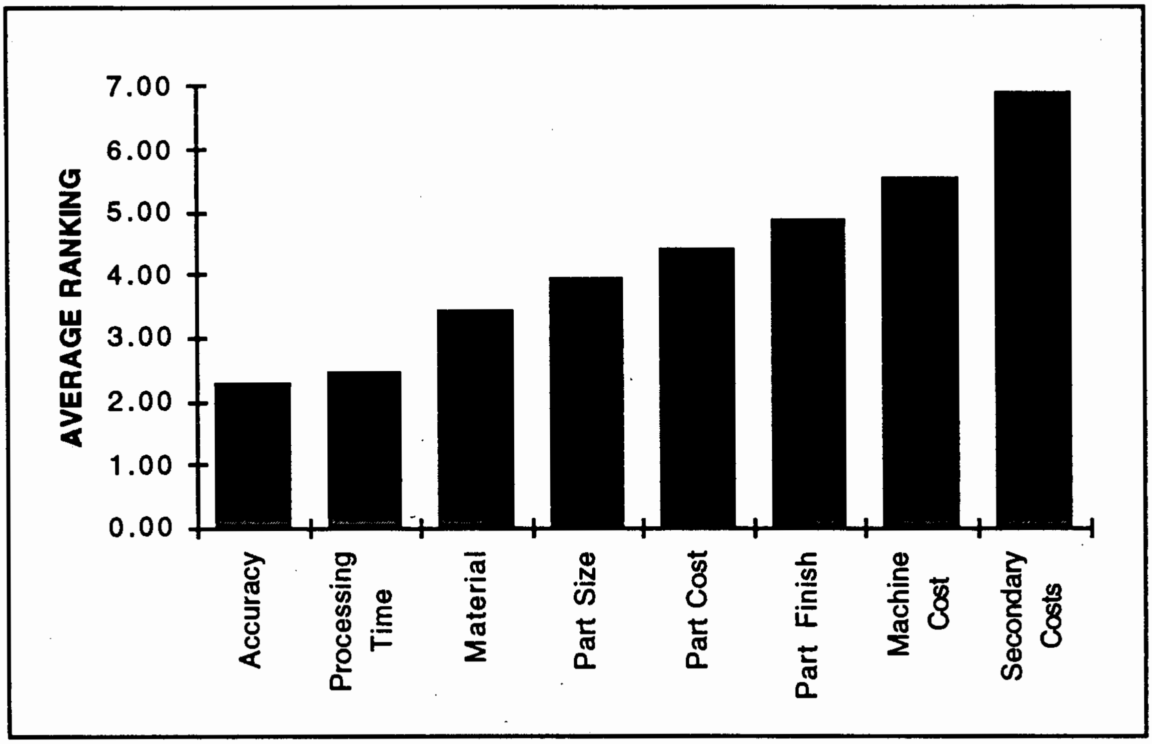

Figure 7. Survey Characteristic Ranking

served adequately by one system. They felt that more than one type of system would be needed to meet the needs of most of the models. Some felt that the volume of models being made could not financially support the equipment, especially if more that one system had to be purchased. Many felt that the technology is changing too rapidly. If a system was to be purchased it would soon be outdated.

Since January of 1994 Deere and Company has produced 22 models. Ten were made by the LOM process, six by the SLA process, five by SLS process, and one by the SGC process. The primary use of the models was for verification of the design. They were used to confirm fit and function of the design.

Key Characteristics

Model Size. Table 15 show the six systems and the size of their respective models. The largest machine is the LOM-2030 while the smallest is the FDM-1600. Bigger models can be produced by fastening two or models together.

Table 15
Model Size

PROCESS	LENGTH (in)	WIDTH (in)	DEPTH (in)	DIAMETER (in)
SOLIGEN DSPC				
DSPC 300	12	12	12	
STRATASYS				
FDM 1600	10	10	10	
HELISYS LOM				
LOM-1015	15	10	14	
LOM-2030	32	22	20	
CUBITAL SGC				
SOLIDER 4600	14	14	14	
SOLIDER 5600	20	14	20	
3D SYSTEMS SLA				
SLA-250 SERIES 30	10	10	10	
SLA-400 SERIES 20	20	20	10	
SLA-500 SERIES 20	20	20	23	
DTM SLS				
SINTERSTATION 2000			15	Ø12

Processing Time and Model Cost. In an attempt to compare the three components of the processing time, each of the six system manufacturers was asked to estimate the time it would take for them to build three varied models. The first model was the small die cast oil filter housing (R95850), the second was the medium sized cast planetary carrier (R96911), and the final part was the large cast reduction gear box housing (R121548). The specifications for the estimates are listed in Appendix A. Table 16 lists the three

PROCESSING TIME	SOLIGEN	STRATASYS	HELISYS	CUBITAL	3D SYSTEMS	DTM
	DSPC	FDM	LOM	SGC	SLA	SLS
R95850						
3.38" X 4.5" X 3.25"						
PRE-PROCESSING (hrs)	-	0.33	0.66 *	0.00	-	-
MACHINE BUILD (hrs)	-	12.00	11.00 *	13.50	-	-
POST PROCESSING (hrs)	-	1.00	3.00	6.75	-	-
MATERIAL VOL (9.8 IN3)						
MATERIAL COSTS	-	$48.00	$27.71	-	-	-
MODEL COSTS	$3,750.00 ***	-	-	$345.00	-	-
R96911						
9.75" X Ø8.88"						
PRE-PROCESSING (hrs)	-	1.50	1.00 *	0.00	-	-
MACHINE BUILD (hrs)	-	140.00	39.00 *	29.40	-	-
POST PROCESSING (hrs)	-	3.00	5.00	14.70	-	-
MATERIAL VOL (138.5 IN3)						
MATERIAL COSTS	-	$600.00	$138.70	-	-	-
MODEL COSTS	$9,000.00 ***	-	-	$4,221.00	-	-
R121548						
18.7" X 15.13" X 11.5"						
PRE-PROCESSING (hrs)	-	4.00	1.00 **	0.00	-	-
MACHINE BUILD (hrs)	-	-	56.00 **	56.25	-	-
POST PROCESSING (hrs)	-	5.00	5.00	28.13	-	-
MATERIAL VOL (616.5 IN3)						
MATERIAL COSTS	-	$2,900.00	$522.67	-	-	-
MODEL COSTS	-	-	-	$22,750.00	-	-
Note. * LOM-1015; ** LOM-2030; *** Price for a Casting						

Table 16. Processing Time, Material Costs, and Model Costs

processing times, material costs, and the model costs estimates received. Four estimates were received. Soligen is not in the business of selling equipment. They are in the business of selling cast parts. They provided an estimate of the rough castings. Stratasys provided estimates for the two smaller models. They did not estimate the larger model because they felt that it was beyond their capability because of its size. They did estimate the material costs and the pre-processing and post processing time for the large reduction gear box casting. Helisys and Cubital did estimate all three models. 3D Systems and DTM failed to respond. Due to the lack of data no conclusions can be drawn from this data. On the small oil filter housing the three respondents have similar build and total processing times. As they step up to the planetary carrier the times become varied. Comparing the build times between the LOM and SGC for the reduction gear box housing, the build times are equal but the post processing on the SGC is five times as long. Cubital (SGC) was the only company that provided a part cost estimate for any of the models. The system manufacturers are not accustomed to providing costs to produce a model. They do not have enough information to figure labor rates, overheads, and machine utilization that a service bureau would have. So, they declined to provide the estimates.

Material. Table 17 shows the advertised material properties for each of these processes. Some of the literature did not reference the ASTM standard as Kimble (1993) alluded to in his study. There is considerable variation in test results depending on the test method, orientation of the loading, and the method used to build the model. The tensile strength ranged from the 1,114 psi of FDM's machinable wax to 9,500 psi for the LOM process.

Accuracy. None of the manufacturers responded in detail to the accuracy that they could provide. Soligen responded that they could provide typical casting tolerances on the part that they build.

Stratasys, Helisys, and Cubital all responded with generic values. No comparison should be made based on this data. See Table 18.

