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ABSTRACT

Rapid prototyping (RP) is a new and quickly growing field in engineering. Because of the diverse technology, rapid development and inadequate direction associated with rapid prototyping, two major problems arise. The novice and expert alike discover it is increasingly difficult to determine the "best" machine for each application. Also, research facilities are presented with the challenge of locating valid research areas.

The objective of this research involves the creation of a program capable of selecting the "best" rapid prototyping machine for each application, noting areas in need of development. To achieve this objective, the research develops a quality function deployment, resulting in a problem understanding form for a rapid prototyping machine selection program.

This research yields a program called the RP Advisor. The program uses input concerning the desired prototype to calculate a normalized time, cost and quality value for each machine. The time, cost and quality values are weighted with respect to the priorities of the user. The program then derives a normalized non-dimensional value from the weighted values for each machine. Upon ranking the machines with respect to this non-dimensional number, the RP Advisor informs the user of the "best" machine and its corresponding data. The RP Advisor also lists alternative machines for comparison. Valid research areas exist when no machine is selected.

Review of previous work indicates the RP Advisor is the first working program available in the United States which employs a rapid prototyping machine selection algorithm.

RAPID PROTOTYPING

MACHINE SELECTION PROGRAM

by

Darrell Kenneth Phillipson

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

ARIZONA STATE UNIVERSITY

December 1996

RAPID PROTOTYPING

MACHINE SELECTION PROGRAM

by

Darrell Kenneth Phillipson

has been approved

December 1996

APPROVED:

_______________________________, Chair

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Supervisory Committee

ACCEPTED:

____

Department Chair

Bianca L. Bernstein

____

Dean, Graduate College

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I wish to acknowledge the United States Air Force for providing the opportunity for further education. Thanks to Arizona State University for providing me with an excellent educational environment for advanced learning and research.

Thanks to my friends and the present and past students in the Product Modeling Lab, for their help, suggestions, and guidance during the course of this research and my Master's program. My sincere thanks to Sheri Rhine and Colleen Gosser in the CIM Systems Office for all their timely help during my association with the CIM Systems Research Center.

Last, but not the least, I thank my parents and family members for their continued moral support throughout my educational career, without which this achievement would not have been possible. I dedicate this work to my future wife, Monique Lyson.

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NOMENCLATURE

Ac_o	overall accuracy
Ac_t	target accuracy
A_s	surface area
Cn	non-weighted rating for cost
Cp	priority value for cost
C_{post}	post processing cost
C_{pre}	pre-processing cost
C_r	runtime cost
C_T	total cost
D_b	beam diameter
L_c	cure length
L_t	laser travel length
ND	non-dimensional value
Qn	non-weighted rating for quality
Qp	priority value for quality
Q_t	total quality
R_{post}	post-processing cost rate
R_{pre}	pre-processing cost rate
R_r	runtime cost rate
S	speed

T_l	time for one layer
Tn	non-weighted rating for time
Tp	priority value for time
T_{post}	post-processing time
T_{pre}	pre-processing time
T_r	runtime
V_b	bounding box volume
V_m	material volume
x_b	bounding width
y_b	bounding length
z_b	bounding box height
$\%V_m$	percent of material volume
#Layers	number of layers to build the part
Δz	layer thickness

CHAPTER 1

INTRODUCTION AND RESEARCH OBJECTIVE

1.1 Rapid Prototyping (RP)

Rapid prototyping is a new and quickly growing field. Rapid prototyping technology has been defined as "various methods by which a computer-aided design of an object can be converted into a precision physical model" (Ashley, 1996a). The term free-form fabrication (FFF) is also used when referring to rapid prototyping. Because these terms are synonymous in most circumstances, both definitions will be included in this work and will be referred to hereafter as rapid prototyping. Free-form fabrication uses additive processes to create a physical geometry directly from a CAD file, replacing methods that remove materials (Ashley, 1995). Figure 1.1 is a compilation of all types of FFF, which in this report will be referred to as rapid prototyping technologies.

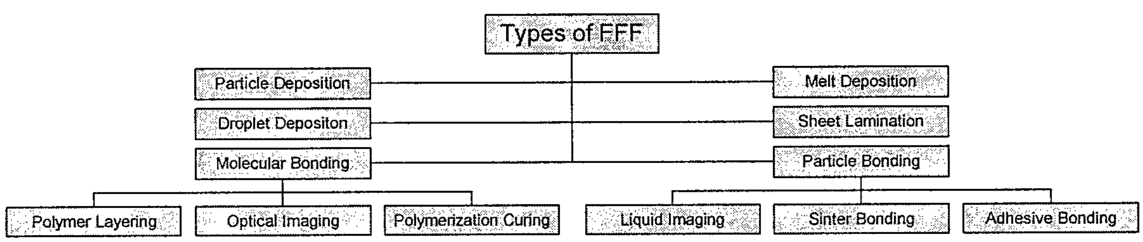

Figure 1.1 Types of FFF (Revised from Johnson, 1994)

Although the term 'Rapid Prototyping' may seem simple on the surface, it is an ambiguous term. The word rapid is relative. Depending on the technology, rapid can vary from minutes to months. A prototype can range from a fragile, inexact model to a production quality, fully testable prototype.

Rapid prototyping technologies vary greatly. These technologies will be discussed in chapter 3, referencing points of contact for further information on each technology.

The rapid prototyping field is growing substantially each year. Figure 1.2 is an indication of how quickly the rapid prototyping industry is growing. This figure reflects the market doubling in 1996 (Wohlers, 1996). It has been noted that “one million physical models are now fabricated each year” by rapid prototyping (Ashley, 1996b).

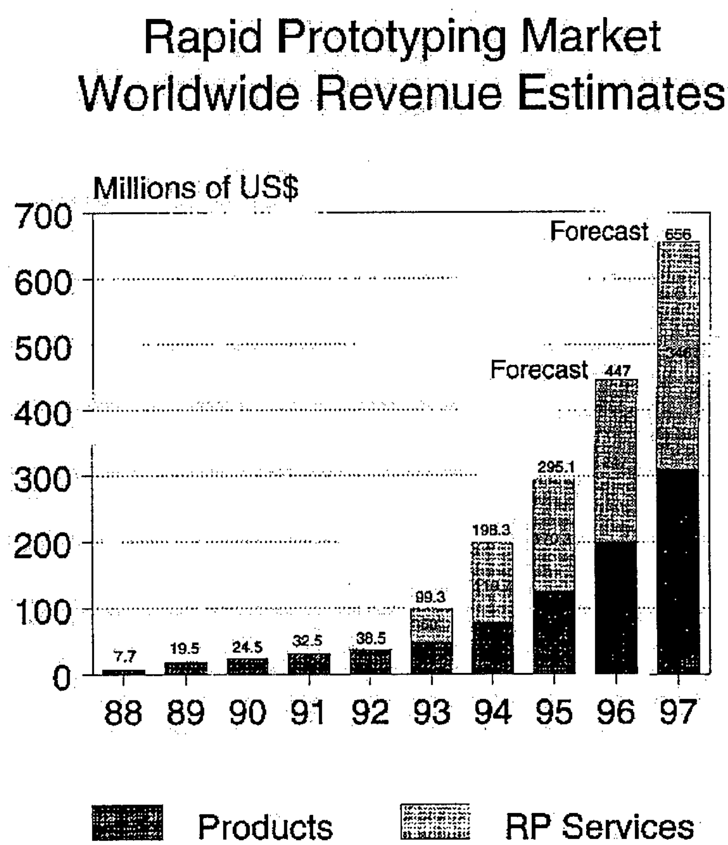

Figure 1.2 Rapid Prototyping Market Worldwide Revenue Estimates

(Wohlers, 1996)

It is important, however, to determine where rapid prototyping fits into the design process.

1.2 Engineering Design Process

The engineering design process has many stages. Engineering design has been defined by Dym as, "the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints" (1994). Recently there have been many advances in the representation and application of the design process. A three step representation of the design process is shown in figure 1.3.

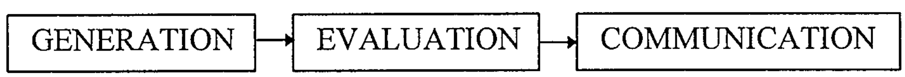

Figure 1.3 Three-Stage Design Process

The most widely cited model of the design process is French's model, shown in Figure 1.4.

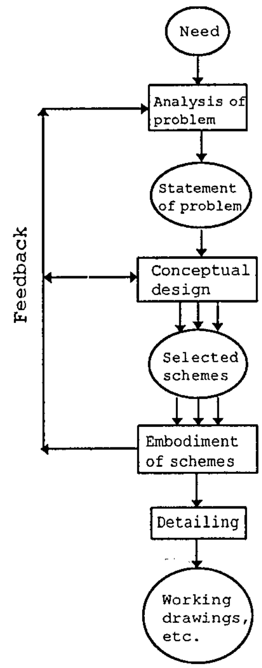

Figure 1.4 French's Model of the Design Process

(Roozenberg & Eekels, 1995)

This model displays the fundamental need for feedback in the design process. Feedback signifies that this process is iterative. The question is: how do the proper organizations working on the design input feedback in a constructive, timely and beneficial manner to shorten design time and produce a better product?

The need for feedback in the design process involves the design engineer, sales personnel, marketing personnel, manufacturing engineers and any other member of the company that has a direct link to the product. To incorporate the ideas of all those involved in the project, several new concepts have been developed. Two of these approaches to product design are concurrent design and simultaneous engineering, shown in Figure 1.5 compared to traditional design.

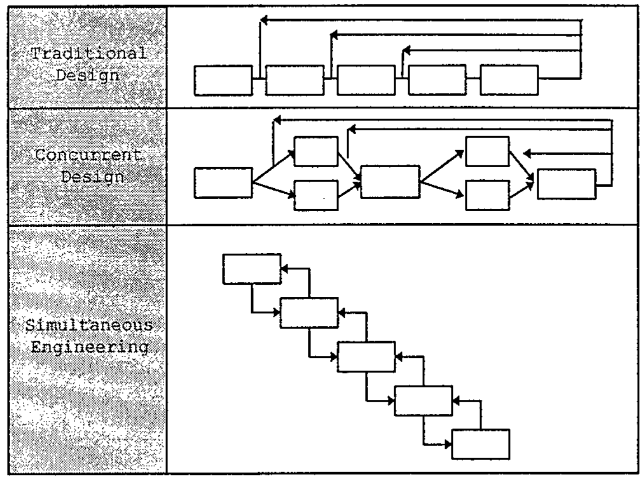

Figure 1.5 Methods to Reduce Development Time

(Grabowski, Erb, & Geiger, 1994a)

The main focus in the evolution of the design process, as seen above, is the interactively between the different stages and those individuals involved in those stages. The primary deterrent to ideal concurrent design is communication. Because the design process involves the mixing of ideas from a pool of thinkers from different disciplines, it is inherently difficult to effectively communicate between team members. All members of the design team may speak the same language, English or Spanish for example. However, the vocabulary will vary for each member. This is apparent when a student in the school of business attends an engineering class or vice-versa. The student who is out of place may feel they are listening to another language.

One method to overcome the written or verbal barrier is the use of pictures or drawings. However, engineering drawings become very complex and, in many instances, it is necessary to visualize three dimensional objects from two dimensional drawings.

For the practiced eye, this is not a problem, but many people cannot make the leap in dimensions. For this reason, it is ideal if the team can have an actual three dimensional model of the design to pass around, discuss, alter and use to better communicate ideas. A three dimensional model is called a prototype. The degree of accuracy needed for this model varies with respect to the design process stage. For example, in the conceptual stage of the design process, the prototype need only be a rough estimate of the product to assist the group with brainstorming. However, when the product is close to production, the prototype may be needed to test form, fit and function.

The debate regarding the best design process is ongoing and dependent on the project in question. For this reason, the remainder of this research will refer to the following generic model of the design process.

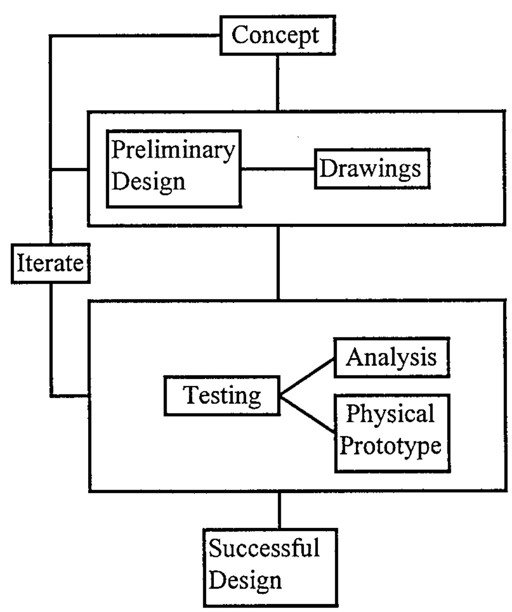

Figure 1.6 Generic Schematic for the Engineering Design Process (Thomas, 1995)

1.3 Mechanical Prototypes

A model of a product is called a prototype. Prototyping mechanical designs has been in integral part of the design process for ages. Prototypes produced by different processes are used for (Ulrich & Eppinger, 1995):

- **communication**, allowing visual and tactile communication between persons of various background such as top management, vendors, partners, customers, team members;
- **integration**, to ensure that components and subsystems coming from different experts and various domains fit and work together. The definition of responsibilities and interfaces is a main issue in integration;
- **learning**, to find errors or unintentional effects as early as possible in the development process.

Traditionally, prototypes were made only by skilled prototype builders and were very expensive. These prototypes took anywhere from weeks to months to finish. The quality of the prototype greatly depended on the experience and skill level of the model maker. However, even with the most skilled model makers, each prototype was an expensive undertaking, both in money and time. Unfortunately, with shrinking design cycle times, it is becoming impractical to wait for a prototype to be produced. The advances in computer-aided design (CAD) packages and computer graphics have helped in the visualization of parts without prototyping, but there is no replacement for a true three dimensional model. The challenge now is to create prototypes quickly, accurately and inexpensively.

Until fifteen years ago, reducing cost and time meant sacrificing quality. However, the future of prototyping may far exceed that which has ever been imagined in the past. Long production times for prototypes are now becoming a part of the past. Prototypes that might have taken months to complete before, can now be accomplished overnight. The advancements that have made this a reality are known as "Rapid Prototyping."

1.4 RP Implementation

As the growth of the rapid prototyping industry continues, the technology grouped under the rapid prototyping label continues to diversify. Trying to join the rapid prototyping community is like trying to jump on a speeding train. And for those who are already on board, it is becoming increasingly difficult to keep up to speed.

At a glance, the largest barrier to companies who wish to use this technology is the capital investment. However, a large barrier is the lack of a concise, easy-to-use source of advice on rapid prototyping. Jacobs has noted that "it is important for users of RP&M (rapid prototyping and manufacturing) services to understand the requirements of their applications and to compare these requirements to the relative capabilities of the available RP&M technologies" (1996). However, knowing all of these capabilities to determine the most appropriate rapid prototyping machine is becoming increasingly difficult. Because the determination is difficult for the buyer "this wide choice confuses the potential buyer and, as mistakes can be costly, acts as a barrier to the adoption of rapid prototyping by smaller companies" (Jelley & Thompson, 1995). The lack of rapid prototyping implementation causes reduction in the possible efficiency of the design process. In many markets, the use of rapid prototyping to streamline the design process is becoming the only way to stay in business.

Companies today can join the rapid prototyping community in two ways. The first and least expensive, is to contract the rapid prototyping work to one of the many service companies who are now producing prototypes with this technology. The other is to purchase a rapid prototyping machine for in-house prototyping.

The first method essentially makes all rapid prototyping machines available to any company. By using a prototyping vendor the customer can choose the vendor who owns the type of machine that produces a model with the correct parameters. One way to find the "best" machine for a particular prototype is to ask around, but it is hard for the inexperienced to know if the person they are seeking advice from has all the facts from which to base a decision. It is also difficult to determine if that source is attempting to further their own cause by the promotion of one machine over another. It is necessary to "depend upon a bureau's expertise in the technology or technologies offered" (Jacobs, 1996). One way to avoid possible bias or incompetence is to make the decision in-house, according to the criteria set forth by the company. However, if no employees have experience with the different rapid prototyping technologies, the decision may not be the "best."

The second way to enter the rapid prototyping community is to purchase a machine to produce prototypes in-house. While investigating which rapid prototyping machine to purchase, the same problems as those encountered when determining the machine to use to make a single part will arise. Actually, the problems with selecting the "best" machine to buy are even greater than those discussed earlier. When determining which machine to buy, all possible prototypes that the company needs to produce must be taken into account. Also, because these machines are expensive, an in-depth cost justification will be required. In short, purchasing the wrong machine has a much greater impact on the company than producing one part with the wrong machine.

1.5 RP Development

Rapid prototyping has been in development for only ten to fifteen years. In fact, most of the development on the available systems has been done in the past five years. Although many new rapid prototyping technologies have been invented, the field is still fertile for development. In today's rapid prototyping world, the "industry is still on a steep learning curve as well, and technical shortcomings linger" (Ashley, 1995). There are many gaps in the available technology. The term "gap," in this research, is used to refer to a fertile area for development of a new technology.

1.6 Quality Function Deployment (QFD)

To help rapid prototyping users and developers overcome the problems discussed in the previous sections, it is necessary to develop a program which determines the "best" rapid prototyping machine for any specified job. This program must also recognize a technology gap if one exists.

Like any other design project, the design of a rapid prototyping advisor begins with the recognition of a need. This need has been outlined above and will be discussed in chapter 4. Once the need is recognized, one way to develop a full understanding of any problem is to perform a quality function deployment.

Quality function deployment is a widely accepted method of outlining and understanding the design problem. This method "was developed in Japan in the mid-1970s and introduced in the United States in the late 1980s" (Ullman, 1992). QFD is composed of six steps:

- Step 1: Identify the customer(s).
- Step 2: Determine customer requirements.
- Step 3: Determine relative importance of the requirements.
- Step 4: Complete competition bench marking.
- Step 5: Translate customer requirements into measurable engineering requirements.
- Step 6: Set engineering targets for the design.

The compilation of the information derived by following the QFD Technique is easily summarized in a form called the problem understanding form (Ullman, 1992). The problem understanding form for the RP Advisor can be seen in figure 4.2, in section 4.4 of this report. Chapter 4 will outline the approach taken for each step in the QFD as applied to the development of a rapid prototyping machine selection program. Figure 1.7 is a general representation of the problem understanding form layout.

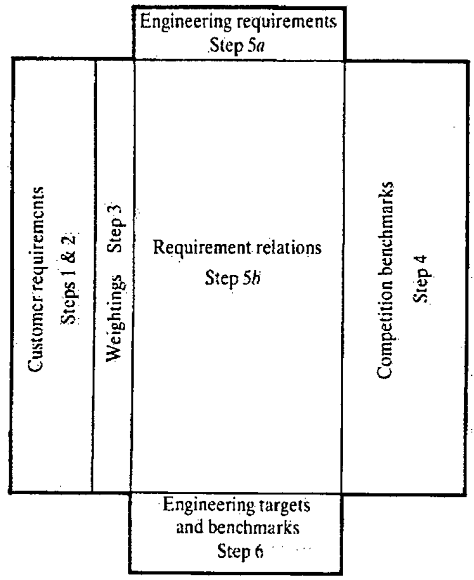

Figure 1.7 The Problem Understanding Form Layout (Ullman, 1992)

1.7 Research Objective

This research will develop a comprehensive rapid prototyping database and user interface which allows queries for pertinent information necessary to make rapid prototyping decisions and produce recommendations with detailed explanations. The system will also recognize when there are no available machines that fulfill the user defined criteria, showing possible areas of development for future work in rapid prototyping. This research will conclude with a proof of concept program called "The RP Advisor" and a validation which proves that the RP Advisor satisfies the quality function deployment produced for a rapid prototyping machine selector. The ability of the RP Advisor to improve the design process will also be shown.

As a summary, the following list of objectives will be used to measure the success of this research:

1) Compile a comprehensive rapid prototyping database to be used within the RP Advisor;
2) Produce a quality function deployment (QFD) analysis for a rapid prototyping machine selector program called the RP Advisor;
3) Design and implement the RP Advisor to meet the customer and engineering requirements set forth in the QFD produced in objective two;
4) Validate the RP Advisors ability to satisfy the QFD;
5) Show the RP Advisor improves the design process.

CHAPTER 2

PREVIOUS WORK

2.1 Introduction

The field of rapid prototyping is in its infant stage. During this stage, many topics concerning rapid prototyping are being overlooked in favor of more trend setting topics. Most research in the rapid prototyping field is directed toward solving accuracy, speed and quality issues to advance technological aspects. Several large companies have been experimenting with the processes from their origin. However, recently there has been a surge to make rapid prototyping more common in the work place. It is also becoming apparent that applications for rapid prototyping span much more than simple product design. Unfortunately, because the field is so new, there have been few research attempts made at providing newcomers with a simple to use, unbiased method of choosing the proper rapid prototyping machine for any one application.

