Making Sense of Prototyping Technologies for Product Design

by

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Abstract

Firms that design mechanical and electro-mechanical products confront a variety of difficult issues in their prototyping activities. For a given part, how can a choice among fabrication technologies be made? Where should investments in new prototyping technology be focused? How can new and existing prototyping technologies be evaluated? The primary goal of this thesis was to develop a systematic method of evaluating prototyping processes in order to determine the best process for a given situation. A secondary goal was to map the "space" of prototyping processes in order to determine future process development needs.

~~Using data from a field study at the Kodak Apparatus Division,~~ a systematic method for evaluating and selecting prototyping processes was developed. The data was drawn from (1) a user survey of prototyping perceptions and needs, (2) a survey to determine the importance of various prototype part performance attributes, and (3) estimates of the fabrication time, cost, and part performance for 104 parts and four prototyping processes.

The systematic method requires estimates of labor, material, and machine resources. A spreadsheet-based estimator (for stereolithography parts) was developed (1) to provide rough-cut estimates for automating the methodology and (2) to establish the required accuracy of estimates.

Thesis Supervisors:

Woodie C. Flowers, *Professor of Mechanical Engineering*

Karl T. Ulrich, *Assistant Professor of Management*

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My parents. Their commitment to their children is second only to their love for each other.

James C Leonard. Lake Leonard will never dry up. The Head of the Charles will have to wait at least another year... And the Tour de France? "None shall pass."

Darren, Stephanie, & Whitney Bush.

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Contents

Abstract.....	3
Acknowledgements.....	5
Introduction.....	9
What is Prototyping?	10
Prototypes as Vehicles to Answer Questions.....	11
The Need for Speed.....	12
The Design For... Diode (DFx Diode)	12
Section 1 <i>Framework & Focus</i>	13
Framework.....	13
Focus.....	15
The Parts	15
The Processes	16
Section 2 <i>Approach & Methodology</i>	18
User Survey of Prototyping Perceptions and Needs	18
Attribute Importance Survey	19
Process/Part Evaluation	20
Section 3 <i>Results & Interpretation</i>	24
Results.....	24
Interpretation of Results	29
Section 4 <i>Conclusions & Directions for Future Work</i>	32
Insights from the Prototyping Study	32
Supporting Design Decision Making.....	34
Improving Prototyping Processes.....	34
References.....	37

Appendix A <i>General Survey of Prototyping Needs</i>	38
The Survey.....	38
Survey Results.....	39
Definitions.....	39
Prototype Characteristics	40
Prototype Logistics	41
Appendix B <i>The Attribute Importance Survey</i>	43
The Survey.....	43
Survey Results.....	44
Appendix C <i>The Stereolithography Estimator</i>	46
Framework.....	46
Performance.....	54

Rapid prototyping is a machinist who works fast.
– Dennis Tianello

Introduction

Prototyping is one of the most critical activities in new product development. Firms that design mechanical and electro-mechanical products confront a variety of difficult issues in their prototyping activities. Some of these issues are tactical: For a given part, how can a choice among fabrication technologies be made? Some of the issues are strategic: Where should investments in new prototyping technology be focused? How can new and existing prototyping technologies be evaluated? I believe that there are useful conceptual frameworks and fundamental relationships that can be developed and used to support prototyping decisions, even though broad generalizations are likely to fail in some particular situations. Such a framework is particularly important today as lead times in product development become more critical [Fitzgerald87, Ulrich91] and as novel prototyping technologies emerge [Dickerson88, Kutay90, Lindsay90].

This thesis describes research addressing these issues. My primary goal was to develop a systematic method of evaluating prototyping processes in order to determine the best process for a given situation. A secondary goal was to map the “space” of prototyping processes in order to determine future process development needs.

The basic methodology was to study prototyping in the context of an industrial manufacturer. By using a data-directed approach based on existing parts and processes, I have provided empirical support for a systematic method of evaluating and selecting processes. My data was drawn from (1) a user survey of prototyping perceptions and needs, (2) a survey to determine the importance of various prototype part performance attributes, and (3) estimates of the fabrication

time, cost, and part performance for 104 parts and four prototyping processes. The primary focus was on parts intended to be injection molded; the prototyping processes included in the study are computer-aided design solid modeling (CAD), stereolithography (STL), computer numerical controlled machining (CNC), and rubber molding (RM).

“Rough-cut” estimating was an integral part of the research. The estimates for the parts were analogous to “first order approximations” to the solutions to engineering problems. This degree of accuracy usually matches the availability and stability of the specifications upon which many estimates are based. I assume that the required degree of accuracy will increase as better estimating tools become available.

This thesis has four sections. In the balance of the introduction I define prototyping and discuss issues relevant to the prototyping process and observations from the industrial setting. In the first section I present a conceptual framework for evaluating prototypes and prototyping processes and describe the research focus. In the second section I present my approach and methodology. The third section details my results. The final section lists my conclusions and suggests areas for future research.

What is Prototyping?

Technically, a prototype is the first thing of its kind. But “prototype” has come to mean many different things in the context of product development. For the developer of commercial satellites, the prototype may be the final product. At the other extreme, the development of a new ballpoint pen may involve more than 10 prototypes before the design is finalized. Some prototypes are used to assess styling, some are used to perform life testing, some are used to verify fit. Other words frequently used to describe the function of a prototype include breadboard, model, and mock up. Each is an example of a prototype; each emphasizes a different aspect of what a prototype does. In my definition of a prototype I include both electronic and physical representations of the part or product.

In most cases prototypes are built to answer questions. In the engineering context, a prototype proves a technology or its application. In the marketing

context, the prototype is a vehicle through which the marketer simulates customer response or finalizes design requirements. In the manufacturing context, a prototype proves a process or procedure. Effective prototyping requires understanding which questions to ask, when to ask them, and how to answer them.

Different types of prototypes are used in many different ways to address different types of questions. Electronic prototypes are often used for simulation. They may be subjected to finite element analysis, mass properties calculations, tolerance analysis, assembly analysis, or motion analysis. Some prototypes are used for verification; often analysis and simulation have been used to make many design decisions, and the prototype is used to detect unanticipated problems. Some prototypes are used to perform tests; they may be used for functional testing, customer perception testing, life testing, assembly planning, etc. Other prototypes serve as crystal balls to anticipate future problems; they may be used to prepare for tooling design, or to compare the evolving product with customer needs.

Prototypes as Vehicles to Answer Questions

~~A~~ **A key element of effective product development** is figuring out what questions a prototype should be able to answer. What are the unknowns that a prototype is supposed to clarify? Which type of prototype is appropriate for a given application? What "path" of processes should be followed when developing a new product or revising an existing product?

One way to analyze which questions are relevant is to remember the various "actors" involved in product development. Prototypes should be used to close the design feedback loop for each actor. For example, prototypes provide designers a method of experimenting with concepts, production engineers a tool for experimenting with process capabilities, and project managers a tool for measuring project evolution. In each case, the prototype serves as the link that feeds back information.

In this respect, prototypes are analogous to drafts of a document; it is one thing to talk about an idea or principle, but quite another to write. The exercise of putting thoughts on paper (or in any form that clearly communicates the idea) quickly

strips away the nebulous periphery and highlights topics that need further clarification. The closing of this loop requires not simply communication of information, but *timely* communication of information.