Table 17

Material Properties

PROCESS	TENSILE STRENGTH ASTM D638 (psi)	TENSILE MODULUS ASTM D638 (psi)	FLEXURAL STRENGTH ASTM D790 (psi)	FLEXURAL MODULUS ASTM D790 (psi)
SOLIGEN DSPC	N/A	N/A	N/A	N/A
STRATASYS FDM				
MACHINABLE WAX	1,114 *	70,000 *	1,293 *	50,000 *
POLYAMIDE	1,765 *	80,000 *	2,113 *	60,000 *
POLYOLEFIN	1,324 *	90,000 *	1,537 *	90,000 *
ABS	5,000 *	360,000 *	9,500 *	380,000 *
HELISYS LOM				
	9,500 *	971,000 *	-	-
CUBITAL SGC				
G5601	4,350	87,020	-	-
3D SYSTEMS SLA				
SL 5149	5,100	160,000	-	-
SL 5170	8,600	542,000	15,500	423,000
DTM SLS				
LPC3000	3,400	177,000	-	152,000
LNF5000	5,200	202,000	-	126,000
* VALUES DID NOT REFERENCE ASTM STANDARDS				

Machine Maintenance and Secondary Costs. Machine specification were not provided to the manufacturers so that they could provide a detailed estimate of the equipment costs. This equipment comes with a variety of options. Each manufacturer was asked to provide a maximum and a minimum cost for the equipment and the maintenance agreement. Table 19 show the values received

ACCURACIES	SOLIGEN	STRATASYS	HELISYS	CUBITAL	3D SYSTEMS	DTM
	DSPC	FDM	LOM	SGC	SLA	SLS
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
R95850						
2X Ø5.9	-	±0.13	±0.25	0.10%	-	-
TRUE POSITION 0.2	-	±0.13	±0.25	0.10%	-	-
70.5 IN X	-	±0.13	±0.25	0.10%	-	-
35 IN Y	-	±0.13	±0.25	0.10%	-	-
FLATNESS 0.025	-	±0.13	±0.25	0.10%	-	-
FLATNESS 0.050	-	±0.13	±0.25	0.10%	-	-
Ø73	-	±0.13	±0.25	0.10%	-	-
R96911						
9 X Ø22.028	-	±0.13	±0.25	0.10%	-	-
TRUE POSITION 0.1	-	±0.13	±0.25	0.10%	-	-
Ø107.45	-	±0.13	±0.25	0.10%	-	-
227.67	-	±0.13	±0.25	0.10%	-	-
Ø81	-	±0.13	±0.25	0.10%	-	-
R121548						
146	-	±0.13	±0.25	0.10%	-	-
286.5	-	±0.13	±0.25	0.10%	-	-
107	-	±0.13	±0.25	0.10%	-	-
179.5	-	±0.13	±0.25	0.10%	-	-
R185	-	±0.13	±0.25	0.10%	-	-
178	-	±0.13	±0.25	0.10%	-	-
188	-	±0.13	±0.25	0.10%	-	-
SURFACE FINISH						
XY PLANE	-	215 micro inch	-	-	12 micro inch	160 micro inch
XZ PLANE	-	250 micro inch	-	-	225 micro inch	240 micro inch

Table 18. Acuracy Estimates

PROCESS	MAX EQUIPMENT COSTS	MIN EQUIPMENT COSTS	MAX MAINTENANCE AGREEMENT	MIN MAINTENANCE AGREEMENT	FLOOR SPACE SQUARE FEET
SOLIGEN DSPC					
DSPC 300	LEASED	LEASED	LEASED	LEASED	
STRATASYS FDM					
FDM 1600	$158,640.00	$89,500.00	$15,000.00	$9,020.00	6
HELISYS LOM					
LOM-1015	$114,718.00	$103,000.00	$9,000.00	-	210
LOM-2030	$225,000.00	$206,400.00	$16,000.00	-	361
CUBITAL SGC					
SOLIDER 4600	$420,800.00	$300,000.00	$68,212.00	$52,000.00	276
SOLIDER 5600	$570,800.00	$470,000.00	$85,212.00	$69,000.00	276
3D SYSTEMS SLA					
SLA-250 SERIES 30	-	-	-	-	180
SLA-400 SERIES 20	-	-	-	-	-
SLA-500 SERIES 20	-	-	-	-	180
DTM SLS					
SINTERSTATION 2000	$400,000.00	$300,000.00	$37,000.00	$34,000.00	-

Table 19. Machine and Maintenance Costs

from the manufacturers. Low equipment costs offer considerable advantage in model costs as shown by the studies by Schmidt and Hicks. Each manufacturer includes delivery, set up, calibration, and key operator training. Training for additional staff would be extra. Some provide the training on site while others provide the training in their facility. The maintenance agreements include all software upgrades. This technology is new and it is heavily dependent on software that changes frequently. Facility preparation is very comparable between machines. Table 19 shows the recommended floor space for each machine. None of the machines require an exceptionally clean area. A typical clean shop environment is acceptable. Most of the machines require ventilation to remove smoke and fumes. For those that do not require external ventilation it would be wise to include it in the site preparation plans.

Model Surface Finish. Only three sample parts were received. The surface finishes are recorded in Table 17. Each of the samples were measured with Pocket Surf by Federal. The XY plane is the surface perpendicular to the build direction. The XZ plane show the surface texture due to the layering process.

Chapter 5

Conclusions and Recommendations

Conclusions

Rapid prototyping is a productive tool that can and is being used to improve the competitiveness of many companies. Users are satisfied with the results. The Chrysler study (Schmidt, 1994) showed that they obtained good to excellent results on 99% of their models. Sixteen of seventeen respondents to the John Deere survey were satisfied with the results of their rapid prototyping projects. There is an abundance of literature that shows other successful case studies. Many companies have a variety of applications of rapid prototyping and the users are taking advantage of all of the processes available. As a company they need to determine their objectives for rapid prototyping. Secondly the company must design a study that factually determines their requirements and the results that they might expect from each of the processes. Finally, after the objectives and requirements are documented the company can ask the manufacturers to design a system for them and do a comparative study.

This study did not provide detailed data as it was intended. A better methodology would have been to build actual models and record the characteristics for each of those models as they were built. This would have provided valid comparable data for accuracy, processing times, part costs, and part finish. This includes four of the top five characteristics as rated by users of rapid prototyping within John Deere. Building models for a study like this becomes very expensive. The models would serve no other purpose. Other companies have done it (Hicks, 1994, Schmidt, 1993). Material properties and physical strengths which was the third highest characteristic in the John Deere survey are being debated among the manufacturers. There is no clear solution to that problem. It is up to the manufacturers to provide accurate and standardized data. If no standard exists, then the manufacturers are responsible for explaining their test procedures and why they use those procedures. Machine costs can only be compared when the manufacturers are provided a detailed specification. The user must determine his needs prior to the investigation.

Recommendations

Future Activities. Companies currently using rapid prototyping and those who plan begin using RP need to understand the process. Here are a number of steps that can be followed to learn the process and provide data for more effective implementation.

- Educate design and manufacturing engineers to the strengths and limitations of rapid prototyping.
- Study the input parameters to CAD modeling that affect the resulting rapid prototyping model. Incorporate those factors into the design process.
- Attempt to project the growth of RP within the organization
- Develop a strong working relation with a core of service bureaus that offer the wide range of prototyping processes and technologies.
- Promote the use of rapid prototyping to build models and to manufacture functional components through secondary operations.
- Catalog a detailed list of rapid prototype models created corporate wide. The list should include geometrical features, size, processing times, turn around time, material used, accuracy of key features, purchased model costs, model surface finish, process used, manufacturing costs of the model and eventual use of the model.
- Develop a rapid prototyping process selection guide that can be incorporated into an expert system. This system would be used to aid the designer in selecting the best system for his application.

Implementation Guidelines. Rapid prototyping is a promising technology that is very inviting. Companies should avoid adding RP without an in-depth evaluation of their needs and the applications of this technology within their organization. It takes this serious self evaluation to make wise and productive decisions about RP. Companies must analyze their needs in respect to model size, complexity of the model, quantity of models to be built, the turn around time at which models are needed, eventual use of the models, build layer thickness, material used to build the models, model surface finish, accuracy, and costs. The evaluators must determine the ability of rapid prototyping to provide a measurable advantage over present and alternative processes (Brown, 1993).

When evaluating the purchase of rapid prototyping equipment, teams should realize that long term success comes from building a competitive advantage. A good financial return on an equipment investment may not yield that advantage. Equipment purchase should be based on a comprehensive strategic plan that considers a variety of operating factors.

One method of obtaining data that can be used to make valid comparisons of processes is to document the key characteristics for the models as they are built. Since models are being built anyway the corporation should take full advantage of the effort going into building those models. This data will be factual because it is being obtained from actual models. There will be no need for estimates and the errors associated with estimates. Manufacturers will be able to record actual build processing times, build parameters, and material costs. Actual models will then be measured to document accuracies. Coordination of this study should be done at the corporate level to facilitate consistent and rapid accumulation of data. Conducting these studies internally will provide data that directly applies to a given situation. It will not require anyone to draw conclusions based on assumptions made by others. It will also provide thorough documentation as was illustrated in the study done by Schmidt (1993).

If a cost analysis is needed to justify the purchase of rapid prototyping equipment, the analysis need to be done before that study is started. Detailed system requirements need to be specified prior to beginning the analysis. Only when systems are quoted against these specifications can valid comparisons be made between systems. Costs will include equipment cost; both mechanical and computer, as well as maintenance, staffing, and software. Training is usually included as part of the equipment costs. But, there may be additional expenses to cover travel and lodging. Although software makes the RP systems very user friendly, there is still a learning curve to become proficient at building high quality models. There is a cost factor due to the time involved in this learning process. Each system has its idiosyncrasies. These are not processes that produce quality models immediately after the systems are set up.