2.2 Rapid Prototyping Machine Selection

Research involving formalized rapid prototyping machine selection consists of three main research attempts. The first exercise was directed at defining many terms and attempting to derive a method to combine all of the factors involved in making a machine selection. This research was done at the Institute for Computer Applications in Planning and Design, University of Karlsruhe, Kaiserstr. The second research initiative took place at Santa Clara University, California. This research ended in the development of an informative program on rapid prototyping. The third project is a work in progress, developing a tool to make the decision of the correct rapid prototyping machine for a particular application. This research is being done by the Bremen Institute of Industrial Technology and Applied Work Science (BIBA).

2.2.1 University of Karlsruhe

In comparing the different processes of rapid prototyping, the first objective is to determine the factors that go into differentiating between the processes. It is important to base the factors on what is important to users of rapid prototyping. Implied in the word "rapid", time is a major factor, but cost and quality cannot be forgotten. This research determines "the use of rapid prototyping technologies is ruled by three principal factors that are time, cost and quality" (Grabowski, Erb, & Geiger, 1994a). This concept can be visualized as a three dimensional problem in figure 2.1.

To compare each machine on the basis of these factors, the first task involves determining how each machine rates per factor. Time, is a function of the variables which affect the time between request and delivery. Some of these variables include whether in-house facilities are being used or the part is being contracted out, availability and burden of machines, lead time, and CAD data quality and data processing requirements (Grabowski, Erb, & Geiger, 1994a). The second factor deals with the quality of a prototype. This is determined by variables such as dimensions, surface characteristics, weight and stability, among others. Finally, the cost of a prototype includes variables like the cost of the technology, the service provider cost and the cost of materials. Figure 2.1 demonstrates the complexity of the decision between rapid prototyping machines.

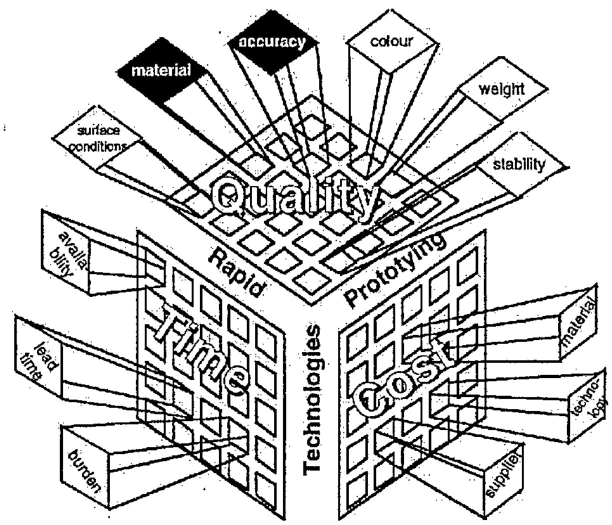

Figure 2.1 "Problem Cube:" Classification Criteria for the Selection of Prototypes (Grabowski, Erb, & Geiger, 1994a)

In dealing with the complexity of the posed question, this research suggests the use of multicriterial optimization theory. As applied to choosing a rapid prototyping machine, this theory requires that each of the three factors, time, cost and quality, be reduced to a function, $f_i(x)$, that is representative of the respective side of the problem cube. This provides the prototype selection algorithm with the following three target functions, which need to be minimized or maximized:

Quality: $\max f_1(x) = f(\text{material, process...})$

Cost: $\min f_2(x) = f(\text{material process, volume...})$

Time: $\min f_3(x) = f(\text{availability, burden...})$

If the function, f(x), is the set of all target functions $f_i(x)$:

$f(x) = [f_1(x), f_2(x), f_3(x)]$,

then a value x* has to be found so that f(x*) becomes an optimum:

$f(x^*) = \text{opt } f(x)$

Because the criteria will inherently be conflicting, the challenge is to find the optimum solution, which can be represented by a range of values on each axis. These solutions are Pareto optimum solutions, which are defined as "the solutions that meet all specified requirements at the same time" (Grabowski, Erb, & Geiger, 1994a). Figure 2.2 shows a set of possible solutions to visualize the Pareto optimum solution.

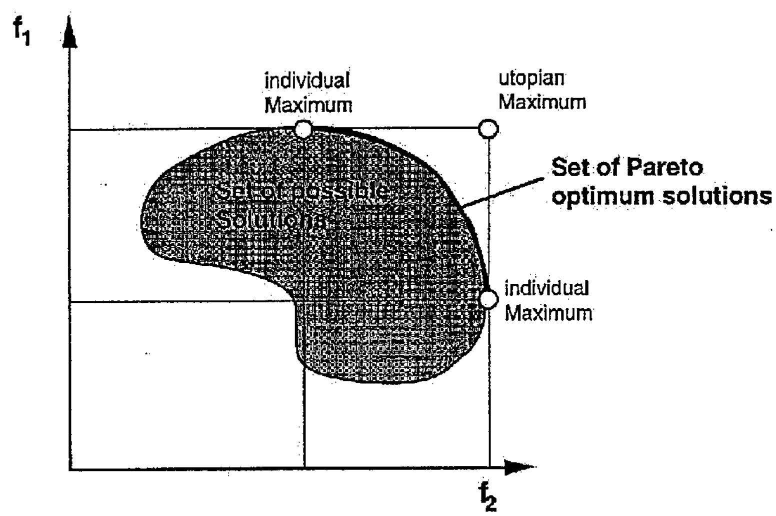

Figure 2.2 Multicriterial Optimization and Pareto Optimum Solutions in Two Dimensions (Grabowski, Erb, & Geiger, 1994a)

As stated in the title, figure 2.2 is a two dimensional representation of the actual three dimensional problem. By including the third dimension, the Pareto solution is no longer an area, but is instead a volume in the problem cube from figure 2.1. To find a machine for the user, the RP advisor plots the Pareto solution corresponding to the criteria set. The result of this plot is a solution volume. The RP Advisor then plots each of the available machines with respect to the criteria. The volume represented by each machine is called the definition volume for that machine. Any definition volume that overlaps the solution volume corresponds to a machine that can be used. However, the definition volume which has the most volume within the bounds of the solution volume is the "best" machine.

2.2.2 Santa Clara University

The research conducted at Santa Clara University is the product of two professors and one undergraduate engineering student. The research develops an informational program on rapid prototyping technologies and available machines. Figure 2.3 shows a screen dump from the program, introducing the authors of the program.

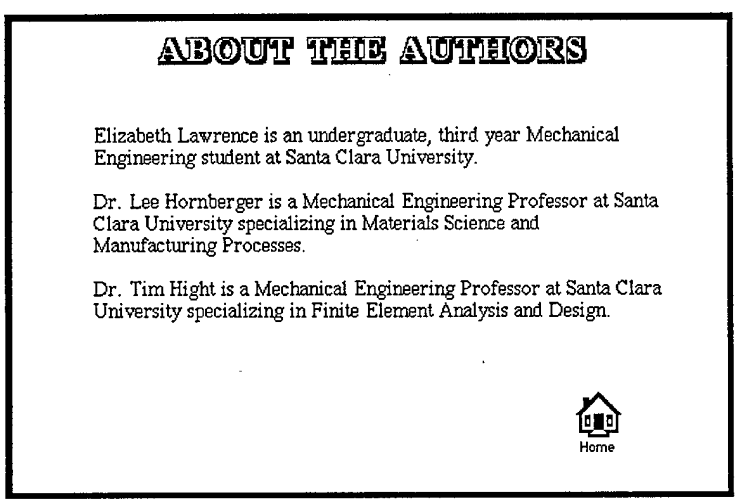

Figure 2.3 Santa Clara University Program Authors

Figure 2.4 displays the options the user has while using this rapid prototyping educational program.

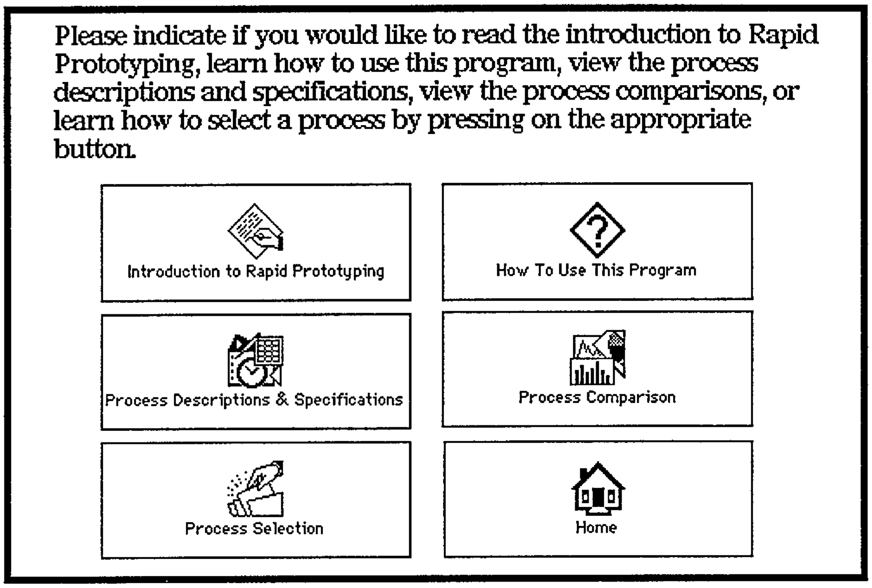

Figure 2.4 Program Options

It is important to note that this program serves as an educational tool. The program provides general information about rapid prototyping, many machine specifications, a simple process comparison, and suggestions for process selection. However, the program is not developed to make a decision for the user.

The introduction to the rapid prototyping section of this program simply provides the user with minimal text explaining the concept of rapid prototyping. The process descriptions and specifications section describes each of the rapid prototyping technologies and provides machine data on machines available in 1993. The process comparison option takes the user to the screen displayed in figure 2.5.

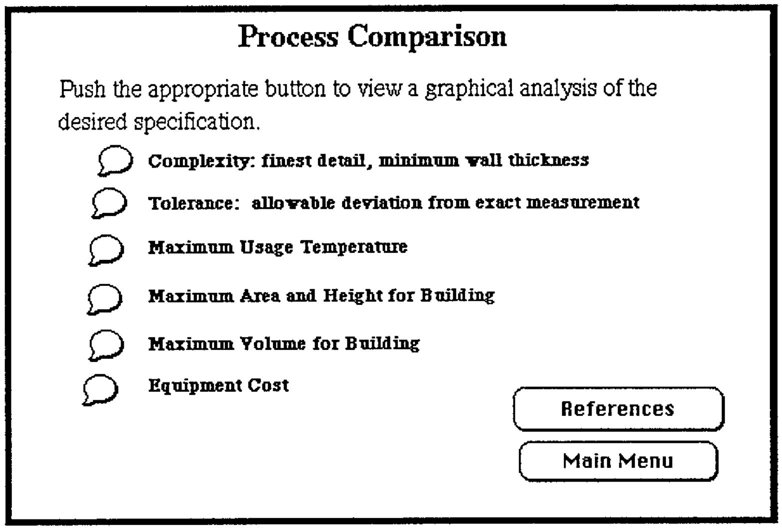

Figure 2.5 Process Comparison Screen

As each of the options shown on the figure above are selected, a graph is displayed with general information on each rapid prototyping technology, as shown in figure 2.6 for equipment cost.

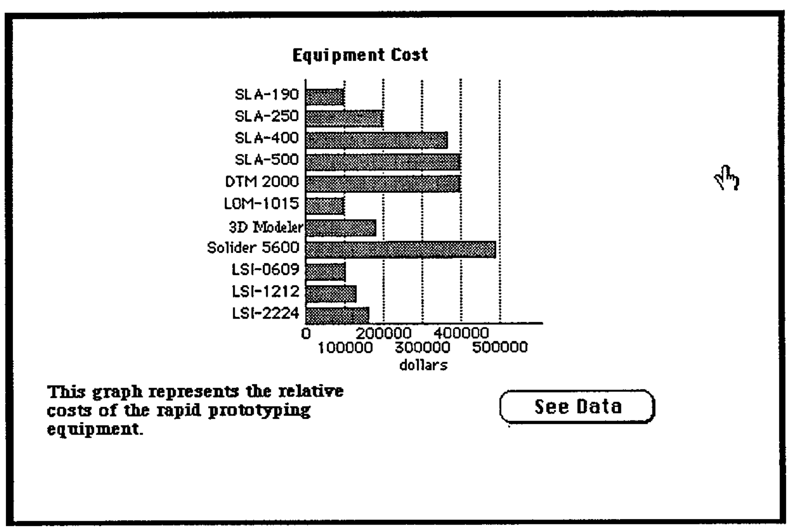

Figure 2.6 Cost Comparison

The most applicable option to the research represented in this paper is the process selection option from the main menu. This portion of the program will be used in chapter

4 as a bench mark program. However, the purpose of the rapid prototyping educational program and the RP Advisor are different. Therefore, the educational program is not intended to satisfy all of the requirements of the RP Advisor. Unfortunately, this is the only program available with a similar function that can be reviewed and compared to the RP Advisor.

Figure 2.7 pictures the process selection initial screen within the rapid prototyping educational program.

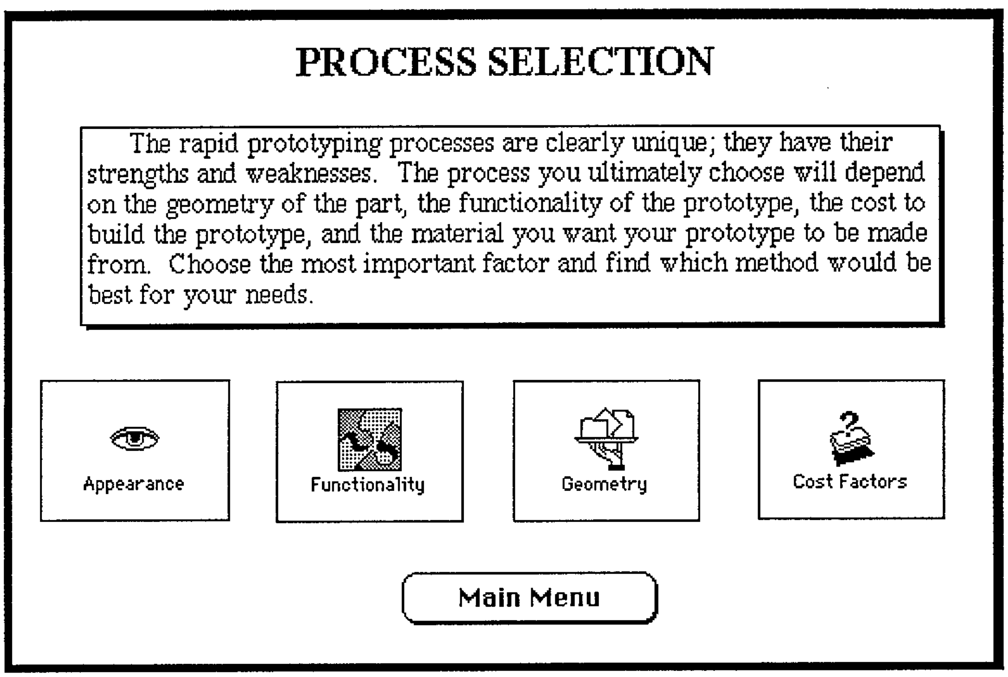

Figure 2.7 Process Selection Screen

This screen allows the user to investigate the rapid prototyping technologies with respect to appearance, functionality, geometry or cost factors of the model to be generated. However, each of these factors are dealt with one at a time. For example, when the "Appearance" option is selected, the screen shown in figure 2.8 is presented to the user.

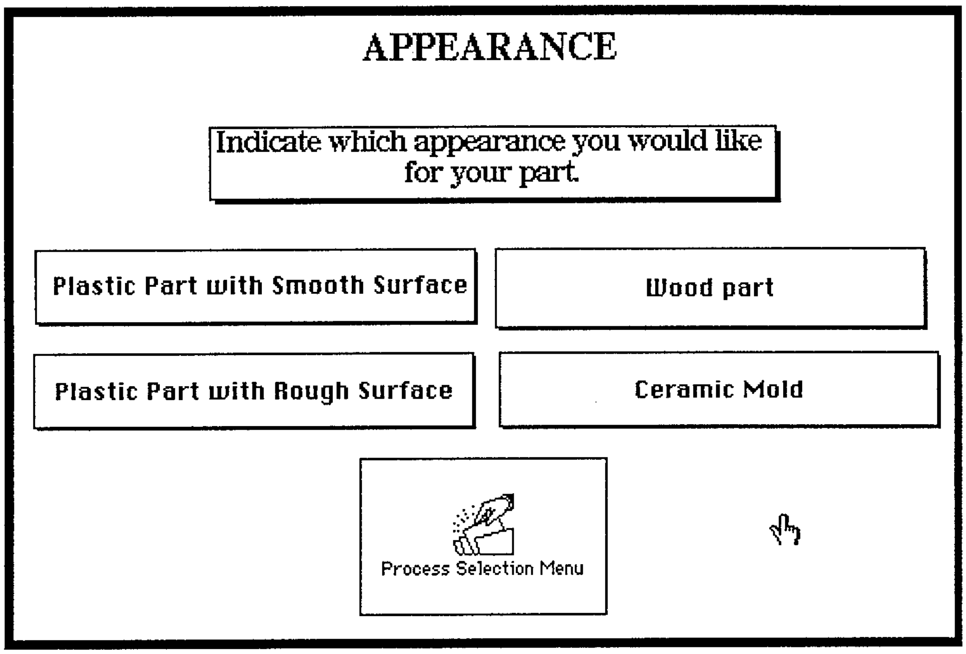

Figure 2.8 Appearance Selection Screen

From this screen the user is allowed to select the way the part is intended to look from four general descriptions. For example, if the user selects "Plastic Part with Smooth Surface," the user is presented with the screen in figure 2.9.

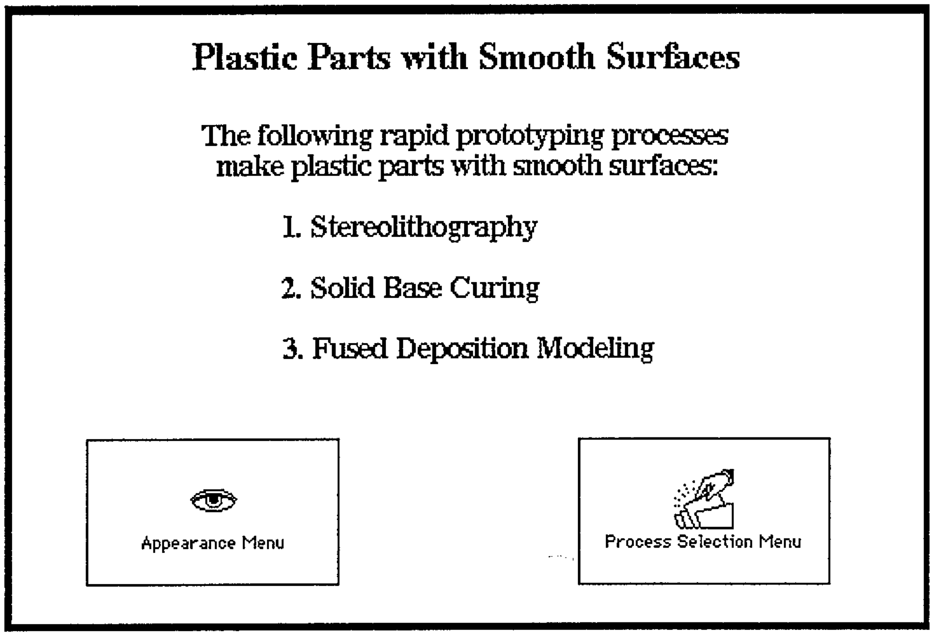

Figure 2.9 Plastic Parts with Smooth Surfaces Screen

This is the end product of the search for a technology which produces a part with the appearance of a smooth surface. As can be seen, the actual machines are not given and the technologies are not given a rating. The result is a simple list of the type of technologies that fit the general description the user selected.

From this list of technologies, the user now has a defined list of possible machines to investigate for that one attribute chosen through the selection of the process selection criteria. However, to obtain a suggestion for the "best" specific machine for the job, the user must revert to the inaccurate and possibly bias methods discussed in section 1.4.

2.2.3 BIBA

The documentation for the research done at BIBA is in the form of an introduction of a product which was designed to make the decision of rapid prototyping systems. Because of this, it is known that BIBA is doing significant research in this field, but is not publishing the techniques used. Acquisition of this product was not possible for reasons not explained by those involved in the BIBA project.

2.3 Summary

Three main groups are documented for their research in the field of rapid prototyping machine selection. The first, the University of Karlsruhe documents issues involving the decision-making involved in making the choice between different rapid prototyping machines. However, upon contacting the authors of this document the research is discontinued. The second, Santa Clara University, fails to combine the variables to find the "best" rapid prototyping machine. This research results in a program that informs the user of the technologies and their differences. The third, BIBA, is attempting to market a product that selects the "best" rapid prototyping machine for a given situation, however, this group has yet to share the specifics of their research.

