2001

# Rapid prototyping technologies and build time models

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# RAPID PROTOTYPING TECHNOLOGIES AND BUILD TIME MODELS

June 2001

# "Rapid Prototyping Technologies and Build Time Models"

by Lisa Armano

A Thesis
Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science

In
The Department of Industrial and Manufacturing Systems Engineering

Lehigh University

5/04/01

This thesis is accepted and approved in partial fulfillments of the requirements for the Master of Science.

May 3/2001
Date

Thesis Advisor

Chairperson of Department

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## Abstract

Rapid prototyping, a processing technique that produces parts quickly, has proven to be valuable in product development. The unique method of building a three-dimensional part by layers from bottom to top is advantageous since it is done directly from a computer-aided drawing. Although there are a variety of rapid prototyping processes being used in industry, improvements in each process are still necessary. These improvements are driven by the need to further reduce product cycle time, whether rapid prototyping is used for design feasibility or manufacturing reasons. The aim of this paper is to study each of the developed rapid prototyping processes and to formulate mathematical equations that predict prototype build time and prototype cycle time. The total cycle time includes any pre- and post- processing times and the total build time focuses only on the layer-by-layer building portion of the process. A study is presented for one rapid prototyping technique, laminated object manufacturing, comparing the automated and manual assembly times associated with building a prototype, and identifying the most important factors affecting these times. A practical application of the mathematical model created for this process is also presented, as well as existing problems and research issues associated with it.

## Chapter 1: Introduction

Since 1988, rapid prototyping (RP) has become an important part of product development. The RP process involves rapidly building a physical model of a part, layer by layer, based on a 3-D CAD drawing. Although there are various RP systems, including stereolithography, selective laser sintering, and fused deposition modeling, the basic rapid prototyping process remains the same. Thin cross-sectional slices are generated by computer software on a 3-D drawing, and thin layers of material are created from these slices. The object is built by layering the slices from bottom to top. The starting materials used for rapid prototyping can be solid, liquid, or powder, depending on the specific process.

The purpose of RP technology is to produce physical models quickly. This allows designers to not only communicate their ideas to others with the use of an actual object, but also to run functionality tests. In the end, final products can be brought to market faster and with better quality.

Rapid prototyping serves a variety of applications. Companies in the automobile, aerospace, and consumer products industries have used RP technologies to build models. Even those companies that do not have their own RP equipment can send designs over the Internet and receive a model in a couple of days. Some of the more complex developments include using RP processes to create physiological models of human bones. Using data from computed tomography (CT) images and magnetic resonance imaging (MRI), an accurate model can be built, which enables surgeons to make pre-surgical plans and to practice performing the surgery. Another example is NASA's use of images taken from the Mars Pathfinder camera after it landed. Using the laminated object manufacturing method, NASA was able to create a 3-D topographical map of the Pathfinder landsite. This was later used in planning a safe route for the Mars Sojourner.

The most recent RP research is directed in a few different areas. Collaborations of university researchers, equipment manufacturers, and government agencies are constantly working on improving rapid prototyping systems. Some are interested in creating fabrications from new materials (ceramic, composite, or metal feed stocks); others are interested in making advances in the area of rapid tooling. Researchers are also continuing to develop agile tooling by using RP processes to build molds for mass production of plastic parts, and improving software and accuracy in current systems. The field is growing rapidly and it is very likely that rapid prototyping technology will continue to have a significant impact on design and manufacturing.

Problem Statement

Given these recent developments, it is important for engineers to understand and become familiar with rapid prototyping concepts and be able to differentiate between the many processes that exist. Seven rapid prototyping processes are further discussed in this paper. They are: stereolithography, selective laser sintering, fused deposition modeling, 3-D printing, solid ground curing, ballistic particle manufacturing, and laminated object manufacturing.

It is also of interest to predict "build times" as a function of process parameters with the use of mathematical models. With these predictions, one will not only be able to estimate how long it will take to create a specific prototype, but will also be able to determine how much the prototype build cycle time differs from the previous method of machining. This is important for design for manufacturing and design for assembly applications. Also from these mathematical equations, the level of impact that each parameter has on the total build cycle time can be determined, and can lead to further research on making improvements to those parameters.

Hypotheses

The research hypotheses for this study are that (1), prototype "build times" for various RP processes can be estimated with the use of mathematical models, and that (2), laminated object manufacturing is an economical and time-saving rapid prototyping process that is useful for educational purposes and for constructing small prototypes or subparts of larger prototypes.

## Chapter 2: Literature Research

Extensive research in the field of rapid prototyping has been conducted over the past ten years. The existing rapid prototyping (RP) literature generally covers the following technologies: stereolithography, selective laser sintering, fused deposition modeling, laminated object manufacturing, solid ground curing, ballistic particle manufacturing, and three dimensional printing. Advantages and disadvantages of these technologies, limitations encountered with each technology, practical applications, and possible areas of future research are commonly presented in journal articles and books.

Most resources agree that rapid prototyping minimizes the time to market and improves product quality. Researchers from Daimler-Benz say this is due to the ability to make design changes early and find the optimum solution as well as fixing errors early during the product development stage. However, RP is applied to product development in areas other than design engineering, such as manufacturing and marketing. It is also part of the process planning issue. Multiple factors must be considered in the planning and selecting the best choice, such as cost, cycle time, physical performance, and geometric accuracy.

It is appropriate at this time to briefly describe the main RP processes. More specific details and pictures of each process will be presented in a later chapter.

### Stereolithography (SL)

This process, like most other RP processes, builds the part from bottom up. A vat of liquid resin is spread above an elevator table. A laser beam moves in an x-y direction above the liquid, tracing over the cross section forming a solid layer. The elevator table then drops a specified distance and the next layer is built. The process continues until the part is complete. Parts made by stereolithography often need predesigned supports to hold overhanging regions or tall and thin shapes. Post-curing is thus needed to further solidify the prototype.

The materials generally used in this process are liquid resins (epoxy, photopolymers). The applications most common for this process are models for conceptualization, prototypes for design and functional testing, masters for prototype tooling, patterns for investment casting, sand casting, and molding, and tooling for fixture and tooling design. Some of the main disadvantages of stereolithography are that parts made by this process possess less favorable mechanical and thermal characteristics and age rapidly, and the associated costs per part are significantly higher. Some of the advantages are that it is generally faster and more accurate than other RP processes.

**Selective Laser Sintering (SLS)**

This process is very similar to the SL process, except that the working material is powder. A laser beam traces the cross-section on the powder surface, solidifying it. Another layer of unsintered powder is layered on top and the laser traces another cross section. This process is repeated until the prototype is completed.

The materials used with SLS are nylon, composite or fine nylon, metal powders, or polycarbonate. Some of its applications include concept models, functional models/working prototypes, wax casting patterns, and metal tools. A conceptual model of a hedge trimmer manufactured by Little Wonder, using an SLS system developed by the DTM Corporation, is shown below in figure 1. It was built using selective laser sintering and was used to check design features. Some of the advantages of the selective laser sintering process are that materials are cheaper than SL resins and are nontoxic, it uses a low powered laser, produces high throughput, needs no support, requires little post-processing, and no post-curing. Its main disadvantage is that it has a long cooling cycle.

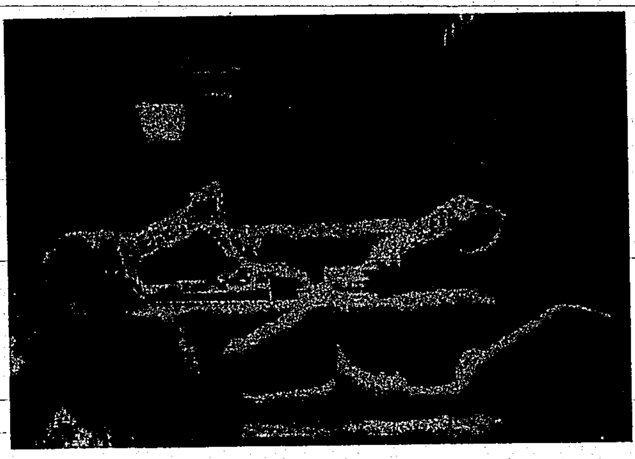

Figure 1 - Little Wonder hedge trimmer (DTM Corporation) [1]

**Fused Deposition Modeling (FDM)**

In this process, wax or plastic is heated and melted in a dispenser, which then deposits the wax or plastic at the desired position. The deposited wax/plastic solidifies to form a hardened layer. Thermal heating causes each layer to be bonded to the previous layer. This process is repeated until the prototype is formed.

The materials used in FDM are investment casting wax and ABS. Its practical applications include models for conceptualization and presentation, prototypes for design, analysis, and functional testing, and patterns and masters for tooling (e.g., molding, investment casting, and sand casting). Figures 2 and 3 show parts that were built with fused deposition modeling, a system manufactured by Stratasys, Inc. Figure 2 shows a medical device that was built for design review and then used for casting. Figure 3

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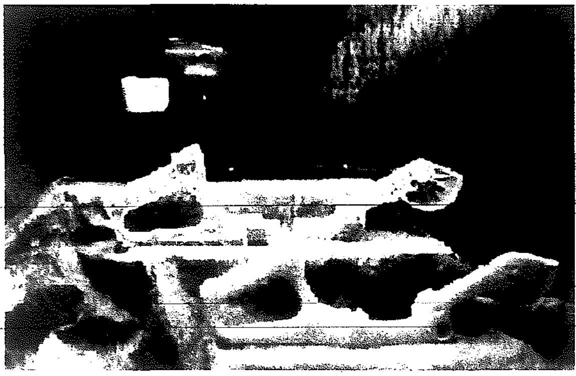

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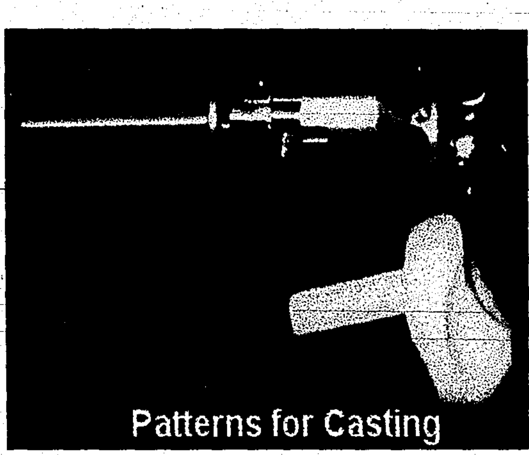
shows parts that were built to test functionality between them. The advantages of FDM are that it is easy to use, there are a variety of cheap materials available, it has multiple safety benefits, there's no waste associated, and no postcuring is required. The main disadvantage is that surface finish is inferior to parts made with SL.



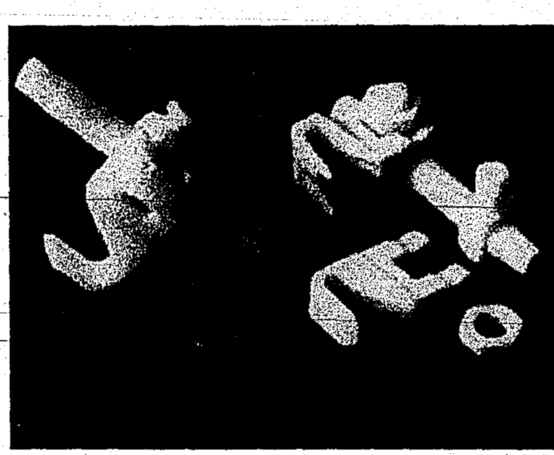



Figure 2 - Wright Medical (Stratasys, Inc)[2] Figure 3 - Danek Group, Inc (Stratasys, Inc)[3]

**Three-dimensional Printing (3-D Printing)**

This process is very similar to the selective laser sintering process. Powder is layered, but an ink-jet printer head traces and ejects binder on the areas that are to be solid. The loose powder acts as support for the part. A platform is lowered to complete the next layer. This process continues until the part is formed. The prototype must then be heat-treated.

The materials used in this process are aluminum oxide and alumina-silica ceramic powders. Some of its applications are in building functional parts and tooling for

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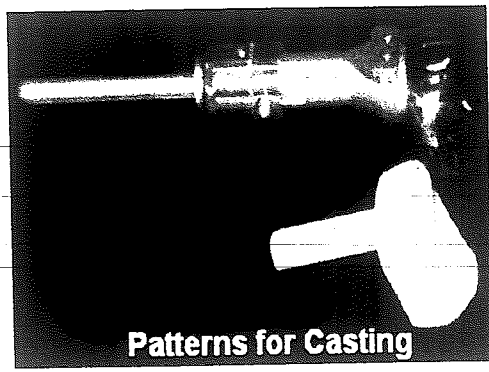


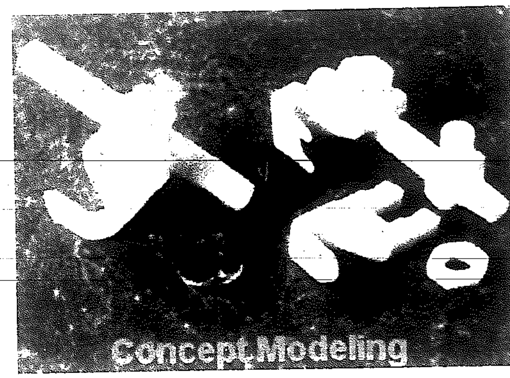


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prototypes. An advantage for this process is that it needs no support structure, but a disadvantage is that it requires heat treatment.