Another factor that is worth evaluation is the method used to generate the CAD model. Users tend to underestimate the importance of the CAD file that is the corner stone of this whole process. The RP model cannot be any more accurate than the CAD model. RP models cannot be directly from two dimensional CAD geometry. That geometry would have to be converted to a three dimensional format. Models can be produced from wire frames and surface models but they may not produce the desired results. They may also require additional enhancements and manipulations prior to building the model. Solid models produce the best results. Chrysler has found that they have problems with 23% of their CAD models used to generate SLA models (Schmidt, 1994). This creates additional work for the machine operators and adds delay to the procurement time.

Alternatives To Rapid Prototyping. Companies also need to be aware of all of the alternatives to rapid prototyping. Those alternatives may already be available to the user. Rapid prototyping processes are not the only processes that can be used to produce prototype models in a short period of time. There are alternatives. Computer numerical control (CNC) machine tools, virtual reality, holograms, computer animation, and service bureaus may help the design process.

The computer technology explosion that paved the way for the RP processes has also advanced the CNC technology. Multi axis CNC machines like mills, lathes, EDM, routers, and lasers can also produce models directly from CAD files. These tools can make the models from a variety of material such as metals, aluminum, plastics, composites, and wood. With these materials and the subtractive process of CNC there are not the concerns with sag, warp, and curl as with the RP processes. Depending on the material selected the model or tool can be much more durable. Accuracy is generally better with the CNC process. Another significant point about CNC equipment is that they are abundant. While approximately 380 RP systems are in operation within the United States (Wholers, 1994), there are many more CNC machines more evenly dispersed through out the country. The machine operators are experienced and capable of producing quality models (Metelnick, 1994a).

Virtual reality may be another alternative to rapid prototyping in the future. Right now virtual reality is where CAD was back in the 60's. Some day virtual reality will be incorporated into the CAD system. It is debatable how soon that will happen. By 1998 the growth will be five times what it is today (Schmidt, 1994). This new software will allow the designer to interact with the design much in the same way designers interact with prototypes today. It will allow for visualization and verification of designs. This coupled with animation may eliminate the need for large expensive system mock ups. RP can produce models one at a time. When complex systems consisting of many models are needed virtual reality may be the more appropriate tool (Gottschalk, 1994; Mogal, 1994; Schmitz, 1994).

In addition to these computer generated models there are the conventional modeling methods that have been used for years. Clay and wood models have not lost their utility.

One alternative to purchasing rapid prototyping equipment is the use of service bureaus. Service bureaus are job shops that specialize in fabrication of rapid prototypes and rapid tooling. Prototype job shops have been around for many years. The innovative prototyping shops have acquired RP equipment as an extension of their present business. It is a natural transition for a CNC machine operator to acquire the expertise of RP. Service bureaus offer a variety of processes that can be used to build prototypes. This expertise and flexibility is a tremendous asset. The flexibility allows the service bureau and design engineer to collectively select the best process for the particular geometry. The RP machine operators at the service bureaus have already developed the expertise to run the latest in RP equipment. Many of these bureaus have the capability to take the model and produce functional parts through secondary processes (Aronson, 1993; Metelnick, ,1994a, 1994b). Secondary processes allow the engineer to take full advantage of the model that has been created. These processes can produce functional components out of stronger and more durable materials for test and even limited production.

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Appendix A

Model Building Guidelines

Model Building Guidelines

Please base your estimates on the assumption that John Deere designed each of these models as a solid object on a Pro/Engineer CAD system. Also assume that the parameters used to design these models were adjusted with the understanding that the data would eventually be used to construct high accuracy rapid prototyping models. Finally assume that John Deere converted the CAD file to a suitable .STL file.

To be able to make valid comparisons of systems and estimates the following guidelines must be followed:

- The construction layers should be 0.005" or smaller.
- The data must be accurate, repeatable, and reproducible as if it were verified by an on site run off.
- All walls are to be solid and 100% cured within the total processing time that is estimated.
- Porosity is to be less than 5%.
- List any data manipulation and enhancement that might be done to the .STL file prior to the start of the build cycle.

Drawings for each of the three parts have been enclosed. A number of key characteristics have been high lighted in yellow on each of the drawings. Please estimate the +\- accuracy which you can build these features. Also the drawings list the volume of the part. This was calculated using our specified weight and a standard density for aluminum and cast iron.

The characteristics listed below are to be itemized in the estimate for each of the three models:

- Accuracy as stated above
- Pre-processing time. This is the amount of time that is required to prepare the .STL file for entry into your machine. It would include the time required to add supports or any enhancements to the file.
- Machine build time is the actual run time for the machine as it builds the model.
- Post processing time is the time required to clean, sand, seal polish, post cure etc. the model.
- Material used to construct model and its cost based on the estimated volume.
- Construction layer thickness.

Models

R95850 Housing, Transmission Oil Filter, Die Cast Aluminum, 9.8 in^3
The objective of this model is to have a strong durable highly accurate model of the finished part.

Accuracy Features:
Ø5.98 Dowel Pin Hole
True Position 0.02 Between Two Dowel Pin Holes
70.5 In X Direction Locating Hole #4
35 In Y Direction Locating Hole #4
Flatness Of 0.025:25 Of Datum -A-
Flatness Of 0.05:25 Of Filter Mounting Face
Ø73 Filter Mounting Face

R96911 Carrier, Output Planetary, Green Sand Cast Iron, 138.5 in^3
The objective of this model is to have a strong durable highly accurate model of the finished part.

Accuracy Features:
Ø22.028 Pinion Shaft Bores
True Position 0.02 Between Pinion Shaft Bores
Ø107.45 Bearing Bore
227.67 Length
Ø81 Bearing Bore

R121548 Housing, Reduction Gear, Green Sand Cast Iron, 616.5 in^3
The objective of this model is to have a strong durable highly accurate model of the as cast part part. Do not include cores as part of your estimate.

Accuracy Features:
146 Distance From Datum -F-G-
286.5 Distance To Datum -H-
107 Distance
179 Distance
R185
178 Distance
188 Distance

Appendix B

Survey Instrument

Rapid Prototyping Survey Instrument

Name______________________________Date_______________
Phone_____________________Fax_________________________
Job Description____

What has been your most recent experiences with rapid prototyping?

Process Used

- DSPC - direct shell production casting
- FDM - fused deposition molding
- LOM - layer object manufacturing
- SGC -selective ground curing
- SLA - stereo lithography apparatus
- SLS - selective laser sintering

Objective

- Visualization - ability to see and hold the physical model
- Verification - verify that the model fits and functions
- Iteration/Optimization - the development process to optimize the part
- Fabrication - to produce prototype or production parts using the rapid prototyping model

Type Of Part Fabricated	Process Used	Objective	Date

What do you consider to be the most important objective of rapid prototyping?____

Rapid Prototyping Survey Schedule

Please rank these characteristics of a rapid prototyping system in order of importance with 1 being the most important.

	Rank
Part Size - the physical size of the model that can be built	______
Processing Time - time it takes to build the model	______
Material - strength of the material used to build the model	______
Accuracy - the degree to which the model matches the CAD model	______
Machine Costs - capital expenditures for the machine and related software	______
Part Costs - cost of material and labor to produce the model	______
Secondary Costs - machine maintenance and site preparation	______
Part Finish - the surface finish of the model	______

Are there any other characteristics that you consider to be applicable to rapid prototyping? Please list them below and rank them along with those listed above.

____ ______

____ ______

Referring to latest rapid prototyping model Date________________

What level of accuracy was needed for your model?
(please circle) 0.020" 0.015" 0.010" 0.005" 0.002"

What was the accuracy obtained with your model?________________

How did you measure your accuracy?
(please circle) CMM Fit Gauge Visual Other________________

Overall, was the model to your satisfactions? (please circle) Yes No
If not - what was wrong:________________________________

Rapid Prototyping Survey Schedule

Would you recommend that Deere and Co. expand its rapid prototyping capability by purchasing a rapid prototyping system? ________

If yes what system would you recommend? ____________________

Why?____

____

____

____

If not please explain why you would not recommend the purchase of a rapid prototyping system.____