CHAPTER 3

RAPID PROTOTYPING

3.1 Introduction

New rapid prototyping technologies are being developed at a quick pace. Consequently, new rapid prototyping machines are being produced at a rate that makes it difficult to stay current. The growth of rapid prototyping is evident in figure 1.6. It is necessary to determine where this technology fits in with traditional manufacturing and develop a taxonomy of all rapid prototyping processes.

3.2 RP in Manufacturing

Manufacturing processing methods can be divided into four categories: casting, forming and shaping, machining and joining (Kalpakjian, 1995). Finishing operations may be implemented as additional processes to any of the above. Machining operations are often referred to as subtractive processes, where joining operations are often referred to as additive processes. Rapid prototyping methods fall into the category of additive processes because they are based on the concept of layered manufacturing. By this, it is meant that models are produced by forming layer by layer. As each layer is formed, it is added to the previous layer. The following organizational chart demonstrates where rapid prototyping fits into the structure of all manufacturing processes.

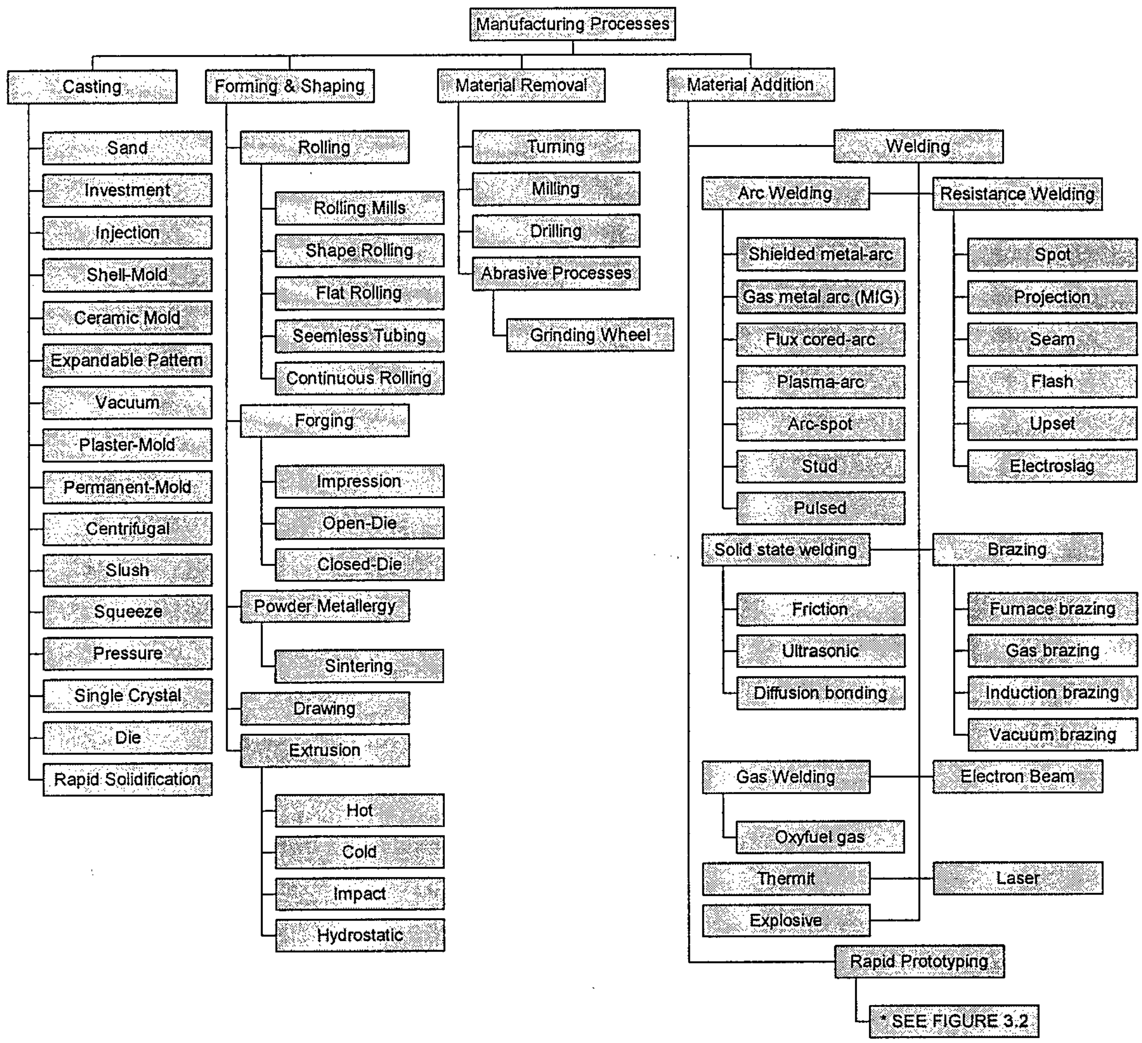

Figure 3.1 Manufacturing Process Organizational Chart

(Adapted from Kalpakjian, 1995)

3.3 Taxonomy of Rapid Prototyping

To develop a taxonomy of rapid prototyping technologies, it is important to define what a taxonomy is and what it is intended to accomplish. The taxonomy being formed in this research is an orderly classification of rapid prototyping technologies according to their presumed natural relationships. The purpose of this taxonomy is to develop a categorized list of all rapid prototyping technologies.

An issue that arises when developing a taxonomy of rapid prototyping technologies is that there are new technologies being developed as the research progresses. Also, as each new technology is released to market it is given a new name even if it is essentially the same as another. This makes it difficult to determine the number of truly unique technologies of rapid prototyping. To organize these technologies, the following taxonomy has been developed throughout this research to classify all rapid prototyping into two separate categories, Proven Systems and Developing Systems.

Proven Systems are those systems which are currently on the market. Developing Systems are those which are currently being developed and not available for immediate purchase. The following table shows the result of this taxonomy.

Table 3.1 Taxonomy of RP Systems

PROVEN SYSTEMS	DEVELOPING SYSTEMS
StereoLithography	**Shape Melting**
Laminated Object Manufacturing	**Electrosetting**
Design-Controlled Automated Fabrication	**Three-Dimensional Printing**
Solid Ground Curing	**MD**
Fused Deposition Modeling	**Direct Shell Production Casting**
Selective Laser Sintering	**Photochemical Machining**
Ballistic Particle Manufacturing	**Conveyed-Adherent Autofab**
Multi-Jet Modeling	

Figure 3.2 shows an organizational chart representation of all proven systems, which includes those individual technologies which fall into the categories listed above and a list of all machines available in these categories.

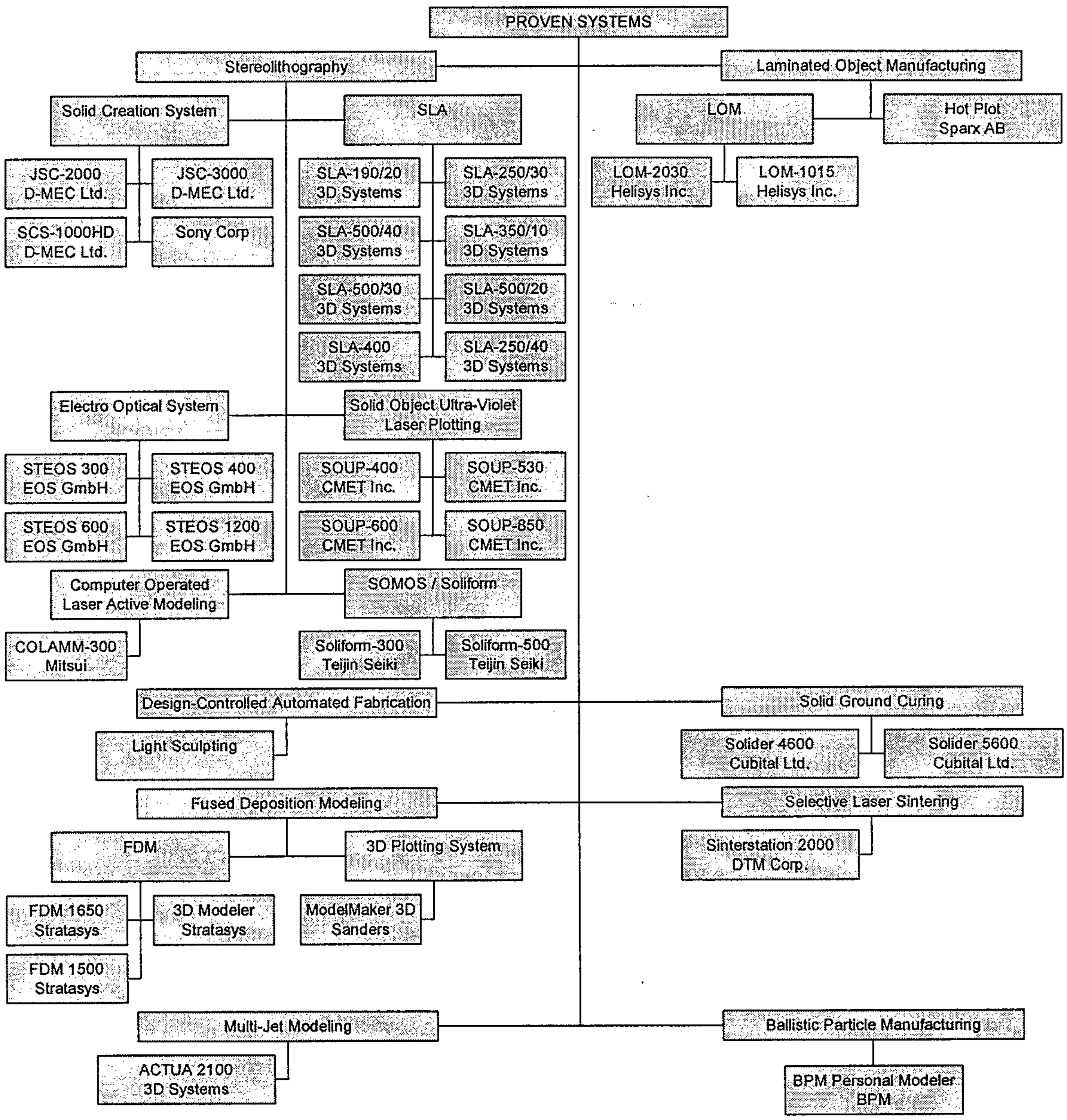

Figure 3.2 Rapid Prototyping Proven Systems

Figure 3.3 is a similar organizational chart containing the developing systems.

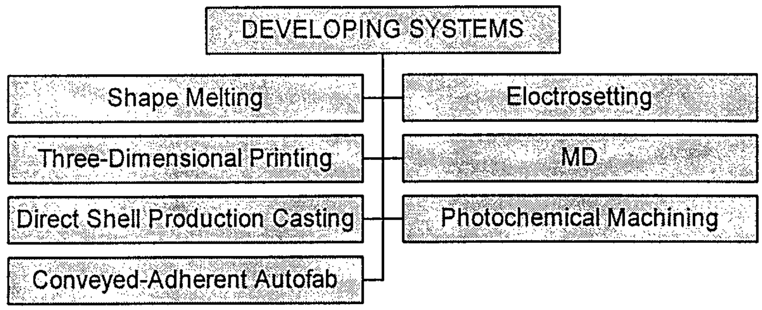

Figure 3.3 Rapid Prototyping Developing Systems

The creation of the figures above is a result of this research. The information shown has been compiled by conversations with experts in rapid prototyping and manufacturers of rapid prototyping equipment, as well as an extensive literature review on rapid prototyping. The sources from which this information was gathered can be found in the references at the end of this document. Points of contact at each of the manufacturers can be found in appendix A.

3.4 Rapid Prototyping Producers

Five companies dominate the rapid prototyping industry in the world today. These companies are 3D Systems, Stratasys, Helisys, Sanders Prototype and DTM. They now hold approximately 99% of the industry market share (Wohlers, 1996). The following sections will briefly touch upon each company, including a brief history, a description of the technology, and a list of available machines.

3.4.1 3D Systems

3D Systems is based in Valencia California and is the leading producer of rapid prototyping machines in the world. According to the State of the Industry: Rapid Prototyping 1995-96 Worldwide Report, this company currently holds an impressive 32%

of the worldwide rapid prototyping market (Wohlers, 1996). The company was founded by Mr. Charles Hull and Mr. Ray Freed. They first introduced a product in November of 1987 at the AutoFact trade show.

The technology which 3D Systems incorporates in all but two of it's production machines is called StereoLithography. This process was developed by Mr. Hull in 1984 and the patent was issued for the StereoLithography system in 1986. A comprehensive description of the process can be obtained through 3D Systems or found in various publications by Paul Jacobs. However, for the purposes of this thesis, a short description is included in the following paragraphs.

The StereoLithography process begins with a CAD file of the part to be produced. The accompanying software analyses this data for errors and corrects them automatically. At this point, the software separates the model into several 'slices', which are two dimensional cross-sections of the part. These cross-sections have the thickness of one layer in the layering process, which is variable. At this point, the three dimensional problem of producing a part is reduced to a two dimensional problem of producing each cross section. To produce each cross section, in StereoLithography, a platform is lowered in a vat of photopolymer liquid, so that one layer thickness of material is over the platform. Then a laser beam is directed onto the surface to trace out the cross-section of the part, as shown below.

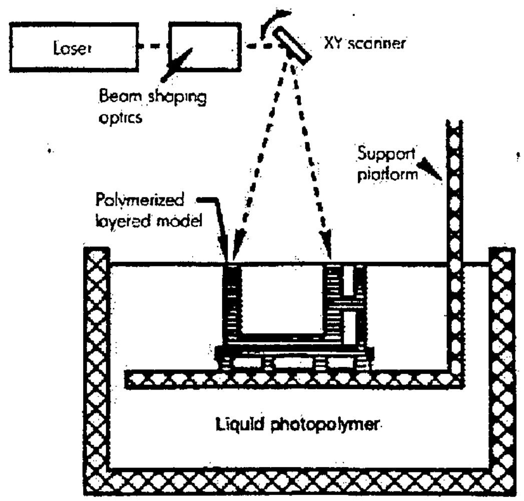

Figure 3.4 StereoLithography Process (Thomas, 1995)

As the laser contacts the photopolymer, the material cures, leaving the solid material that forms the prototype. After each layer is completed, the platform lowers into the vat to distribute resin on top of the prototype and raises to one layer below the surface of the resin. The machine is now ready to repeat the process until the entire part is cured and submerged below the surface of the resin. At this point, the part is not fully cured, so it is necessary to extract the part from the resin and submit it to ultraviolet light for a period of time for final curing.

The StereoLithography process has been implemented in a wide variety of machines produced by 3D Systems. They have produced a 190, 250, 350, 400 and 500 series of machines employing these technologies.

3D Systems has also developed another technology, called Multi-Jet Modeling (MJM) technology. This is a new process being used only in the Actua 2100. This machine is used for concept modeling. The process uses a technique similar to ink jet printing in three-dimensions. The MJM "Head" moves back and forth over the build platform as does an ink jet printer head, depositing a layer of specially developed thermopolymer material only where it is needed. The platform is lowered a layer and the process is repeated until the part is fully produced. The part requires no post curing and is ready to remove the supports and use as a prototype immediately. For further information, contact 3D Systems.

The 3D Systems machines available for purchase are given in table 3.2.

Table 3.2 3D Systems Production Machines

Stereolithography
SLA-190/20
SLA-250/30
SLA-250/40
SLA-350/10
SLA-400
SLA-500/20
SLA-500/30
SLA-500/40
ACTUA 2100

3.4.2 DTM Corporation

DTM Corporation is based in Austin, Texas, and the process used by this company is selective laser sintering (SLS). This process was developed by Carl Deckard at the University of Texas at Austin. In 1986, Dr. Paul F. McClure became aware of Mr. Deckards work and founded DTM Corporation. According to the State of the Industry: Rapid Prototyping 1995-96 Worldwide Report, DTM currently holds 10% of the worldwide rapid prototyping market with 40 machines in service throughout the world (Wohlers, 1996).

Selective laser sintering is very similar in concept to the StereoLithography process. However, the build platform for the SLS process is a circular platform and instead of using a resin, this process uses a powder. First, the powder is spread over the platen the thickness of one layer. Then, a laser sinters the cross section of the part much in the same way the StereoLithography process cures the resin. The platform is lowered one slice thickness, powder is spread over the surface and the process is continued. At the end of this process, the prototype is submersed in a keg of powder as opposed to a vat of liquid. Also, this part needs no post curing. The parts made from this process are typically porous in nature, but the process has a much greater range of materials that can be used to obtain desirable material properties.

The following figure is a cutaway picture of the SLS process, which may aid in understanding the set up of the machine.

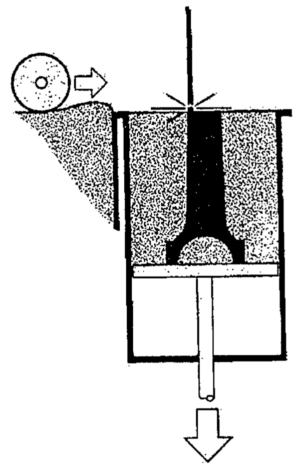

Figure 3.5 Selective Laser Sintering Process (Computer Aided Rapid Prototyping, 1996)

DTM is currently marketing the SINTERSTATION 2000 as their production machine.

3.4.3 Helisys, Inc.

Laminated Object Manufacturing (LOM) was developed in 1985 by a Mr. Michael Feygin. At that time, Mr. Feygin was the president of Hydronetics, Inc. in Chicago, IL. However, upon the development of this process, Mr. Feygin changed the name of his company to Helisys, Inc. and moved its headquarters to Torrance, Ca. According to the State of the Industry: Rapid Prototyping 1995-96 Worldwide Report, this company currently holds 17% of the worldwide rapid prototyping market, with 70 machines in service world wide (Wohlers, 1996).

The LOM process uses layers of paper, plastic, or composite sheet material and a laser to produce prototypes. The process begins by positioning one layer of the material over the cutting platform. The laser is then directed to cut the cross section of the part to be prototyped. After this is completed, the laser cross hatches all areas that do not belong to the part. The material is then rolled to the next section, a hot roller simultaneously compresses the layer and raises the temperature to create the chemical reaction that forms the bond, and the process is continued. The figure below is a diagram of the process.

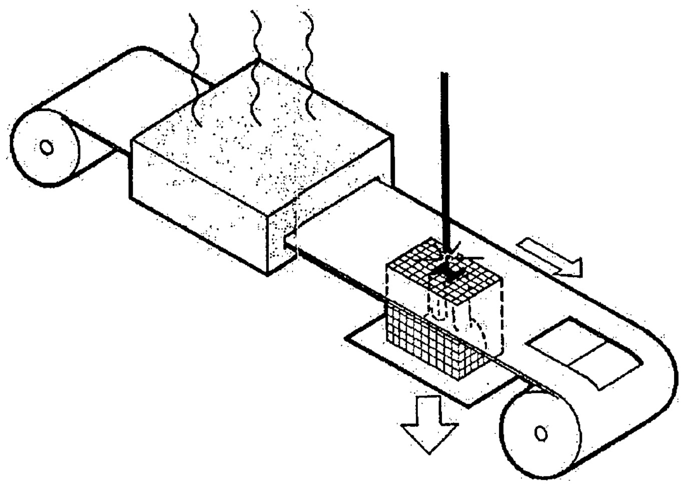

Figure 3.6 Laminated Object Manufacturing Process (Computer Aided Rapid Prototyping, 1996)

Helisys, Inc. is currently offering two LOM machines for purchase. These machines are the LOM-1015 and LOM-2030.

3.4.4 Stratasys, Inc.

Stratasys, Inc. is based in Minneapolis, MN and was founded by Scott Crump, who is currently the president of the company. Mr. Crump was also the developer of the Fused Deposition Modeling (FDM) process. According to the State of the Industry: Rapid Prototyping 1995-96 Worldwide Report, Stratasys, Inc. currently holds 30% of the worldwide rapid prototyping market, with 121 machines in service world wide (Wohlers, 1996). However, it should be noted they are quickly approaching the number one producer of rapid prototyping machines, 3D Systems.

FDM is a non-laser-based process and the material for this process is a thermoplastic filament, which is similar to a wire. The platform is raised to within one layer thickness to begin the first layer. The spool of material is directed through an extrusion head as the head is directed by the two dimensional data produced through the slicing process. As the material passes through the head it is heated to approximately 1 degree F above its solidification state to be deposited. This allows the material to adhere to the previous layer and solidify within 0.1 seconds of its deposition. After each layer, the platform is simply lowered one more layer thickness and the process is repeated. The figure below is a diagram of this process for clarification purposes.