**Ballistic Particle Manufacturing (BPM)**

During this process tiny droplets of material are dropped from an ejector head to the position where they are needed. When these droplets land on the previous layer, the material of the previous layer is softened. Both layers bind together as they are solidified. A base plate then lowers for the next layer. The process continues until the prototype is finished.

Possible materials for this process include thermoplastics, aluminum, and wax. Its main application is in creating concept models for visualization. Advantages of this process are its low cost in comparison to other RP technologies and its ease of use. The disadvantage is that it needs a support structure.

**Solid Ground Curing (SGC)**

In this process masked illumination is used to create each layer image. A liquid photopolymer resin, that solidifies when exposed to a UV light, is spread over the masked image. This is repeated for every layer. In most cases, liquid wax is applied after the unused liquid is cleared away to fill up any gaps created by the liquid resin. Each layer is then milled down to its correct thickness.

The materials generally used for this process include liquid and cured resins. Its applications include tooling and casting, mold and tooling, medical imaging, and conceptual applications. Some of the advantages of this type of system are that no post-curing and no support structure are necessary, it has a high-speed throughput, and it produces accurate parts.

## Laminated Object Manufacturing (LOM)

In this process, a laser beam cuts the profile of the 2D shape generated by the CAD slice files on the sheet material. After each sheet is cut, it is glued or welded together to the preceding sheets, until the prototype is complete. Excess material is then removed. No support or post-curing is needed.

The possible materials for LOM include paper, plastic, or composite sheet stock. Its applications include industrial equipment for aerospace, automotive, consumer products, medical devices, visualization, test for form, fit, & function. Figure 4 shows match plates that were created using Helisys, Inc.'s LOM system, and sand cast to produce prototype metal projectiles. LOM's advantages include low material and investment costs compared to SL and SLS, it allows for subsequent processing (milling, sanding, drilling), it is faster, and little internal stress or undesired deformation exists in completed prototypes. Its disadvantages are that surface finish is questionable, hollow parts are difficult to make, large amounts of scrap are involved, and manning is required.

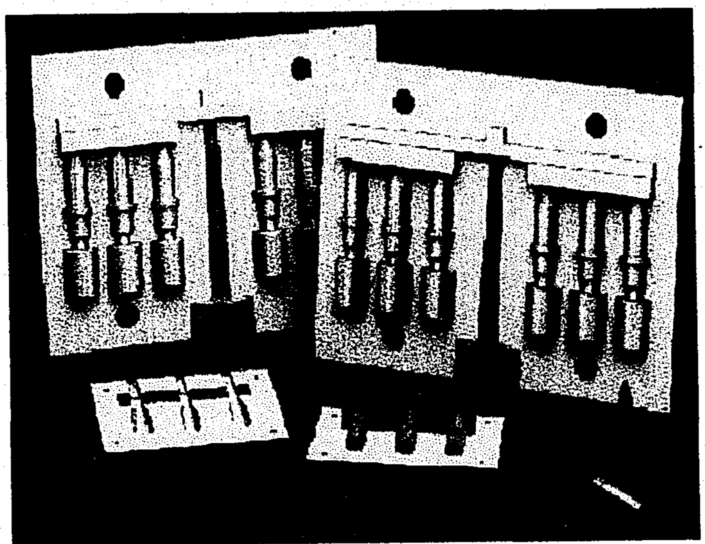

Figure 4 - Lufkin R&D Testing of New Projectile (Helisys, Inc) [4]

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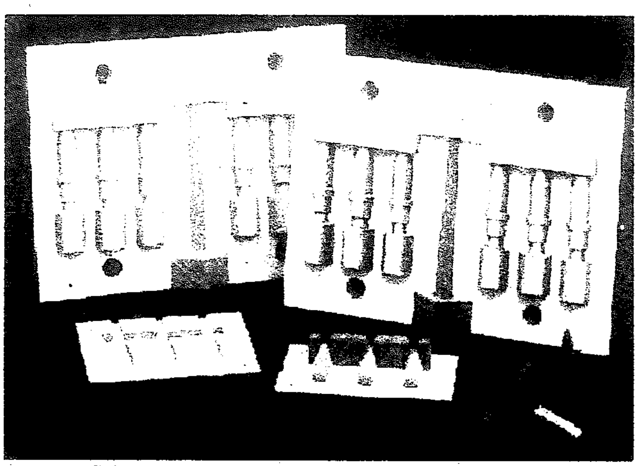

Figure 4 - Lufkin R&D Testing of New Projectile (Helisys, Inc) [4]

[4] Kai and Fai: CD-ROM

Another type of laminated object manufacturing has been named LOM3. The process is similar to the LOM process, except that instead of using a laser, a mechanized knife is used to cut the profiles. This process also requires more manual assembly, but it is less expensive.

**Problem Areas**

Zue Yan and P. Gu cite specific problem areas in rapid prototyping to be part accuracy, limited material variety, and mechanical performance [13]. Other key issues that need to be addressed: making CAD systems more user-friendly, increasing information processing speeds, improving the consistency of good surface finish, increasing cutting speeds, and limiting the necessity of supports during the build process.

There are various research papers that address some of these problems, many from the ***Rapid Prototyping Journal***, which is published in multiple volumes annually. Charity Lynn-Charney and David W. Rosen, from the Georgia Institute of Technology, co-wrote a paper addressing accuracy problems in stereolithography [9]. When parts are designed, there are associated tolerances placed on them. It is difficult to predict whether or not these tolerances can be accomplished with a rapid prototyping system. Charity and Rosen propose an empirical model for stereolithography accuracy that can be used in process planning and evaluating the trade-offs associated with accuracy, surface finish, and build time. Their research indicated four variables as having significant effect on part accuracy with stereolithography: z-wait, hatch overcure, fill overcure, and sweep period, all defined in the paper. Once these variables' responses for common geometric tolerances were determined by graphical means, an accuracy model was built. From this model, process variable values were selected to achieve a specified accuracy, based on prototype specifications. Their paper presents an example demonstrating this as well as a method to incorporate process planning using the accuracy models. [5]

Another major advance in the area of stereolithography is the development of "small spot" and micro stereolithography by the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland. This process is evolving because of an increasing demand for products with small volume and intricate details, and the need to improve the resolution of the stereolithography process. The micro stereolithography machine is in its advanced stages at the Institute. Some of its potential applications are in the manufacture of small mechanical components, the manufacture of parts with smooth surfaces, and molding of small objects [2]. This RP system addresses the issue of size and surface finish limitations with current rapid prototyping technologies.

The micro stereolithography apparatus developed at EPFL uses an integral process, in which each layer is cured over its entire surface in one step, as opposed to a vector-by-vector process, in which each layer is cured over specific points on a surface. A schematic diagram of an integral micro stereolithography apparatus can be seen in Figure 5.

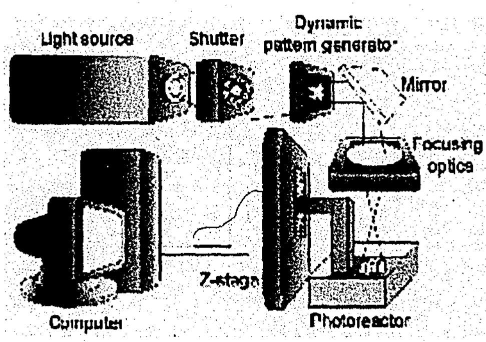


Figure 5 - Micro stereolithography apparatus developed at EPFL [6]

[5] Charity Lynn-Charney and David W. Rosen, "Usage of accuracy models in stereolithography process planning" ***Rapid Prototyping Journal*** 6 (2000): 77,86.
[6] Arnaud Bertsch, Paul Bernhard, Christian Vogt, and Phillippe Renaud "Rapid prototyping of small size objects" ***Rapid Prototyping Journal*** 6 (2000): 260.

One example of a prototype made by this type of system is the scale model of a car (figure 6). The car is made up of 673 layers that are each 5um thick. Details such as the side view mirrors, windows, and the wheels can be seen in this model. Any other rapid prototyping method would not be able to provide such detail.

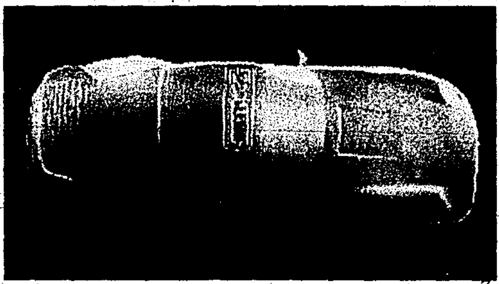

Figure 6 - Scale model of a small car [7]

Some future applications for which EPFL thinks the micro stereolithography process will be useful include small mechanical components, parts with smooth surfaces, and the molding of small objects. An example is the cap of a hearing aid, shown in figure 7.

Figure 7 - Part of a hearing aid [8]

There are still limitations with the micro stereolithography apparatus that must be worked out. The amount of materials available for use is very limited, there is difficulty in removing the supports needed in building these microscopic objects, and the build speed and times are slower and longer than in conventional sterelithography. This is why

[7] Bertsch, Bernhard, Vogt, Renaud, 262.
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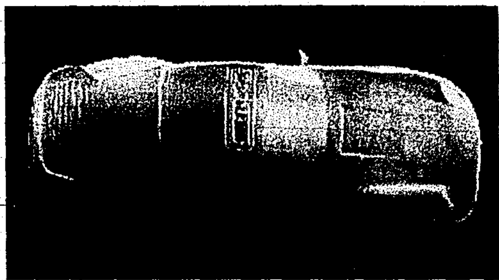

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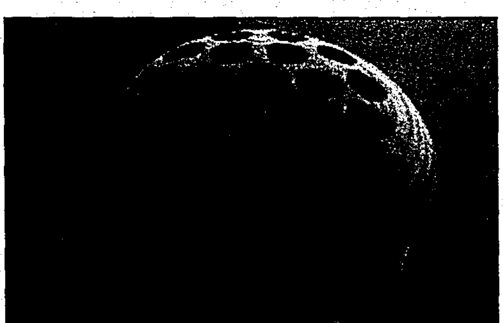

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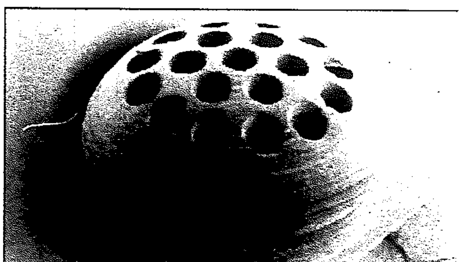

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this technique would only be used in producing high-resolution, small, and complex shaped parts. Although micro stereolithography is not yet commercially available, it is likely that it will be soon.

**New Developments**

The layering techniques used in rapid prototyping have carried over to the fabrication of tooling, called rapid tooling. Most rapid tooling research has been done for blanking dies and dies used in powder metallurgy. New research is being conducted by the University of Warwick's manufacturing group in the area of metal laminating, which is similar to using the LOM technology. Some of the results that the study, called the Lastform programme, was seeking were reduced tooling costs and reduced tooling lead times. A number of universities and industrial partners combined to do research on a process that would make tooling for various processes, based on joining laminated steel sections by cutting each section, applying adhesive or braze, stacking the section, and curing. The researchers were able to rule out particular materials and joining methods due to the nature of the intended process each tool was being made for, as well as the conditions for the tool (tool life, tool operating conditions). The program has developed joining techniques for producing tooling and the universities involved delivered the tooling to their industrial partners. In some cases, these tools are being used to manufacture parts. The program has also demonstrated cost and lead-time savings, which would be especially advantageous in the aerospace industry. [9]

[9] B.G. Bryden., D.I. Wimpenny and I.R. Pashby, "Manufacturing production tooling using metal laminations" ***Rapid Prototyping Journal*** 7 (2000): 52,53,59.

One last research area getting attention is a relatively new technology called stereolithographic (SL) biomodelling. This technology takes three-dimensional computed tomography (CT) to create biomodels, plastic models of biological structures. P.S. D'Urso, R.G. Thompson, and W.J. Earwaker recently did a study on whether SL can realistically be used in the field of paleontology [5]. Typically it is very difficult to make replicas of human anatomy. Internal features can't be reproduced if the traditional method of casting is used. Because human specimens are fragile, physical contact is a major risk factor, which is why biomodelling would be a good alternative. D'Urso, Thompson, and Earwaker generated seven 3-D models of rare fossils from the CT data using their ANATOMICS BIOBUILD system. A typical stereolithography process was used to make the complete solid biomodels and they concluded that the replicates were representative of the actual fossils and that there is definite potential to further use stereolithography in paleontology and similar fields. [10]

Since rapid prototyping is a relatively new field, there are many aspects that are still in question. Individual systems can always be faster, more accurate, and produce higher quality parts. Still, there are other manufacturers looking to develop rapid prototyping systems similar to those that currently exist. Researchers and rapid prototyping equipment manufacturers work together to find ways to improve prototyping build time and reduce the cost of the equipment. These are the current trends and issues that the following pages are built upon.