____

____

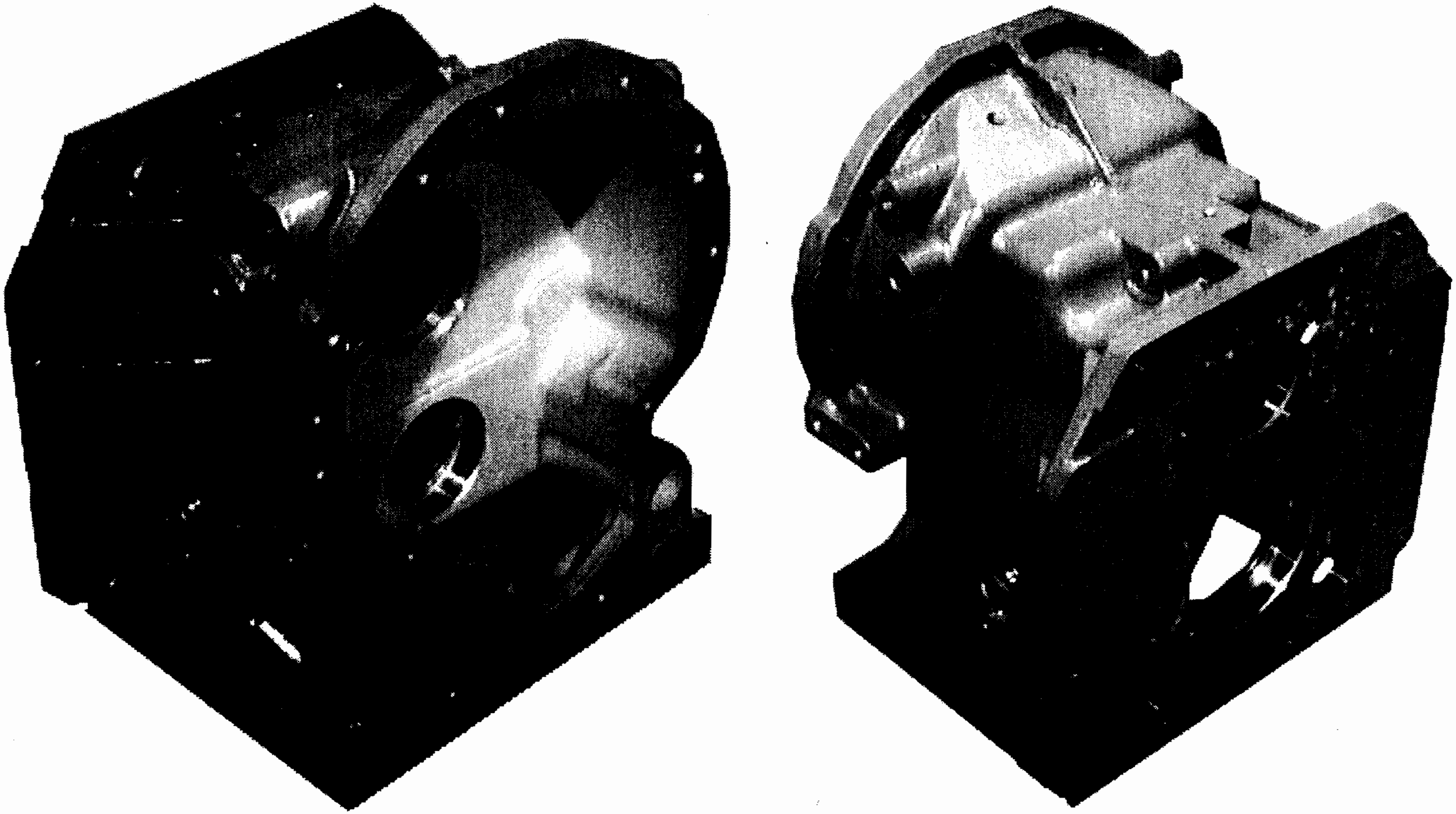
____

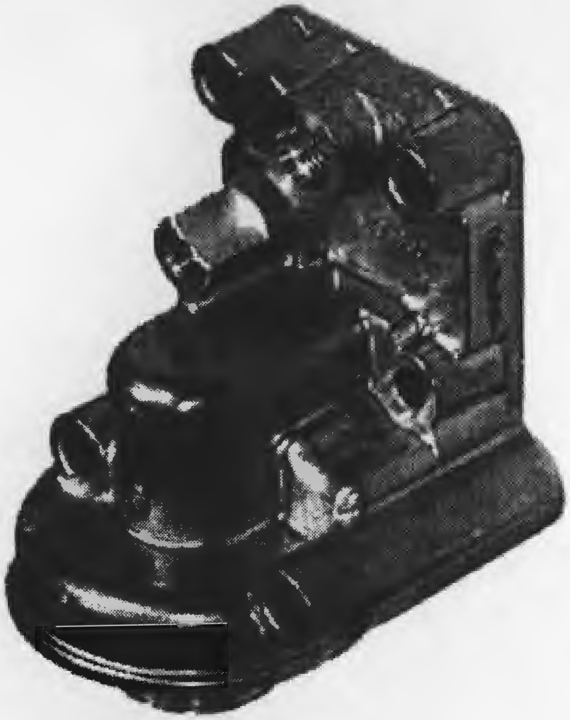
Appendix C

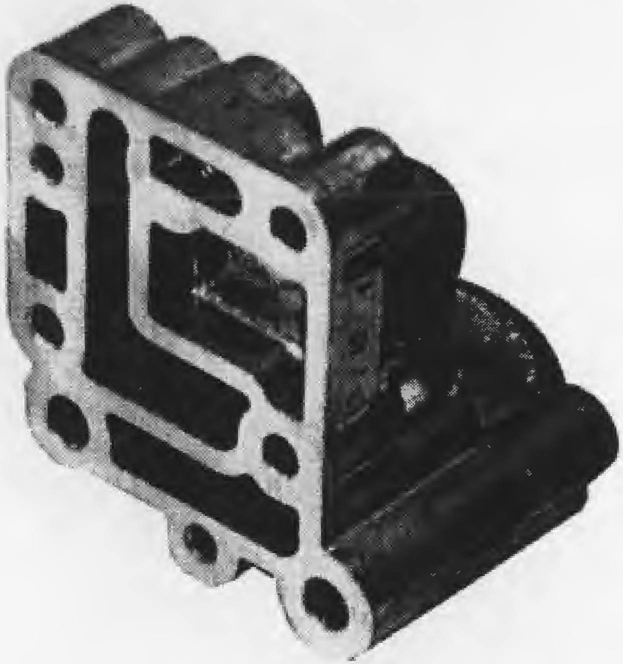
Part Photographs

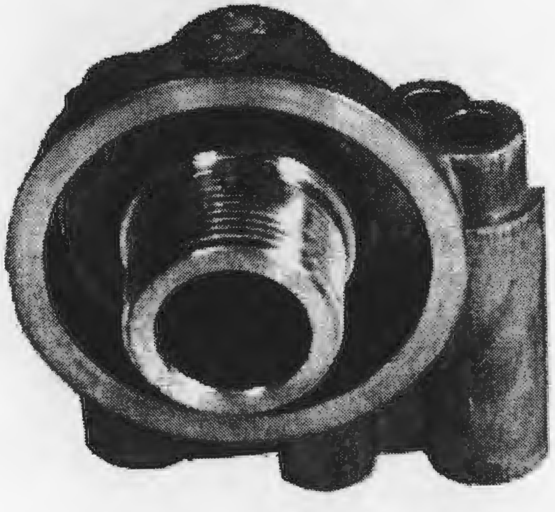
R95850	Housing, Filter
R96911	Carrier, Planetary
R121548	Housing, Reduction Gear