The Need for Speed

"*Rapid prototyping technologies*" is a phrase used to describe processes that have shortened the design-to-first-part cycle. Stereolithography and selective laser sintering, two primary examples of such rapid prototyping technologies, are often touted as the forerunners of a new wave of "desktop manufacturing processes" that will put manufacturing in the hands of the designer.

In some respects, "rapid prototyping" and the emperors new clothes have much in common. Although "rapid" prototyping processes deserve some attention for their unique capabilities, the other aspects of product development cannot be neglected. Improving a manufacturing process is not enough: both organizational and individual practices must be adapted to match the capabilities of a new process.

The Design For... Diode (DFx Diode)

Effective product development and execution requires communication at every stage of the development process. And communication implies *bi-directional* flow of information. The traditional, "throw-it-over-the-wall" method of product development requires the manufacturer to solve problems that could often be avoided. Recently designers have been selected to shoulder more of the responsibility for avoiding these pitfalls; techniques such as *Design for Manufacturability*, *Design for Assembly*, and *Design for Analysis* all require the designer to be aware of the impacts of variations in the product design. In effect, manufacturers had to be omnipotent and designers are now expected to be omniscient. Each of the design for X methodologies places the responsibility of developing a quality product on the shoulders of the designer. Until these methodologies acknowledge manufacturing expertise and require the person wearing the manufacturing hat to shoulder some of the responsibility, the "throw-it-over-the-wall" symptoms of product development will remain. *Design for ...* (or a prototype or simulation, for that matter) cannot fill gaps in skill level and communication.

The analogy of opposites is the relation of light to shadow, peak to abyss, fullness to void. Allegory, mother of all dogmas, is the replacement of the seal by the hallmark, of reality by shadow; it is the falsehood of truth, and the truth of falsehood.

– Eliphas Lévi

Section 1

Framework and Focus

The world of prototyping can not be described nor evaluated on a single set of axes. Having said that, there are some underlying principles upon which prototype selection and evaluation can be based. This section outlines a multi-variable approach to evaluating prototypes from various processes for various applications then describes the set of parts used to test the framework.

Framework

Product development professionals have highly varied prototyping needs. Designers concerned with styling have needs different from those of mechanism designers. Prototypes to support conceptual design have requirements different from those used in pre-production. The design of some parts may demand prototypes with very tight tolerances, while other parts may require special material properties. The required quantity is important in evaluating processes; some situations may require only one part, some may require 100 parts. Finally, in every case the user of a prototype cares about the cost and time required to procure a prototype.

To capture some of these issues, I evaluate prototyping processes along three dimensions: *part performance*, *unit cost*, and *lead time*. Part performance is viewed as an aggregate measure of the fidelity of the properties of a prototype part, made with a particular process, with respect to the properties the part would have if it were made with the intended final production process. This

performance measure is composed of attributes such as appearance, material properties, and dimensional accuracy. Using an importance weighting for each attribute, derived from a particular user's needs, the performance of a process with respect to each attribute can be combined into a single scalar part performance. Part cost and lead time could also be considered to be dimensions of performance, but since designers often think of them independently of physical part attributes, they were separated from other performance measures.

More formally, associated with each part, i , fabricated with a particular process, there is an associated cost, c_i , lead time, t_i , and performance vector A_i . The performance vector for the part and process is composed of the performance of the process with respect to each of the attributes, a_j , or

$$A_i = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \dots \\ a_{n-1} \\ a_n \end{bmatrix}$$

The set of attributes used to define the vector may vary depending upon the application or organizational context. Typical attributes might be strength, stiffness, density, color, surface finish, etc.² Each a_j is assigned a value from 0 to 1 representing the degree of fidelity of the prototyping process to the final production process for the particular part. A score of 0 is a poor match and 1 is a perfect match.

For a given part, the attribute importance weighting vector, W , contains the importance weightings for each of the attributes, or

$$W = \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ \dots \\ w_{n-1} \\ w_n \end{bmatrix}$$

Each w_j is assigned a value from 0 to 1 where 0 is unimportant and 1 is very important. For example, for a part to be used in a structural test, stiffness,

strength, and dimensional accuracy may be very important while non-mechanical material properties like electrical conductivity may be unimportant.

The dot product of the performance vector and the transpose of the importance vector yields the scalar part performance, p_i ,

$$A_i \bullet W^T = p_i$$

The determination of the appropriate weights in the importance vector is thus crucial to the use of this method. Each department in an organization could conceivably use a different weighting vector to determine performance of a process for its applications. A weighting vector might even be different for different parts within the same department (e.g. a duct versus a bracket). The weighting vector may vary with time as well; the vector used at the concept stage of development would differ from that used during the pre-production phase.

In this study, I determined the relevant performance attributes and the importance weightings for a particular class of parts in a particular company. Then, based on estimates of the time, cost, and performance of four processes on over one hundred parts, I was able to determine the average performances, costs, and times for the processes. From this information, a prototyping decision procedure for this particular set of attributes and importance weightings was prescribed. While the specific results are valid only for my industrial setting, the methodology can be applied in other contexts.

Focus

Given the diversity of prototyping applications, processes, and needs, I focused on a particular class of parts and a particular set of processes in order to generate meaningful results. The data were all gathered at the Apparatus Division of the Eastman Kodak Company (KAD) in Rochester, NY.

The Parts

All of the parts used in the study were intended to be plastic in final production. For over 85% of the parts, the final production process had been determined to be injection molding. For the balance of the parts, the final process had not been determined, or, in a few cases, other processes such as vacuum forming were to

be used. The parts were obtained from a database of parts at the stereolithography laboratory at KAD, and were drawn from several types of products including photocopiers, medical imaging equipment, and printers. The parts varied in complexity, size, and shape. I believe that the part sample represents a uniform distribution of part types for injection molded parts in medium volume products. Figure 1 shows two typical parts from the sample.

Figure 1: Sample Parts

The Processes

The study was based on four prototyping processes: computer-aided design solid modeling (CAD), stereolithography (STL), computer numerically controlled machining (CNC), and room temperature vulcanizing rubber molding (RM). It should be noted that the processes are not entirely independent: STL and CNC depend on a CAD model, and RM requires a master (often generated by STL or CNC). The processes are described briefly below.

CAD solid modeling. At Kodak, many models are created as wireframe models with the Unigraphics CAD package, translated via the IGES standard to an Aries solid modeling package, then transformed from wireframe models to solid models. For this study, I assumed that a part design exists; I based the prototype cost and time performance on the resources required to translate a defined design

into a solid model. In many firms, solid modeling is becoming the standard means of creating, representing, and storing design data [Hurt89, Stix91].

Stereolithography. Stereolithography is a process by which solid plastic parts are created by building a stack of cross sections. Each cross section is fabricated by using a laser to cure a thin layer of a liquid, ultraviolet-sensitive photo-polymer. Estimates of STL parts were made based on the performance of a 3D Systems, Inc. SLA500 machine. There are few polymers that can be used in the stereolithography process [Lindsay 90].

Computer Numerically Controlled Machining. Evaluation of CNC parts assumed fabrication on a lathe or five-axis milling machine. Although many parts could be built on a three- or four-axis machine, five axes were assumed in order to minimize the number of fixtures and setups. Some of the parts required setup on both a lathe and a mill [Ford90].