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[10] P.S. D'Urso, R.G. Thompson and W.J. Earwaker "Stereolithographic biomodelling in paleontology: a technical note" ***Rapid Prototyping Journal*** 6 (2000): 212-215

## Chapter 3: Rapid Prototyping Cycle Times

The approach for this section is to examine each rapid prototyping process, to create a mathematical model for prototype "build time", and to study, in closer detail, one of these processes.

### Rationale

The rationale for this study is based on the fact that there exists multiple RP processes, each developed by many companies into different systems. Since each system has its own array of process parameters and ranges of values, mathematical models that estimate the time required to build a prototype must be done individually, rather than creating one single model that can be applied to every RP process. The creation of these mathematical equations should accomplish these goals: First, they should state the important parameters involved in the process, and give a general idea of what the process entails. Secondly, these equations should be fairly accurate so that comparisons with other manufacturing processes can be made based on prototype cycle and build times. Once these equations are constructed, one of them will be used for experimentation.

The general procedure for formulating each build time model was followed for each of the following processes: selective laser sintering, fused deposition modeling, 3-D printing, ballistic particle manufacturing, solid ground curing, and two forms of laminated object manufacturing. The steps are as follows:

1) Identify every variable
2) Identify the steps in the process
3) For each step, determine the time required
4) Add the step times for 1 layer
5) Formulate the mathematical model for total build time

**Selective Laser Sintering (SLS)**

The variables in the process are: the x-y speed of the laser, $v_{laser}$; diameter of the laser beam, D; cross sectional area of layer, A; and powder spreading time, $T_p$.

**Process Steps**

1. Powder is spread by a roller or some other means across the top of the platform.

2. A laser traces the shape of each cross section, fusing the powder.

Unsintered powder acts as a support for the part.

3. Another layer of powder is spread across the top of the previous layer and the laser traces the next cross section.

4. Process continues until the prototype is finished.

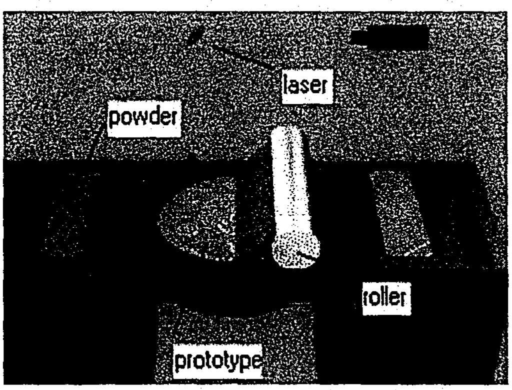


Figure 8 – Selective laser sintering (DTM Corporation) [11]

**Step Times**

For step 1, $t=T_p$

For step 2, $t = \dfrac{A_i}{v_{laser} D}$

[11] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

**Selective Laser Sintering (SLS)**

The variables in the process are: the x-y speed of the laser, $v_{laser}$; diameter of the laser beam, D; cross sectional area of layer, A; and powder spreading time, $T_p$.

**Process Steps**

1. Powder is spread by a roller or some other means across the top of the platform.

2. A laser traces the shape of each cross section, fusing the powder. Unsintered powder acts as a support for the part.

3. Another layer of powder is spread across the top of the previous layer and the laser traces the next cross section.

4. Process continues until the prototype is finished.

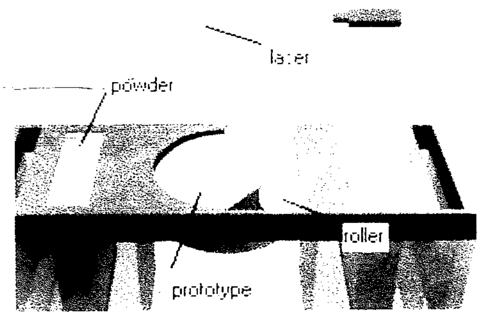


Figure 8 – Selective laser sintering (DTM Corporation) [11]

**Step Times**

For step 1, $t = T_p$

For step 2, $t = \dfrac{A_i}{v_{laser} D}$

[11] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

The time to build one layer is then:

$$T_i = T_p + \frac{A_i}{v_{laser} D} \qquad \text{(Eq.3-1)}$$

And the time to build the entire prototype is:

$$T_b = \sum_{i=1}^{i} T_i \quad \text{where } i \text{ is the layer number} \qquad \text{(Eq.3-2)}$$

The total cycle time is therefore equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-3)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up (importing the CAD drawing, preparing the slice files, and sending the path data to the mechanical system), and $T_{post}$ is the time associated with removing the excess powder to reveal the final prototype.

**Fused Deposition Modeling (FDM)**

The variables in the process are: the x-y speed of the dispenser, $v_{dispenser}$; diameter of the spot size of the wax dispenser, D; and cross sectional area of a layer, A.

**Process Steps**

1. Wax/plastic filament is melted in the dispenser.

2. Dispenser extrudes a thin layer of wax/plastic at the desired position.

3. Deposited wax/plastic solidifies and the dispenser moves upward for the next layer.

4. Process is repeated until the part is formed.

5. Support is removed to reveal the final prototype.

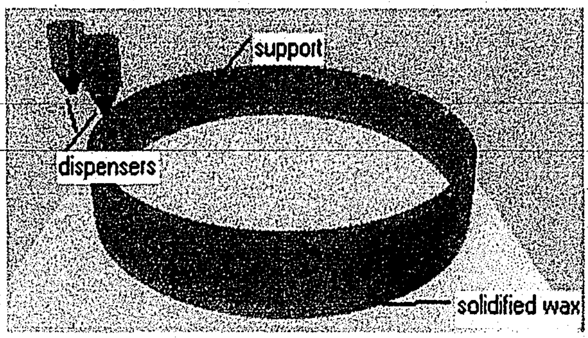


Figure 9 – Fused deposition modeling (Stratasys, Inc) [12]

**Step Times**

For step 2, $t = \frac{A_i}{v_{dispenser} D}$

The time to build one layer is then:

$$T_i = \frac{A_i}{v_{dispenser} D} \qquad \text{(Eq.3-4)}$$

And the time to build the entire prototype is:

$$T_b = \sum_{i=1}^{i} T_i \quad \text{where } i \text{ is the layer number} \qquad \text{(Eq.3-5)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-6)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with removing the built-in support to reveal the final prototype.

**3D Printing**

The variables in the process are: the x-y speed of the ink-jet printer, $v_p$; diameter of the printer head (assume circular), D; cross sectional area of layer, A; powder

[12] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

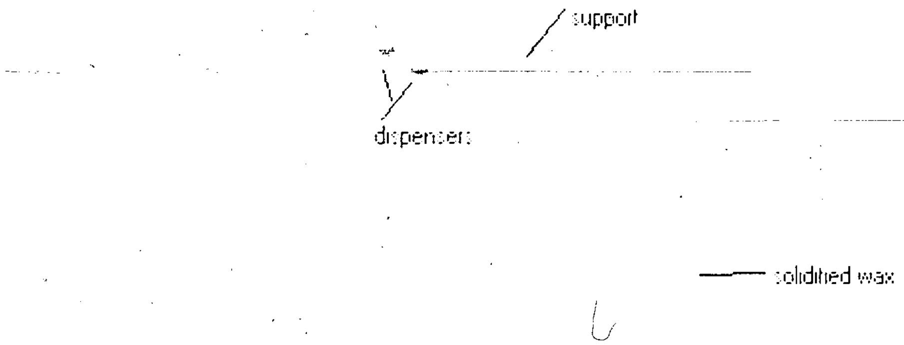


Figure 9 – Fused deposition modeling (Stratasys, Inc) [12]

**Step Times**

For step 2, $t = \dfrac{A_i}{v_{dispenser} D}$

The time to build one layer is then:

$$T_i = \frac{A_i}{v_{dispenser} D} \qquad \text{(Eq.3-4)}$$

And the time to build the entire prototype is:

$$T_b = \sum_{i=1}^{i} T_i \quad \text{where } i \text{ is the layer number} \qquad \text{(Eq.3-5)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-6)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with removing the built-in support to reveal the final prototype.

**3D Printing**

The variables in the process are: the x-y speed of the ink-jet printer, $v_p$; diameter of the printer head (assume circular), D; cross sectional area of layer, A; powder

[12] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

spreading time, $T_p$; and delay time for platform to move, $T_d$.

**Process Steps**

1. Powder is layered.

2. The ink-jet printer head traces and ejects binder on the areas that are to be solid. Loose powder acts as a support.

3. Platform is lowered to complete the next layer.

4. Process continues until the part is formed.

5. Part is heat-treated, and loose powders are removed to reveal the prototype.

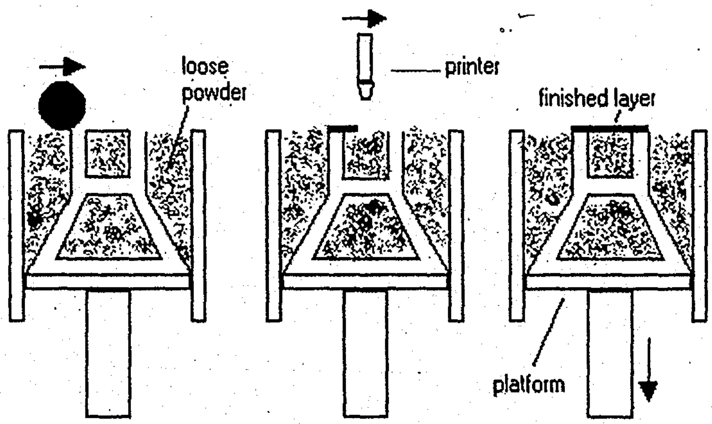


Figure 10 – 3D Printing (steps 1,2, and 3) [13]

**Step Times**

For step 1, $t=T_p$

For step 2, $t=\dfrac{A_i}{v_p D}$

For step 3, $t=T_d$

The time to build one layer is then:

[13] Zue Yan and P. Gu "A review of rapid prototyping technologies and systems" ***Computer Aided Design*** 28 (1996): 312

$$T_i = T_p + \frac{A_i}{v_p D} + T_d \qquad \text{(Eq.3-7)}$$

And the time to build the entire prototype is:

$$T_b = \sum_{i=1}^{i} T_i \quad \text{where } i \text{ is the layer number} \qquad \text{(Eq.3-8)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-9)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with heat-treating the prototype.

**Ballistic Particle Manufacturing (BPM)**

The variables in the process are: the x-y speed of the droplet nozzle, $v_{nozzle}$; diameter of the droplet size of the nozzle, D; cross sectional area, A; and delay time for base plate to move, $T_d$.

**Process Steps**

1. A nozzle deposits droplets on the areas that are to be solid and binds with the previous layer.
2. Platform is lowered to complete the next layer.
3. Process continues until the part is formed.

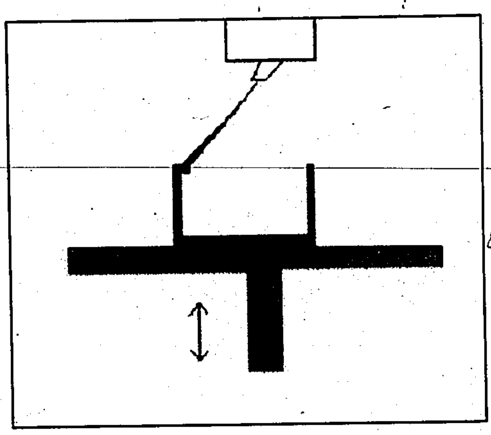

Figure 11 – Ballistic particle manufacturing [14]

**Step Times**

For step 1, $t = \frac{A_i}{v_{nozzle} D}$

For step 2, $t = T_d$

The time to build one layer is then:

$$T_i = T_d + \frac{A_i}{v_{nozzle} D} \qquad \text{(Eq.3-10)}$$

And the time to build the entire prototype is:

$$T_b = \sum_{i=1}^{i} T_i \quad \text{where } i \text{ is the layer number} \qquad \text{(Eq.3-11)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-12)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with removing the support to reveal the final prototype.

[14] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (Singapore: John Wiley & Sons, 1997) 142.

## Solid Ground Curing (SGC)

The variables in the process are: mask preparation time, $T_{mask}$; time to spread resin on work surface, $T_{mat}$; solidification by UV light, $T_{uv}$; time for vacuum suction, $T_{vs}$; time to apply wax, $T_{wax}$; and milling time, $T_{mill}$.

**Process Steps**

1. A charged image is developed electrostatically on a mask plate.
2. Photopolymer liquid resin is applied to the layer.
3. UV light passes through the mask, fully curing all exposed areas.
4. All residual unsolidified resin is wiped off, while the next mask is being created.
5. Wax is applied to fill in all voids left while removing the photopolymer.
6. Layer is milled to correct thickness.
7. Process continues with the next layer until the part is formed.