R121548 Housing, Reduction Gear



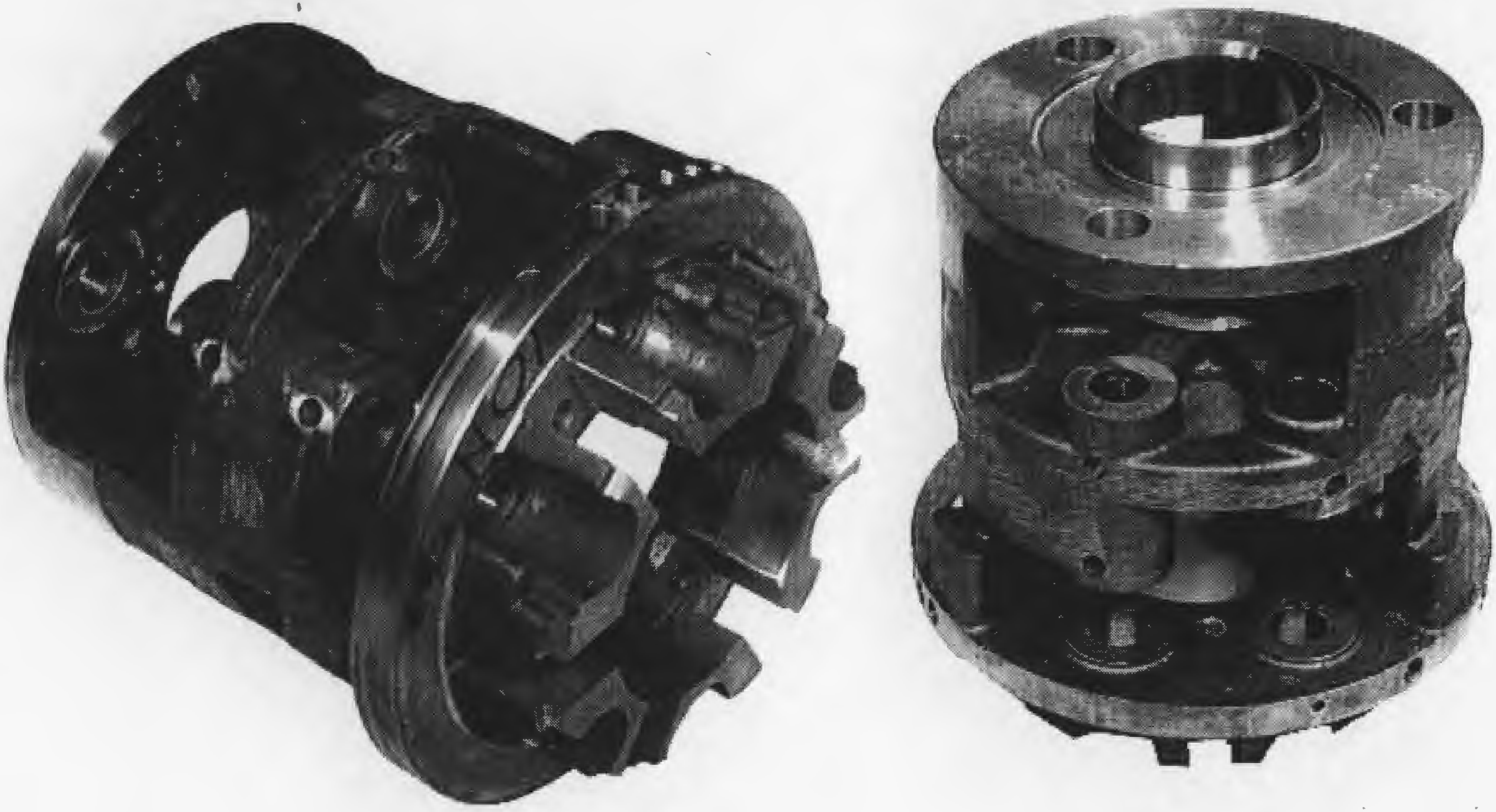






R95850 Housing, Filter

R96911 Carrier, Planetary



Appendix D

Technical Sales Representatives

Technical Sales Representatives

DSPC - Direct Shell Production Casting

Burt Evans
Regional sales Manager
Soligen, Inc.
19408 Londelius Street
Northridge, California 91324
Phone (818) 718-1221
Fax (818) 718-0760

FDM - Fused Deposition Modeling

Sam Krankkala
Central Region Sales Manager
Stratasys, Inc.
14950 Martin Drive
Eden Prairie, Minnesota 55344-2020
Phone (612) 937-3000
Fax (612) 937-0070

LOM - Laminated Object Manufacturing

Tom Rohrbeck
Sales Representative
Helisys, Inc
458 Harvest Lane
Roselle, Illinois 60172
Phone (708) 582-4586
Fax (708) 582-4587

Technical Sales Representatives

SGC - Solid Ground Curing

Pat Maley
Director, North American Operations
Cubital America, Inc.
1151 Titus Avenue
Rochester, New York 14617
Phone (716) 266-0510
Fax (716) 266-2967

SLA - 3D Systems

Larry Soucy
Major Account Manager
3D Systems
1350 Remington Road, Suite K
Schaumberg, Illinois 60173
Phone (708) 490-9021
Fax (708) 490-9025

SLS - Selective Laser Sintering

Kent Nutt
Marketing Communications Manager
DTM Corporation
1611 Headway Circle, Building 2
Austin, Texas 78754
Phone (512) 339-2922
Fax (512) 339-0634

Appendix E

System Schematics

DSPC by soligen Technologies Inc.

FDM by Stratasys Inc.

LOM by Helisys Inc.

SGC by Cubital, Ltd.

SLS by DTM Corp

SLA by 3D Systems

Appendix F

Estimates

DSPC by soligen Technologies Inc.

FDM by Stratasys Inc.

LOM by Helisys Inc.

SGC by Cubital, Ltd.

SLS by DTM Corp

PARTS NOW™

Mar. 13, 1995

Quotation Number 94

Dan Koenig
John Deere WaterLoo Works

Waterloo, IA 50704-0270

Dear Dan,

Based upon the part drawings we received and information you relayed through Bert Evans I am pleased to provide you with the following quote.

Item	Quantity 1	Quantity 10
Filter Housing (R95850)	$ 3,750.00	$ 9,500.00
Planetary Carrier (R96911)	$ 9,000.00	$ 48,500.00

Material: (R95850) A356, Ductile (R96911)

Parts are provided 'as cast', gating and casting marks removed.

Delivery: Quantity 1: Four weeks ARO.
Quantity 10: First article four weeks. Balance 4 weeks after approval.

Payment: Net 30 days. Shipment: FOB Northridge, CA
This quotation is valid for 30 days.

Please note that this quote is for parts of this size and nature. Our manufacturing process (DSPC) is dependent upon size of part more than part complexity. An approved STL file of the part and finalized drawing are required.

Please call me if you have any questions.

Best regards,
Gordon Clark

Division of Soligen, Inc., 19408 Londelius Street, Northridge, CA 91324 (818) 718-1221
Fax: (818) 718-0760 Modem: (818) 718-0143 Internet: QuickQuotes@PartsNow.com

Stratasys®
INC.

Dan Koenig, CQE
Drivetrain Quality Assurance
John Deere Waterloo Works

Waterloo, Iowa 50704-0270

Dear Mr. Koenig:

Subject: Configuration and FDM Modeling Estimates

Thank you for your continued interest in Stratasys Inc. and our FDM Rapid Prototyping Process. I will attempt to answer your questions as well as provide you with a minimum and maximum system configuration. I had to rely on some help from our Senior Application Engineering Staff to get estimates on the three parts you submitted - we have addressed these as precise ly and accurately as possible without an available .STL File.

In any discussion of FDM's strengths we would include:

- Initial Price - One of the lowest in the industry
- Materials - Investment Casting wax-
    Same Properties the foundries traditionally use.
    Polyamide - Low Temp Thermo-Plastic
    Nylon Like Qualities.
    ABS - High temp Thermo-Plastic, High Strength, Great Secondary Finishing Characteristics. An end item material in some cases.
- All materials are environmentally safe.
- Office Environment - No Venting required.
- Low Continued cost of ownership.
- Ease of use.
    3 Days of Training, 1 day of install.
- Automatic Support Generation.
- No Facilities Enhancements Required.
- Multiple materials can be used in the same model.

14950 Martin Drive, Eden Prairie, MN 55344-2020 • Phone (612) 937-3000 • FAX (612) 937-0070
Email: fdm@stratasys.com

When it comes to limitations there are only a couple of items which might come up and Stratasys Engineering is addressing both of these.

1. Size - 10"x10"x10"
2. There is no speed advantage in building more than 1 part at a time.

Operations

Stratasys has spent a great deal of effort in understanding the various material properties and how they relate to the FDM Process. This information is part of a larger material matrix which is contained within the "Quick Slice" software required to prepare the models. Using the default settings the .STL file can be prepared and sent to the FDM 1600 with about 5 button clicks. However Stratasys has left the software open so that the operator may control all aspects of the build parameters such as:

- Wall Thickness (Road Widths) ranging from .012" to .100"
- Slice Resolution (Road Heights) Ranging from .002" to .030"
- Fill Patterns
- Support Structures
- Speeds
- Temperatures
- Shrink Values
- Scale
- Material Parameters

If you have any other questions concerning operator control, please call me.

Systems Configuration and Budgetary Pricing

I. Minimum System Configuration

Includes:

- Base Machine
- One material Package
- Quick Slice software
- Training
- Install
- SGI Indy Workstation

Total One Time Cost
$ 89,500

Hardware Maintenance Including SGI Workstation = $ 7,820/year
Software Maintenance = $ 1,200/year

II. Maximum System Configuration

Includes:

- Base Machine with Air Conditioner
- Three material Packages:
- Investment Casting Wax, Poly Amid, ABS
- Quick Slice with Support Works Software
- Training and Install
- Cart
- SGI Indigo RS4000 XS Workstation

Total One Time Cost
$ 158,640

Hardware Maintenance Including SGI Workstation = $ 12,950
Software Maintenance = $ 2,050/year

The following are estimates based on the assumptions laid out in your model building guidelines. The only exception taken is the construction layer for the FDM Process on parts this size should be .010" to .016"

	R95850 Filter Housing	R96911 Carrier, output Planetary	R121548 Housing Reduction Gear
Accuracy	+/- .005"	+/- .005"	+/- .005"
Pre-Processing Time	20 Min.	1 1/2 Hours	1 Hour / qtr.*
Machine Build Time	Approx. 12Hrs.	Approx. . 140 Hours	No experience with this size part *
Post Processing	1 Hour + any Threading	3 Hours	1 Hour / qtr. 1 Hour Assembly*
Material Cost	ABS $48.00	ABS $600.00	ABS $2900.00
Layer Thickness	.010	.010 - .012	.010 - .016

Notes: Any Threading would be a Post Process Issue.
*Requires the Designer to cut into 4 logical pieces that would fit in the FDM Build chamber and 4 separate .STL Files - Thus building 1/4th of the housing at a time and assembling them later.

Dan, I do hope we have answered your questions satisfactorily, However, as you review the information questions may arise, if so please feel free to call me at (612) 937-3000.