Rubber Molding. Many plastic parts can be made by casting a polymer such as polyurethane in a silicone rubber mold. This process involves first casting the rubber mold around a part master and then filling the resulting mold cavity with the desired part material. Molding compounds are available that approximate the properties of many thermoplastics used in injection molding.

*Some men see things as they are and say 'why'? I
dream things that never were and say 'why not'?
- George Bernard Shaw*

Section 2

Approach and Methodology

I used estimates and surveys to answer the following questions for my focused domain:

- What attributes are important for prototype parts (i.e. Which attributes make up A)?
- What are the relative importances of these properties (i.e. What is W)?
- How well do the different processes perform with respect to these importances (i.e. What are the values for the a_j 's in A)?
- What are the lead times and cost for the processes (i.e. what are c and t)?

A *User Survey of Prototyping Perceptions and Needs* was used to identify critical attributes. An *Attribute Importance Survey* was developed to establish the importance of each attribute at various phases of development (the values of the elements of W). A *Process/Part Evaluation* was designed to determine cost, lead time, and process performance for each attribute (the values for c , t , and the elements of A).

User Survey of Prototyping Perceptions and Needs

In order to gather general information about prototyping perceptions and needs, I conducted an informal written survey of 24 designers, engineers, and managers at 6 of the lines of business within Eastman Kodak. The survey asked for such things as a definition of "prototype", the purpose of prototypes within the

organization, material and process needs, standard procedures for procuring prototypes, the characteristics of the ideal prototyping facility, and the perceived allocation of time during product development. A copy of the survey is shown in Appendix A.

Based on the responses to this survey I identified the performance attributes given in the right column of Table 1. In order to simplify the presentation of the results, the attributes have been aggregated into four higher-level categories.

Table 1: Performance Attributes Identified in the User Survey

The aggregate attributes are averages of the constitutive attributes listed to their right. Aggregate attributes were used to make the performance evaluation easier to understand and present.

aggregate attributes	constitutive attributes
appearance	overall part appearance
strength/stiffness	strength stiffness
form accuracy	dimensional accuracy geometric accuracy surface finish feature definition
material properties (other than strength and stiffness)	hardness weight melting temperature opacity conductivity color

Attribute Importance Survey

A written survey was sent to over 900 designers, engineers, tool- and instrument-makers, and project managers at Eastman Kodak. 171 (18%) of the surveys were returned. The survey asked each respondent to rate the importance of each of the attributes in Table 1 at the concept, engineering, and pre-production phases of development. At each phase, each attribute received a ranking from "unimportant" to "very important." The survey also requested information about the respondents' primary function (design, engineering, or management) and discipline (mechanical, electrical, optical, etc.). The respondents were selected from a mailing list of users of the Unigraphics CAD system at Eastman Kodak and from personal contacts made by the authors. A

copy of the survey is shown in Appendix B. These data were used to establish the importance weighting vector for the study.

Process/Part Evaluation

Parts were evaluated along the three dimensions —performance, time, and cost— for each of four processes. Estimates of time and cost were made by experienced employees at KAD. In order to reduce variability due to communication issues, the majority of the estimates were made with the part in hand. Table 2 lists the assumptions upon which the estimates were based and the components of the time and cost estimates. The performance of each part was calculated using the attribute rating system described in Section 1, *Framework & Focus*, and the attributes listed in Table 1.

Table 2: Components of Estimates and Assumptions.

components of cost	CAD	STL	NC	RM
labor	• 1 skilled CAD operator	• 1 skilled CAD operator • 1 skilled SLA operator	• 1 skilled CNC programmer • 1 skilled CNC operator	• 1 skilled mold-maker
machine	• CAD workstation	• SLA500 curing oven	• 5-axis CNC mill • CNC lathe	• vacuum pump • ventilation hood
materials	• free electrons	• Ciba-Geigy resin	• fixture material • part material	• mold material • resin for part • gloves, syringes, etc. for handling resins
components of time				
	• translation of drawing or defined concept to CAD solid model	• generation of support structures • translation and manipulation of build files • build time • cure time • hand finishing	• definition of tool path • debugging of program • setup time • run time • hand finishing and/or post machining where needed	• design of mold • fabrication of inserts, supports, etc. • fabrication of mold • mold cure time • pouring of part • part cure time

A number of factors make estimating processing time and cost difficult. First, the reliability and consistency of the estimator had to be established. In many organizations estimating is still more art than science; often the estimators

would produce one estimate then start over as they realized a more elegant solution to the fabrication problem. Second, I had to define where one process finished and another started, and I had to define the "average" target level of performance for each process. For example, a stereolithography part destined for the paper path of a copier required more hand finishing time than a similar stereolithography part designed to hold rolls of film. Third, the skill levels of the operators were also an issue. Fourth, I often found variations within a given process; a given part can often be fabricated by a given process a number of different ways. Finally, the capacity utilization of a process determines the time a part will spend waiting for the process. For the time estimates, I assumed that capacity utilization was low enough that the queueing effects were negligible. This will only be true in organizations that allocate enough capacity to prototyping that jobs move through the shop without contending for resources.

Rather than spend a great deal of time calculating an exhaustive estimate with a very tight margin of error, the estimators were instructed to maintain consistency between parts; the accuracy of one part relative to another was more important than the estimate for any given part. It should also be noted that the estimators were explicitly told that they would not be held to their estimates (I tried to de-couple the estimating process from the organizational incentives within KAD). Also, the estimators were familiar with many of the parts; in some cases they had fabricated the parts within the past year.

In an attempt to bring consistency to the estimating process and to provide the first step in automating the methodology, a spreadsheet estimator for stereolithography parts was developed. Standard PC spreadsheets (Microsoft Excel and Lotus 1,2,3) were used to generate estimates for stereolithography parts on both the SLA500 and SLA250 machines. Although preliminary estimates were quite accurate, the spreadsheets were not tested sufficiently to include estimates from the spreadsheets in this research. Details about the estimator are included in Appendix C.

For each part, performance in each attribute category was rated on a scale of 0 to 1. The basis for the rating was the answer to the question, "How well does the prototype part approximate the production part?" In some cases, the question was, "How much information does the prototype part tell about the production

part?" For some of the attributes [and for the CAD process] one question makes more sense than the other. A score of 1 meant that the prototype part matched the production part for that attribute (or that the prototype part provided as much information as the production part). For example, Tables 3a & 3b show the estimates for and evaluation of the two sample parts in Figure 1.

Once these evaluations were performed for all 104 parts, the part performance ratings, the cost estimates, and the time estimates were averaged to rank the processes in terms of performance, cost, and time.

The methodology requires a consistent method of measuring part performance. Unfortunately, making objective evaluations of part performance is no trivial task. But even as a systematic approach to estimating makes the estimates uniform, a clearly defined set of performance measures can reduce the variability in evaluations of performance.