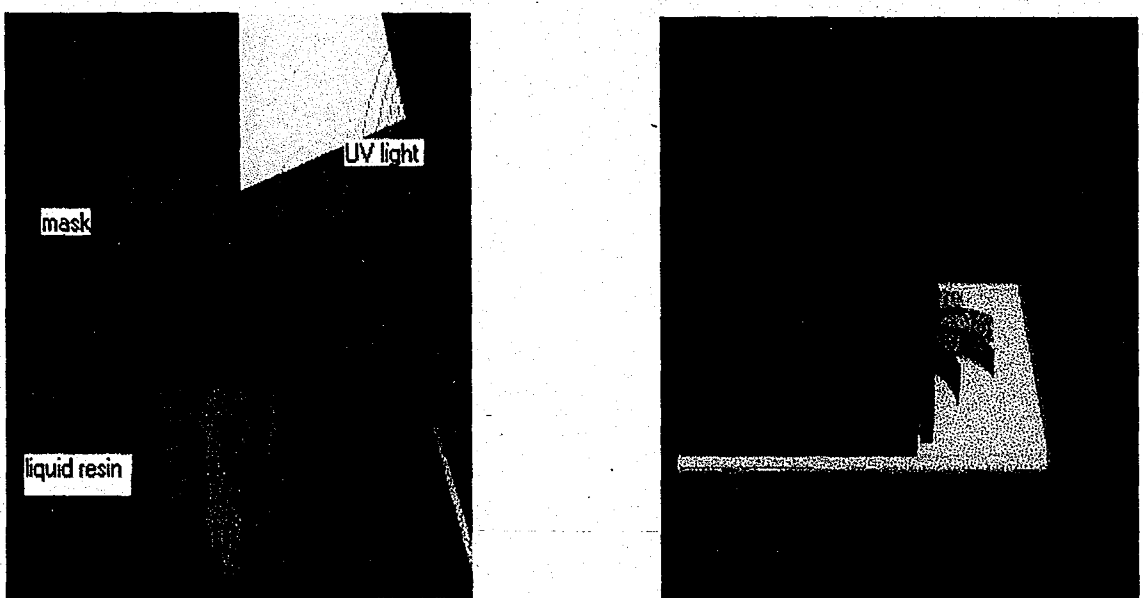


Figure 12, 13 – Solid ground curing, steps 3 and 4 (Cubital, Ltd) [15]

[15] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

## Solid Ground Curing (SGC)

The variables in the process are: mask preparation time, $T_{mask}$; time to spread resin on work surface, $T_{mat}$; solidification by UV light, $T_{uv}$; time for vacuum suction, $T_{vs}$; time to apply wax, $T_{wax}$; and milling time, $T_{mill}$.

**Process Steps**

1. A charged image is developed electrostatically on a mask plate.

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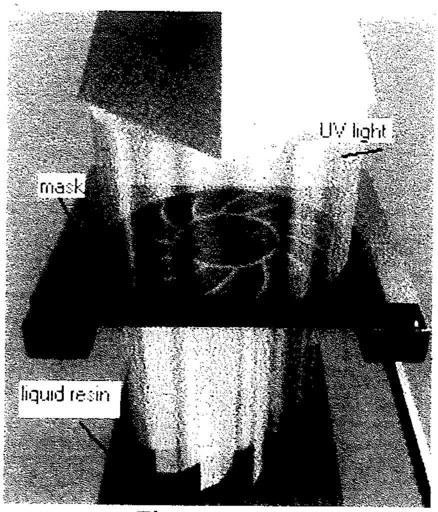
3. UV light passes through the mask, fully curing all exposed areas.

4. All residual unsolidified resin is wiped off, while the next mask is being created.

5. Wax is applied to fill in all voids left while removing the photopolymer.

6. Layer is milled to correct thickness.

7.Process continues with the next layer until the part is formed.



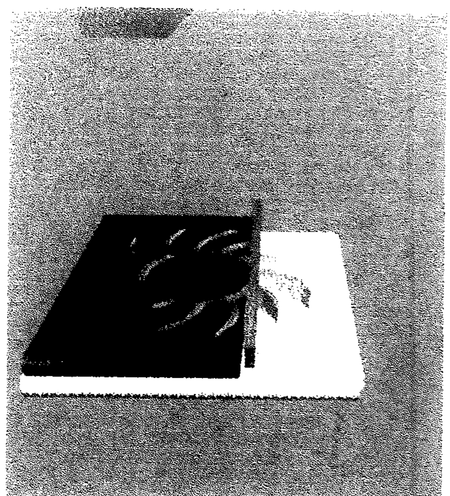



Figure 12, 13 – Solid ground curing, steps 3 and 4 (Cubital, Ltd) [15]

[15] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

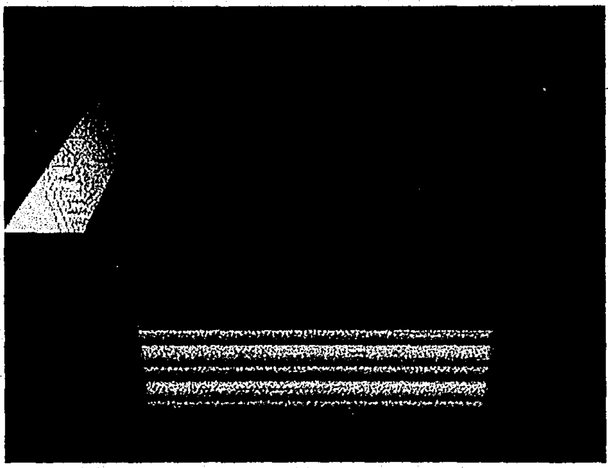


Figure 14 – Solid ground curing, step 6 (Cubital, Ltd) [16]

**Step Times**

For step 1, $t = T_{mask}$

For step 2, $t = T_{mat}$

For step 3, $t = T_{uv}$

For step 4, $t = T_{vs}$

For step 5, $t = T_{wax}$

For step 6, $t = T_{mill}$.

The time to build the first layer is:

$T_1 = T_{mask} + T_{mat} + T_{uv} + T_{vs} + T_{wax} + T_{mill}$

Since the mask preparation is done concurrently with steps 4-6, the time to build the second through final layers is:

$$T_i = T_{mat} + T_{uv} + T_{vs} + T_{wax} + T_{mill} \qquad \text{(Eq.3-13)}$$

[16] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

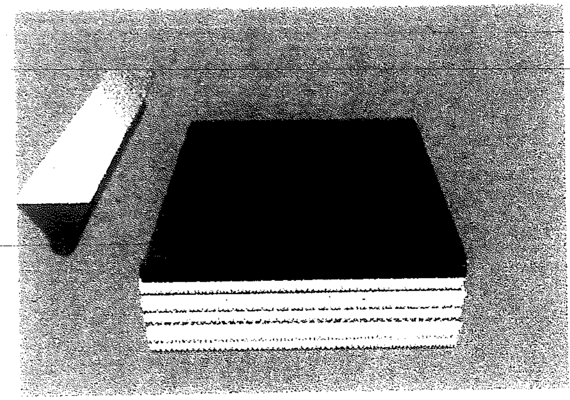


Figure 14 – Solid ground curing, step 6 (Cubital, Ltd) [16]

**Step Times**

For step 1, $t = T_{mask}$

For step 2, $t = T_{mat}$

For step 3, $t = T_{uv}$

For step 4, $t = T_{vs}$

For step 5, $t = T_{wax}$

For step 6, $t = T_{mill}$

The time to build the first layer is:

$T_1 = T_{mask} + T_{mat} + T_{uv} + T_{vs} + T_{wax} + T_{mill}$

Since the mask preparation is done concurrently with steps 4-6, the time to build the second through final layers is:

$$T_i = T_{mat} + T_{uv} + T_{vs} + T_{wax} + T_{mill} \quad \text{(Eq.3-13)}$$

[16] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing*** (CD-ROM) (Singapore: John Wiley & Sons, 1997)

And the time to build the entire prototype is:

$$T_b = T_l + \sum_{i=2}^{i} T_i \text{ where } i \text{ is the layer number} \quad \text{(Eq.3-14)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \quad \text{(Eq.3-15)}$$

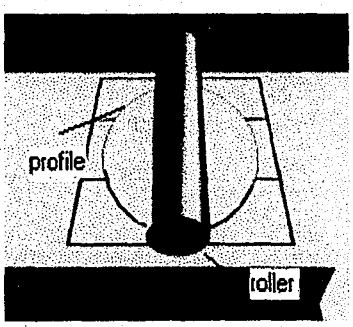
where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with melting away the support wax to reveal the final prototype.

**Laminated Object Manufacturing (LOM)**

The variables in this process are: the x-y speed of the laser, $v_{laser}$; the perimeter of the 2-D shape and the enclosing boundary, $P_i$; and delay time for platform to move, $T_d$.

**Process Steps**

1. Laser cuts 2-D profile on a sheet of material, which is bonded to the previous layer
2. The platform lowers, a new sheet is added, and the process repeats until the entire part is built.
3. Excess blocks of material are removed to reveal desired part.



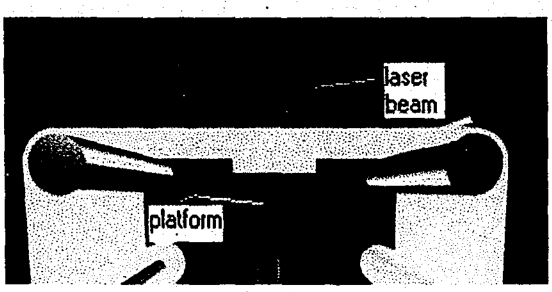




Figure 15, 16 - Laminated object manufacturing, steps 1 and 2 (Helisys, Inc) [17]

[17] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing (CD-ROM)*** (Singapore: John Wiley & Sons, 1997)

And the time to build the entire prototype is:

$$T_b = T_l + \sum_{i=2}^{l} T_i \text{ where } i \text{ is the layer number} \qquad \text{(Eq.3-14)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-15)}$$

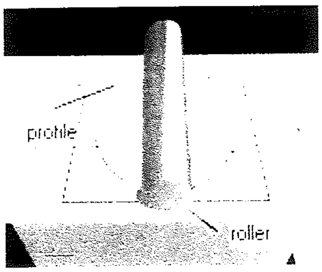
where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with melting away the support wax to reveal the final prototype.

### Laminated Object Manufacturing (LOM)

The variables in this process are: the x-y speed of the laser, $v_{laser}$; the perimeter of the 2-D shape and the enclosing boundary, $P_i$; and delay time for platform to move, $T_d$.

**Process Steps**

1. Laser cuts 2-D profile on a sheet of material, which is bonded to the previous layer
2. The platform lowers, a new sheet is added, and the process repeats until the entire part is built.
3. Excess blocks of material are removed to reveal desired part.



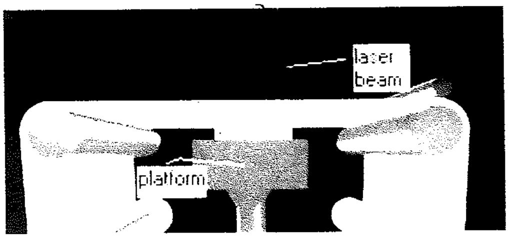




Figure 15, 16 - Laminated object manufacturing, steps 1 and 2 (Helisys, Inc) [17]

[17] Chua Chee Kai and Leong Kah Fai, ***Rapid Prototyping, Principles and Applications in Manufacturing (CD-ROM)*** (Singapore: John Wiley & Sons, 1997)

**Step times**

For step 1, $t = \frac{P_i}{v_{laser}}$

For step 2, $t = T_d$

Step 3 is not included at this point since it happens after all layers are completed

The time to build one layer is then:

$$T_i = T_d + \frac{P_i}{v_{laser}} \qquad \text{(Eq.3-16)}$$

And the time to build the entire prototype is:

$$T_b = \sum_{i=1}^{i} T_i \quad \text{where } i \text{ is the layer number} \qquad \text{(Eq.3-17)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{post} \qquad \text{(Eq.3-18)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{post}$ is the time associated with removing the excess material to reveal the final prototype.

**LOM3**

(For a part with uniform cross-sectional area)

This version of the LOM process uses a cutter instead of a laser to cut slice profiles and surrounding enclosures on adhesive paper. The slices are then manually stacked to form the prototype. The variables in this process are: the x-y speed of the cutter, $v_{cutter}$; the perimeter of the 2-D shape, and enclosure if necessary, $P_i$; number of cuts, c; and number of slices on sheet *i*, $n_i$ (separator cuts and registration hole cut time are assumed to be negligible).