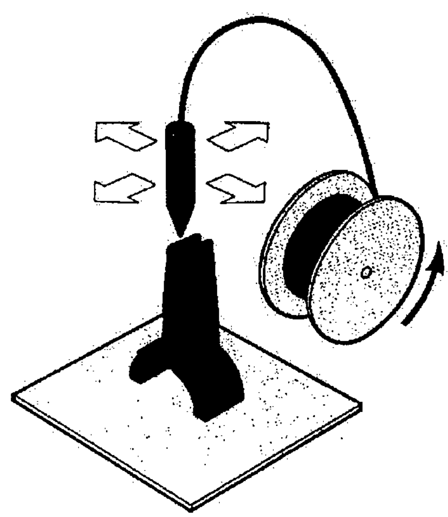

Figure 3.7 Fused Deposition Modeling Process (Computer Aided Rapid Prototyping, 1996)

Stratasys, Inc. currently produces two machines using the FDM process. These machines are the FDM1650 and FDM8000. However, they have recently released a concept modeler called the GENISYS 3D Printer. This machine also uses extrusion, but it uses wafers of material in stead of spools. The process is relatively the same except that this machine is faster and not as versatile or accurate, hence the reason it is a "concept" modeler.

3.4.5 Sanders Prototype, Inc.

Sanders Prototype is based in Wilton, NH and according to the State of the Industry: Rapid Prototyping 1995-96 Worldwide Report, they currently hold 10% of the worldwide rapid prototyping market, with 41 machines in service (Wohlers, 1996).

The Sanders machine employs Inkjet Modeling Technology to produce prototypes. The process uses two jets, one producing droplets of a wax support material and one of a thermoplastic model material. The process uses the sliced solid model, as the other processes do, to determine where supports are needed. As the layers are built, the dual head emits droplets of either thermoplastic or wax as needed. When the part is completed, the model is separated from the wax by washing the part in a kerosene type fluid that dissolves the wax but does not harm the thermoplastic. The following is a figure of the ink-jet modeling technology for clarification purposes.

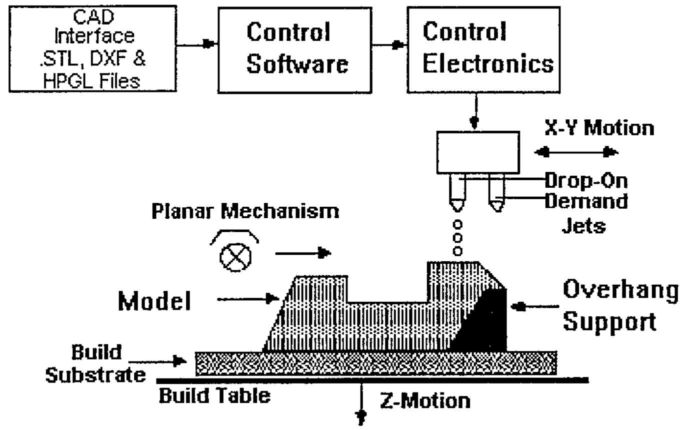

Figure 3.8 Inkjet Modeling Technology (Model-Maker 3D Modeling System, 1996)

The MM-6PRO is the only Sanders machine available at this time. This machine has a rather small build platform, but is known for its ability to produce very accurate small models with excellent surface characteristics.

3.5 Summary

The processes discussed in this chapter compose 99% of today's rapid prototyping market (Wohlers, 1996). However, it should not be forgotten that there are other systems being sold and many more in development stages. Table 3.3 is a summary of general information about the machines discussed in this chapter. For a more complete table of information, see appendix B.

Table 3.3 Abbreviated Rapid Prototyping Machine Information Table

Machine	Technology	Manufacturer	Purchase Cost	Build Envelope (Inches)	Overall Accuracy (Inches)
SLA-190/20	STL	3D Systems	$135,000.00	7.5x7.5x9	0.0028
SLA-250/30	STL	3D Systems	$215,000.00	10x10x10	0.0028
SLA-250/40	STL	3D Systems	$250,000.00	10x10x10	0.0028
SLA-350/10	STL	3D Systems	$425,000.00	13.8x13.8x15.7	0.0028
SLA-400	STL	3D Systems	$450,000.00	15x15x15	0.0028
SLA-500/40	STL	3D Systems	$560,000.00	20x20x23.75	0.0028
SLA-500/20	STL	3D Systems	$495,000.00	20x20x23.75	0.0028
SLA-500/30	STL	3D Systems	$540,000.00	20x20x23.75	0.0028
FDM 1650	FDM	Stratasys	$107,000.00	10x10x10	0.005
STRATASYS 8000	FDM	Stratasys	$250,000.00	17x20x24	0.005
GENISYS	FDM	Stratasys	$55,500.00	8x8x8	0.014
LOM-1015	LOM	Helisys	$95,000.00	15x10x14	0.01
LOM-2030	LOM	Helisys	$180,000.00	32x22x20	0.01
Sinterstation 2000	SLS	DTM	$397,000.00	12x12x15	0.015
MM-6PRO	Inkjet	Sanders	$50,000.00	6x6x6	0.005

CHAPTER 4

PROPOSED SYSTEM

4.1 Introduction

Several issues surface in the selection of the proper or appropriate rapid prototyping machine. Some parts require precision and accuracy, others emphasize quick turnaround and still other applications require low cost. For example, when prototyping close tolerance assemblies to check the fit, precision is probably the supreme priority. Purely aesthetic prototypes proposed as several options during conceptual design most likely need to be produced in many variations and as quickly as possible with little regard for precision. Another application involves training students in design, in which case, low cost is the primary concern.

The vast amount of information about the many systems available is overwhelming, making decisions difficult. Also, research facilities help in finding technology gaps. Technology gaps are candidate areas for research. For these reasons there exists a need for an automated rapid prototyping advisor. This chapter outlines a system which will provide the solution.

4.2 Dual Purpose System

To provide solutions for both of the needs outlined above, only one system need be developed. The system which advises new users of rapid prototyping for both using and purchasing rapid prototyping technologies, can also be used to find technology gaps. The sets of criteria where the advisor has no solution identifies the technology gap.

Therefore, the development of a machine to target that set of related criteria is a research area in need of exploration.

For this reason, the remainder of this chapter discusses the proposal of a system directed at new users attempting to enter the rapid prototyping world.

4.3 The RP Advisor Quality Function Deployment

As discussed in chapter 1, to gain a full understanding of any problem, a quality function deployment (QFD) is an excellent exercise. The following sections detail the progression of a QFD on a rapid prototyping selection program to be known as the RP Advisor. Each of the six steps to QFD, as listed in section 1.6, will be discussed in the following text.

4.3.1 Identify the Customer(s)

As the Japanese say, "Listen to the voice of the customer" (Ullman, 1992). To apply this, it is necessary to first define the customer. Figure 4.1 is a flow chart of the RP Advisor customers.

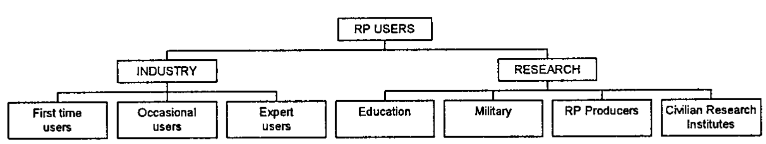

Figure 4.1 Customer Tree for the RP Advisor

The remainder of the problem definition must keep these customers in mind.

4.3.2 Determine Customer Requirements

Once the customer is defined, it is possible to determine what that customer wants to be designed.

At this point, the needs of the customer may be determined using the customer's terminology. In other words, exact specification are not needed. For instance, the customer of the RP Advisor requires the program to advise the "best" rapid prototyping machine for a set of parameters. This general statement contains several terms that need defining. At this stage it is appropriate to use it as a customer requirement.

Several methods are used to obtain a list of customer requirements. These methods include reviewing the literature pertaining to the problems, interviewing the customer and surveying the customer. Interviews include Mr. Kou-Rey Chu[1], Mr. Robert Foss[2] and Mr. Sean O'Reilly[3], as well as other experts in rapid prototyping during informal conversations. Attendants of the 3rd Annual Eugene C. Gwaltney Manufacturing Symposium on Rapid Prototyping for Product Development, Design and Tooling: Making the New Technologies Pay Off for You, were questioned by the author about the customer requirements of such a system. This symposium was held on October 1-3, 1996 at Georgia Institute of Technology, Atlanta, Georgia. Also, the collected literature noted in the references section was used to add to this list of requirements.

The following table compiles a list of these customer requirements for the RP Advisor. Because many of these requirements are vague, a description of each requirement is added for clarity.

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[1] Kou-Rey Chu is the Director of Manufacturing Technology at Phoenix Analysis and Design Technologies (1465 N. Fiesta Boulevard, Suite 102, Gilbert, Arizona 85233).

[2] Robert Foss is the manager of the Rapid Prototyping and Materials Science Consolidated Production Facilities (CPF) Government and Space Technologies Group at Motorola (8220 E. Roosevelt, P.O. Box 9040, Scottsdale, Arizona 85252).

Table 4.1 Customer Requirements

Customer Requirement	Explanation
chooses "best"	Advises the user of the number one choice.
Suggests alternatives	Informs the user of other machines that will work.
Lets you define what is "best"	Allows the user to specify what he/she feels is important.
Compares technologies	Compares the machines to advise the user.
Single part analysis	Analysis when user is looking to use a service company.
Purchase machine	Analysis when user is looking to purchase a machine.
sets up process chain	Informs the user of a set of processes including the RP machine.
Factors in material properties	Takes into consideration the needed material properties.
Factors in costs	Takes into consideration the cost of the prototype.
Factors in time	Takes into consideration the time to make the prototype.
Factors in quality	Takes into consideration the needed quality of the prototype.
Looks attractive	Program screens should be appealing to look at.
Many features	Program should allow user to do more than just find the "best" machine.
easy to install	It should be easy to get the program up and running.
Easy to use	Any person should be able to use the program with minimal training.
Runs fast	It should only take an experienced user a short time to get an answer.
Intuitive	The program should make sense to the user.
Inexpensive	The program should not cost very much to own.
To market fast	The program is needed in the market as soon as possible
Internet accessible	Queries should be able to be run over the Internet.
Works as it should	Program should give no errors aside from user errors.
Easily updatable	The table and calculations should be easily updatable.
Easily expandable	As new machines are put on the market it should be easy to add them.
Latest technology	The program should utilize the fastest latest technology.
info at finger tips	The user should have the information visible when needed.
Allow for customization	Users should be able to modify the program to fit their situation.

[3] Sean O'Reilly is the Staff Technology Specialist, Computer Aided Manufacturing Engineering, Advanced Manufacturing Technology Development at Ford Motor Company (24500 Glendale Avenue, Detroit, Michigan 48239).

4.3.3 Determine Relative Importance of the Requirements

The customer requirements now need to be rated in order of importance with respect to the entire problem. To do this, it is necessary to interact with the customer and make several engineering judgments. On occasion, unrelated customer requirements need to be compared. This makes the decision difficult when both requirements are important for entirely different reasons. Therefore, it is increasingly important to understand the problem to make an informed decision.

A first step to rating the requirements is to divide them into two groups. The first group of requirements composes the *musts*. This group need not be prioritized or ranked. In the problem understanding form it is necessary only to annotate these constitute "must satisfy" criteria. In figure 4.3, an asterisk (*) denotes these criteria in the 'Weight' column. The remaining requirements, the *wants*, make up the second group. It is necessary to rate the *wants* by giving each a weight, which can be integrated into the problem understanding form defined by Ullman as the compilation of the information obtained through a quality function deployment (Ullman, 1992).

To determine the relative importance, "a pairwise comparison technique is often used" (Ullman, 1992). To use this method, two requirements are compared at a time by asking the question, "Which is more important to the success of this product?" For two unrelated requirements, this question is difficult to answer, but it is still necessary to determine the dominant requirement.

According to Ullman a simple way to structure a pairwise comparison is to build a chart similar to the example in table 4.2 (1992).

Table 4.2 Pairwise Comparison Example

Requirement #			COMPARISONS				Total	Rating
1	1	0	1				2	33%
2	0			0	1		1	17%
3		1		1		1	3	50%
4			0		0	0	0	0%
Total							6	100%

By comparing the requirements two at a time and giving the most important a 'one' and the least important a 'zero' the problem is reduced to simple addition of the accumulated points of each requirement. The percentage on the far right is the assigned weight that is assigned to each requirement. The sum of the weights of the *wants* must equal 100.

This method becomes quite cumbersome if the number of requirements is large. In fact, given that N is the number of requirements, the number of possible combinations to compare is governed by the equation

$$Number\_of\_Combinations = \frac{N*(N-1)}{2} \tag{4.1}$$

The result of this requirement comparison can be seen in the 'Weights' column of the problem understanding form in figure 4.2.

4.3.4 Complete Competition Benchmarking

Benchmarking compares the solutions of like problems against the criteria set forth. Once these benchmarks are in place, it is simple to compare any possible solution to the problem at hand to those products already on the market. This not only helps ensure a competitive edge on preexisting products, but it also highlights that there is an existing product satisfying the customer requirements. Often times research into finding suitable benchmarking products leads the designer to information about other products that could save time and increase the quality of the product.

A program developed by Santa Clara University serves as a benchmark for the RP Advisor (Hornberger, Hight & Lawrence, 1993). This program is discussed in detail in section 2.2.2. However, the purpose behind the creation of the Santa Clara University program differs form that of the RP Advisor. The customer and engineering requirements in the Santa Clara University program differ from those determined for the RP Advisor. In any case, because the Santa Clara University program is the only known program available involving process selection for rapid prototyping, it serves as a benchmark.

To benchmark, the author compares the program in question to the customer requirements. Five ratings are used for the relation between the benchmark program and each of the customer requirements. These ratings are not very refined, but still provide information to the designer. The following lists the ratings used for the competition benchmarking of the Santa Clara University program with the RP Advisor customer requirements (Ullman, 1992):

1 = the design does not meet the requirement at all.
2 = the design meets the requirement slightly.
3 = the design meets the requirement somewhat.
4 = the design meets the requirement mostly.
5 = the design meets the requirement completely.

The result of the authors competition benchmarking of the Santa Clara University program is shown in figure 4.2, the problem understanding form for the RP Advisor. The ratings for the Santa Clara University program total 80 points, where the total of the points for the RP Advisor program equals 112. The ratings indicate the RP Advisor is more suited to the customer needs, which is expected, given the RP Advisor was developed to match these specific customer requirements.

4.3.5 Translate Customer Requirements into Measurable Engineering Requirements

The abstract requirements of the customer must be translated into exact, measurable requirements that can be monitored by the designer. Some of the customer requirements, such as 'runs on a PC' are directly measurable as a binary yes or no answer. However, other requirements such as 'easy to use' are general and need refining to be measurable. For this case, 'easy to use' could be measured by such quantifiable requirements as, number of steps to start up, number of steps to find help, number of steps to find answer, etc. The engineering requirements must have a specific measurable unit of measurement. Specifying these units completes the row below the last customer requirement on the problem understanding form.

After the engineering requirements have been added to the problem understanding form, the relationship matrix of the problem understanding form is completed. Each engineering requirement relates to each customer requirement. By following the row of one customer requirement across the form, the cell in that row belonging to an engineering requirement, contains a numerical value corresponding to the strength of the relationship between the customer and engineering requirement in question.

The strength of the relationship varies. Four numerical values convey this relationship (Ullman, 1992):

9 = strong relationship
3 = medium relation
1 = weak relation
Blank = no relation at all

By evaluating this for every possible combination of customer and engineering requirement, the entire center portion of the problem understanding form is completed.

The translated customer requirements for the RP Advisor and corresponding relationships with respect to the customer requirements can be viewed on the problem understanding form in Figure 4.2.

4.3.6 Set Engineering Targets for the Design

This step sets a goal for each engineering requirement. Each engineering requirement is analyzed and a specific value is recorded with respect to how the designer would like the product to rate after it is designed. Table 4.3 displays most of the engineering requirements along with the targets set for each. The remaining engineering targets can be seen on the problem understanding form (figure 4.2). The engineering requirements not shown in table 4.3 are simple binary (yes/no) requirements.

Table 4.3 Engineering Targets

Engineering Requirement	Units	Target
# steps to refine search	Steps	5
# steps to run choice	Steps	1
# steps to change type of search	Steps	2
# steps to change machine list	Steps	3
# steps to print out data	Steps	1
# steps to look at 1 machine	Steps	2
# steps to install	Steps	3
# factors leading to decision	#	20
# technologies that it will work for	#	All
pre-training time	min	10
time to become fluent with program	min	10
time for experienced user to get results	min	1
support equipment costs	$	0
product cost	$	0

To determine the number of step for the first seven engineering requirements, the designer of the RP Advisor used knowledge attained from the use of various engineering programs, keeping in mind the goal of keeping the RP Advisor easy to use. The number of factors leading to decision was chosen to be twenty in order to challenge the designer for this version of the RP Advisor. This number should increase for every version of the program. The number of technologies the program works for is a numerical value, however, the target is stated as "All." The structure of the RP Advisor should be able to accept all existing technologies, however, the only technologies that can be counted are those included in the database. The next three engineering requirements are measured in minutes. The targets are estimates by the designer with input from members of the rapid prototyping community. The concern with these three requirements was to develop a program that would not discourage the use of the product. Finally, the idea behind developing the RP Advisor on a personal computer was to utilize a piece of equipment that most design companies would already own. If this is true, they should have no support equipment costs. Also, because this program advises about rapid prototyping machines and service companies, the manufacturers and service companies could be charged a fee for being included in the database. This eliminates the cost of the product for the users.

After these targets are established, the designer attempts to design the product not only to satisfy the customer and engineering requirements, but also to meet the goals set forth in this step.

The target values for the RP Advisor can be viewed in figure 4.2.

4.4 RP Advisor Problem Understanding Form

As the QFD Technique is followed, a problem understanding form organizes the information gathered in a concise manner. Figure 4.2 compiles information about the RP Advisor problem as obtained in the previous sections of this chapter.

ENGINEERING REQUIREMENTS

CUSTOMER REQUIREMENTS

	RP ADVISOR	USER	Weight	# Steps to refine search	# steps to run choice	# steps to change type of search	# steps to change machine list	# steps to print out data	# steps to look at 1 machine	# steps to install	# of factors leading to decision	# technologies that it will work for	Pre - Training Time	Time to become fluent with program	Time for experienced user to get real results	Support equipment costs	Product cost	makes decision	Provides purchase data only when needed	Text stands out from backgrounds	Network accessible	PC - Based
Functions	chooses 'best'		*								9	3						9				
	suggets alternatives		*								1	3						3				
	lets you define what is best		*								3							3				
	compares technologies		*									9						3				
	single part analysis		*								3							1	9			
	purchase machine		*								3							1	9			
	sets up process chain		2													1	1	1				
	Factors in material properties		2								3							1				
	Factors in costs		8								3							1				
	Factors in time		8								3							1				
	Factors in quality		8								3							1				
Aesthetics	looks attractive		1										1	1	1		1		3	9		
Usability	many features		5										1		1	3	3				3	
	easy to install		4										1	1	3		1					9
	easy to use		8	9	9	9	9	9	9	9			9	9	9					3		9
	runs fast		4	3	3	3	3	3	3	3			9	3	9							
	intuitive		5	3	3	3	3	3	3	3			3	9	3				9	1		9
	inexpensive		4													9	9					3
	to market fast		6														3					
	Internet accessible		2													3					9	
	works as it should		*								3	3	1	1	1		3	3	3	3		
	easily updatable		8									3		3	1	3	3				1	
	easily expandable		9									3		3	1	3	3				1	
	latest technology		2									3	1			3	3				3	
	info at finger tips		7	3	3	3	3	3	3	3			3	3					3	1		
	allow for customization		7									1				3	3					
	Units			Steps	Steps	Steps	Steps	Steps	Steps	Steps	#	#	min	min	min	$	$	Y/N	Y/N	Y/N	Y/N	Y/N
	Targets			5	1	2	3	1	2	3	20	All	10	10	1	0	0	Y	Y	Y	Y	Y
	THE RP ADVISOR			3	1	1	3	1	2	1	12	5+	5	10	<1	0	0	Y	Y	Y	N	Y
	Santa Clara University Program			1	1	2	N/A	N/A	N/A	1	1	5	1	5	<1	0	0	N	N	Y	N	N

RP ADVISOR	Includes Accuracy	Includes surface finish	Includes health risks	Includes material hardness	Includes material density	Includes tensil strength	Includes compressive strength	Includes elasticity	Includes ductility	Includes malleability	Includes thermal expansion	Includes electrical conductivity	Includes viscosity	Includes solubility	Includes toxicity	Bench marks: THE RP ADVISOR	Bench marks: Santa Clara University Program
chooses 'best'																5	2
suggets alternatives																5	5
lets you define what is best																5	3
compares technologies	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	5	4
single part analysis																5	5
purchase machine																5	1
sets up process chain																1	1
Factors in material properties	1	1	9	9	9	9	9	9	9	9	9	9	9	9	9	2	2
Factors in costs	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	2
Factors in time	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	2
Factors in quality	9	9	1	1	1	1	1	1	1	1	1	1	1	1	1	4	2
looks attractive																4	3
many features																4	3
easy to install																5	3
easy to use																5	5
runs fast																5	5
intuitive																4	4
inexpensive																5	5
to market fast																5	5
Internet accessible																1	1
works as it should																5	5
easily updatable																5	1
easily expandable																5	1
latest technology																5	4
info at finger tips	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	5
allow for customization																5	1
Units	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N		
Targets	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		
THE RP ADVISOR	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N		
Santa Clara University Program	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N		

Figure 4.2 The Problem Understanding Form for the RP Advisor

The final section refers to the bottom of the form. The section composes two rows of numbers with the headings of RP Advisor and Santa Clara University Program. The numbers in these rows represent the results of the programs when the author evaluated with respect to the measurable engineering requirements. These values can be compared to the targets set forth in step 6, section 4.3.6., setting engineering targets for the design.