Table 3a: Example of Estimates
(times in hours:minutes)

process	process component	"bracket"	"duct"
CAD	time to create solid model	4:00	6:00
STL	time to generate support structures	1:00	0:15
	time to prepare files for slicing & building	0:30	0:15
	time to create build file	0:15	0:10
	time to build part on SLA500	3:45	5:00
	time to cure part in UV oven	2:00	1:00
	time to hand finish	2:00	1:00
CNC	time to program	14:00	7:00
	time to setup and debug	12:00	5:00
	time to run 1 part	1:45	1:30
	time to build fixture	0:00	3:00
	number of special fixtures	0	1
RM	time to build special tooling	8:00	0:30
	time to setup and fabricate mold	12:00	10:00
	time to pour one part	1:00	0:45
	time to cure one part	12:00	12:00
	time to cure mold	32:00	32:00
	qty of part material	10 cubic inches	9 cubic inches
	qty of mold material	150 cubic inches	132 cubic inches
	number of pieces to mold	2	2

Table 3b: Examples of Evaluations

attribute	"bracket"				"duct"			
	CAD	STL	CNC	RM	CAD	STL	CNC	RM
strength / stiffness	0	0.55	0.9	0.85	0	0.65	0.95	1.0
strength	0	0.5	0.9	0.9	0	0.6	0.9	1.0
stiffness	0	0.6	0.9	0.8	0	0.7	1.0	1.0
form accuracy	0.83	0.85	0.85	0.98	0.75	0.85	0.83	0.95
dimensional accuracy	1.0	0.8	0.9	0.9	1.0	0.8	0.9	0.9
geometry	1.0	0.9	0.7	1.0	1.0	0.9	0.8	0.9
surface finish	0.3	0.8	0.9	1.0	0.1	0.8	0.8	1.0
feature definition	1.0	0.9	0.9	1.0	0.9	0.9	0.8	1.0
appearance	0.5	0.8	0.9	1.0	0.7	0.8	0.8	1.0
overall appearance	0.5	0.8	0.9	1.0	0.7	0.8	0.8	1.0
material properties	0.23	0.52	0.98	1.0	0.23	0.37	0.98	1.0
hardness	0	0.9	1.0	1.0	0	1.0	1.0	1.0
weight	0.9	0.8	0.9	1.0	0.9	0.9	0.9	1.0
melting temp	0	0	1.0	1.0	0	0	1.0	1.0
opacity	0	0.3	1.0	1.0	0	0.3	1.0	1.0
color	0.5	0	1.0	1.0	0.5	0	1.0	1.0
conductivity	0	0	1.0	1.0	0	0	1.0	1.0

*People are generally better persuaded by the reasons
which they have themselves discovered than by those
which have come into the minds of others.*

- Pascal

Section 3

Results and Interpretation

This section contains the results of the surveys and an application of the methodology using the survey data. The results reflect the prototyping practices and experience at KAD; specific results of using the methodology will vary depending on the practices and abilities within the organization.

Results

The results of the study are summarized in Figures 2-10. Figure 2 shows the ~~importance of each attribute set based on replies to the~~ Attribute Importance Survey. The results of the time and cost elements of the Part Evaluation are shown in Figures 3-6. The performance vector and weighting vectors were used to calculate the performance of each part plotted in Figure 7. Averages of the part performance data across all of the parts in Figure 7 yielded the aggregate process performance results shown in Figure 8. Finally, Figures 9 & 10 illustrate the relative time- and cost-performance of each process based on lot sizes of 1 and 25.

Figure 2: Mean and Standard Deviation of the Importance of Performance Attributes, Time, & Cost at Various Phases of Development

The components of each set of attributes are listed in Table 1. Notice that the importance of each set of attributes increases as the project progresses. Also, time was rated most important at every phase of product development. There was some variation between respondents who classified themselves as "engineering" or "design" and those who claimed "management" (see Appendix B). Source: 171 responses to the Attribute Importance Survey.

The weighting vector established by responses to the Attribute Importance Survey was $W^T = [0.73 \ 0.74 \ 0.53 \ 0.49]$ for the attribute sets strength/stiffness, dimensional accuracy, appearance, and material properties other than strength and stiffness.

Figure 3: Lead Time for Each Part (lot size of 1)

Figure 4: Lead Time for Each Part (lot size of 25)

Lead time to fabricate a single part for each of the processes depended loosely upon part complexity (where complexity was related to the number of geometric primitives needed to define the part). The data were sorted in order of increasing lead time by CNC lot size of 1. Source: estimates of 104 parts in the Process/Part Evaluation.

Figure 5: Cost of Each Part (lot size of 1)

Figure 6: Cost of Each Part (lot size of 25)

Cost per part for each of the processes depended loosely upon part complexity (where complexity was related to the number of geometric primitives needed to define the part). The data were sorted in order of increasing time by CNC lot size of 1. Source: estimates of 104 parts in the Process/Part Evaluation.

Figure 7: Aggregate Performance of Parts

The aggregate performance of each part was calculated using a performance vector based on the attributes in Table 1 and the weighting vector, $W^T = [0.73 \ 0.74 \ 0.53 \ 0.49]$, derived from the Attribute Importance Survey. The data were sorted as in Figures 3-6.

Figure 8: Mean and Standard Deviation of Performance, Time, & Cost Ratings for Different Processes

The process performances were calculated by averaging the performance of each of the 104 parts in the survey for each of the 4 processes. For each process, the time and cost scores are normalized values relative to the other processes, where 1 is fastest/least expensive and 0 is slowest/most expensive. Time and cost ratings are for a lot size of 1.

Figure 9: Mean and Standard Deviation of Process Lead Times

Figure 10: Mean and Standard Deviation of Process Costs

This pair of charts is used to determine the performance of one process relative to another in terms of time or cost. Five processes are compared: CAD, STL, CNC, and RM (from CNC and STL masters). Each point on the chart represents the average of lead time or cost for 104 parts.

Interpretation of Results

A decision among processes for prototyping a particular part can be made based on the data in Figures 8-10. The first step is to determine, using Figure 8, which processes will provide the information required of the prototype. Then Figures 9 & 10 are used to determine which of these processes is best in terms of time or

cost for a given lot size. For example, the bracket shown in Figure 1 must be made of a conductive material. Based on this fact and the process ratings in Figure 8, the alternative processes are RM(CNC), RM(STL), and CNC. If we assume that 25 parts are required and that time is the driving factor in the process decision, Figure 9 shows that CNC is the preferred process. If we extend the example and assume instead that cost were the driving factor, Figure 10 shows that rubber molding from a stereolithography master is preferred. Note, however, that if only one part were required then CNC would be preferred once again.

Table 4 summarizes the process decisions for a small set of decision drivers. The table uses time, cost, the four attribute sets, and lot size as the factors that determine which process to use. Each entry in the table was made by (1) narrowing the set of possible processes for the appropriate attribute set (using Figure 8), and (2) determining the best time or cost performance for the appropriate lot size (using Figures 9 & 10).

Notice that in many cases the aggregate performance measure degenerates into a binary decision. If each of the processes could duplicate the capabilities of the others, then calculation of aggregate performance measures would yield a continuous spectrum of process alternatives. But since, for example, stereolithography cannot produce a part with all of the properties of a CNC-machined polystyrene part, some quantization or "thresholding" occurs in the ranking of processes.

Table 4: Prototyping Guidelines Based on Results.