**Process Steps**

1. Sheet loaded

2. Cutter cuts all profile slices, separator cuts on one sheet

3. Sheet is removed and step 1 repeated

4. Manual assembly on registration board

**Step times**

For step 1, $t = T_{sheet}$

For step 2, $t = cn_i \frac{P_i}{v_{cutter}}$

For step 4, $t = T_{manual}$

The time to complete one sheet is then:

$$Ti = T_{sheet} + cn_i \frac{P_i}{v_{cutter}} \qquad \text{(Eq.3-19)}$$

For x number sheets with identical number of slices,

$$T = x * T_i$$

And the time to build the entire prototype is:

$$T_b = x * T_i + T_{manual} \qquad \text{(Eq.3-20)}$$

The total cycle time is therefore, equal to:

$$T_c = T_{manualprep} + T_b + T_{final} \qquad \text{(Eq.3-21)}$$

where $T_{manualprep}$ is the manual preparation time of setting the system up and $T_{final}$ is the time associated with putting a finishing coat on the final prototype.

**Procedures**

The last rapid prototyping process mentioned was used in experimentation. The first objective of the experimentation was to look at the build times of prototypes being constructed with the LOM3 process and to compare the automated and manual sections of the build time. This information will further be used in designing a laboratory experience for college students. The second objective is to observe the effect on build time of varying process parameters.

The equipment used for experimentation is the Rapid Prototyping JP System 5 developed by the Schroff Development Corporation. This laminated object manufacturing process uses a cutter to cut paper sheets and requires manual assembly. A registration board, pins, and adhesives are available to aid in the manual assembly portion. Prototypes were built on the equipment described above and times associated with the initial preparation of the system, the automated portion of the build time, and the manual portion of the build time were recorded. All of the system parameters, including cutting speed, cutting depth, and pressure were set at the optimal values. Actual prototype build times were recorded by the use of a watch. These build times were then used to determine what would be a good prototype to construct during a 3 hour lab period.

The second part of experimentation was to observe the effect on build time of varying the cutting speed or the cutting pressure and to investigate the system's limitations, as well as its unique attributes.

## Chapter 4: Discussion

### JP System 5

The JP System 5 system developed by the Schroff Development Corporation is a laminated object manufacturing system. The difference between this particular system and most other LOM systems is that it is less expensive because it does not use a laser for cutting. Instead it uses a knife device to cut the slices. Generally, it produces significantly smaller prototypes and does not have the same accuracy as the more expensive systems. However, it is a good inexpensive introduction to rapid prototyping and is suitable for students as well as for industry purposes.

The system is made up of the following components, 3-D modeling software, JP System 5 software, a printer for cutting, and a registration board used for manual assembly of the prototype. The 3-D modeling software is used to create a CAD drawing of the part to be built, which is imported as an STL file into the JP System 5 software. The drawing is then sliced into cross-sectional layers and these layers are arranged on sheet layouts to prepare for cutting. After all of the system parameters are set, the slice information is sent to the printer, which cuts the paper or plastic sheets. The slices are then assembled manually on the registration board to build the prototype. A finish coating is necessary at the end. [18]

The system must be configured in order for this process to work properly. The JP System 5 configure tab allows for this to happen. Under this command, the type of material and material size, as well as the configuration of the registration board, can be

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[18] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5*** Schroff Development Corporation, Kansas 1999, 1-1.

set. This includes the distance between major registration pins, which are critical in performing the manual operation, as well as the spacing between the minor registration pins, which are also critical during manual assembly. If these numbers are not set correctly, the sheets will not fit onto the registration board and the slices will not line up correctly. The prototype would be difficult to assemble and would most likely be inaccurate.

Once the system software is configured, the printer settings should be checked. The two parameters that are most important are the cutter pressure and the cutter velocity. Typically, the cutter pressure ranges from 15-17 psi, and the velocity is about 30.[19]

**Prototype Example**

The following is an example of a prototype built by the JP System 5 rapid prototyping system, and the steps taken to build it.[20]

1. A model is drawn with a CAD program, which is shown in Figure 15. The CAD software provided with the JP System 5 is Silverscreen Modeler.

2. This model is then imported into the JP System 5 and properly oriented. The flattest portion of the model should lay flat against the x and z axes, as shown in Figure 16.

3. The software slices the model. A picture of the model with slices can be seen in Figure 17.

4. The layout of the cross-sectional layers is examined and changed if necessary.

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[19] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5,*** Schroff Development Corporation, Kansas 1999, Appendix C-6.

[20] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5,*** Schroff Development Corporation, Kansas 1999, 2-1.

Pictures of the sheet layouts are shown in Figures 18 through 20.

5. The sheets are cut, and are ready for manual assembly.

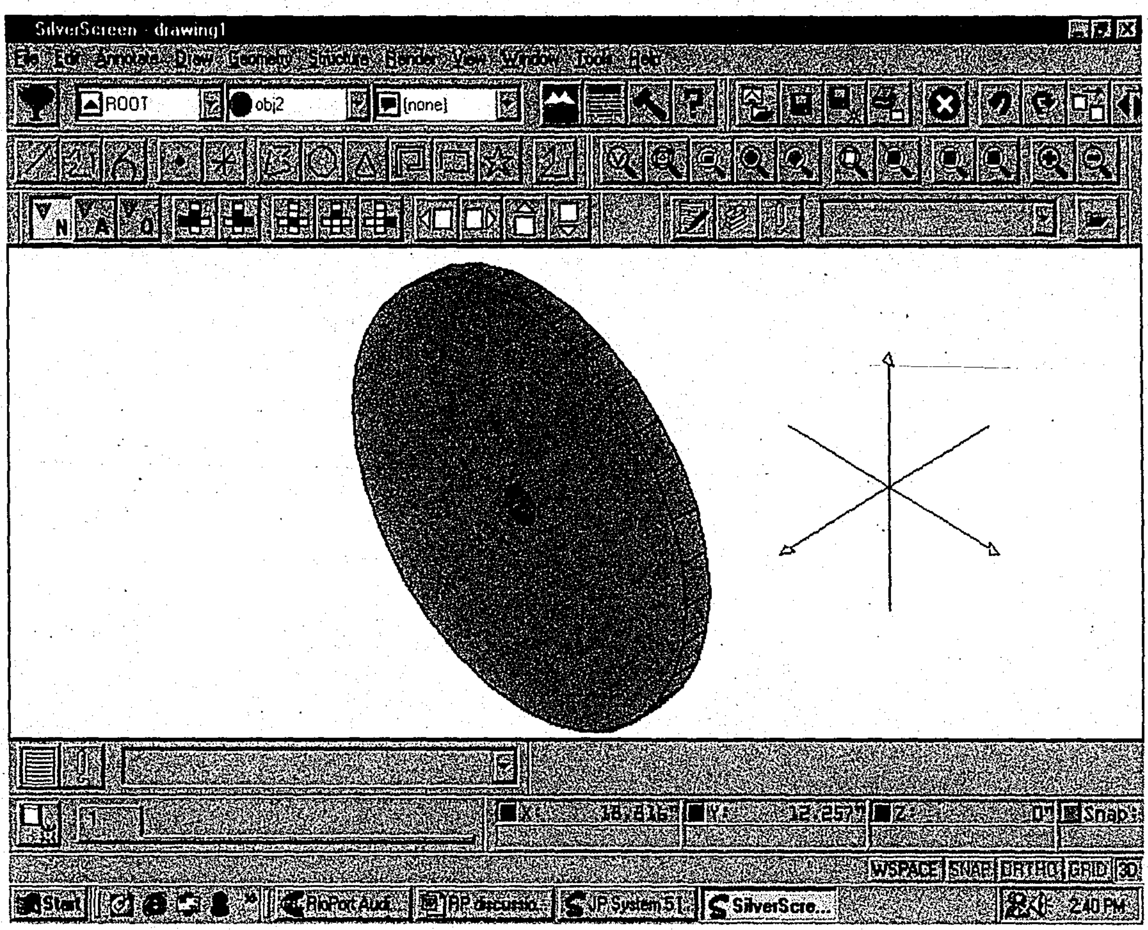


Figure 15 - Silverscreen Modeler 3-D CAD drawing

Pictures of the sheet layouts are shown in Figures 18 through 20.