4.5 Summary

In this chapter, a need for a rapid prototyping machine selection system is shown for rapid prototyping technology implementation and development. One program is able to satisfy both of these needs. A quality function deployment is performed on a system to satisfy these needs.

The program being developed to meet the needs set forth in this chapter is called the RP Advisor. From the information presented in the problem understanding form in figure 4.2, the reader can determine the customer requirements and related engineering requirements for the RP Advisor. This form also displays a weighting factor given to each of the customer requirements and the relationship between the engineering requirements and each of the customer requirements. From this information, the designer of the RP Advisor can determine what program attributes to focus on in the development of the program. The final information contained in the problem understanding form includes the benchmarking of a program developed by Santa Clara University and a comparison of the RP Advisor and this benchmarking program with the engineering requirements set for the rapid prototyping machine selection program.

The result of the quality function deployment for a rapid prototyping machine selection program are shown in the problem understanding form, figure 4.2. The *must* requirements are determined to be:

1) chooses "best"
2) suggests alternatives
3) lets you define what is best
4) compares technologies
5) single part analysis
6) purchase machine
7) works as it should

Descriptions of these criteria can be reviewed in table 4.1. If any of these requirements are left unsatisfied, the RP Advisor is a failure.

The most significant *want* requirements were determined by the author to be those requirements scoring a seven or greater weight. The following is a list of these requirements:

1) Factors in cost
2) Factors in time
3) Factors in quality
4) easy to use
5) easily updatable
6) easily expandable
7) information at fingertips
8) allow for customization

Cost, time and quality are the three major variable when determining the "best" rapid prototyping machine. Therefore, it is reasonable to assume the factoring of each of the three functions rates among the most important requirements. Throughout the interview process, the "easy to use" requirement was verified as a top priority of the RP Advisor. The author was able to verify that "easily updatable," "easily expandable" and "allow for customization" belong among the most important requirements through discussions with many members of the rapid prototyping community. Finally, the purpose of the RP Advisor is to make the decision between rapid prototyping machines easy, so it follows that the information that the user needs should be where and when it is needed. In other words, the information should be at the users fingertips.

The requirement for "factors in material properties" is only weighted a two in the problem understanding form. However, throughout the interviews discussed in chapter 6 it is noted several times that this is a very important factor. There are two approaches to evaluate this discrepancy. One is that the weighting needs to be higher. The other is that the interviewees rated this requirement high because all of the other requirements had already been implemented. Regardless, this requirement is very important for later versions of the RP Advisor and will be discussed in chapter 7.

CHAPTER 5

SYSTEM IMPLEMENTATION CALCULATIONS

5.1 Introduction

As discussed in chapter 2 the three factors important in choosing an appropriate rapid prototyping technique are time, cost and quality, shown in figure 2.1 as the problem cube. The purpose of this chapter is to inform the reader how the RP Advisor uses the input to calculate values for these factors. This chapter also provides an explanation of how these values are brought together to form a non-dimensional weighted rating for each machine.

It is assumed that the user has a correct StereoLithography (STL) file of the part they wish to prototype. Many programs produce an STL file that is not "good." These files need correcting to be able to start at a fixed point. Also, the criteria defined describe the prototype properties before surface finishing work is performed.

The data for the machines in the RP Advisor can be reviewed in appendix B. For various reasons, not all companies release the numbers needed to complete this table. The information shown is the best information collected on each machine. The companies that produce these machines should not be, and are not, bound in any way to the information contained in the tables. Fortunately, because of the ease of updating this program, it is a trivial task to correct the table with more accurate information when the information becomes available.

5.2 Time Calculations

The first RP Advisor calculation is the time calculation. The cost calculation is dependent on the time calculation. The three categories of time for each machine are run time, pre-processing time and post-processing time. The most involved calculation is the run time. Each technology uses a different method to build the prototype and requires a different time calculation. However, some methods are so similar that the time calculation for another method may work. This overlap is likely to become more apparent as new technologies, using old technologies as a basis, are introduced. To accommodate these, the existing technologies are divided into 'speed categories.' As new machines are introduced, they are placed in a speed category with a similar speed calculation. The following table depicts the speed categories for the five technologies presently incorporated in the RP Advisor.

Table 5.1 Speed Category Table

Speed Category	Technology
1	StereoLithography
2	Fused Deposition Modeling
3	Selective Laser Sintering
4	Laminated Object Manufacturing
5	Inkjet Technology

There are no standards on reporting speed in the rapid prototyping community. Presently, speed is reported in units of inches per second or cubic inches per hour. However, this speed has a different meaning for each technology. In the following sections, the time calculations for the five major rapid prototyping technologies are reviewed.

5.2.1 Speed Category I: StereoLithography

The run time greatly depends upon material volume of the part to be made. In the case of StereoLithography, the entire material volume of the part is cured with a laser, which has a controllable thickness, cure depth and travel speed. The following equation determines the run time for a StereoLithography machine:

$$T_r = \# Layers\left(\frac{V_m}{z_b * D_b * S}\right) \tag{5.1}$$

T_r = runtime
V_m = material volume
z_b = bounding box height
D_b = beam diameter
S = speed

The first step is to determine the material volume of the part. When using the RP Advisor, the user has the option on the part parameters form to enter a specific volume or inform the system of the part material. If the user enters an exact volume, the material volume is evident. However, when the user specifies a general volume of plastic or metal, the problem becomes slightly more complex. If the user is running the RP Advisor to find a machine to purchase, he/she enters a general volume of the average part to be made. Because the search is not part specific, the user does not have an exact volume. Also, the general option allows the user to find the "best" machine before the STL file is actually created. Using a rule of thumb, material volume for metal parts is 15 - 25% of the bounding box volume (Chu, 1996). In the case of a plastic part, the material volume is 6 - 15% of the bounding box volume (Chu, 1996). However, these rules of thumb are not specific. To determine an approximate value for percentage of material volume, the RP Advisor uses the user-specified complexity. The following table is a summary of material volume as calculated as a percent of the bounding box volume.

Table 5.2 Percent Material Volume Decision

General Volume	Complexity	% Volume
Plastic	Simple	6
Plastic	Medium	10
Plastic	Complex	15
Metal	Simple	15
Metal	Medium	20
Metal	Complex	25

After the RP Advisor determines the percent of the bounding box volume of the material , it multiplies the width, length and height of the part, also defined by the user in the part parameters form to find the bounding box volume. The multiplication of the previously determined percent and the calculated bounding box volume gives the RP Advisor the material volume. This is the volume to be cured by the laser, as shown in the equation below.

$$V_m = V_b \bullet \%V_m \tag{5.2}$$

V_m = material volume
V_b = bounding box volume
$\%V_m$ = percent of material volume

At this point, the RP Advisor knows the material volume. Dividing the material volume by the bounding height of the part reduces the problem to two dimensions. Now, the RP Advisor is concerned only with calculating the time involved to produce one layer of the part. The RP Advisor calculates the number of layers required to build the part and uses this number to find the run time for the part.

The RP Advisor is faced with a two dimensional problem involving a surface area that must be cured per layer with a variable beam diameter to achieve the cure. The variable beam diameter allows the user to vary the accuracy and surface finish of the part. To determine the beam diameter, the RP Advisor uses the values of dimensional accuracy and surface finish entered on the part parameters form. For this calculation, it is not necessary to use exact values for either the dimensional accuracy or surface finish. Because of this, the following table identifies the rating given for each of the two terms with respect to the general or specific values entered by the user.

Table 5.3 Dimensional Accuracy and Surface Finish Rating Determination

Variable	Range	Rating
Dimensional Accuracy	> 0.0125 in	1
Dimensional Accuracy	0.004 - 0.0125 in	2
Dimensional Accuracy	< 0.004 in	3
Surface Finish	> 266 micro in.	1
Surface Finish	16 - 266 micro in.	2
Surface Finish	< 16 micro in.	3

From this table, the RP Advisor combines the dimensional accuracy and surface finish ratings into a composite value which will be known as the quality rating (not to be confused with the calculation of the total quality discussed in section 5.4). The quality rating of the part is determined by using table 5.4 as a guide.

Table 5.4 Determination of Quality Rating

Dimensional Accuracy Rating + Surface Finish Rating	Quality Rating
1	1
2-5	2
6	3

The quality rating is a 1, 2 or 3, which allows the RP Advisor to select the beam diameter to be the maximum, average or minimum beam diameter respectively. Now that the RP Advisor has determined the beam diameter, the following formula reduces the two dimensional problem of surface area to a one dimensional problem of cure length per layer.

$$L_c = \frac{A_s}{D_b} \tag{5.3}$$

L_c = cure length
A_s = surface area
D_b = beam diameter

The cure length is the length required to completely cure one layer of the part and is also referred to as the distance of laser travel per layer. Category one, speed information, is given in inches per second. The next step is to multiply the speed by the cure length, which results in a run time with units of seconds per layer. The following formula shows this relationship.

$$T_l = L_c * S \tag{5.4}$$

T_l = time for one layer
L_c = cure length
S = speed

The RP Advisor now determines the number of layers necessary to build the part. The layer thickness is variable, which means the values entered by the user must be used to determine the layer thickness for the part in question. Figure 5.1 is an example of the effect of layer thickness on surface finish.

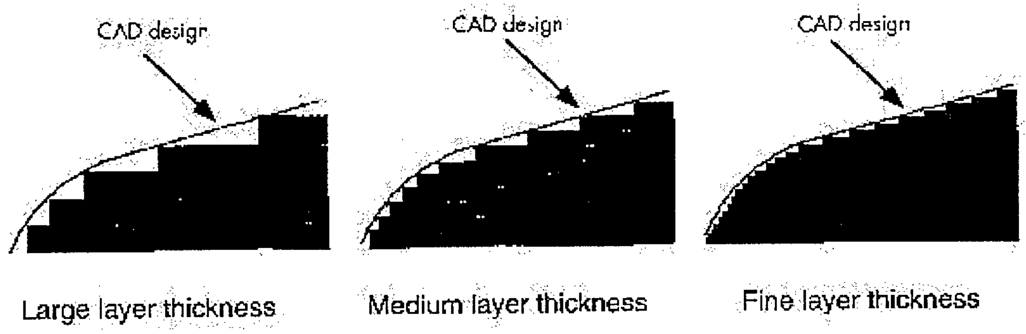


Figure 5.1 Effect of Layer Thickness on Surface Finish and Dimensional Accuracy (Jacobs, 1996)

The RP Advisor has previously calculated a quality rating to determine the beam diameter. This quality rating is also used to determine the layer thickness. A quality rating of 1, 2 or 3 results in a layer thickness of the maximum, average, or minimum setting respectively.

At this point, the RP Advisor has a value for the layer thickness of the part. By dividing the bounding height of the part by this thickness, the RP Advisor determines the number of layers to produce the part. A simple multiplication of the run time per layer and the number of layers results in a run time in seconds.

5.2.2 Speed Category II: Fused Deposition Modeling

The speed estimates for category two machines are given in inches cubed per hour. This simplifies the calculation of run time for a category two machine.

The first step, determining the material volume of the part, is accomplished as described in section 5.2.1. The RP Advisor uses the specific material volume, if given. However, if the part is identified as plastic or metal, table 5.2 is used to determine the percentage of the bounding box volume to use for the material volume.

Once this volume is determined, the only calculation needed divides the material volume by the speed. This results in the run time in seconds. This is a very general calculation and is a simple approximation of the run time.

This runtime calculation is simplified and is not accurate with respect to the number of seconds reported. However, the magnitude of the answer is accurate. The magnitude is sufficient for the RP Advisor to make a decision.

5.2.3 Speed Category III: Selective Laser Sintering

Although selective laser sintering is different from StereoLithography, the speed is calculated in much the same way. Both systems use a laser with a variable diameter to transform some medium to a solid, have the flexibility to vary layer thickness, and report speed in inches per second. For these reasons, the RP Advisor treats category III speed calculations identically with category I calculations. For an in-depth discussion of this calculation refer to section 5.2.1.

Differentiating between these two speed calculations allows for simple modification of the RP Advisor. This allows the use of separate time calculation engines to recognize the differences in the rapid prototyping machines.

5.2.4 Speed Category IV: Laminated Object Manufacturing

With layered object manufacturing, the speed is reported in units of inches per second. This is the same as categories I and III. However, the calculation for this speed category is different. The laminated object manufacturing technology is based on a laser cutting the outline of the part, as opposed to curing the entire volume.

To calculate the run time for a category IV speed calculation, the first step determines the travel distance of the laser for each layer. To accomplish this, the following equation is a rule of thumb as developed by the author.

$$\frac{L_t}{Layer} = \left(x_b \bullet y_b\right) \bullet 1\% \tag{5.5}$$

L_t = laser travel length
x_b = bounding width
y_b = bounding length

The percentage value in the equation above varies with the complexity of the part. However, in order to derive an average percentage value, the author tests the RP Advisor, comparing against known runtimes. The result of this testing is a one percent factor of surface area. With this, the RP Advisor determines the average travel distance of the laser per layer. Dividing this by the speed results in the run time per layer as seen in the equation below.

$$\frac{T_r}{Layer} = \frac{L_r \,/\, Layer}{S} \tag{5.6}$$

T_r = runtime
L_t = laser travel length
S = speed

The remaining step is to determine how many layers it takes the machine to produce the part. The following equation performs this calculation:

$$\#\,Layers = \frac{z_b}{\Delta z} \tag{5.7}$$

#Layers = number of layers to build the part
z_b = bounding box height
Δz = layer thickness

Determining the layer thickness is performed as outlined in section 5.2.1. The number of layers is then multiplied by the run time per layer to find the total run time.

5.2.5 Speed Category V: Inkjet Technology

During the ink-jet technology process the extrusion head not only builds the part but also builds a solid support structure. This support structure dissolves in a solution after the build is complete. The following equation, developed by the author as a rule of thumb, determines the percentage of material volume of the model plus the supports with respect to the bounding box volume when the exact volume is unknown. This is a general equation and can be improved upon with experience.

$$V_m = \frac{\left(x_b \bullet y_b \bullet z_b\right)}{2} \tag{5.8}$$

V_m = material volume
x_b = bounding box width

y_b = bounding box length
z_b = bounding box height

The speed for category V calculations is reported in inches cubed per hour. This means the volume is divided by the reported speed to determine the number of hours of run time. However, the other calculations result in a run time reported in seconds. Therefore this build time must be converted from hours to seconds. This is achieved by multiplying by 3600 seconds per hour.

5.2.6 Pre-Processing and Post-Processing Time Calculations

Because each technology uses a different method to process the StereoLithography file, the amount of pre-processing time varies. Likewise, the post-processing time also varies. StereoLithography requires a post cure to completely solidify the part. It also requires breaking away of support structures. Fused Deposition Modeling post-processing requires breaking away support structures. Selective laser sintering produces the part in a keg of powder from which the part is extracted and then cleaned. Laminated object manufacturing produces a part in a block of wood like material which are manually extracted. Finally, ink-jet technology parts are submersed in a kerosene type solution to dissolve supports. This a basic description of the post-processing activities for each technology, but in general, the pre- and post-processing time is related to complexity, size, dimensional accuracy and surface finish required by the user. Because the run time already factors in these variables, a correlation exists between runtime and pre- and post-processing times. The RP Advisor uses a percentage of the run time to calculate the pre- and post-processing times. Table 5.5 shows the percentages used.

Table 5.5 Relationship Between Pre- and Post-Processing Times and Run Time

Speed Category	Pre vs. Run Time	Post vs. Run Time
1	0.038	0.169
2	0.095	0.050
3	0.050	0.100
4	0.021	0.111
5	0.050	0.075

For speed categories I, II and IV, the ratio between run time and pre- and post-processing times is generated from figures 5.2, 5.3 and 5.4. The figures are the results of an IMS[1] study done on rapid prototyping technologies. The ratio for the remaining two categories is derived from discussions with experts in the field.

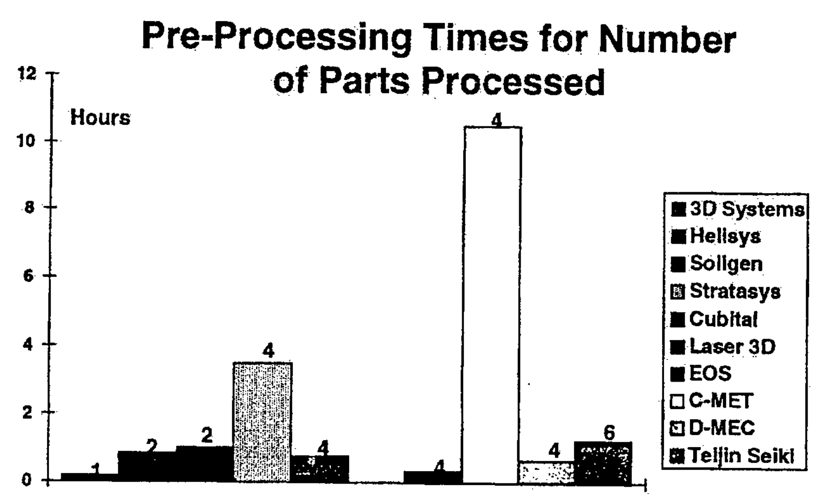


Figure 5.2 Pre-Processing Time (Aubin, 1994)

[1] IMS - Intelligent Manufacturing Systems

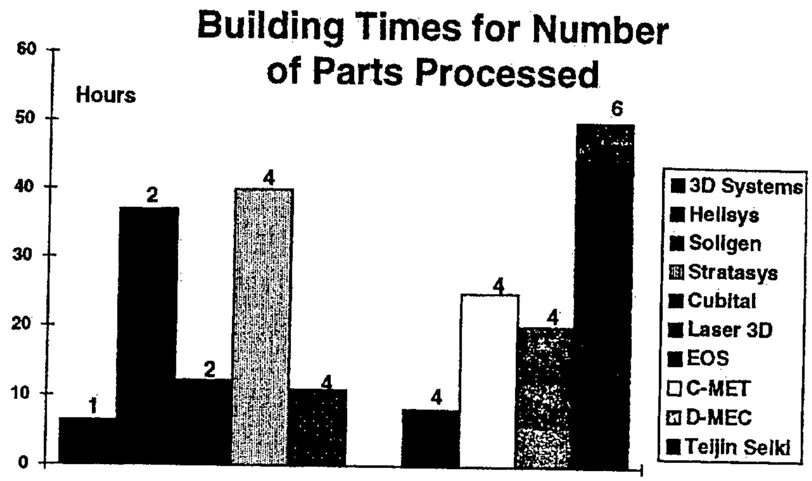


Figure 5.3 Run Time (Aubin, 1994)

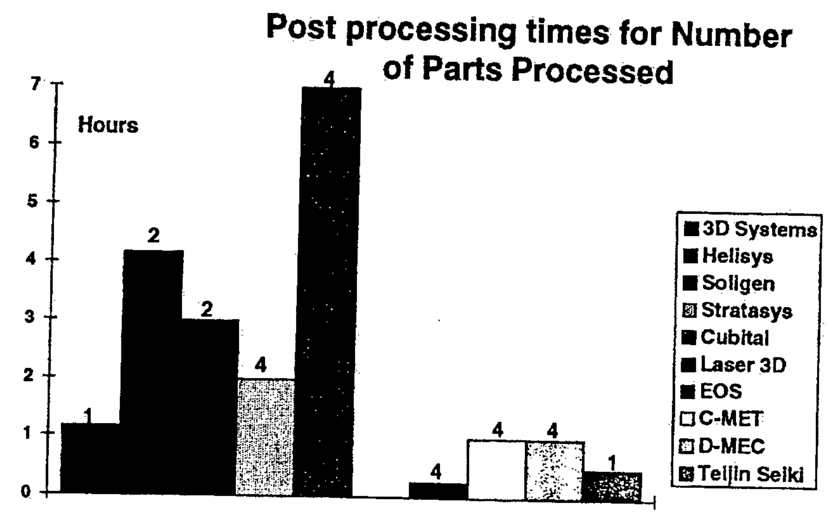


Figure 5.4 Post-Processing Time (Aubin, 1994)

The RP Advisor, with the information given in table 5.7, calculates a pre- and post-processing time for all machines.

5.2.7 Non-Weighted Time Rating

At this point, each machine has a value for the run time, pre-processing time and post-processing time. These time calculations are general and leave out a number of factors such as the deterioration of laser power necessary in determining the exact times. However, they are used only to compare relative to the other machines. At no time does the RP Advisor attempt to give the user an exact run time. To compare the machines, the normalized time of each machine is needed.