Sincerely

Sam Krankkala
Midwest Region Sales Manager

STK/glf

P.S. Dan
I'll BE AT THE DESIGN 2001 SHOW IN
CHICAGO FROM 3/13 - 3/17 If you HAVE
ANY QUESTIONS PLEASE LEAVE ME A MESSAGE & I'll
Get BACK to you.

HELISYS

HELISYS, INC.
24015 GARNIER ST.
TORRANCE
CA 90505
TEL 310 891-0600
FAX 310 891-0626

March 08, 1995

Mr. Dan Koenig
Dept. 530
John Deere Waterloo Works

Waterloo, IA 50704-0270

Dear Mr. Koenig:

Enclosed is the Helisys' Laminated Object Manufacturing part build data for the three drawings you supplied. The build times are based on "normal" parameter settings on the LOM machine. With some optimization of these parameters (speed settings) the build times could possibly be altered by +/-10%.

The minimum package system costs are shown in chart A (LOM-1015) and Chart B (LOM-2030). The maximum package system costs are shown on the two sample quotations enclosed. These quotes give detailed specifications of the computer, laser, training, and service contracts. The pricing for the service contracts is also listed on the quotes.

I trust the information I have provided you will allow John Deere to accurately complete its Rapid Prototyping evaluation.

Additionally, the information provided to you has been done so for the sole use of John Deere and is not to be released to any of the other participants in the Rapid Prototyping evaluation.

If you have any additional questions, please contact me at 708-582-4586.

Respectfully,

Thomas Rohrbeck
Regional Sales Manager

HELISYS

LOM-1015 MINIMUM CONFIGURATION COST

PART SIZE 15”x14”x10”

Equipment Description	Unit Price
LOM-1015 Software and Computer	$99,000.00
Installation and Training (On-site)	$4,000.00
Total Price	**$103,000.00**

LOM-2030 MINIMUM CONFIGURATION COST

PART SIZE 32”x22”x20”

Equipment Description	Unit Price
LOM-2030 Software and Computer	$199,000.00
Laser Chiller	$3,400.00
Installation and Training (On-site)	$4,000.00
Total Price	**$206,400.00**

HELISYS

HELISYS, INC.
24015 GARNIER ST.
TORRANCE
CA 90505
TEL 310 891-0600
FAX 310 891-0626

SAMPLE

Helisys Customer Quotation
LOM-2030 System

March , 1995

A. PRICING

1. Parties and Addresses:

Helisys, Inc., located at 24015 Garnier Street, Torrance, CA 90505, USA, quotes a system price to:

Name and Address

2. System, Installation and Service Description:

LOM-2030 System includes:
* Prototype dimensions up to 32" L x 22" W x 20" H
* 50 Watt CO_2 Laser with Laser Power Meter
* 486/33 MHz computer with 16 MB RAM, 240 MB HD, VGA Graphics and 3 1/2" and 5 1/4" floppy disk drives
* LOMSlice software license for MS-Windows NT (two-user license)

On-Site Installation and Training includes:
* system installation, configuration and test
* comprehensive one-week, on-site training program (system operation, maintenance, minor troubleshooting, part building technique)
* travel and lodging for Helisys service staff

First Year Service Contract includes:
* repair or replacement of parts
* laser replacement with recharged laser
* remote diagnostics and support
* on-site service
* software upgrades
* excludes travel and lodging expenses for Helisys service staff

3. **System, Installation and Service Pricing:**

Item	Qty.	Equipment Description	Unit Price	Extended
1	1	LOM-2030	$199,000.00	$199,000.00
2	1	16 MB RAM Upgrade to 32 MB	$1,120.00	$1,120.00
3	1	520 MB HD Disk Upgrade	$880.00	$880.00
4	1	66 MHz CPU Upgrade	$600.00	$600.00
5	1	Laser Chiller	$3,400.00	$3,400.00
6	1	Extra Part Platform	$1,650.00	$1,650.00
7	5	Roll 27" wide .0038" thick paper	$240.00	$1,200.00
8	5	Roll 27" wide .0075" thick paper	$216.00	$1,080.00
9	2	Roll 4" wide foam tape	$109.00	$218.00
10	1	On-Site Installation & Training	$4,000.00	$4,000.00
11	1	Annual Service Contract	$16,000.00	$16,000.00
			Total Price	**$229,148.00**

4. **System Delivery:**
Helisys promises its best efforts to achieve an estimated delivery of 10-12 weeks after receipt of order.

B. STANDARD TERMS AND CONDITIONS

1. **Pricing:**
Prices are in U.S. dollars and exclude all taxes and freight charges. Quotations are valid for 30 days beginning the date of this quotation. Prices may differ from the quotation if the purchaser later requests revisions in such things as the design of the system or its components; delivery dates or locations; documentation or training; storage; or other factors materially affecting costs. Taxes and other costs imposed by governmental action are due whether or not quoted.

2. **Timing and Method of Payments:**
Fifty percent (50%) is due with the buyer's purchase order; no order is accepted without this payment. Forty percent (40%) is due upon delivery. The remaining ten percent (10%) is due upon successful installation and training or within 30 days of date of delivery, whichever is sooner.

3. **All Other Payment Conditions:**
Helisys may suspend work and withhold delivery if it has reason to believe that any of the buyer's payments may not be forthcoming in a timely manner. The buyer agrees to pay the lower of 18% PER ANNUM or the maximum interest allowable under applicable law on any payments made later than at the times specified above.

HELISYS

Helisys, Inc.
24015 Garnier St.
Torrance
CA 90505
Tel 310 891-0600
Fax 310 891-0626

SAMPLE

Helisys Customer Quotation
LOM-1015 System

March 1995

A. PRICING

1. Parties and Addresses:

Helisys, Inc., located at 24015 Garnier Street, Torrance, California 90505, USA, quotes a system price to:

Name and Address

2. System, Installation and Service Description:

LOM-1015 System includes:

- Prototype dimensions up to 14.5" L x 10" W x 14" H
- 25 Watt CO_2 Laser with Laser Power Meter
- 486/33 MHz computer with 16 MB RAM, 240 MB HD, VGA Graphics and 3 1/2" and 5 1/4" floppy disk drives
- LOMSlice software license for MS-Windows NT (two-user license)

On-Site Installation and Training includes:

- system installation, configuration and test
- comprehensive one-week, on-site training program (system operation, maintenance, minor troubleshooting, part building technique)
- travel and lodging for Helisys service staff

First Year Service Contract includes:

- repair or replacement of parts
- laser replacement with recharged laser
- remote diagnostics and support
- on-site service
- software upgrades
- excludes travel and lodging expenses for Helisys service staff

3. **System, Installation and Service Pricing:**

Item	Qty.	Equipment Description	Unit Price	Extended
1	1	LOM-1015	$99,000.00	$99,000.00
2	1	16 MB RAM Upgrade to 32 MB	$1,120.00	$1,120.00
3	1	520 MB HD Disk Upgrade	$880.00	$880.00
4	1	66 MHz CPU Upgrade	$600.00	$600.00
5	1	Extra Part Platform	$620.00	$620.00
6	5	Roll 13.5" wide .0038" thick paper	$120.00	$600.00
7	5	Roll 13.5" wide .0075" thick paper	$114.00	$570.00
8	2	Roll 2" wide foam tape	$59.00	$118.00
9	1	On-Site Installation & Training	$4,000.00	$4,000.00
10	1	Annual Service Contract	$9,000.00	$9,000.00

Total Price **$116,508.00**

4. **System Delivery:**
   Helisys promises its best efforts to achieve an estimated delivery of 10-12 weeks after receipt of order.

B. STANDARD TERMS AND CONDITIONS

1. **Pricing:**
   Prices are in U.S. dollars and exclude all taxes and freight charges. Quotations are valid for 30 days beginning the date of this quotation. Prices may differ from the quotation if the purchaser later requests revisions in such things as the design of the system or its components; delivery dates or locations; documentation or training; storage; or other factors materially affecting costs. Taxes and other costs imposed by governmental action are due whether or not quoted.

2. **Timing and Method of Payments:**
   Fifty percent (50%) is due with the buyer's purchase order; no order is accepted without this payment. Forty percent (40%) is due upon delivery. The remaining ten percent (10%) is due upon successful installation and training or within 30 days of date of delivery, whichever is sooner.

HELISYS

HELISYS, INC.
24015 GARNIER ST.
TORRANCE
CA 90505
TEL 310 891-0600
FAX 310 891-0626

March 2, 1995

Mr. Dan Koenig
Dept. 530
John Deere Waterloo Works
[redacted]
Waterloo, IA 50704-0270

Dear Mr. Koenig:

Thank you for your letter to Mr. Tom Rorhbeck. He has forwarded your letter and the drawings to my attention in order to provide you with estimated time and cost for building LOM parts. The following should be considered as accurate estimates.