5. The sheets are cut, and are ready for manual assembly.

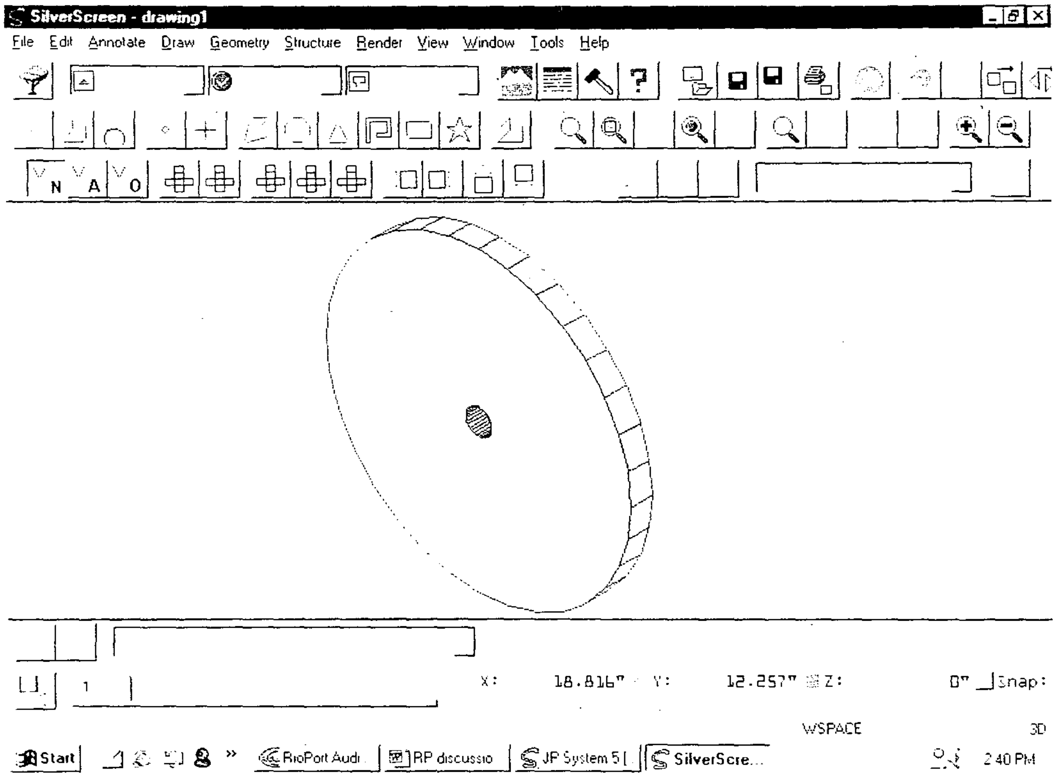


Figure 15 - Silverscreen Modeler 3-D CAD drawing

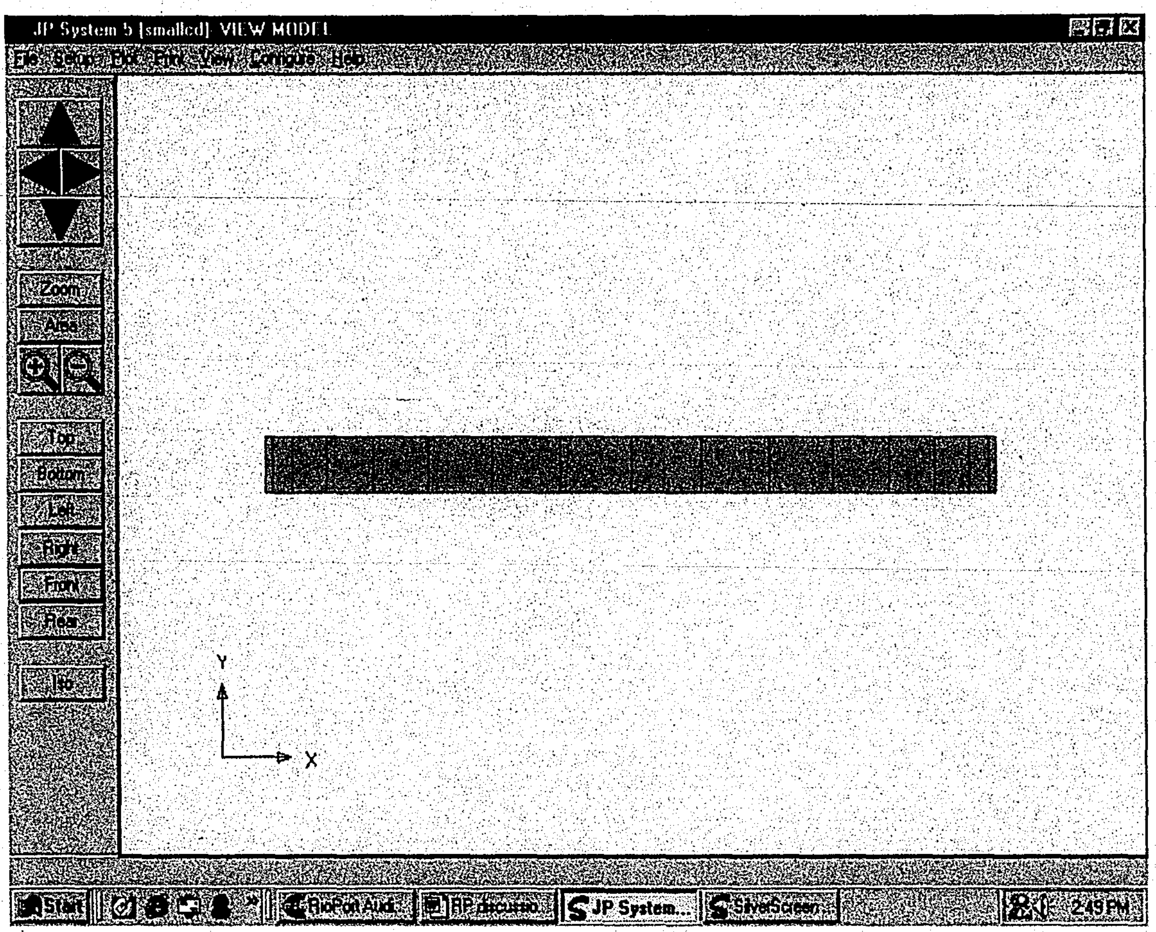


Figure 16 – Model imported and rotated to proper position

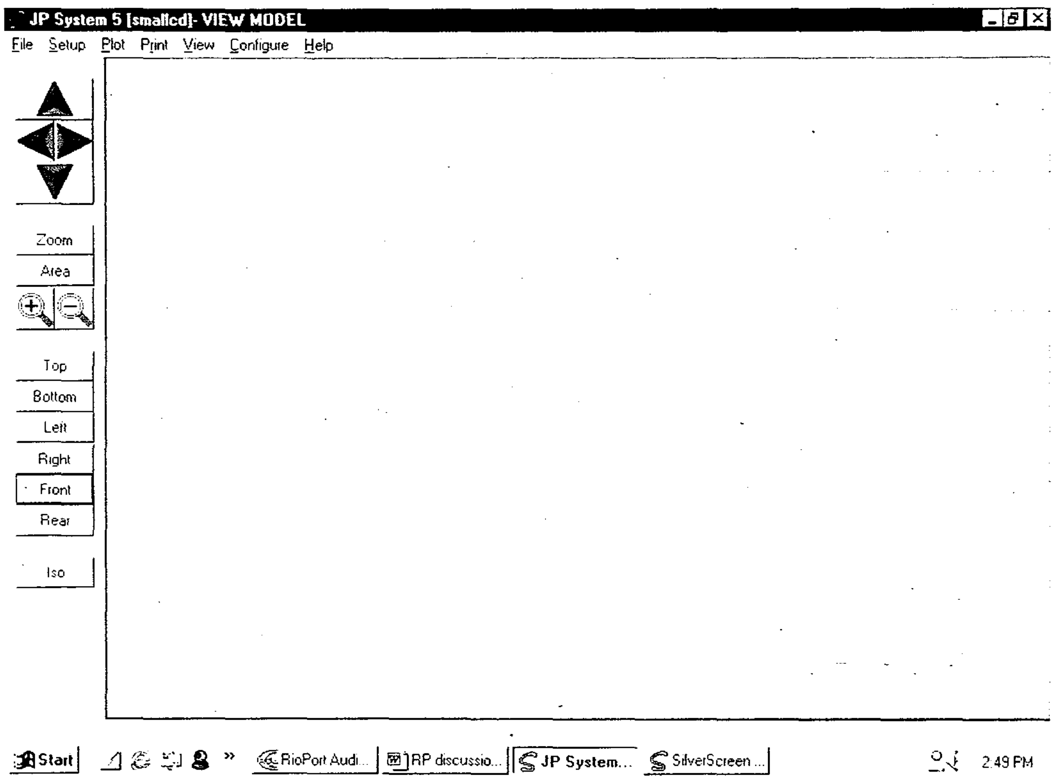


Figure 16 – Model imported and rotated to proper position

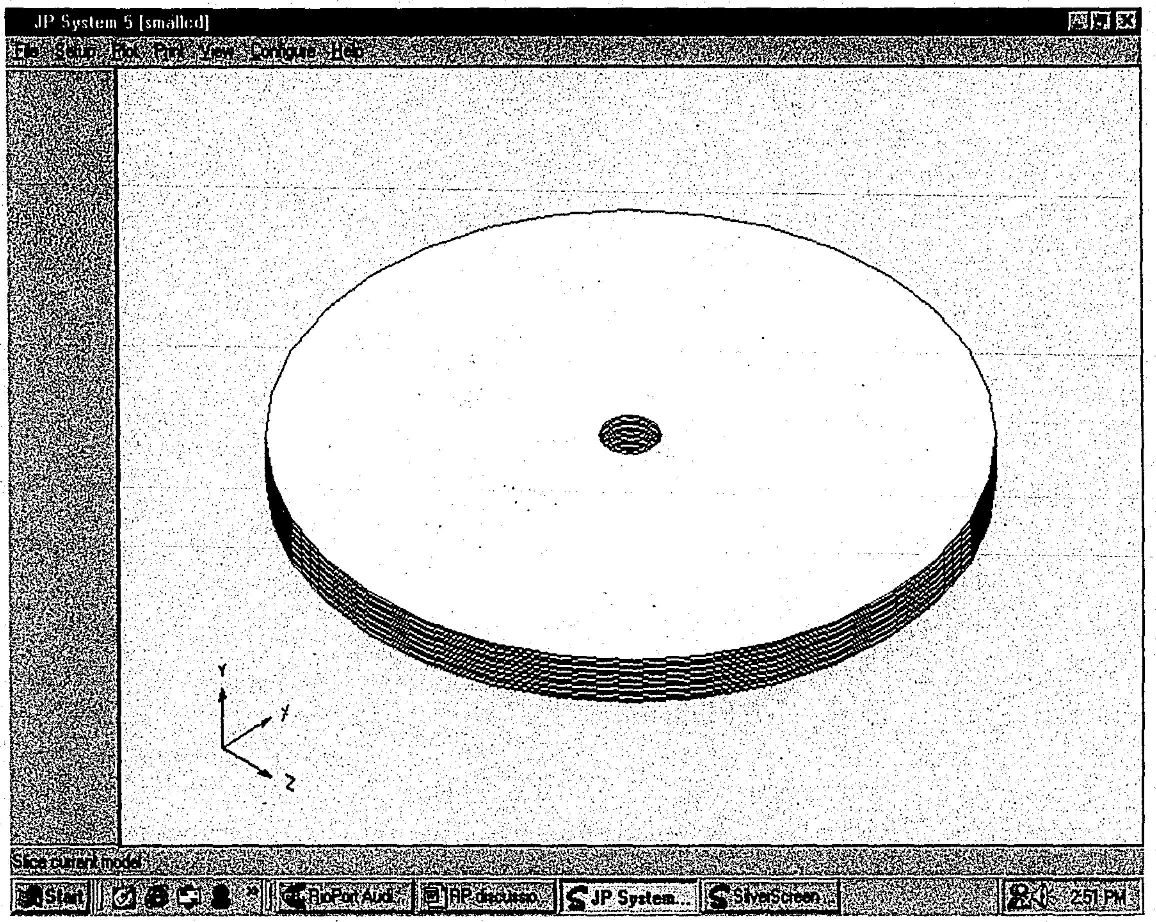


Figure 17 – Sliced CAD drawing

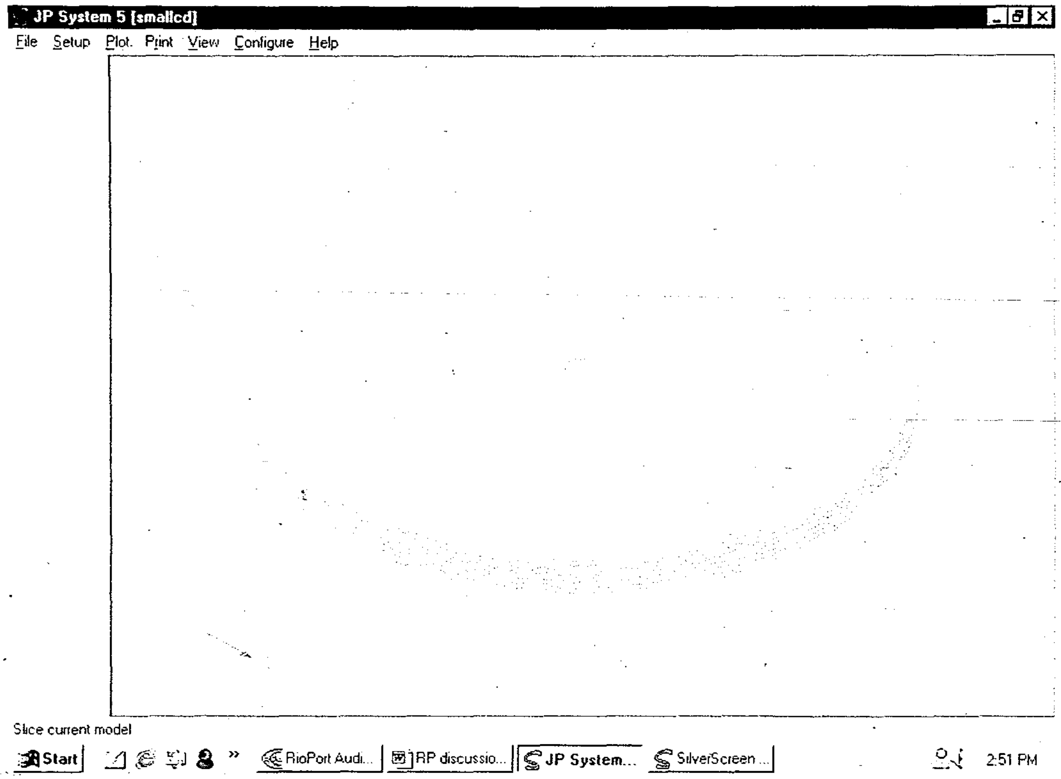


Figure 17 – Sliced CAD drawing

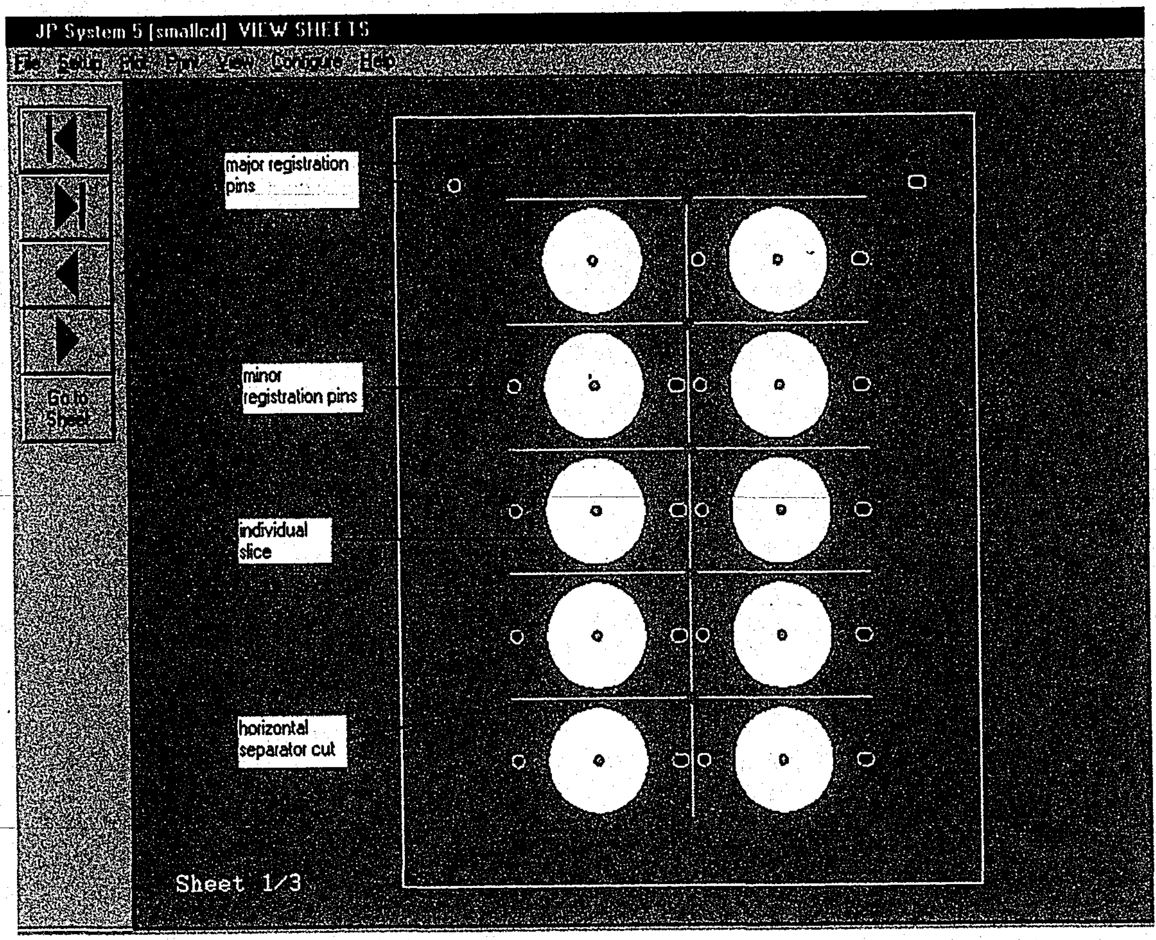


Figure 18 – Sheet layout 1

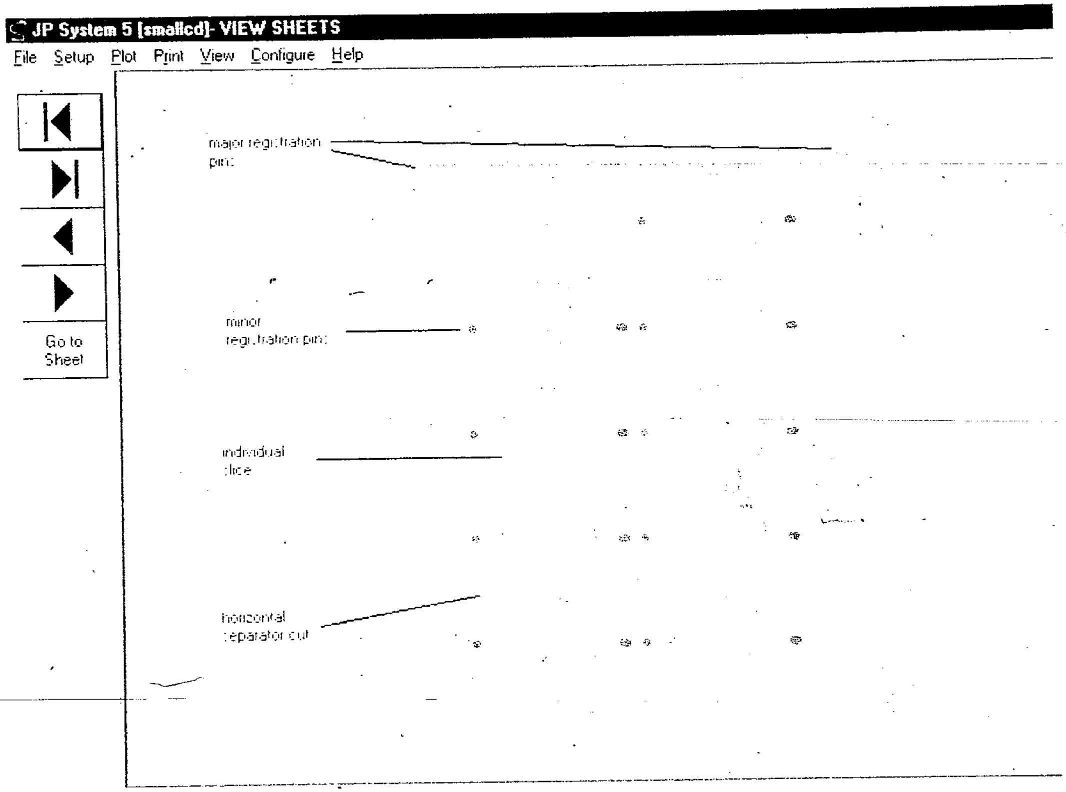


Figure 18 – Sheet layout 1

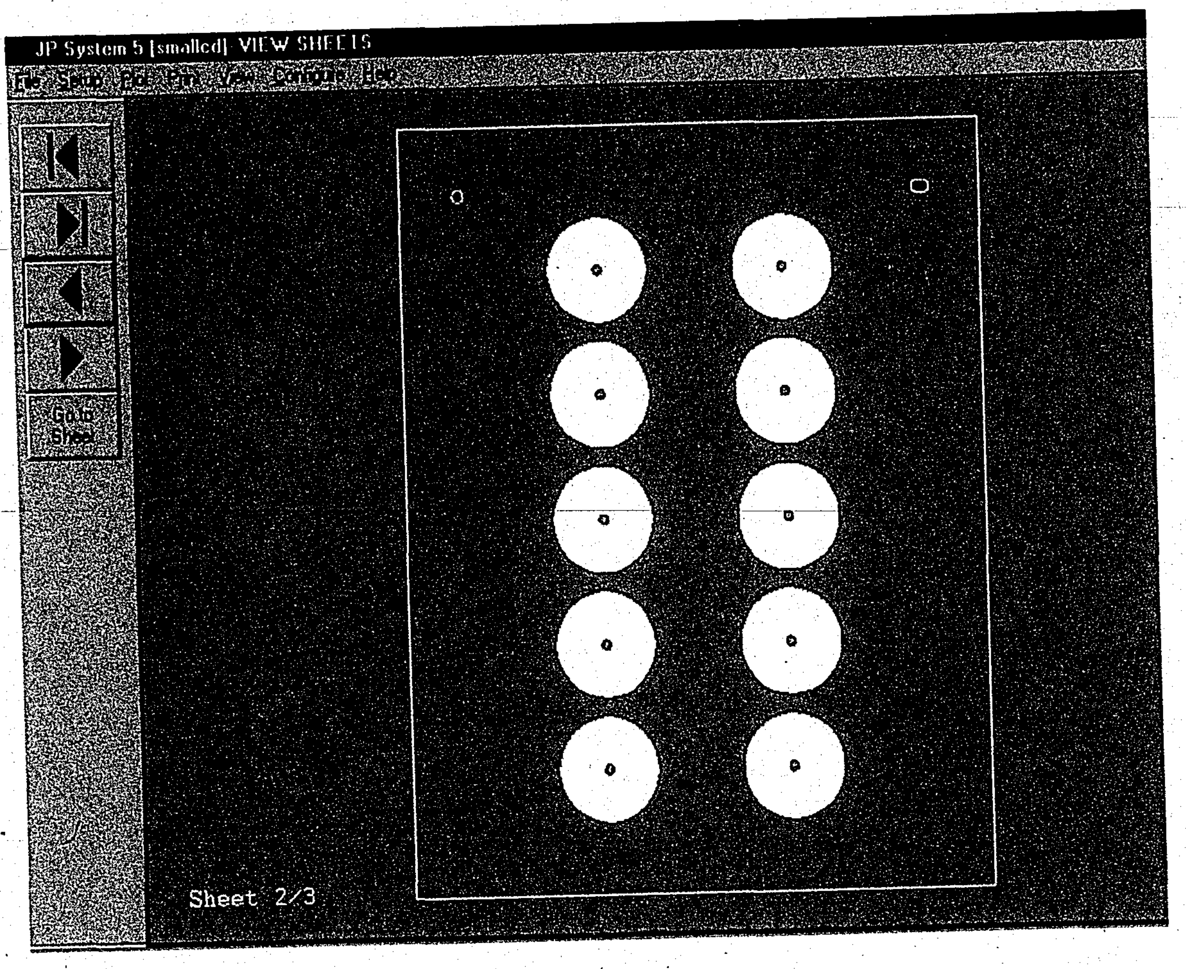


Figure 19 – Sheet layout #2

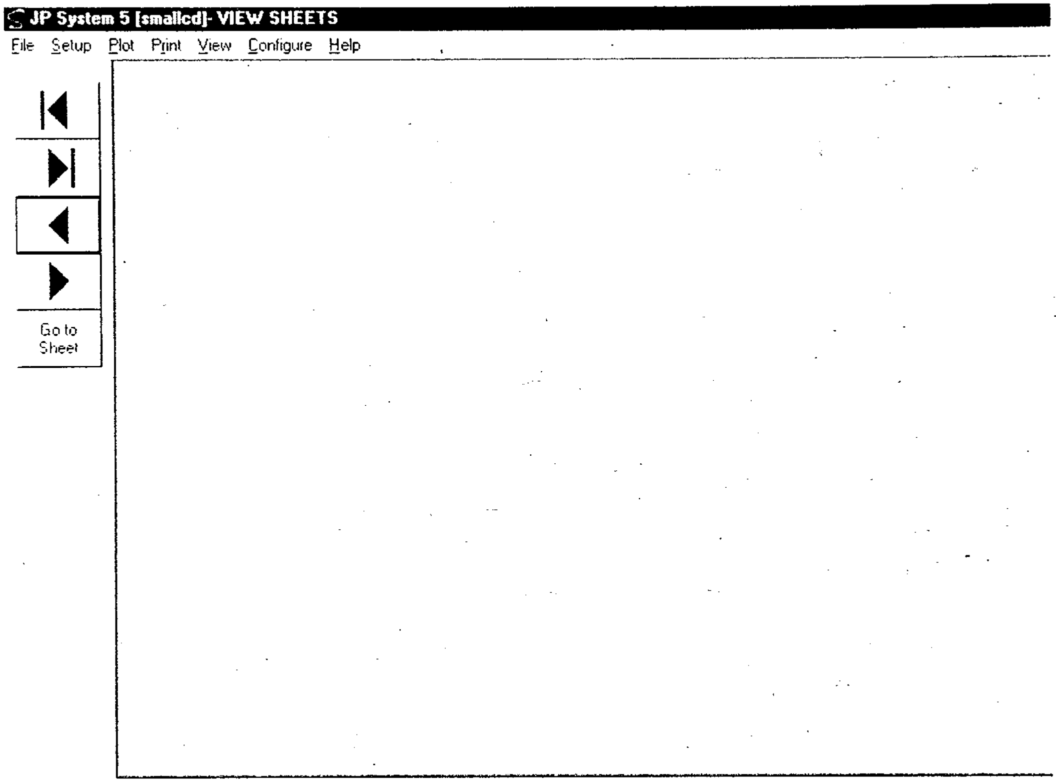


Figure 19 – Sheet layout #2

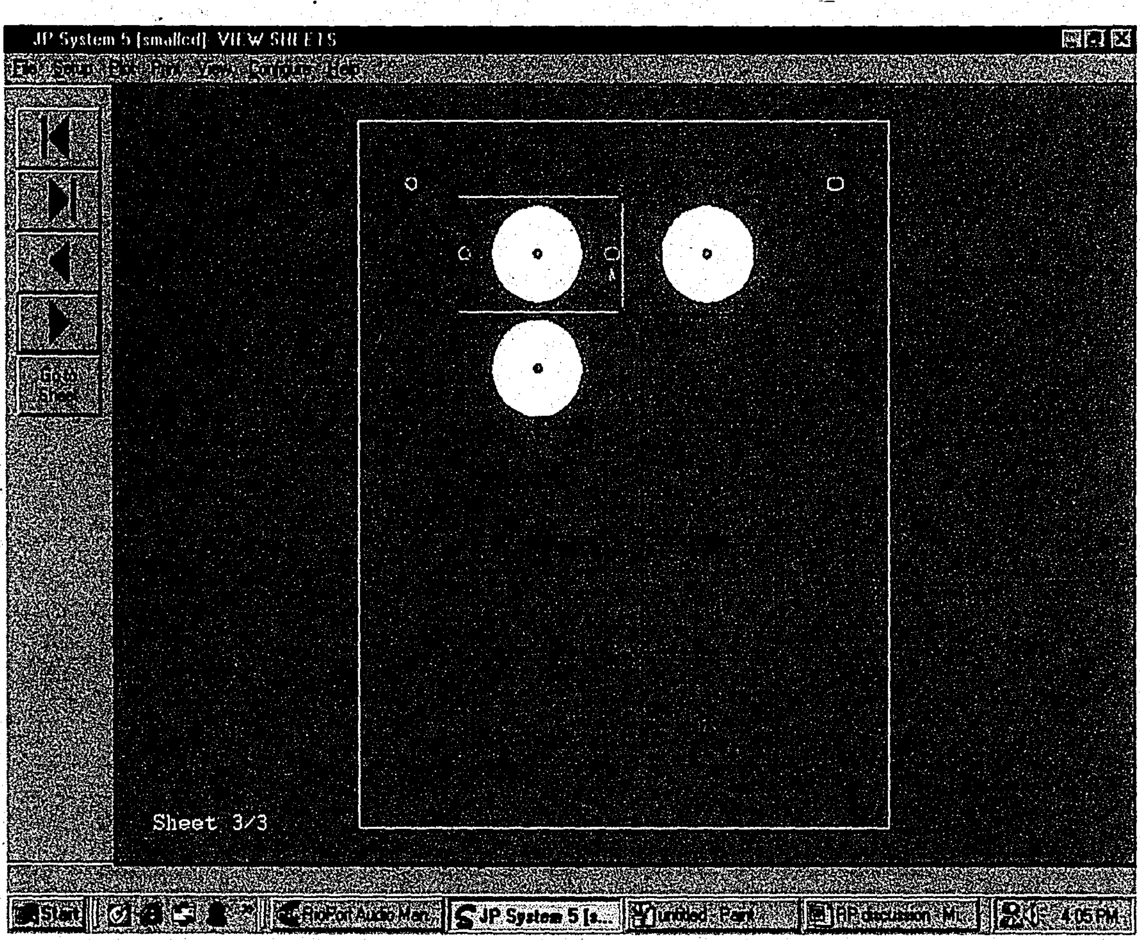


Figure 20 – Sheet layout #3

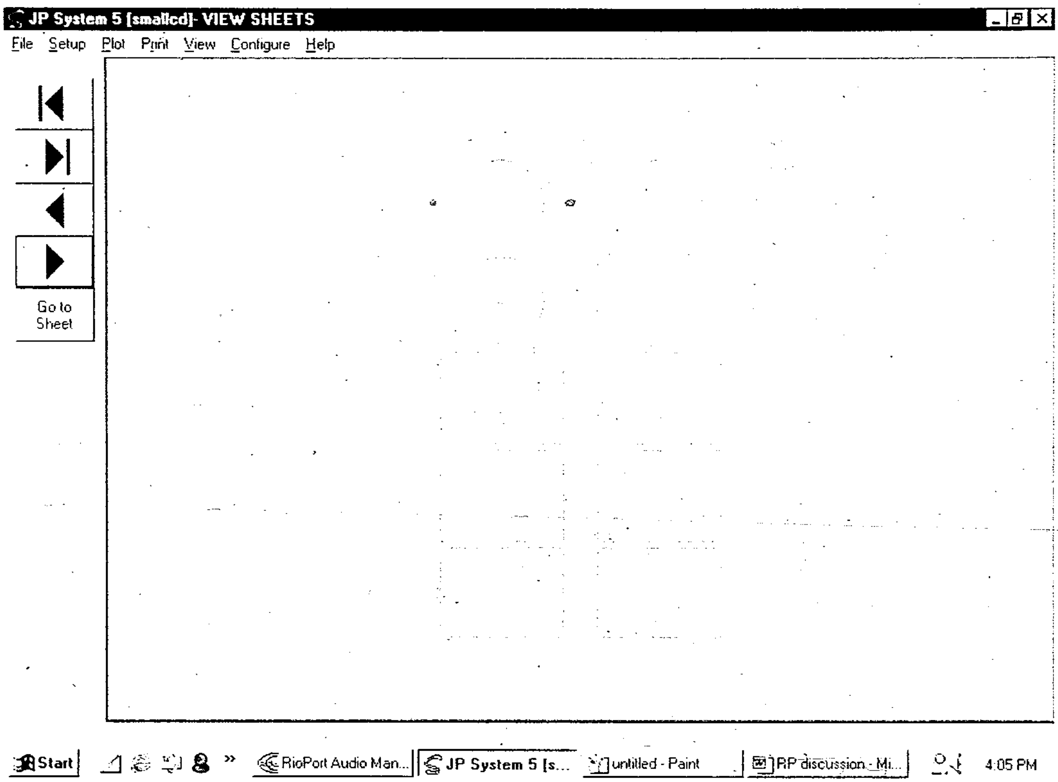


Figure 20 – Sheet layout #3

6. The first sheet is placed on the registration board and pins, followed by the mask, in order to apply adhesive to the first sheet's slices.

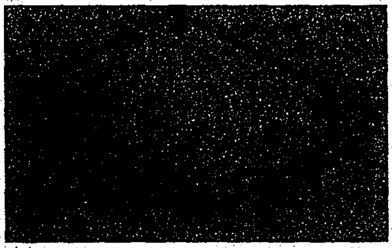

Figure 21– Registration board with major registration pins [21]

7. The second sheet is then placed over the first sheet, and the support backing is removed.

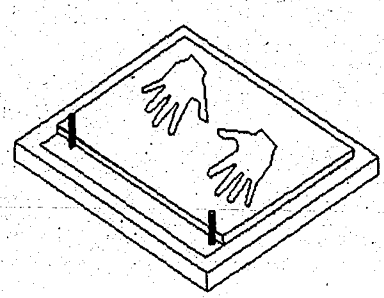

Figure 22 – Applying pressure to top sheet against bottom sheet with application board [22]

8. Each section is labeled and separated as shown in figure 23. Starting with the first section, (A), each is layered one on top of the previous over the minor registration pins, removing the support back when necessary.

[21] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5***, Schroff Development Corporation, Kansas 1999, 2-5.
[22] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5***, Schroff Development Corporation, Kansas 1999, 6-6.

6. The first sheet is placed on the registration board and pins, followed by the mask, in order to apply adhesive to the first sheet's slices.

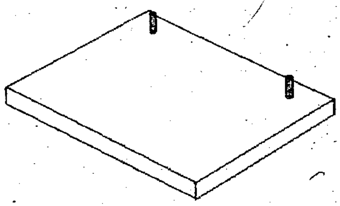

Figure 21– Registration board with major registration pins [21]

7. The second sheet is then placed over the first sheet, and the support backing is removed.

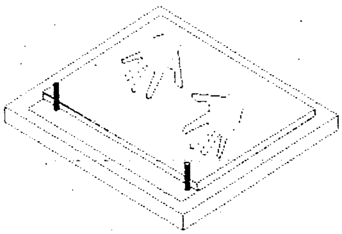

Figure 22 – Applying pressure to top sheet against bottom sheet with application board [22]

8. Each section is labeled and separated as shown in figure 23. Starting with the first section, (A), each is layered one on top of the previous over the minor registration pins, removing the support back when necessary.

[21] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5***, Schroff Development Corporation, Kansas 1999, 2-5.
[22] Andrew L. Anderson, ***Rapid Prototyping: Using the JP System 5***, Schroff Development Corporation, Kansas 1999, 6-6.

| | |
|---|---|
| A | B |
| C | D |
| E | F |
| G | H |
| I | J |

Figure 23 – Labeling sections

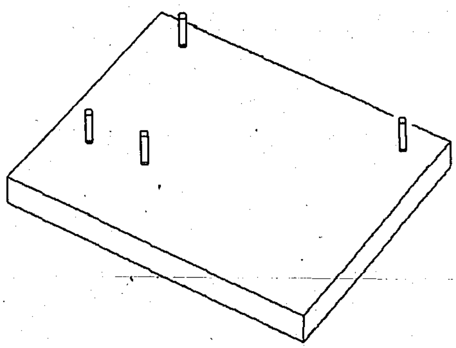

Figure 24 – Registration board with major and minor registration pins

9. The finished prototype is then coated with glue.

**LOM3 Build and Cycle Time**

The LOM3 equation that was developed in Chapter 3 consisted of two parts, the automated build time and the manual build time. The manual build time makes up a significant portion of the total build time. Here are some comparisons of the automated and manual times recorded from building a prototype of a compact disk (CD).

| Build Number | Automated Time (T) | Manual Time ($T_{manual}$) | Total Build Time ($T_b$) | Percentage ($T_{manual}/T_b$) |
|---|---|---|---|---|
| 1 | ~2 min | 29 min | 31 min | 93.5% |
| 2 | ~2 min | 25 min | 27 min | 92.6% |
| 3 | ~2 min | 22 min | 24 min | 91.7% |
| 4 | ~2 min | 26 min | 28 min | 92.9% |

Table 1 – comparison of automated and manual times in building a prototype of a CD

Since these build times were significantly under three hours, it was decided that a CD prototype would be an appropriate object to have students build during a lab period.

Manual assembly accounts for the highest proportion of the total cycle time of a prototype built with the laminated object manufacturing process. A lot of factors come into play and can potentially affect this manual assembly time.