For each machine, the RP Advisor sums the run time, pre-processing time and post-processing time to determine a total time value. Each value is then divided by the maximum total time value resulting in normalized total times, which are considered non-weighted ratings. However, the ratings are not intuitive, which is one of the customer requirements in chapter 4. Most people consider a machine with a high rating to be a better machine. As it is, the higher the rating, the longer the part takes, therefore the lower the rating the better the machine. To rectify this, the RP Advisor subtracts each rating from one. The result is a set of time ratings which vary from zero to one. The machine with a time rating of zero is the slowest machine and the machine with the highest rating is the fastest available machine. The user can now intuitively compare the total time of each machine.

5.3 Cost Calculations

The second calculation that the RP Advisor takes into consideration is the cost. To determine how cost is evaluated, it is important to understand how cost is estimated throughout industry. In general, the field of study which focuses on cost throughout a project is called cost engineering.

5.3.1 Cost Engineering

According to The American Association of Cost Engineers (AACE), cost engineering is "that area of engineering practice where engineering judgment and experience are utilized in the application of scientific principles and techniques to the problems of cost estimation, cost control and profitability" (Clark & Lorenzoni, 1985). The main focus of this section is on the cost estimation aspect of this field. To explain the concepts, examples are in the context of the design and manufacturing industry.

To complete a cost estimate, the first step determines what is to be evaluated. The set of actions that compose the activity to be evaluated is classified as a project, which contains few or many processes. For example, it is possible to apply all the following techniques to the estimation of cost for a single drilling operation or to the entire design process from product definition to production. By building a project, a company confines the responsibilities of those involved and narrows what is to be done within the bounds of the project. The following figure exemplifies a typical life cycle of a project for an average-size process plant.

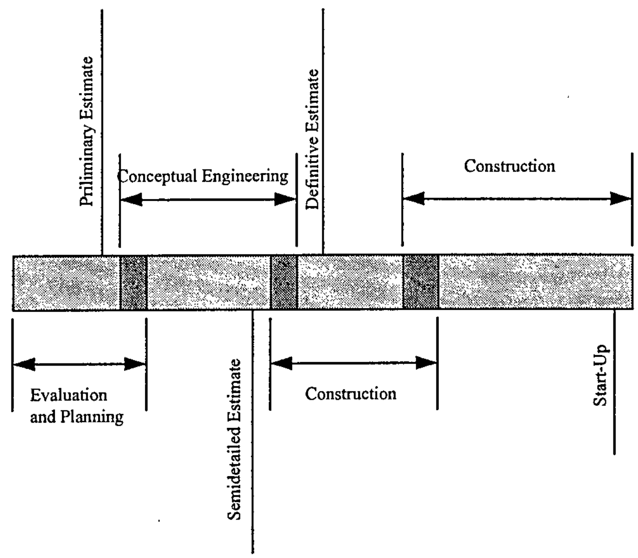


Figure 5.5 Historical Project Phases (Clark & Lorenzoni, 1985)

After a project is formed, the next step determines where cost estimates are beneficial. The above figure generalizes where certain processes can benefit from a cost estimate. The project is assumed to have four phases: Evaluation and planning, Conceptual engineering, Detailed engineering and Construction.

The evaluation and planning phase are the most critical times to do a complete cost estimate. Unfortunately, this is the most difficult time to perform an accurate estimate. At this point, the project is not well defined and a great deal of engineering judgment and experience is needed to make the estimate a valuable tool. This phase covers the period from the start of the project until the plan of action for completion of the project. Questions, such as what will be built, where will it be built, and why will it be built, are answered during this phase. The result of the cost estimate during the evaluation and planning phase compares alternate processes and determines the best way for the project to accomplish its goal. Because of this, the main emphasis of cost estimation during this phase is placed on comparing the differences in cost between the processes, as opposed to the actual amount of the cost estimate.

After the preliminary estimate is completed, the group in charge of the project has the information needed to narrow down the processes that will be used to complete the project. With this more specific plan, a second, semi-detailed estimate is needed which focuses more on the actual costs of the processes that were chosen in the previous project stage. This estimate is close to the actual cost of the project and is used to control the cost of the project throughout completion.

The final cost estimate is conducted midway through the detailed engineering phase of the project. This estimate more accurately evaluates the actual cost of the construction before it is implemented. In this phase, there are few options to be evaluated. It is mostly a calculation of the costs to help track and control costs throughout the finalizing of detailed engineering and into construction.

5.3.2 Preliminary Cost Estimating

As noted in the previous section, preliminary cost estimating focuses on the differences between the costs of each process. To decide which rapid prototyping machine to use for any given application requires the comparison of all rapid prototyping machines but does not make it necessary to calculate an accurate dollar value. Because of this, the RP Advisor need only complete a preliminary estimate.

Preliminary cost estimations are performed before the design has taken its specific form or shape, early in the stages of its evolution. Because of a lack of facts and specific information, the estimator is required to use various methods, rules of thumb, and simple calculations to produce a quick and relatively inexpensive estimate. This initial estimate is usually used for screening and eliminating unfit options in an inexpensive manner.

This type of cost estimate may not be individually conclusive because of the ambiguity inherent in the lack of facts that the estimate is based on and is often referred to in terms such as conceptual, battery limit, schematic, order of magnitude and mean preliminary estimate (Ostwald, 1984). More detailed cost estimations provide the estimator with more quantitative and tangible results but require much more information, take longer to produce, and are more expensive to accomplish.

5.3.3 Cost Estimating For a Rapid Prototyping Advisor

When dealing with cost of rapid prototyping, it is essential to realize a comparison between available machines instead of an actual dollar amount is needed. The user of the RP Advisor evaluates machines with respect to having a part made by a service company or making a machine purchase.

5.3.4 Single Part Cost Analysis

The cost analysis of building a part on a rapid prototyping machine takes into account many parameters:

1) Material cost
2) Electricity cost
3) Personnel training cost
4) Equipment maintenance costs
5) Factory floor space costs
6) Many other overhead costs

Fortunately, when dealing with a service company, the responsibility of this calculation is placed on that company. However, emerging service companies calculate the cost of building a prototype in different ways. To be able to accommodate a variety of cost calculations, the RP Advisor allows the user to define parameters such as material cost, labor cost and overhead. For the purposes of this version of the RP Advisor, a set of hourly rates for run time, pre-processing time and post-processing time are derived by the author through interviews with experts in rapid prototyping. This set of rates is presented in table 5.6.

Table 5.6 Estimated Cost per Hour Run Time of RP Technologies

Machine	Technology	Pre-Processing ($/hr)	Post-Processing ($/hr)	Run Time ($/hr)
SLA-190/20	STL	65	65	55
SLA-250/30	STL	65	65	55
SLA-250/40	STL	65	65	55
SLA-350/10	STL	65	65	65
SLA-400	STL	65	65	85
SLA-500/20	STL	65	65	95
SLA-500/30	STL	65	65	95
SLA-500/40	STL	65	65	95
FDM 1650	FDM	65	65	50
STRATASYS 8000	FDM	65	65	65
GENISYS	FDM	35	35	10
LOM-1015	LOM	65	65	60
LOM-2030	LOM	65	65	85
JP-SYSTEM 5	LOM	4.25	4.25	1
Sinterstation 2000	SLS	65	65	100
MM-6PRO	Inkjet	65	65	50
X-1 (ASU)	STL	85	85	100
X-2 (ASU)	STL	85	85	100
X-3 (ASU)	STL	85	85	100
X-4 (ASU)	STL	85	85	100
X-5 (ASU)	STL	55	55	80
X-6 (ASU)	STL	55	55	80
X-7 (ASU)	STL	55	55	80
X-8 (ASU)	STL	55	55	80

The table above shows eight fictitious machines. These machines are denoted by "(ASU)" after the machine name. The purpose of these machines is to demonstrate the ability of the RP Advisor to deal with new machines and to propose RP machines which are very different from existing machines.

To calculate a total cost value for each machine, the RP Advisor uses the following formulas:

$$C_{pre} = (T_{pre})(R_{pre}) \tag{5.9}$$

C_{pre} = pre-processing cost
T_{pre} = pre-processing time
R_{pre} = pre-processing cost rate

$$C_r = (T_r)(R_r) \tag{5.10}$$

C_r = runtime cost
T_r = runtime
R_r = runtime cost rate

$$C_{post} = (T_{post})(R_{post}) \tag{5.11}$$

C_{post} = post processing cost
T_{post} = post-processing time
R_{post} = post-processing cost rate

$$C_T = C_{pre} + C_r + C_{post} \tag{5.12}$$

C_T = total cost
C_{pre} = pre-processing cost
C_r = runtime cost
C_{post} = post processing cost

The next step is to create a non-weighted cost rating for each machine.

5.3.5 Non-Weighted Cost Rating

At this point, the RP Advisor calculates a dollar amount for the cost of producing the part for each machine. The utility of these numbers is realized in using them to compare the technologies against each other as opposed to quoting actual costs. To use these values, it is necessary for the RP Advisor to create a non-weighted cost rating for each machine.

The RP Advisor accomplishes this in the same way it created the non-weighted rating for the total time. The rating is the normalized value of the total cost. To calculate the normalized values, the RP Advisor divides each total cost by the value of the greatest total cost. Unfortunately, as was the case with the non-weighted time rating, the result of this calculation is counter intuitive. The higher the number, the more the part cost. To convert this rating so that the higher the value, the lower the cost, the normalized values are subtracted from one.

Remaining is a non-weighted cost rating ranging from zero to one. The machine with a cost rating of zero is the most expensive machine for the situation. The machine with the highest rating is the least expensive available machine. This allows the user to intuitively compare the costs of the different machines.

5.3.6 Machine Purchase Consideration

When the user decides to purchase a rapid prototyping machine, the RP Advisor takes this into consideration. The RP Advisor prompts the user for a budget range which allows the elimination of machines not within the budget. The remaining machines are then rated by a simple purchase analysis. The user enters values describing a typical part to be produced on the machine.

5.4 Quality Calculations

The third and final calculation is the quality calculation. The RP Advisor requires the user to input a value for dimensional accuracy on the part parameters page, as discussed in earlier sections. The user selects one of the three options in the general category for accuracy. Alternatively, the user enters a specific value. To calculate an estimate of each machines' ability to satisfy this quality value, a relationship is built between the maximum capability of the machine and the requirement of the user.

5.4.1 Quality Elimination

To eliminate from the available machines list all those machines that are not capable of producing the desired level of accuracy, all machines that have an overall accuracy of greater than the amount entered on the part parameters form are eliminated.

5.4.2 Quality Formula

The equation for differentiating between the remaining machines is given below. The solution is considered the total quality for each machine.

$$Q_t = (AC_o)/ (AC_t) \tag{5.13}$$

Q_t = total quality
Ac_o = overall accuracy
Ac_t = target accuracy

The target accuracy is the value of accuracy which the user entered. Because only machines that have an equal or lower overall accuracy are considered, the result of this equation will always be a value between zero and one. However, this is not the non-weighted quality rating that is needed by the RP Advisor.

5.4.3 Non-Weighted Quality Rating

To determine a rating factor for the quality of each machine, it is necessary to normalize the quality factors found in the previous section.

The RP Advisor accomplishes this the same way it creates the non-weighted rating for both total time and total cost. The RP Advisor divides each quality factor by the largest quality factor. Like the time and cost ratings though, the rating found after this division is not intuitive. Therefore, each number is subtracted from one to fix this. After this adjustment, the higher the number, the greater the ability of the machine to surpass the target accuracy.

5.5 RP Advisor Decision

At this point, the RP Advisor calculates a non-weighted rating for time, cost and quality. However, to combine these ratings into a total non-dimensional rating which reflects what the user feels is important, it is necessary to obtain more information from the user. The priority values are used to determine the importance the user places on getting a model made fast, cheap or of excellent quality.

On the priorities form, the user rates the importance of each of the three factors with a scale of one to one hundred. This allows the user, for example, to make the value of getting a part fast outweigh the other ratings. Using these priorities, the system calculates a non-dimensional value for each of the available machines. This value is calculated by using the following formula:

$$ND = \left[\left(T_n * T_p\right) + \left(C_n * C_p\right) + \left(Q_n * Q_p\right)\right] \tag{5.14}$$

ND	= non-dimensional value
Tn	= non-weighted rating for time
Tp	= priority value for time
Cn	= non-weighted rating for cost
Cp	= priority value for cost
Qn	= non-weighted rating for quality
Qp	= priority value for quality

To make the non-dimensional value usable, it is necessary to normalize each value. This is done by dividing the non-dimensional value by the largest non-dimensional value. At this point, the RP Advisor succeeds in calculating a non-dimensional weighted rating for each available machine. The only action left is to notify the user that a decision has been made. The machine with the highest non-dimensional weighted rating is the "best" machine for the purpose of making the prototype defined by the user. The remaining machines are listed in descending order with respect to the same value and suggested as alternatives.

5.6 Summary

In summarizing this chapter, it is important to note that preliminary estimations of all kinds are based on many assumptions, rules of thumb and bits of knowledge compiled from experts in the respective field. This chapter outlines the compilation of the most important factors of the decision between rapid prototyping machines and shows how the

RP Advisor uses this information to make a decision for the user. Appendices C and D are summaries of the macros and queries that run the RP Advisor. The following table summarizes the main formulas used by the RP Advisor in the determination of the "best" rapid prototyping machine. All nomenclature is defined within this chapter and in the beginning of this document. Each formula is discussed in this chapter.

Table 5.7 Equation Summary Table

Equation #	Equation	Calculation
5.1	$T_r = \# Layers\left(\frac{V_m}{z_b * D_b * S}\right)$	runtime (CATI)
5.2	$V_m = V_b \bullet \% V_m$	material volume (CATI)
5.3	$L_c = \frac{A_s}{D_b}$	cure length per layer
5.4	$T_l = L_c * S$	time per layer
5.5	$\frac{L_t}{Layer} = \left(x_b \bullet y_b\right) \bullet 1\%$	laser travel length (CATIV)
5.6	$\frac{T_r}{Layer} = \frac{L_r \,/\, Layer}{S}$	runtime per layer (CATIV)
5.7	$\# Layers = \frac{z_b}{\Delta z}$	#layers per part
5.8	$V_m = \frac{\left(x_b \bullet y_b \bullet z_b\right)}{2}$	material volume (CATV)
5.9	Cpre = (Tpre)(Rpre)	cost of pre-processing
5.10	Cr = (Tr)(Rr)	cost of runtime
5.11	Cpost = (Tpost)(Rpost)	cost of post-processing
5.12	CT = Cpre + Cr + Cpost	total cost
5.13	Qt = (ACo)/ (ACt)	total quality
5.14	$ND = \left[\left(T_n * T_p\right) + \left(C_n * C_p\right) + \left(Q_n * Q_p\right)\right]$	non-dimensional value

CHAPTER 6

RESULTS/VALIDATION AND DISCUSSION

6.1 Introduction

Chapter 1 discusses at length the need for a rapid prototyping system. The first purpose of the RP Advisor is to assist in the selection of rapid prototyping equipment for users and service companies. The second purpose is to provide a tool for the exploration of research areas for research facilities and rapid prototyping machine producers. In chapter 4 the RP Advisor proposes the solution to the need for a selection system for rapid prototyping. The details of the calculations necessary for the RP Advisor are presented in chapter 5. And finally, appendix E presents a users manual for the RP Advisor.

To validate the RP Advisor, it is necessary to validate the functionality and applicability of the program.

Three test cases are presented in this chapter. These cases are designed to emulate real world situations while utilizing the full functionality of the RP Advisor. The test cases demonstrate the ability of the RP Advisor to meet the customer requirements set forth in the problem understanding form, figure 4.2. The derivation of each test case discusses the importance of the selected criteria and the applicability of each to real world situations. Screen dumps from the RP Advisor are included as the test cases progress. Appendix E contains flow charts and screen dumps of the entire system which may assist the reader in following the case studies.

Section 6.4 highlights two interviews. These interviews are used to validate the applicability of the RP Advisor.

6.2 Metrics for Validation

The test cases and interviews in this chapter evaluate the RP Advisor and are summarized at the end of the chapter. The following metrics are used for evaluating the capabilities of the RP Advisor:

1) Chooses the "best" machine for the job
2) Suggests alternatives
3) Let the user define what is "best"
4) Compares Technologies
5) Distinguishes between making a single part and purchasing a machine
6) Works as it should
7) Factors in Costs
8) Factors in Time
9) Factors in Quality
10) Easy to use
11) Easily Updatable
12) Easily Expandable

During the development of the following validation, whenever one of the metrics is dealt with directly, the metric which is displayed is brought to the reader's attention. This displays a brief note enclosed in a bounding box similar to the one for this paragraph.

6.3 Validation of Functionality through Case Studies

This section contains a thorough development and discussion of three test cases.

6.3.1 Case Study I - The ASU Scenario

The first case is the Arizona State University Scenario. In this case, the Partnership for Research in Stereo Modeling (PRISM) is used. The criteria set for the search was chosen according to limitations and needs set forth by Dr. Anshuman Razdan, technical director of PRISM, during a recent purchase of the Stratasys Genisys Modeler.

Parts that PRISM is interested in producing are relatively small, with a low accuracy and surface finish. Most prototypes produced are for parts that have a production material of plastic and are of simple complexity. PRISM's concern with minimizing the time and cost of the prototypes as long as the quality meets a minimum value. The following paragraphs progress through the RP Advisor to set the fore mentioned criteria.

After selecting 'START' from the start screen when the program begins, shown in figure 6.5, the user enters the main screen of the program, figure 6.8. From here, the first decision made by the user is the determination of which machines he/she wants included in the search. In this case, PRISM has no preference on the manufacturer or technology, so the choice was "All Machines." This selection is shown in figure 6.1.

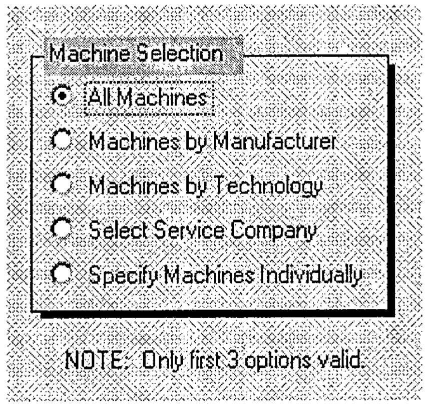


Figure 6.1 CASE I - Machine Selection

Because PRISM wishes to purchase a machine, the next criteria, which is either a single part or machine purchase, is obvious. The machine purchase button is selected. The program prompts the user for a budget range. The budget for PRISM ranges from one dollar up to sixty thousand dollars. Figure 6.2 demonstrates the input of the budget values.

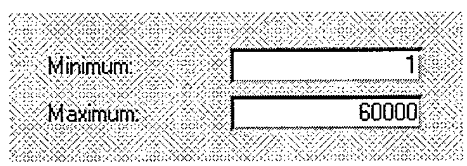


Figure 6.2 CASE I - Machine Purchase Budget

This shows that the user is able to distinguish between single part analyses and machine purchase. The entering of the budget demonstrates the system uses different information for each case to make a distinction (metric #5).

The next step involves filling in the "Part Parameters" screen of the program, shown in figure 6.19. This screen allows the user to specify the size of the part and several factors which determine the time, cost and quality of the part.

The first variable on this form is the bounding box size of the part being made. Because PRISM has the flexibility to scale most models being made, PRISM decides to run the search with a small bounding box size. The size agreed upon is a two inch square, as shown in figure 6.3.

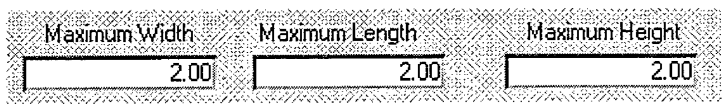


Figure 6.3 CASE I - Max Bounding Box

The next variables are the dimensional accuracy and surface finish. Most of the initial work to be done by PRISM with the new machine does not require a high dimensional accuracy or surface finish. Because no specific values for either of these variables are determined, PRISM chooses the least restrictive dimensional accuracy and surface finish in the general categories. Figures 6.4 and 6.5 display these choices.

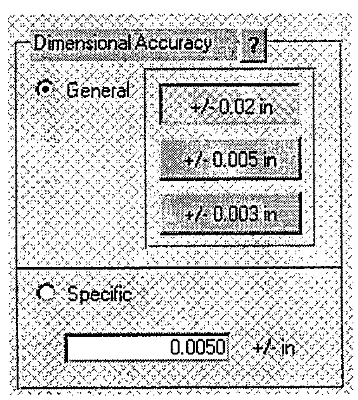


Figure 6.4 CASE I - Dimensional Accuracy

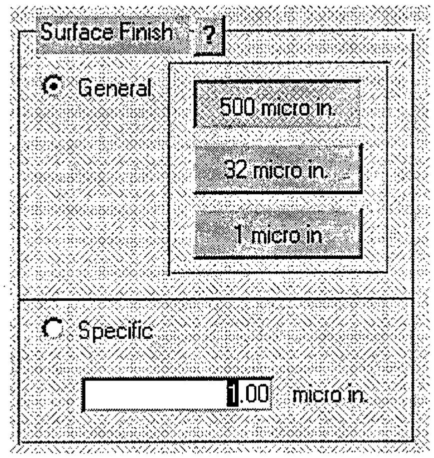


Figure 6.5 CASE I - Surface Finish

The next step enters the material volume of the part. Once again, the PRISM parts vary depending on the actual project; however, PRISM determines that most of the end products would be made of plastic. The program calculates an estimated material volume for parts with a final production material of plastic, as explained in section 5.2.1.