The parenthesized entries in the "form accuracy" row indicate the preferred process if a physical part is required. In some cases either STL or CNC would be the "preferred" process; whereas the average values indicated one process, the standard deviations were large enough to suggest that the other might be a viable alternative.

critical attribute	Cases where time is the driver		Cases where cost is the driver	
	Qty: 1	Qty: 25	Qty: 1	Qty: 25
strength / stiffness	CNC	CNC	RM from STL (CNC)	RM from STL (CNC)
form accuracy	CAD (STL)	CAD (CNC)	CAD (STL)	CAD (RM from STL)
appearance	STL	CNC	STL	RM from STL (STL or CNC)
material properties	CNC	CNC	RM from STL (CNC)	RM from STL (CNC)

Table 4 lists the guidelines for a particular class of parts, processes, attributes, and lot sizes, but the procedure described above can be applied more generally to different classes of parts, attribute sets, weighting vectors, and lot sizes. The procedure for evaluating processes is thus:

- (1) Determine which of the performance attributes are most critical.
- (2) Determine which processes produce parts which have adequate performance for these attributes.
- (3) Choose between processes based on time, cost, or both (depending on the relative importance of time and cost for the part procurement).

Most people are in favor of progress; it's the changes they don't like.

- author unknown

Section 4

Conclusions & Directions for Future Work

I have evaluated a set of prototyping technologies for a focused domain of applications. In doing so I have demonstrated a methodology for assessing and representing performance needs for a prototype part and for evaluating different processes with respect to these needs. I have been able to prescribe the most promising prototyping processes for a specific situation, given the performance characteristics that are most important for the part and given either a time- or cost-driven decision process. In the course of this study, I have also developed some insights into some of the broader issues in prototyping. In this final ~~section I present some of these insights and discuss some areas for future work in~~ supporting design decision making and in improving the prototyping processes themselves.

Insights from the Prototyping Study

Time is almost always very important to the customer of a prototyping process. This result resonates with recent emphasis on shortened product development cycles. It is also consistent with findings in [Ulrich91] indicating that for plastic parts, the economic impact of lead time dominates materials cost and labor cost issues in design decision making. The criticality of time suggests that firms should maintain enough prototyping capacity that queueing delays do not influence the lead time of the product. Justifying the associated capital outlay is difficult without some explicit estimate of the value of prototyping lead time to the organization.

Conventional CNC machining is among the best prototyping alternatives. For plastic parts, process performance depends on the details of the application. Nevertheless, it is interesting that the best choice of prototyping technology (Table 5) is dominated by CNC machining for the time-driven case. I have observed that many designers are surprised by this result because the trade literature has given a lot of attention to so-called *rapid prototyping* processes. Although I see tremendous opportunities for rapid prototyping technologies like stereolithography, machining is often the best available prototyping technology. In the subsequent discussion of process development I articulate the process developments that may change the relative strengths of these processes.

Rapid is a relative term for prototyping. The promise of instant models from CAD data is still largely unfulfilled. The average lead time to acquire a physical prototype from stereolithography was 9.3 hours for the part sample, assuming that there was no queue for the stereolithography machine. However, in general SLA parts can not be used in functional tests because of the relatively poor material properties of the stereolithography resins. The average time to acquire a part with good strength and stiffness properties was 24.2 hours (CNC machining). This can be as long as three calendar days for a one-shift prototype shop.

Processes tend to perform better on simple parts than complex parts. This result is intuitive but because I have not displayed the geometry of each of the 104 parts, it is not clear from the presentation of the data. In general, the differences between processes were greater than the differences in time, cost, and performance between parts, but simpler parts (measured by the number of geometric primitives in the CAD file) in general obtained higher performance ratings. One implication of this insight is that part designers might consider simplifying or tailoring part geometry in anticipation of prototyping requirements. A related idea was suggested for analysis tools in [Suri89] and seems equally appropriate for prototyping.

There is still no substitute for a skilled operator. Many views of "desktop manufacturing" neglect the knowledge and skills of machine operators by trying to make the designer omniscient. I found that many ideas are born when concepts are communicated between those who design prototypes and those who fabricate them.

Supporting Design Decision Making

A complex electro-mechanical product may contain thousands of parts with diverse intended functionality and diverse intended final production processes. When integrated into the design process, a rough-cut prototyping process evaluation system could be a powerful tool for the designer, engineer, and manager. A computerized implementation may be imagined as follows. As the project is initiated, attributes and importances are defined and agreed upon for different classes of parts. Decisions about the number of prototypes that will be required at various stages of the process are established. This information can be used to inform the designer what the recommended prototyping process is and what the associated time, cost, and performance measures for the current part or assembly are. The designer could then add this information to the information available for other evaluation criteria in order to make better detailed part design decisions. As the needs of the project evolve, the project team might change the desired lot sizes or call for re-evaluation of attribute importances. Such a tool would fit naturally into a group design environment utilizing comprehensive, interactive design software.

Improving Prototyping Processes

Figure 11 summarizes the labor, machine, and materials components of the cost of a part for CNC, STL, and RM. Figure 12 summarizes the process components for CNC, STL, and RM. Table 5 summarizes the lead times for each process. Along with the average process performance results shown in Figure 8, these results help to focus prototyping process development.

Figure 11: Components of Cost

Figure 12: Process Components as a Fraction of Time (lot size of 1)

Table 5: Average Lead Times (hours)

	STL	CNC	RM
1 part	9.3	24.2	59.2
25 parts	130.9	88.8	370.9

STL and CNC figures do not include time to create CAD model. RM figures do not include time to fabricate a master. Note that the lead times for 25 parts have a high variance built in due to parallel processing alternatives. For example, if the parts are small enough, more than one can be built simultaneously on the SLA500 platform. Or, if more than one master is available, multiple parts can be molded simultaneously.

Each of the processes has weaknesses and could benefit immensely from research and development. The figures illuminate important areas for process development:

- Nearly 50% of the time to fabricate one CNC part is programming time. If that time is reduced (by automated generation of cutter paths, for example) then CNC becomes even more useful as a prototyping tool.
- STL performs very well on average except where material properties are critical; the available resins are too limited. An improvement in resins would immediately make STL the dominant prototyping technology for plastic parts.
- CAD is very fast and has high geometrical accuracy. But, it falls short in evaluating strength, stiffness, and other material properties. I did not assess finite element analysis methods of prototyping which address some of these weaknesses. However, the state-of-the-art in simulation is still an inadequate substitute for a physical model. Advances in non-linear, dynamic simulation of multiple parts would enable CAD to emerge as an even more important prototyping technology.
- Rubber molding is an attractive process because it can be used for small scale production. But the process is slow. There is a clear need for either fast-curing polymers or for technologies that allow thermoplastics to be molded from quickly-procured tooling. Developments in spray metal tooling may eventually enable the fabrication of batches of 100 plastic parts relatively quickly [Weiss90].

I hope that the specific results from this study soon will be obsolete because of rapid advances in process development. I believe, however, that the methodology I have developed can be used to make intelligent and rational prototyping decisions as processes change and in differing product development contexts. The methodology supports the tactical decisions surrounding part design and choice of prototyping technologies as well as the strategic decisions surrounding investment in process development.

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Appendix A

General Survey of Prototyping Needs

The general survey of prototyping needs was sent to over 900 designers, engineers, and project managers from six different lines of business. The lines of business included Business Information Systems, Consumer Imaging Division, Copy Products, Health Science Division, Professional Photography Division, and PPG-Design. Products from these lines of business range from 35mm cameras to high-end image capture, editing, and printing systems; from blood analyzers to packaging systems; from office copiers to microfilm equipment.