The configuration of slices is one of these factors. If more sheets are used and less rows/columns of slices on each sheet are used, the assembly time will more than likely be much faster. This is because when multiple sheets are stacked, each section ends up with more sliced layers. The user ends up stacking fewer sections and finishing the build quicker.

Another consideration is whether or not enclosements are used. One has the option of placing rectangular enclosements around the slices. This has both a positive and negative influence on the manual assembly time. On one hand, placing enclosements around the slices can sometimes make the assembly easier with less hassle and, therefore, faster. This is especially the case if there are a lot of rows/columns of slices and multiple sheets or if the object is somewhat small. However, the enclosed areas must be removed before assembling the sheets together, which takes time. This is also the case if there are holes or other features that need to be removed prior to assembly.

Size of the model obviously has a significant effect on manual assembly. The bigger the model, the longer it's going to take to assemble. Also, the more complex a model is, the longer it will take to assemble. This is due to the fact that there are more layers to stack, and that complex sections need more careful attention.

The efficiency of the operator is probably the most important factor affecting manual assembly time. Familiarity with how the system works is key. The system is greatly subject to human error. If proper technique is not followed and careful attention not taken, it is quite possible to have to start from scratch and re cut the sheets. Among the many potential mistakes are loading the paper wrong, getting something stuck on the sticky part of the paper, cut out holes getting stuck on the cutter so it doesn't cut properly, and not aligning the paper correctly while loading the printer. Experience will reduce the frequency of these mistakes.

**Effects of Process Parameters**

Cutter velocity does not have much effect on build time since the automated time is very short compared to the manual time. Also, the range of speed recommended for the system is not very wide. The speed remains constant.

Cutter pressure essentially affects the depth of cut of the cutter. The deeper the cut, the fewer number of cuts needed. If the depth of cut is too deep, then one cut may end up being too much for things such as the slice cuts, which cannot go through the support part of the paper. If the depth of cut is not deep enough, then one cut may not be enough to sufficiently cut the slices so that they easily peel off. A good balance is necessary so as to not require too many cuts, which will cause the cutter to wear excessively and/or damage the cutting surface.

## Limitations of the System

One of the main limitations with this system is in the types of objects that can be built with it. Models that have small cross-sections, or any one small dimension (length, width, height), are very difficult to manually assemble. This is because it is difficult to get the cut slices off the support base without damaging those slices, and sometimes the slices may be subject to curling. Complex parts, especially those with intricate details, cannot be built with this type of system. The size of the prototype is restricted by the height of the registration posts. Anything taller than the height of these posts must be split into subparts and assembled independently, before constructing the entire prototype. One other limitation is that assembly is difficult for parts that have major unsupported sections. The cutter is capable of cutting any cross sectional profile; the trouble comes with the manual assembly of the prototype. The accuracy of the final prototype is also questionable since it is put together by hand which will always lead to some sort of error while constructing.

## Unique Attributes of the System

Although there are drawbacks to the JP System 5, there are some interesting things that it can do. Once the CAD drawing is loaded into the system, there is an option to convert the object to a mold. The user can define the dimensions of the mold and the system automatically generates the 3-D mold drawing. This can be sliced and the mold can be built.