Part #: R95850, Housing, Filter -- Max. Dim: X=3.54, Y=3.15, Z=3.54
Machine: LOM-1015
Material: LPH 042 140, High Performance LOMPaper, 0.0042" thick, 14" wide roll

Total number of layers: 843 + 20 (base) = 863 layers

Each layer: 4" + 2" (margin between layers) = 6"/layer ==> 5178" total = 431 feet total

Material cost: $0.0643/linear foot ==> $27.71
Note: 2 identical parts could be built side by side with the same amount of material

Data preprocessing time: 20 minutes (computer time)

Machine set-up: 20 minutes (operator time)

Build time: 11 hours (machine time, unattended)
Note: Build time in LOM-2030: 9 hours
Note: 2 parts building = 15 hours, 4 parts building = 22 hours

Part de-cubing: 1 hour (operator time)

Part finishing: 2 hours (operator time + sanding sealer drying time)

Total Production time: 14 hours, 40 minutes

Part #: R96911, Carrier, Planetary -- Max. Dim: X=8.94, Y=8.94, Z=9.8

Machine: LOM-1015
Material: LPH 042 140, High Performance LOMPaper, 0.0042" thick, 14" wide roll

Total number of layers: 2333 + 20 (base) = 2353 layers

Each layer: 9" + 2" (margin between layers) = 11"/layer ==> 25883" total = 2157 feet total

Material cost: $0.0643/linear foot ==> $138.70

Data preprocessing time: 30 minutes (computer time)

Machine set-up: 30 minutes (operator time)

Build time: 39 hours (machine time, unattended)
Note: Build time in LOM-2030: 33 hours

Part de-cubing: 2 hours (operator time)

Part finishing: 3 hours (operator time + sanding sealer drying time)

Total Production time: 45 hours

Part #: R121548, Housing, Reduction -- Max. Dim: X=17.7, Y=19.6, Z=11.3
Machine: LOM-2030
Material: LPH 042 240, High Performance LOMPaper, 0.0042" thick, 24" wide roll

Total number of layers: 2690 + 20 (base) = 2710 layers

Each layer: 18" + 3" (margin between layers) = 21"/layer ==> 56910" total = 4743 feet total

Material cost: $0.1102/linear foot ==> $522.67

Data preprocessing time: 30 minutes (computer time)

Machine set-up: 30 minutes (operator time)

Build time: 56 hours (machine time, unattended)

Part de-cubing: 2 hours (operator time)

Part finishing: 3 hours (operator time + sanding sealer drying time)

Total Production time: 62 hours

The accuracy for all parts is expected to be +/- 0.010" for all features and dimensions.

I hope this information is helpful. Please contact either myself or Tom Rohrbeck with any additional questions.

Sincerely,

Michael Tsenter
VP Sales & Marketing

cubital

Cubital America Inc.
1151 Titus Avenue
Rochester, NY 14617
Tel: (716) 266-0510
Fax: (716) 266-2967
Email: cubitalame@attmail.com

FAX MESSAGE

To:	**JOHN DEERE WATERLOO WORKS**	**Date:**	**Friday, February 24, 1995**
Attn:	**Dan Koenig, CQE**	**From:**	**Patrick M. Maley**
Fax No:		**Copies:**	
Country:	**U.S.**	**Pages:** (cover +13)	**14**

MESSAGE:

Dear Dan,

Enclosed for your review is Cubital America's response to your Request For Information (RFI). I hope it is complete, and should you require additional information or have any questions, please call me at 716-266-0510. Thank you for your interest in Cubital America, Inc.

Sincerely,

Patrick M. Maley
Director,
North American Operations

cubital

Cubital America Inc.
1151 Titus Avenue
Rochester, NY 14617
Tel: (716) 266-0510
Fax: (716) 266-2967
Email: cubitalame@attmail.com

CUBITAL AMERICA INC.
SOLIDER SYSTEM
NORTH AMERICAN SERVICE BUREAUS

ALBERTA RESEARCH COUNCIL
6815 - 8th Street NE
Calgary, Alberta
Canada T2E 7H7
Contact: George Thorpe
Tel: 403-297-7546
Fax: 403-297-7548

ALLIED SIGNAL AEROSPACE
Controls & Accessories Division
717 North Bendix Drive
South Bend, IN 46620
Contact: Allen Keltner
Tel: 219-231-3512
Fax: 219-231-3383

BAXTER HEALTHCARE CORPORATION
Route 120 & Wilson Road
RLP-30
Round Lake, IL 60073
Contact: Terry Kreplin
Tel: 708-270-4067
Fax: 708-270-3969

GENERAL MOTORS CORPORATION
MidSize Car Division
30001 Van Dyke Avenue
Room S45-66
Warren, MI 48090
Contact: John Bolognino
Tel: 810-575-1165
Fax: 810-575-4418

GENERAL PATTERN COMPANY
3075 84th Lane, N.E
Blaine, MN 55449
Contact: Bob Grainger
Tel: 612-780-3518
Fax: 612-780-3770

PROTOGENIC, INC.
2820 Wilderness Place, D
Boulder, CO 80301
Contact: Paul Karr
Tel: 303-442-4604
Fax: 303-442-1368

STATURE PROTOTYPING
20201 Hoover Road
Detroit, MI 48205
Contact: Ernie Guinn
Tel: 313-839-8245
Fax: 313-839-3932

TOLEDO MOLDING & DIE, INC.
4 East Laskey Road
Toledo, OH 43612
Contact: Steve Lenhart
Tel: 419-476-0581
Fax: 419-476-6053

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Cubital America Inc.
1151 Titus Avenue
Rochester, NY 14617
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JOHN DEERE Service Quotation
Solider 5600 Minimum and Maximum Configurations

Product #	Description	List Price	Annual Maint.
5600-MPM	Solider 5600 Model Production Machine Including DFE Workstation with Standard Software Configuration, 12 Month Warranty, and On-site Installation and Training.	$470,000	$69,000
5600-ADM	Automatic Dewaxing Machine (optional)	$25,000	$2,800
		$495,000	$71,800

Product #	Description	List Price	Annual Maint.
5600-MPM	Solider 5600 Model Production Machine Including DFE Workstation with Standard Software Configuration, 12 Month Warranty, and On-site Installation and Training.	$470,000	$69,000
5600-ADM	Automatic Dewaxing Machine (optional)	$25,000	$2,800
5600-DFE	2nd DFE Workstation & Software	$55,000	$7,700
5600-STL/o	STL Output Converter	$5,600	$784
5600-STRIM	SOLITRIM Compression Package	$3,400	$476
5600-SBIND	SOLIBIND Intersurface Data Correction	$3,400	$476
5600-SCUT	SOLIFILE Cutter Package ("CUT")	$5,000	$700
5600-SWIDE	SOLIFILE Widener	$3,400	$476
5600-FVOL	FLEXI-VOLUME Software	Included	$2,800
		$570,800	$85,212

2/23/95

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JOHN DEERE Service Quotation
Solider 4600 Minimum and Maximum Configurations

Product #	Description	List Price	Annual Maint.
4600-MPM	Solider 4600 Model Production Machine Including DFE Workstation with Standard Software Configuration, 12 Month Warranty, and On-site Installation and Training.	$300,000	$52,000
4600-ADM	Automatic Dewaxing Machine (optional)	$25,000	$2,800
		$325,000	$54,800

Product #	Description	List Price	Annual Maint.
4600-MPM	Solider 4600 Model Production Machine Including DFE Workstation with Standard Software Configuration, 12 Month Warranty, and On-site Installation and Training.	$300,000	$52,000
4600-ADM	Automatic Dewaxing Machine (optional)	$25,000	$2,800
4600-DFE	2nd DFE Workstation & Software	$55,000	$7,700
4600-STL/o	STL Output Converter	$5,600	$784
4600-STRIM	SOLITRIM Compression Package	$3,400	$476
4600-SBIND	SOLIBIND Intersurface Data Correction	$3,400	$476
4600-SCUT	SOLIFILE Cutter Package ("CUT")	$5,000	$700
4600-SWIDE	SOLIFILE Widener	$3,400	$476
4600-FVOL	FLEXI-VOLUME Software	$20,000	$2,800
		$420,800	$68,212

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1995 PRICE LIST FOR USA

(All prices are in USD, FOB Israel)

SOLIDER 5600 SYSTEM, BASIC CONFIGURATION:

	List Price:	Annual Maint:
SYSTEM PRICE, which includes:	**$470,000**	**$69,000**

Model Production Machine (MPM)
Data Front End Workstation (DECstation 5000/M260)
& Standard Software (DFE)
12-Month Support Package
On-site Installation & Training

HARDWARE OPTIONS:

5600 DFE - Fully Configured Station	$55,000	$7,700
5600 DFE - "Production" Station	$21,000	$2,940
Video Camera and Monitor	$3,400	$476
Automatic Dewaxing Machine (ADM)	$25,000	$2,800
Add-on 8MB Memory Increment	$1,600	N/C
Additional 665MB Disk	$2,000	$280
Additional 1.0GB Disk	$2,500	$350
1/4" Tape Cartridge Drive and Expansion Box	$2,400	$336
TZ30 Tape Cartridge Drive and Expansion Box	$2,500	$350
Driver Expansion Box	$500	N/C