The Survey

The survey had three sections: *definitions*, *prototype characteristics*, and *prototype logistics*. In addition, each respondent was asked to include information about his/her job description (e.g. design, engineering, management,...), discipline (e.g. optics, mechanical parts, electronics, software,...) and line of business (e.g. copy products, consumer imaging division, business information systems,...).

~~The definitions section asked general questions such as "How do you define 'prototype'?", "Why do you build prototypes?", "Who uses your prototypes?", and "When do you build prototypes?"~~

The prototype characteristics section was designed to gather specific information about the prototypes built by each respondent. Questions in this section included "What purpose(s) do your prototypes serve?", "What materials do you use for your prototypes?", "What processes do you use to build your prototypes?", "How many iterations do you expect for the average prototype?", and "Which factors are most important in your evaluation of prototype performance?"

The prototype logistics section was designed (1) to help the Apparatus Division understand the prototyping process needs of the lines of business and (2) to determine other areas related to prototype fabrication where the Apparatus Division could add value. Questions in this sections included "Where is your time spent during the development of a new product? (brainstorming, testing, engineering analysis, prototype fabrication, etc.)", "How much of your

prototyping work is done within Kodak?", "What is the biggest problem you encounter when you have a prototype built?", "When you have a prototype built, do you expect to receive information about manufacturability or alternative processes? What other information could be 'bundled' with the prototype that would be useful to you?", and "Describe the ideal prototyping facility."

Survey Results

The following paragraphs describe the principal results of the general survey of prototyping needs.

Definitions

As discussed in the Introduction, "prototype" does not mean the same thing to everyone. Definitions of "prototype" ranged from "any 1 of a kind model of a new or modified mechanism" to "3D illustration of idea that illustrates form & user function" or "an alternate process part which is used to prove a concept". But nearly every response to "Why do you build prototypes?" included the words "check", "verify" or "verification"; specifications or goals had been established and the prototype was built to validate the status of the project. One respondent wrote that prototypes are built "to *understand* product idea and *communicate* concepts (designs) to the team players (marketing, management, manufacturing, etc.)".

Not only do the types of prototypes vary from discipline to discipline, but the timing of prototype fabrication varies as well. In some cases respondents built prototypes "as soon as you have something worth testing", whereas others simply replied "ASAP". In many cases prototypes were used as gates in a project development plan.

As communication tools, prototypes are used by nearly everyone in the organization. From the legal department to sales, from customer service to quality assessment, from design to assembly, prototypes are used to communicate ideas and unearth issues critical to every aspect of product development.

Prototype Characteristics

Responses to "How important are the following factors in the fabrication of your prototypes?", "Where is time spent during product development?", and "What purpose do your prototypes serve?" are shown in Figures 13-15.

Figure 13. Mean & Standard Deviation of Responses to "How important are the following factors?"

The responses to this question were used to develop the six categories of attributes used in the study.

Figures 14a-b. Mean & Standard Deviation of Responses to "Where is time spent during product development?"

This question was asked in two parts: (1) where is the time spent when developing a part and (2) where is the time spent when developing an assembly. Note that respondents claimed that brainstorming occupies nearly $\frac{1}{3}$ of the product development time. Unfortunately, actual times were not available.

**Figure 15. Mean & Standard Deviation of Responses to
"What purposes do your prototypes serve?"**

Although there was some variation between lines of business, "function" dominated the answer to this question. The need for functional prototypes is reflected in the responses to "What process(s) do you use to build your prototypes?" – the processes used to build prototypes usually matched the processes used in production.

Materials and processes varied widely depending on the type of prototype to be fabricated. But a common thread through all of the responses was a desire to simulate the final production process.

Apparently the (usually) severe time constraints placed on prototype fabrication have produced a conservative attitude toward prototype fabrication. The responses to this section of questions convey an attitude of "we'll stick to the tried-and-true processes for doing our prototyping work – we can't afford to experiment."

Prototype Logistics

Most respondents cited "unwritten unit policy" or similar guideline for determining where prototyping work should be done. But most also mentioned the importance of their relationship with the prototyping shop personnel; although a one-to-one working relationship was not crucial, trust and mutual understanding of skills and expectations were. Quality (accuracy), turnaround time, convenience, and cost were cited as factors for determining where the work would go. But experience was equally important.

There was an even split between respondents who felt that the interaction with the prototype fabricator was necessary/helpful. Some stated that input from the prototype builder (early vendor involvement) and interfacing directly with the toolmaker were of primary importance to easing the product into full scale production. Others stated that they didn't care *how* the prototype was built – by the time they ordered the prototype they were ready to move on to the next phase of the design.

According to survey replies, the ideal prototyping facility would be flexible. Interaction with model makers would be possible and facilities would be available to designers and engineers directly as well. CAD capabilities are a given. A wide variety of processes is also desirable. A few glimpses of future computer-aided development tools were also described: "In the initial stage of the design, the facility would provide prototypes from wireframes & sketches that are incomplete. The ability to explain (handwave) the missing info is essential at this stage." "[The] ideal prototype facility is identical to production (same people, tools, mfg process, etc.)." Once again, in nearly every response quick turnaround time and rapid response to engineering and design changes were very important.

When asked "When you have a prototype built, do you expect to receive information about manufacturability or alternative processes?", most replies were something like "I don't expect it, [but it's] nice to get when offered." What information would be useful? Answers ranged from manufacturability issues, alternative processes, and tooling proposals to first order cost estimates, complete bill of materials, and an accurate assessment of when the job will be done. Often, however, the respondents did not expect such information from the prototype builder; "I can get that information from experts other than the prototype maker."

Appendix B

The Attribute Importance Survey

Name:

Date:

LoB:

Please return to:

Matthew Wall

2-4-EP mail code: 35326

Primary Function (choose one):

- ☐ engineering
☐ design
☐ management
☐ other

Primary Discipline (choose one):

- ☐ mechanical
☐ electrical
☐ optical
☐ other

At what stage(s) of the product development cycle are you involved with prototype design, fabrication, or assembly?

- ☐ concept development
☐ product engineering
☐ pre-production

Given that prototypes are built for different purposes, how important (on average) are the following attributes in your prototype *parts* during the phases of product development listed to the right?

	<i>concept</i>		<i>engineering</i>		<i>pre-prod</i>	
	unimportant	very important	unimportant	very important	unimportant	very important
stiffness or compliance	☐	☐	☐	☐	☐	☐
dimensional accuracy	☐	☐	☐	☐	☐	☐
geometry	☐	☐	☐	☐	☐	☐
surface finish	☐	☐	☐	☐	☐	☐
hardness	☐	☐	☐	☐	☐	☐
manufacturing tolerance variability	☐	☐	☐	☐	☐	☐
weight	☐	☐	☐	☐	☐	☐
melting temperature	☐	☐	☐	☐	☐	☐
opacity or transparency	☐	☐	☐	☐	☐	☐
color	☐	☐	☐	☐	☐	☐
conductivity or resistivity	☐	☐	☐	☐	☐	☐
method of integration into system	☐	☐	☐	☐	☐	☐
strength	☐	☐	☐	☐	☐	☐
feature definition	☐	☐	☐	☐	☐	☐
overall appearance	☐	☐	☐	☐	☐	☐
functionality	☐	☐	☐	☐	☐	☐
cost	☐	☐	☐	☐	☐	☐
turnaround time	☐	☐	☐	☐	☐	☐
manufacturing process	☐	☐	☐	☐	☐	☐
assembly procedure	☐	☐	☐	☐	☐	☐

Survey Results

Table 6 summarizes the disciplines and functions of the 171 people who responded to the survey. Figures 16-18 show the responses of those claiming "mechanical" as their primary discipline.