It is possible to use the "partial slice" option, which allows the user to select, say, only half of the object for slicing. There are three reasons for selecting this option. First, models of a bigger size may be too large for the system's capabilities. If there is an error made in cutting the model and/or building the model, a second portion of the model can be rebuilt. The final reason would be to save cutting materials and less wear on the cutter.

One last convenient option is that it is possible to build more than one prototype of a model at a time. The system will arrange the sheet layouts to accommodate for the specified number of prototypes requested to be built at the same time.

**Conclusion**

Rapid prototype build time can be predicted with the use of mathematical models. The models are very similar among the processes presented in this paper, since each process follows the same basic rapid prototyping principles. The nature of rapid prototyping technology allows for the construction of the equations to be simple. These equations are useful for planning purposes and future research. It gives researchers the ability to pinpoint areas that require further research, especially those that affect prototype cycle time. The predicted build times that come from the presented mathematical models are helpful when there are time constraints placed on the building of the prototype, as in the case of planning a three hour lab for college students. The LOM technology has proven to be a good economical introduction to rapid prototyping, especially for students.

The equations formulated reflect the current RP processes in use as of the time of this paper. They may be subject to change if additional steps are incorporated, if some steps are eliminated, or if in the future some of the steps are completed simultaneously. Similar mathematical models can be formulated for other rapid prototyping processes not covered here or for those processes that are in the development stages. Although not exact, the models will approximate prototype build time very closely.

Although much work has been done to improve each of the already developed processes, future research is directed in the following areas. Some of the major issues in stereolithography and many of the other RP processes include making overall process improvements and developing new applications, especially rapid tooling. 3D Systems, the premier manufacturer of the stereolithography apparatus, is especially interested in the ability to use new materials that possess better mechanical properties, and are faster and easier to process. The fused deposition modeling system is currently sold by Stratasys, Inc., a company that is also interested in new modeling materials, as well as improving the software and processing times so that the system is more user friendly. BPM Technology, Inc. was formed in 1992 to market their ballistic particle manufacturing system. The company is currently working on a simpler design and experimenting with a vast array of nozzles. The Massachusetts Institute of Technology, developers of 3D Printing, is looking to increase building speed with multiple adjacent jets and to improve surface finish.

Outside of the rapid prototyping manufacturers, other research should be conducted in areas such as the development of new rapid prototyping systems, as with the micro stereolithography system mentioned earlier, as well as expanding the number of applications that each rapid prototyping process can be used in. The goal with all of the RP research is to make rapid prototyping processes faster, easier and more accurate for simulating an actual model. The models made cannot yet be used as working parts although it is optimistic to think in the future they will be. It is expected that many changes and developments in rapid prototyping will surface in the coming years and the goal will ultimately be achieved.

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## Vita

Lisa Armano was born in Lawrence, MA on September 8, 1977. Her parents are John and Lorraine Armano, both from North Andover, MA. Lisa attended Lehigh University and received a Bachelor of Science degree in mechanical engineering with honors in 1999. She is expecting to receive a Master of Science degree in industrial engineering, also from Lehigh University, in June 2001.

# END

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