SOFTWARE OPTIONS:

SDRC Universal File Format Converter	$2,200	$308
VDA 2.0 File Format Converter	$8,000	$1,120
STL Output Converter	$5,600	$784
SOLIFILE Compression Package (SOLITRIM)	$3,400	$476
Intersurface Data Correction (SOLIBIND)	$3,400	$476
SOLIFILE Cutter ("CUT")	$5,000	$700
SOLIFILE Widener	$3,400	$476
FLEXI-VOLUME Software	Included	Included

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1995 PRICE LIST FOR USA

(All prices are in USD, FOB Israel)

SOLIDER 4600 SYSTEM, BASIC CONFIGURATION:

	List Price:	Annual Maint:
SYSTEM PRICE, which includes:	**$300,000**	**$52,000**

Model Production Machine (MPM)
Data Front End Workstation (DECstation 5000/M260)
& Standard Software (DFE)
12-Month Support Package
On-site Installation & Training

HARDWARE OPTIONS:

4600 DFE - Fully Configured Workstation	$45,000	$6,300
4600 DFE - "Production" Workstation	$17,000	$2,380
Video Camera and Monitor	$3,400	$476
Automatic Dewaxing Machine (ADM)	$25,000	$3,500
Add-on 8MB Memory Increment	$1,600	N/C
Additional 665MB Disk	$2,000	$280
Additional 1.0GB Disk	$2,500	$350
1/4" Tape Cartridge Drive and Expansion Box	$2,400	$336
TZ30 Tape Cartridge Drive and Expansion Box	$2,500	$350
Driver Expansion Box	$500	N/C

SOFTWARE OPTIONS:

SDRC Universal File Format Converter	$2,200	$308
VDA 2.0 File Format Converter	$8,000	$1,120
STL Output Converter	$5,600	$784
SOLIFILE Compression Package (SOLITRIM)	$3,400	$476
Intersurface Data Correction (SOLIBIND)	$3,400	$476
SOLIFILE Cutter ("CUT")	$5,000	$700
SOLIFILE Widener	$3,400	$476
FLEXI-VOLUME Software	$20,000	$2,800

UPGRADE TO SOLIDER 5600 SYSTEM	$170,000	$23,800

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Solid Ground Curing
Model Making Cost Estimates
&
Accuracy Specifications

A. Cost Assumptions

1. The "street price" for R.P. models presently seems to fall into the range of $7.00 to $9.00 per cubic inch. These cubic inches are calculated using the "bounding box" of each part, which we've recently discussed.

2. In Cubital's Solid Ground Curing process, most of our service bureaus can sometimes offer better pricing than this. This is because of our unique ability to nest parts in the z-axis of the build and nest parts-within-parts. In this way, the overall cost of the parts can be shared over a greater number in the build, and therefore allowing better price-per-part quotes.

3. For this response however, there are many scenarios:

    a. The Reduction Gear Housing will be run by itself, or
    b. The Oil Filter Housing and Planetary Gear can be run together, or
    c. All three components could be produced in a single run, or
    d. Each part run individually.

For the sake of simplicity, we will calculate part cost as if we ran each separately.

B. Accuracy & Production Rates

1. Cubital advertises part accuracy of 0.1% point-to-point. This equates into 0.001" per inch, or 0.001mm per mm. However, achieved accuracies are dependent upon the part geometry and orientation in the build volume. Most of our customers report accuracies very close to the 0.1% parameter, but it does vary from time-to-time, depending upon such things as, the part geometry, packing rate, height of the whole build volume, etc.

2. Total production time for the SGC process is as follows: for every one (1) hour of production in the machine, an operator will spend an additional half-hour in post-production. Post-production is defined as wax removal, part sanding, part finishing, surface painting, etc. In addition, we will assume that the largest overall dimension of each part will be the height in the z-axis. This assumption will give us the most conversative build times for each part. (i.e. the taller the build volume in "z", the longer the job will take to run). Therefore, total production time quoted will include all of these items.

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Cost & Production Time Estimates

1. **R95850** Transmission Oil Filter Housing, calculated volume = 49.4 in^3

   a. approximate dimensions are: 3.375" x 4.5" x 3.25"
   b. total production time = build time x 1.5 = 13.5 hours x 1.5 = 20.25 hours total.
   c. Price range ($7.00 to $9.00 per cubic inch) = $345.00 to $445.00

2. **R96911** Planetary Carrier, calculated volume = 603 in^3

   a. approximate dimensions are: 9.75" height x 8.875" diameter
   b. total production time = build time x 1.5 = 29.4 hours x 1.5 = 44.1 hours total.
   c. Price range ($7.00 to $9.00 per cubic inch) = $4,221 to $5,427

3. **R121548** Reduction Gear Housing, calculated volume = 3,250 in^3

   a. approximate dimensions are: 18.6875" x 15.125" x 11.5"
   b. total production time = build time x 1.5 = 56.25 hours x 1.5 = 84.4 hours total.
   c. Price range ($7.00 to $9.00 per cubic inch) = $22,750 to $29,250

Summary:

The total price range for all three (3) parts is: $27,316 to $35,122. Most service bureaus will probably be able to offer much better pricing, because:

a. All three parts can be run in a single job volume (in a Cubital system), and
b. Other parts could be run along with these to maximize the volume and spread the cost over a greater number of parts, and
c. Each service bureau's own "creativity" and "flexibility" in pricing.

The $7.00 to $9.00 per cubic inch is a "ballpark" range and guideline only. Most service bureaus take into account other factors before quoting a job:

-- first time customer,
-- how soon the deadline is for the parts,
-- what the possibilities of future business with your firm may be,
-- whether or not you made need cast parts made from the R.P. models,
-- other secondary applications or tooling requirements, etc.

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CUBITAL Proprietary Data Front End (DFE) Software:

(these software features come standard with the system)

- "**RECEPTION**" data conversion tools for conversion of input files into Solifile format.

  Functions:
  - ◊ ASCII and binary .STL to Solifile
  - ◊ .CFL to Solifile
  - ◊ Solifile to .CFL

- "**ACADEMY**" interactive display, analysis and correction package for input data files.

  Functions:
  - ◊ Full color, rendered view of parts
  - ◊ Wireframe or solid display modes, or any combinations thereof
  - ◊ Multiple projections and viewing angles
  - ◊ Depth-clipping for internal structures
  - ◊ Optional display of directions of normals
  - ◊ Control of facet directions
  - ◊ Changing scale and units
  - ◊ Rotation and orientation of parts
  - ◊ Editing connected sub-parts
  - ◊ Reduction of redundant points and facets
  - ◊ Filling holes in parts envelopes

- "**SHOW EDITOR**" interactive package for composing production files.

  Functions:
  - ◊ All of the graphic tools of "Academy"
  - ◊ Interactive positioning of parts on stage
  - ◊ Automatic duplication of parts
  - ◊ Creation and editing of Show files
  - ◊ Consolidation of complex compositions

- "**PRODUCTION**" interactive graphical package for slicing and reviewing slices of executable Show files.

  Functions:
  - ◊ Fast calculation of production slices
  - ◊ Preview of slice geometry on screen
  - ◊ X and Y axis calibration factors
  - ◊ Control of layer thickness
  - ◊ Automatic Flexi-Volume Adjustment

DTM CORP.

Dan Koenig
5 April 1995

146
179.5

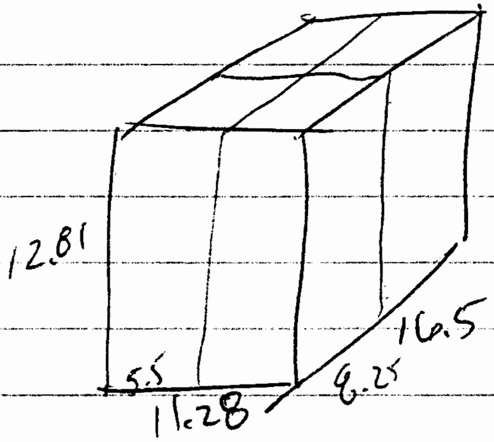
325.5

286.5

195
195
30

420

12.81 11.28 16.5



R121548
4 PARTS

GLASS FILLED OR
FINE NYLON

DATUMS ARE $\boxed{-F-}$

± .025 mm OR ± .001

ALL OTHER DIMS ARE
Non-specified tolerance

R121548

(160 HRS.)

R 95850 - 100 x 100 x 100 12 HRS

R 96911 - 227 Ø X 227 + 19.3

250 = 10"

10" = 26 HRS

Appendix G

Copyright Approval

SME
Society of
Manufacturing Engineers

March 6, 1995

Mr. Dan Koenig
John Deere Waterloo Works

Department 530
Waterloo, Iowa 50704

Dear Koenig:

Your request for permission to use portions of Table 13-4 from the **Rapid Prototyping & Manufacturing: Fundamentals of StereoLithography** book has been approved subject to the following condition:

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Thank you for your interest in the publications of SME.

Sincerely,

Karen Wilhelm
Manager, Book Publishing
Publications Division

KW/fk

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