Table 6. Functions & Disciplines of Survey Respondents

	design	engineering	management	other
mechanical	52 (30.4%)	63 (36.8%)	18 (10.5%)	9 (5.3%)
electrical	5 (2.9%)	1 (0.6%)	5 (2.9%)	1 (0.6%)
optical		2 (1.2%)	2 (1.2%)	3 (1.8%)
other	2 (1.2%)	6 (3.5%)	3 (1.8%)

Figure 16. Mean and Standard Deviation of the Importance of Various Attributes - Respondents Classifying Their Function as "Design"

Figure 17. Mean and Standard Deviation of the Importance of Various Attributes - Respondents Classifying Their Function as "Engineering"

Figure 18. Mean and Standard Deviation of the Importance of Various Attributes - Respondents Classifying Their Function as "Management"

Appendix C

The Rough-Cut Estimator for Stereolithography Parts

Framework

The idea for developing an estimator evolved as estimates were gathered for the parts in the survey. It soon became clear that much of the estimating process could be automated; the estimators usually followed the same process for making each estimate. The spreadsheet estimator was developed as an attempt (1) to improve the quality of estimates from KAD's stereolithography lab and (2) to develop a first-order system for automating the prototype decision-making methodology.

Simplicity was a key requirement in the design of the estimator. Many systems have been developed for detailed estimating. Often these systems are based on expert system shells and use large databases. But many early estimates don't *need* to be incredibly detailed – there are often many unknowns or features subject to change that make such detailed estimating unnecessary.

The stereolithography estimator was based on a spreadsheet estimator developed ~~by Scott Pearson for complex injection molds.~~ Pearson used the spreadsheet as a worksheet for the person making the estimate; the spreadsheet was basically a checklist laid out to follow the procedure used to make estimates for making injection molds.

The first step in building the stereolithography estimator was to clarify each part of the process of estimating stereolithography parts. A detailed flowchart was made that included items relevant to making the estimate (e.g. part dimensions, file format, number of geometric primitives in the part). From this detailed chart of processes and resources, "knowns" and "unknowns" were determined and desired outputs were defined. A detailed spreadsheet was then created.

The original spreadsheet was required too much information to make an estimate and calculated many relatively unimportant components of the estimate. An ad hoc sensitivity analysis was performed to determine which factors contributed most to the accuracy of the estimates. Also, the number of inputs was reduced (1) to match the information available at the time an

estimate was made and (2) to make the inputs “machine understandable”, i.e. use only inputs that could be read from a CAD file or simple database record (this also facilitated the task of making an estimate using the spreadsheet).

The final spreadsheet is shown in Figures 19a-f. It has three sections (six pages): one page for entering data and one page for displaying the estimate and its components; two pages of calculations; and two pages of constants. The constants consist of rates, average weights, and costs.

The final result was a straight-forward, adaptable, user-oriented spreadsheet. The constants could be changed (1) to make the estimates match the actuals and (2) to follow advances in the process technology and improvements in operator abilities. Also, the checklist style makes the spreadsheet easy to understand. As a result, the automated estimation process is accessible to the operator and encourages experimentation and further development.

Worksheet for Estimating Stereolithography Parts

date <u>10 Dec 90</u>		part name _____		SLA250 _____
name of estimator _____		number of parts _____		SLA500 <u>x</u>

File Management Information

initial format:	aries solid _____	final format:	aries solid <u>x</u>
	ug wireframe <u>x</u>		ug solid _____
	ug solid _____		
	sketch _____		file size _____ megabytes
	IGES _____		

Part Geometry Information

enclosing	height (z) <u>0.000</u> in	part "density" <u>0.00</u> %
volume	width (x) <u>0.000</u> in	
	length (y) <u>0.000</u> in	

geometric primitives for creation of solid	rectangular	_____	skin	simple	_____
	cylindrical	_____		average	_____
	conic	_____		difficult	_____
	spherical	_____	extrusion	simple	_____
	fillet/chamfer	_____		average	_____
			difficult	_____	

Support Structure Information

number of boxes	simple	_____	number of webs	simple	_____
	average	_____		average	_____
	difficult	_____		difficult	_____

Part Preparation Information

number of ranges	<u>0</u>	laser power (250 only)	<u>0.00</u> (5-25) mw
maximum number of wipes	<u>0</u> wipes/layer	fraction of z height	<u>0.000</u> %
minimum number of wipes	<u>0</u> wipes/layer	fraction of z height	<u>0</u> %
maximum dip delay	<u>0</u> sec	fraction of z height	<u>100</u> %
minimum dip delay	<u>0</u> sec	fraction of z height	<u>0</u> %
maximum layer thickness	<u>0.000</u> in	fraction of z height	<u>100</u> %
minimum layer thickness	<u>0.000</u> in	fraction of z height	<u>0</u> %

Part Cure Information

average time per orientation	_____ hr/orientation	number of orientations	_____
------------------------------	----------------------	------------------------	-------

Part Finish Information

features requiring finishing	small	_____	quality of finish	coarse	_____
	simple	_____		fine	<u>x</u>
	average	_____		extra fine	_____
	difficult	_____		ultra fine	_____
	large	_____			

Figure 19a. Data Entry Page from the Stereolithography Estimator (Page 1)

Summary of Estimate

part name: 0
to be built on: SLA500
number of parts: 0

estimate prepared on: 10 Dec 90
estimate prepared by: 0

billing rates

labor rate: \$75.00 /hr
machine rate: \$25.00 /hr
resin rate: \$99.00 /kg

for 1 part

labor hours: 1.9 hr \$143
SLA hours: #NUM! hr #NUM!
resin use: 0.050 kg \$5

labor hours: _____ hr
SLA hours: _____ hr
resin use: _____ kg

total cost: #NUM!

total cost: _____

materials usage

for 1 part

actual

actual

resin usage: 0.050 kg _____

breakdown by function

for 1 part

actual

actual

administration: 0.8 hr _____
file transfer & backup: 0.8 hr _____
conversion to solid model: 0.0 hr _____
generation of support structures: 0.0 hr _____
file preparation: 0.0 hr _____
computer time: 0.0 hr _____
build: #NUM! hr _____
cure: 0.0 hr _____
finish: 0.4 hr _____

breakdown by machine/labor

for 1 part

actual

actual

labor hours: 1.9 hr _____
computer hours: 0.0 hr _____
SLA hours: #NUM! hr _____
oven hours: 0.0 hr _____
total hours: #NUM! hr _____

notes

"other": 1.5 hr
"design": 0.0 hr
"finish": 0.4 hr

Figure 19b. Estimator Output Page (Page 2)