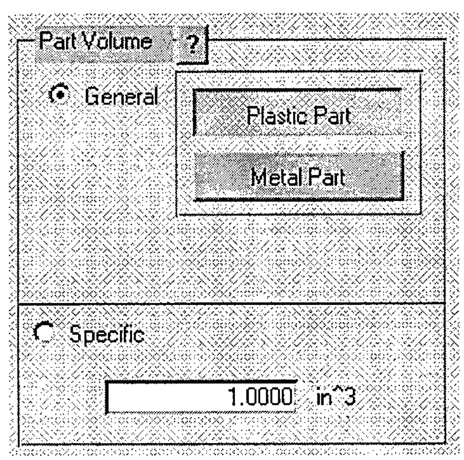


Figure 6.6 CASE I - Part Volume

The next variable is the part complexity. Figure 6.7 demonstrates that most parts would be or could be simplified to be simple part complexity.

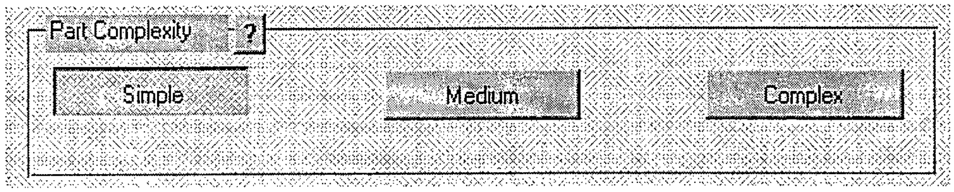


Figure 6.7 CASE I - Part Complexity

With this, the part parameters are set and ready to be accepted. After the "accept parameters" button is pressed, the final activity before running the search involves designating the priorities to be placed on each of the three main categories of criteria: Time, Cost and Quality. For this case, making parts fast and cheap is the priority. The quality is not a major factor as long as it met the level already specified on the part parameters sheet. Therefore, the time and cost rate one hundred times more important than quality, as seen in figure 6.8.

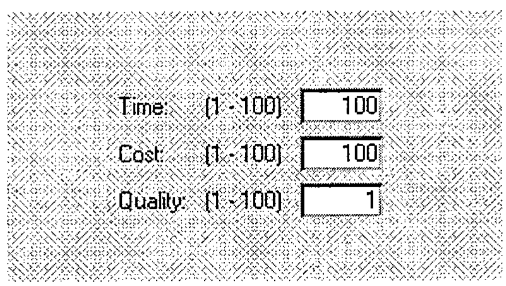


Figure 6.8 CASE I - Priorities

The previous settings on the part parameters and priorities pages demonstrate the ability of the RP Advisor to let the user define what is "best" in terms of cost, time and quality (metric # 3,7,8 and 9).

To review the criteria, the user presses the corresponding button on the main form. The user prints the criteria for later review or to be attached to the recommendation by the RP Advisor. Figure 6.9 presents a copy of the criteria summary sheet for the PRISM scenario.

Criteria Summary

Available Machines: All Machines

Type of Analysis: Machine Purchase

Budget Range: $1.00 - $60,000.00

Max Part Size		Priorities			
			Dimensional Accuracy:		
X: 2.00	Time	100		Type of Value:	General Value: 0.02 inches
Y: 2.00	Cost	100	Surface Finish		
Z: 2.00	Quality:	1		Type of Value:	General Value: 500 micro inches
			Part Volume		
				Type of Value:	General Value: Plastic Part
			Complexity		
				Level of Complexity:	Simple

Figure 6.9 CASE I - Criteria Summary

After reviewing the criteria summary sheet and confirming that the criteria match the intent, the final step is to run the search by pressing the "Run Main Query" button on the main form. The "best" machine choice appears on the screen with the pertinent information for the search. In this case, because the query runs as a machine purchase, information including the machine cost and warrantee are displayed. Figure 6.10 displays a screen dump of the "best" machine for this case.

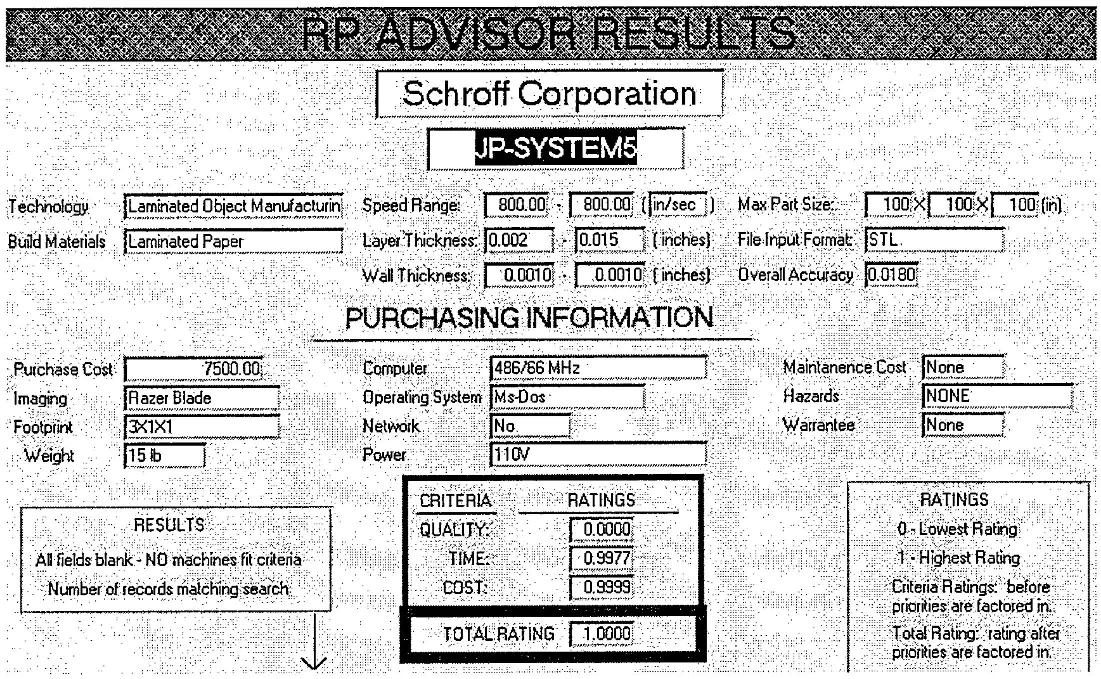


Figure 6.10 CASE I - First Choice

This demonstrates that the program is capable of determining a single machine as a recommendation for the given criteria (metric #1).

To make the choice, the RP Advisor evaluates each machine individually, then compares the machine ratings amongst each other, which involves comparing all of the technologies (metric # 4).

The user now has the option to scroll through information on the machines that the RP Advisor has suggested, print out the data sheets for all machines that fit the criteria in rated order, view a summary table of the results, or print out that table of results. Because more than one machine fit the criteria, a quick view of the results table summarizes the results in a concise manner. Figure 6.11 shows a copy of the table of results for case one.

RP ADVISOR RESULTS

Machine	*Manufacturer*	*TIME*	*COST*	*QUALITY*	*TOTAL*
JP-SYSTEM5	Schroff Corporation	0.9977	0.9999	0.0000	1.0000
GENISYS	Stratasys	0.9953	0.9988	0.2222	0.9994
X-5 (ASU)	ASU	0.9727	0.9599	0.8889	0.9719
MM-6PRO	Sanders	0.0000	0.0000	0.7222	0.0036

Figure 6.11 CASE I - Table of Results

The figure above demonstrates the RP Advisors ability to give alternative suggestions (metric #2).

As described in chapter 5, the time, cost and quality values are each normalized with respect to the other machines that match the criteria. These are raw values, which do not factor in the priorities of the user. However, the total column is a weighted total, which does take into account the user's priorities. Therefore, the rank of the machines is determined by descending order of the total rating. Note that the first three choices are close in total score, while the fourth is much lower.

The number one choice is the JP System 5, by Schroff Corporation. This machine has the lowest quality rating by far. However, quality is not a priority for case one;

therefore, it is the "best" selection. The JP System 5, which was purchased during the summer of 1996, is currently in use at Arizona State University in the Computer Integrated Manufacturing (CIM) Research Center laboratory. The next selection, with a significantly greater purchase cost, is the Stratasys Genisys, which was Arizona State University's second purchase for the CIM Research Center laboratory. This case study shows the RP Advisor would have made suggestions matching PRISM decisions if it had been available.

Because the recommendation of the RP Advisor match the recommendation of many hours of research performed by the PRISM technical director and several experts in the field, the results demonstrate that the RP advisor gives reasonable results (metric #6).

6.3.2 Case Study II - The Cellular Phone Casing Scenario

The second case is a cellular phone casing scenario. The criteria set for the search are chosen according to the parameters for producing a prototype of a typical cellular phone casing, shown in figures 6.12 and 6.13.

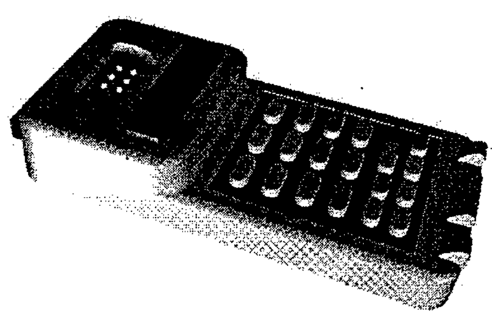


Figure 6.12 Generic Cellular Phone View 1(Trispectives, 1995)

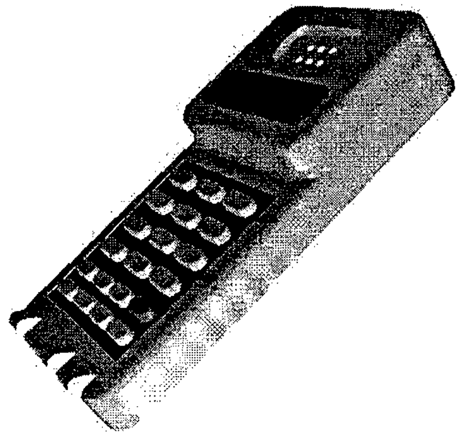


Figure 6.13 Generic Cellular Phone View 2 (Trispectives, 1995)

A cellular phone is a medium sized part with a high accuracy and surface finish. This prototype has a production material of plastic and is complex. The cellular phone manufacturer is concerned with minimizing the time while creating a good quality prototype. Cost is not a concern, because it is vital to get the prototype built. The following paragraphs progress through the RP Advisor to set the fore mentioned criteria.

The first decision made by the user determines which machines he/she wants included in the search. In this case, it is assumed that the company producing this phone has no preference on the manufacturer or technology, so the choice is "All Machines." This selection is shown in figure 6.14.

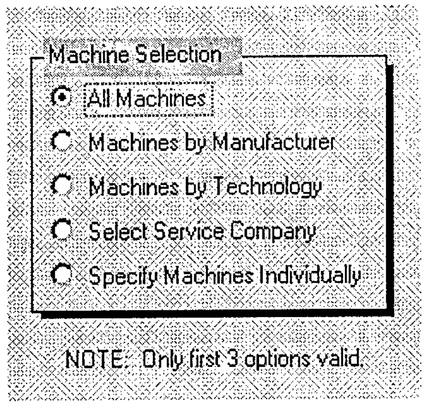


Figure 6.14 CASE II - Machine Selection

Because the phone manufacturer is not in the market to purchase a rapid prototyping machine, a single part analysis is chosen. Because the user wants only one part and is contracting the work, it is not necessary to specify a budget for purchase.

For case one, the RP Advisor uses budget information, whereas this case does not. This demonstrates that the RP Advisor distinguishes between a single part analysis and a machine purchase (metric #5).

The next step is to fill in the "Part Parameters" screen of the program, shown in figure 6.19.

The cellular phone measures approximately 4 inches long, 2 inches wide and 1.5 inches high. Figure 6.15 shows these values entered into the program.

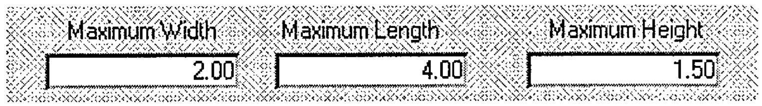


Figure 6.15 CASE II - Max Bounding Box

The next variables are the dimensional accuracy and surface finish. The model of the casing need to be assembled with the other pieces of the phone, so the accuracy of the prototype is very important. Figure 6.16 demonstrates the selection of the most stringent general selection for dimensional accuracy.

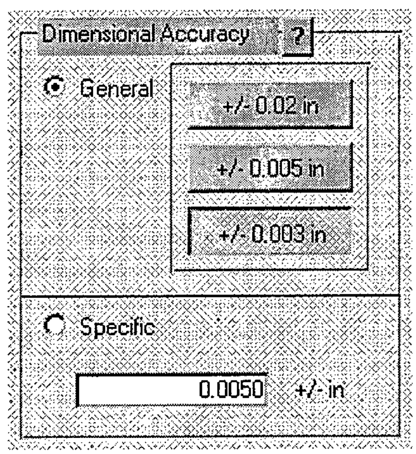


Figure 6.16 CASE II - Dimensional Accuracy

The purpose of the model is to sell the idea to customers at trade shows. Therefore, the surface finish is also very important. To satisfy this need, the highest general surface finish, shown in figure 6.17, is selected.

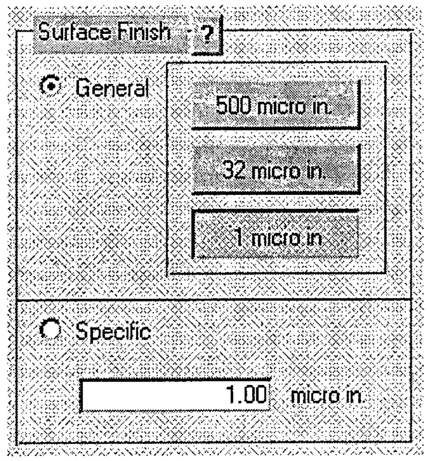


Figure 6.17 CASE II - Surface Finish

This part is to be made out of plastic; however, the specific volume is not calculated. By selecting plastic, shown in figure 6.18, the program calculates an estimated material volume, as explained in chapter 5.

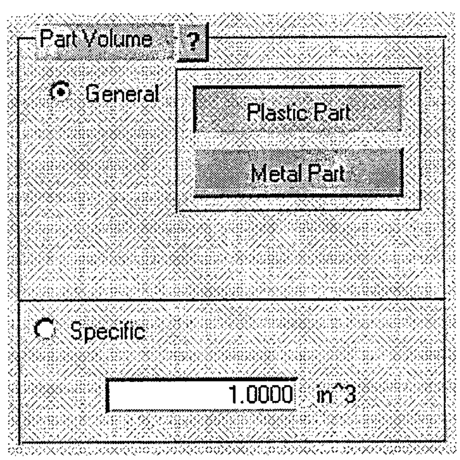


Figure 6.18 CASE II - Part Volume

The next variable sets the part complexity. Figure 6.19 shows this cellular phone's complexity to be complex, because of the contouring of the phone as a series of complex surfaces.

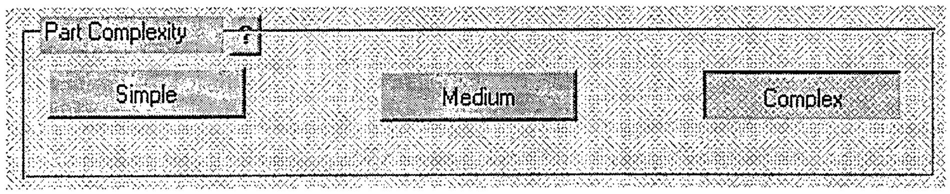


Figure 6.19 CASE II - Part Complexity

The final activity before running the search designates the priorities needed in each of the three main categories of criteria: Time, Cost and Quality. For this case, it is most important to make parts fast to get the product out to the next trade show. The quality is also important but not as important as the time. And finally, the cost is the least important factor. Therefore, the time rates a 100, the quality rates a 50, and the cost only rates a 1, as seen in figure 6.20.

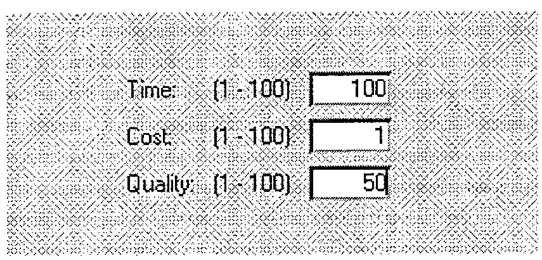


Figure 6.20 CASE II - Priorities

The previous settings on the part parameters and priorities pages demonstrate the ability of the RP Advisor to let the user define what is "best" and factor in cost, time and quality (metric # 3,7,8 and 9).

Figure 6.21 displays a copy of the printout of the criteria summary sheet for the cellular phone casing scenario.

Criteria Summary

Available Machines: All Machines

Type of Analysis: Single Part Analysis

Max Part Size	Priorities		Dimensional Accuracy:	
X: 2.00	Time:	100	Type of Value: General	Value: 0.003 inches
Y: 4.00	Cost:	1	Surface Finish	
Z: 1.50	Quality:	50	Type of Value: General	Value: 1 micro inches
			Part Volume	
			Type of Value: General	Value: Plastic Part
			Complexity	
			Level of Complexity: Complex	

Figure 6.21 CASE II - Criteria Summary

After reviewing the criteria summary sheet and confirming the criteria, the user presses the "Run Main Query" button on the main form. In this case, because the query is not run as a machine purchase, cost related information is not displayed. Figure 6.22 shows a screen dump of the "best" machine for this case.

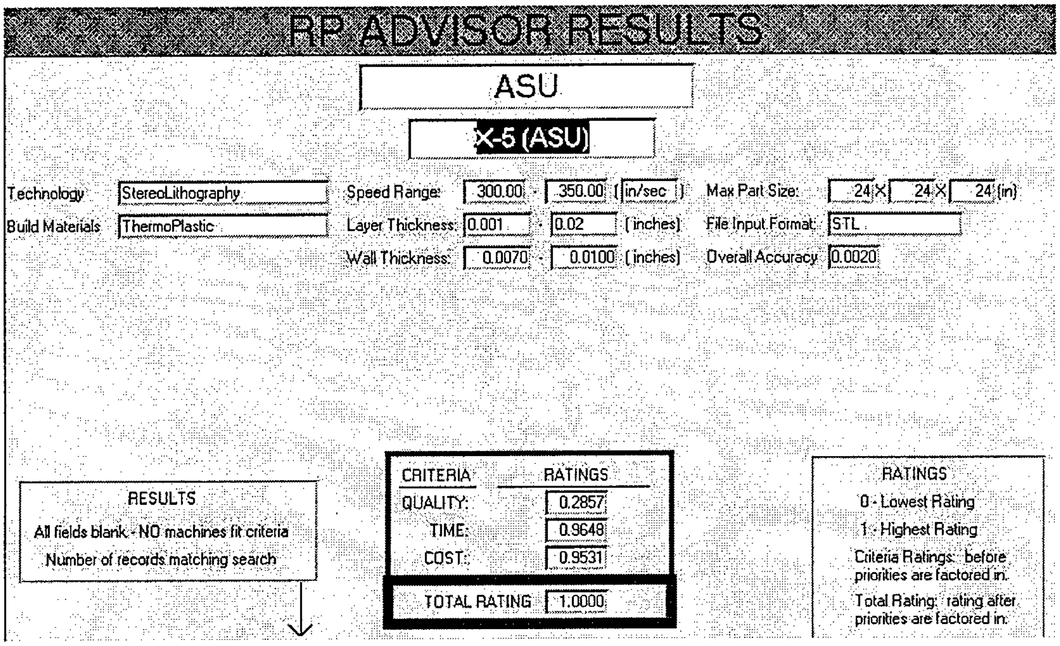


Figure 6.22 CASE II - First Choice

This demonstrates that the program is capable of determining a single machine as a recommendation for the given criteria (metric #1).

To make the choice, the program needs to be able to compare all of the technologies (metric # 4).

The user now has the option to scroll through information on all chosen machines, print out the data sheets for all machines that fit the criteria in rated order, view a summary table of the results, or print out that table of results. Again, more than one machine fit the criteria. Figure 6.23 is a copy of the table of results for case two.