Intermediate Calculations

part name: 0	to be built on: SLA500
--------------	------------------------

translation calculations	0.75 hours
---------------------------------	-------------------

time to move file(s) and change formats <u>0.75</u> hr	
backup time <u>0.00</u> hr	

solid model calculations	0.00 hours
---------------------------------	-------------------

part volume <u>0.00</u> in in in	
cross sectional area <u>0.00</u> in in	simple skin <u>0</u> hr
maximum dimension <u>0.00</u> in	average skin <u>0</u> hr
	difficult skin <u>0</u> hr
rectangular <u>0</u> hr	
cylindrical <u>0</u> hr	simple extrusion <u>0</u> hr
conic <u>0</u> hr	average extrusion <u>0</u> hr
spherical <u>0</u> hr	difficult extrusion <u>0</u> hr
fillet/chamfer <u>0</u> hr	

support structure calculations	0.00 hours
---------------------------------------	-------------------

simple box <u>0</u> hr	simple web <u>0</u> hr
average box <u>0</u> hr	average web <u>0</u> hr
difficult box <u>0</u> hr	difficult web <u>0</u> hr

preparation calculations	0.00 hours
---------------------------------	-------------------

labor times	
range preparation <u>0</u> hr	labor total: <u>0</u>

computer times	
.stl time <u>0.00</u> hr	compute total: <u>0</u>
slice time <u>0.00</u> hr	
merge/bff time <u>0.00</u> hr	

cure calculations	0.00 hours
--------------------------	-------------------

cure time <u>0</u> hr	
-----------------------	--

finish calculations	0.40 hours
----------------------------	-------------------

box removal <u>0</u> hr	small features
web removal <u>0</u> hr	simple <u>0</u> hr
	average <u>0</u> hr
part washing time <u>0.4</u> hr	difficult <u>0</u> hr
time to reorient part for curing <u>0</u> hr	
	large features
	simple <u>0</u> hr
quality multiplier <u>1.25</u>	average <u>0</u> hr
	difficult <u>0</u> hr

Figure 19c. First Page of Intermediate Calculations (Page 3)

Intermediate Calculations

part name: 0		to be built on: SLA500
build calculations		#NUM! hours
per base layer		
recoat delay	30 sec/layer	
dip delay	10 sec/layer	
compute time	0 sec/layer	
laser scan time	0 sec/layer	
number of layers in base	35	
		base build time (fixed) 0.39 hr
		base build time (variable) 0.00 hr
per part layer		
recoat delay	30 sec/layer	
dip delay	0 sec/layer	
compute time	0 sec/layer	
laser scan time	0 sec/layer	
wipe time	20 sec/wipe	
average layer thickness	0.000 in	
number of layers in part	#NUM!	
number of wipes per layer	0 wipe/layer	
		part build time (fixed) #NUM! hr
		part build time (variable) #NUM! hr
laser power	na mw	
SLA250 laser power factor	na	
		total build time (fixed) #NUM! hr
		total build time (variable) #NUM! hr
administration calculations		0.75 hours
paperwork time 0.25 hr		
transportation time 0.25 hr		
machine setup time 0.25 hr		
material usage calculations		0.050 kg
quantity of resin in part	0.000 cubic in	
	0.000 kg	
		resin on platform: 0.050 kg
residual resin	0.000 kg	

Figure 19d. Second Page of Intermediate Calculations (Page 4)

Constants and Pseudo-Constants

average times for translating files

to aries solid from:	aries solid	0	hr	to ug solid from:	aries solid	0.75	hr
	ug wireframe	0.75	hr		ug wireframe	0	hr
	ug solid	0.75	hr		ug solid	0	hr
	sketch	0	hr		sketch	0	hr
	IGES	0.75	hr		IGES	0.75	hr

average times for creating solid geometry primitives

	from sketch	from wire			from sketch	from wire
time to create rectangular	0.34	0.17	hr/solid	time to create skin	simple 0.8	0.4
time to create cylindrical	0.34	0.17	hr/solid		average 0.9	0.7
time to create conic	0.34	0.17	hr/solid		difficult 1.5	1.25
time to create spherical	0.34	0.17	hr/solid			
time to create fillet/chamfer	0.34	0.17	hr/solid	time to create extrusion	simple 0.25	0.17
					average 0.6	0.4
					difficult 1	0.8

average times for creating support structures

time to make box	simple 0.09	hr/box	time to make web	simple 0.02	hr/web
	average 0.15	hr/box		average 0.08	hr/web
	difficult 0.4	hr/box		difficult 0.15	hr/web

average times for file preparation

time to define/edit range	250 0.4	500 0.09	hr/range	average .std time	aries 0.09	ug 0.09	hr/MB
average slice time	250 0.25	500 0.09	hr/MB				
average merge/bff time	250 0.25	500 0.09	hr/MB				

average finishing times

finish factor multipliers	coarse 1		average wash time	0.4	hr
	fine 1.25		average time to reorient part	0.25	hr/orientation
	very fine 1.75				
	ultra fine 2				
time to finish a feature	small simple 0.02	large 0.08	hr/feature		
	average 0.03	0.1	hr/feature		
	difficult 0.05	0.15	hr/feature		
time to remove supports and finish support area	box simple 0.25	web 0.05	hr/support		
	average 0.4	0.08	hr/support		
	difficult 0.5	0.15	hr/support		

Figure 19e. First Page of Constants (Page 5)

Constants and Pseudo-Constants

average machine parameters

per base layer	250	500	
average recoat delay	20	30	sec/layer
average dip delay	10	10	sec/layer
average compute time	1	0	sec/layer/in in
average laser scan time	0.8	0.4	sec/layer/in in
			average base layer thickness 0.010 in
			average base height 0.350 in

per part layer	250	500	
average recoat delay	20	30	sec/layer
average compute time	4	0	sec/layer/in in
average laser scan time	1.4	0.6	sec/layer/in in
average wipe time	15	20	sec/wipe

	(250 only)
minimum laser power	5 mw
maximum laser power	25 mw

miscellaneous

average backup time	0.25 hr/MB	average time for paperwork	0.25 hr
average transportation time	0.25 hr	average machine setup time	0.25 hr

material parameters

resin density	0.019 kg/cubic in	resin retained on platform	250 0.025 500 0.050 kg
"cling" factor	50.0 %		

\$ dollars \$

	250	
machine	\$15.00 /hr	
resin	\$88.00 /kg	
		labor \$75.00 /hr
	500	
machine	\$25.00 /hr	
resin	\$99.00 /kg	

Figure 19f. Second Page of Constants (Page 6)

Performance

At the time the spreadsheet was developed the Apparatus Division did not keep accurate records of process performance; estimates were made and recorded, but no record of *actual* design time, build time, finishing time, etc. was made. However, build times were available (the SLA250 maintains a build log and build times for the SLA500 were recorded for comparison to the SLA250). As a result, only the build time component of the stereolithography estimator could be evaluated.

The estimated build times closely matched the actual build times. Figure 20 shows the estimated time versus the actual time for the parts in the SLA250 build log. Figure 21 shows the equivalent data for the SLA500.

Figure 20. Estimated vs Actual Build Times for the SLA250.

The SLA250 estimates tended to be slightly higher than the actual build times. Also, the variability of the estimates increased as the build time increased.

Figure 21. Estimated vs Actual Build Times for the SLA500.

The SLA500 estimated build times were slightly shorter than the actual build times.