RP ADVISOR RESULTS

Machine	*Manufacturer*	*TIME*	*COST*	*QUALITY*	*TOTAL*
X-5 (ASU)	ASU	0.9648	0.9531	0.2857	1.0000
X-4 (ASU)	ASU	0.9648	0.9396	0.2857	0.9999
X-6 (ASU)	ASU	0.8720	0.8291	0.2857	0.9158
X-3 (ASU)	ASU	0.8720	0.7801	0.2857	0.9154
SLA-350/10	3D Systems	0.9600	0.9542	0.0000	0.8678
SLA-400	3D Systems	0.9500	0.9281	0.0000	0.8586
SLA-500/30	3D Systems	0.9500	0.9208	0.0000	0.8586
SLA-500/20	3D Systems	0.9500	0.9208	0.0000	0.8586
SLA-500/40	3D Systems	0.9500	0.9208	0.0000	0.8586
SLA-250/40	3D Systems	0.6667	0.6667	0.0000	0.6027
SLA-250/30	3D Systems	0.6667	0.6667	0.0000	0.6027
SLA-190/20	3D Systems	0.0000	0.0000	0.0000	0.0000

Figure 6.23 CASE II - Table of Results

The figure above demonstrates the RP Advisors ability to give alternative suggestions (metric #2).

In this case study, the first four choices are ASU machines which are hypothetical machines invented to test out the capabilities of the RP Advisor. To determine the "best" currently existing machine, follow the table down to the first non-ASU machine. The 3D Systems SLA350/10 is the "best" existing machine. All of the values for quality are zero for the 3D systems machines because they have the same accuracy and surface finish characteristics. However, it is interesting to note the differences in time and cost for each of the machines. In this case, it is not necessarily better to choose the 3D System's newest machine. This is because the cost to operate the newer machine is prohibitive for a small part.

Because the recommendation of the RP Advisor corresponds to what would be noted in an evaluation of the criteria by an expert in the rapid prototyping field, it can be determined that the RP advisor works reasonably well (metric #6).

6.3.3 Case Study III - The Automobile Scenario

The third and final case to be examined is an automobile scenario. The criteria set for the search is chosen according to the parameters for producing a prototype of a full size car. This demonstrates the ability of the RP Advisor to determine where there are no machines that fulfill the criteria.

The prototype of an automobile is a large part with a low accuracy and surface finish. This prototype has a production material of metal and is complex. The automobile manufacturer is concerned with minimizing the time and cost as long as the quality meets minimum values. The following paragraphs progress through the RP Advisor to set the fore mentioned criteria.

In this case, the company producing this vehicle has no preference on the manufacturer or technology, so the choice is "All Machines" (figure 6.24).

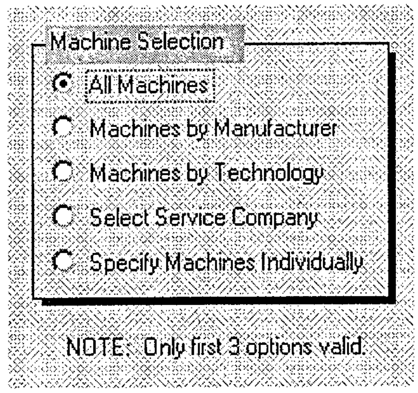


Figure 6.24 CASE III - Machine Selection

Because the car manufacturer is not in the market to purchase a rapid prototyping machine, the single part analysis button is selected. Because the user is making only one car and is contracting the work, it is not necessary to specify a budget for purchase.

For case one, the RP Advisor uses budget information, where this case does not. Therefore, the RP Advisor distinguishes between a single part analysis and a machine purchase (metric #5).

The first variable on the main form is the bounding box size of the intended part. The car measures approximately 144 inches long, 72 inches wide and 54 inches high (figure 6.25).

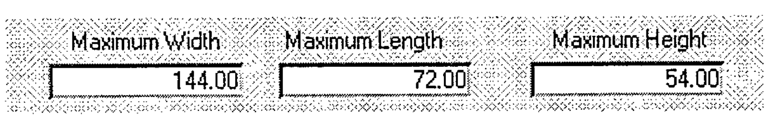


Figure 6.25 CASE III - Max Bounding Box

The next variables are the dimensional accuracy and surface finish. Because this is simply a concept model of a full size car, the accuracy and surface finish do not need to be high. The lowest general ratings for dimensional accuracy and surface finish are selected (figure 6.26 and 6.27).

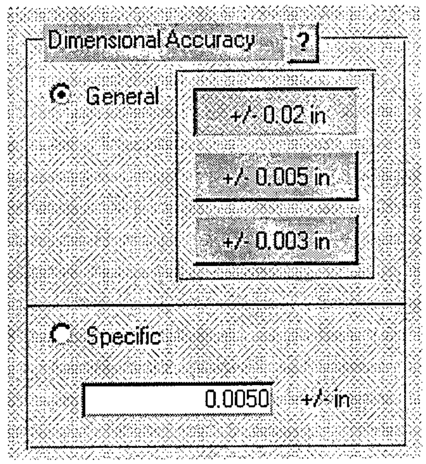


Figure 6.26 CASE III - Dimensional Accuracy

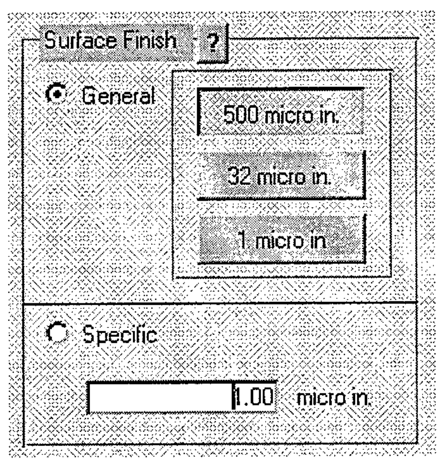


Figure 6.27 CASE III - Surface Finish

This part is to be made out of mostly metal; however, the specific volume has not been calculated. By selecting metal, shown in figure 6.28, the program calculates an estimated material volume, as explained in section 5.2.1.

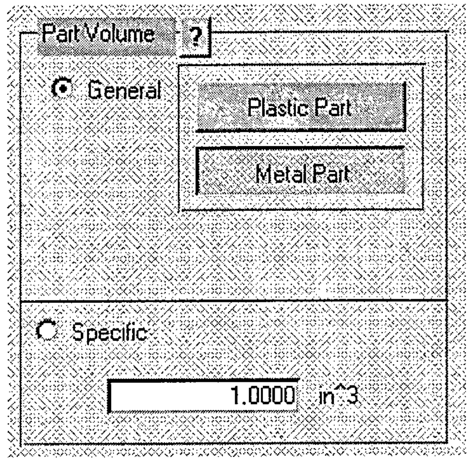


Figure 6.28 CASE III - Part Volume

The car has many complex surfaces that define the skin of the hood and fenders. Figure 6.29 shows that for this model, the complexity is complex

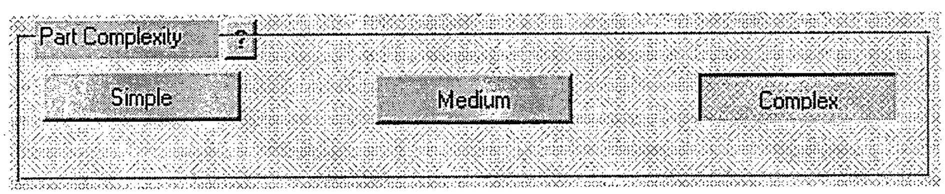


Figure 6.29 CASE III - Part Complexity

For this case, it is most important to be able to make parts fast and inexpensive. The quality is not as important to the manufacturer because a great deal of work will be done on the model after it is received in the shop. Therefore, the time and cost rate a 100 and the quality rate a 1, as seen in figure 6.30.

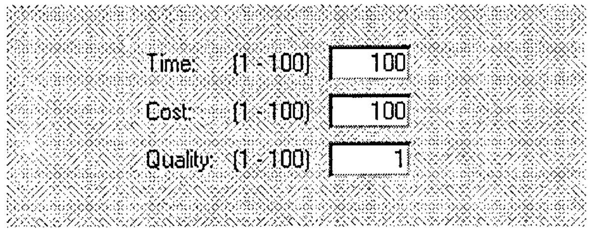
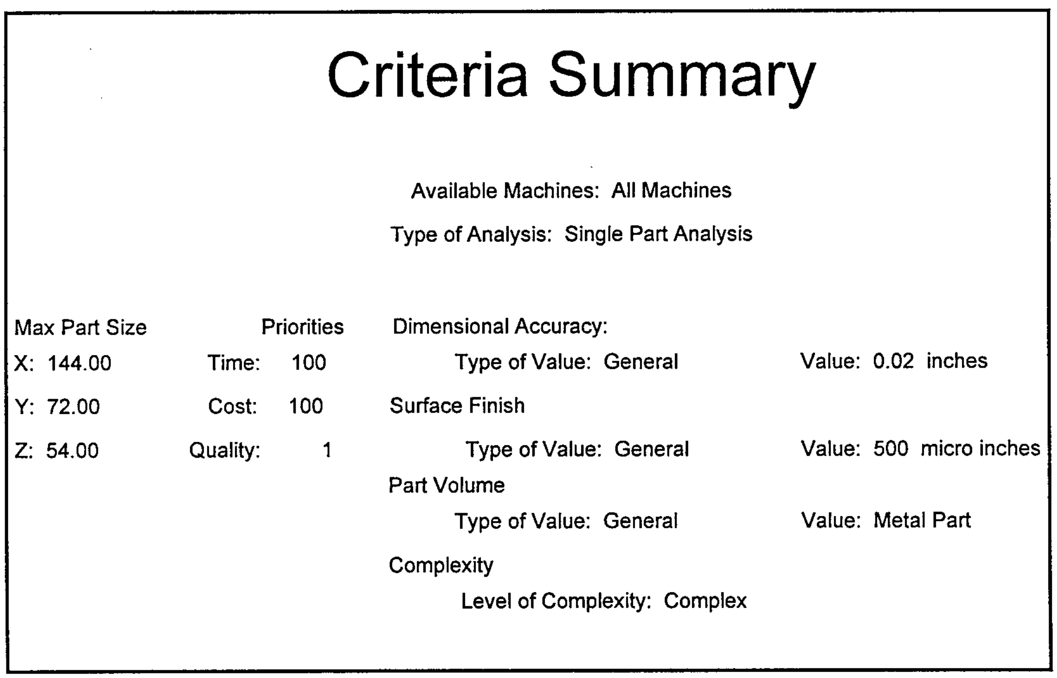


Figure 6.30 CASE III - Priorities

The previous settings on the part parameters and priorities pages demonstrate the ability of the RP Advisor to let the user define what is "best" and factor in cost, time and quality (metric # 3,7,8 and 9).

Figure 6.31 displays a copy of the printout of the criteria summary sheet for the automobile scenario.



Criteria Summary

Available Machines: All Machines

Type of Analysis: Single Part Analysis

Max Part Size	Priorities			
		Dimensional Accuracy:		
X: 144.00	Time: 100		Type of Value: General	Value: 0.02 inches
Y: 72.00	Cost: 100	Surface Finish		
Z: 54.00	Quality: 1		Type of Value: General	Value: 500 micro inches
		Part Volume		
			Type of Value: General	Value: Metal Part
		Complexity		
			Level of Complexity: Complex	

Figure 6.31 CASE III - Criteria Summary

In this case, the size of the automobile is larger than any current technology is capable of producing, even with the lowest standards of quality and surface finish. The RP Advisor has no suggestion for rapid prototyping machines. Figure 6.32 is a screen dump of the solution to this case, which shows the user the "best" choice does not exist. However, the current version of the RP Advisor does not explain the reason for the technology gap. This capability is a must for later versions. This case is also tested with varying priorities; however, the limiting variable is the large size of the automobile, so the results do not change.

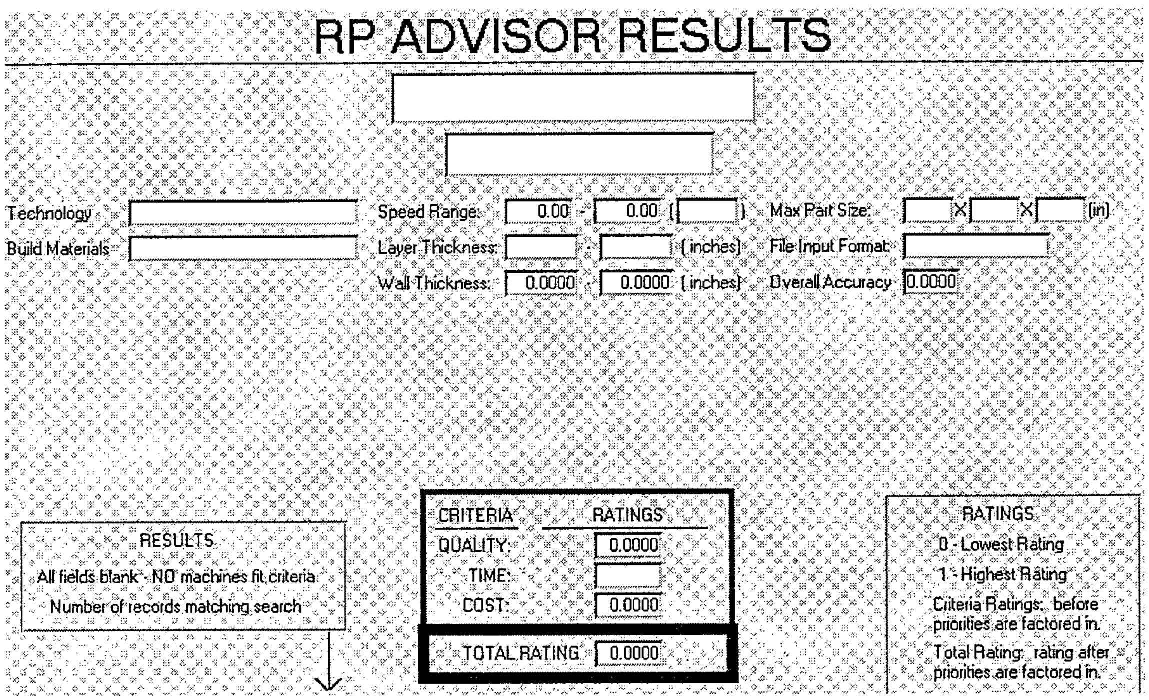


Figure 6.32 CASE III - First Choice

To make the choice, it is necessary for the program to compare all of the technologies (metric # 4).

Figure 6.33 presents a copy of the table of results for case three.

RP ADVISOR RESULTS					
Machine	***Manufacturer***	***TIME***	***COST***	***QUALITY***	***TOTAL***

Figure 6.33 CASE III - Table of Results

The RP Advisor has locates a technology gap in rapid prototyping technology, as seen in figure 6.33.

6.4 Validation of Applicability Through Interviews

To validate the usefulness of the RP Advisor, it is necessary to have people in industry take it for a test drive, so to speak. The goal in having industry representatives use the program and complete an interview is to determine what role the RP Advisor can realistically fulfill and assess the ability of the RP Advisor to meet the customer and engineering requirements set forth in chapter 4. Each interview asks the following questions along with feedback regarding all aspects of the program:

1) What are the major weaknesses?
2) How best could this program be used at (Name of company)?
3) Could this program be used as a training tool for employees who are becoming involved with rapid prototyping?
4) What are some things that could be added for functionality?
5) What are some strong points?
6) Does the program answer the questions that you would want to know, when you need to know them?
7) On a scale of 1-10, compared with other engineering software, how easy was

this program to use? (1 = difficult 10 = Easy)

The two interviews summarized in the following sections include Mr. Robert Foss from Motorola and Mr. Kou-Rey Chu from Phoenix Analysis and Design Technologies.

6.4.1 Mr. Robert Foss, Motorola

Mr. Robert Foss is the manager of the Rapid Prototyping and Material Science Division of the Consolidated Production Facilities Department at Motorola in the Government and Space Technology Group based in Scottsdale, Arizona.

The interview begins with a five minute explanation of the program, after which, Mr. Foss starts using the RP Advisor. Because Mr. Foss has the assistance of the interviewer, who is intimately familiar with the program, it is not necessary to read all of the help screens provided. After approximately ten minutes of studying the screens, Mr. Foss displays competency with the program, by the observations of the author.

This shows that the program is easy to use (metric #10).

At this point, with his curiosity peaked, Mr. Foss begins immediately testing real scenarios to see how close the RP Advisor is to his expert opinion. Because his department owns one StereoLithography machine, he tests the RP Advisor to support the choice of machine he made when buying Motorola's machine. After running the search he says, "That's what I was looking for!" As successive cases are input by Mr. Foss, it becomes obvious that the RP Advisor makes decisions comparable to an expert in the field. On another instance, Mr. Foss says, "I see what this has done on the search we just did and I certainly agree with the first couple that came up, just from the standpoint of the fused deposition modeling."

The accuracy of the output demonstrates that the RP Advisor chooses the "best" machine for the job (metric #1).

Mr. Foss often traverses through the results to investigate the suggested alternatives (metric #2).

One question Mr. Foss has about the RP Advisor is whether the time calculation for StereoLithography took, "into account when you are asking for a higher quality part, it makes the layers thinner." As discussed in chapter 5, the RP Advisor does factor part quality into the layer thickness to determine the number of layers and therefore the run time. To this, Mr. Foss replies, "Excellent!"

This demonstrates one aspect of how time and quality are factored into the decision (metric #8 and 9).

After Mr. Foss has a chance to use the RP Advisor for a period of time, the survey questions are discussed with him in order.

The first question is, "What are the major weaknesses?" In his opinion, the major weakness is that the RP Advisor "needs to take into account material properties." The current RP Advisor simply gives the user an idea of the materials used by each selected machine. However, the type of material used to make the model is having more impact on the decision of the a rapid prototyping machine. This concern is reflected in the problem understanding form in chapter 4 of this report.

Question number two, "How best could this program be used at Motorola?" is then asked. With respect to this question, Mr. Foss says "companies like Motorola, when we justify this machine (a rapid prototyping machine), just to do the research as to which machine to buy and where the pay back was, it is very time consuming and expensive. There is a real need to be able to pull that up with less pain." Although the proof of concept version of the RP Advisor is not sophisticated enough to lend enough credibility to justify an actual machine purchase on its own, Mr. Foss says that a more sophisticated RP Advisor could be used "for someone to justify this (rapid prototyping) equipment."

The next question is, "Could this be used as a training tool for employees who are becoming involved with rapid prototyping?" To this, Mr. Foss replies, "I think it (the RP Advisor) is a good tool for engineering during further education." In fact, Mr. Foss feels that as is, the RP Advisor could be used as "part of a training tool." Because of the limits of the proof of concept program however, Mr. Foss feels that it would be best used in a classroom environment until it was made more sophisticated.

"What are some things that could be added for functionality," is the following question. In response to this, Mr. Foss suggests that the output be able to be printed out in table format for a quick review of the results. As demonstrated in the test cases presented earlier in this chapter, this suggestion is implemented into the program following the interview.

When asked the question, "What are some strong points," it is obvious that Mr. Foss approves of the concept represented by the RP Advisor. He says, "I like the idea of having a database for rapid prototyping. I don't know if there's one that exists, but you may be the first guy who's looked at this." He also states, "It's the first (rapid prototyping selection program) I've seen that tries to do a comparison between this (rapid prototyping) technology, between different pieces of equipment."

The next question, "Does the program answer the questions that you would want to know when you need to know them," also receives a very positive answer. Mr. Foss replies that for a user who isn't versed in rapid prototyping "Yes, it would be very helpful in answering questions." It is important to note that Mr. Foss does not say that this is a fully bonified program. Mr. Foss recognizes this program as a proof of concept program that can already be used for particular applications. However, it should be used with caution. Because the program gives valuable information when needed, Mr. Foss says, "I think it (the RP Advisor) would give them (newcomers to rapid prototyping) a real head start. Like I said, this is hundreds of hours of investigation time to benchmark what is out there."

The final question deals with how easy the program is to use. Although Mr. Foss does not rate the program on a scale of 1-10, he does say, "I think you get use to it real fast, as to how to run it." The strongest proof of the ease of use is demonstrated by Mr. Foss running his own searches within 10 minutes of starting the program.

Beyond the scope of the questions, Mr. Foss also notes that "it's really encouraging what these guys are doing over at ASU right now; I feel good about it." Throughout the course of the interview, several small additions and corrections are suggested for the program, which have been implemented in the final version of the RP Advisor.

6.4.2 Mr. Kou-Rey Chu, Phoenix Analysis and Design Technologies

Mr. Chu is the director of Manufacturing Technology at Phoenix Analysis and Design Technologies. This company, along with providing various other services, is a service company for rapid prototyping.

The same interview process as with Mr. Foss, is repeated with Mr. Chu. After a short explanation of the program, Mr. Chu begins using the RP Advisor. With only a few questions about the program, which are covered in the help screens, Mr. Chu is able to run test cases independently.

When asked the first question on the survey, "What are the major weaknesses?," he replies that the major weakness is accuracy of the information in the database. After the interview, upon his suggestions about the data, the information in the table is reviewed and more accurately completed. Unfortunately, as agreed by Mr. Chu, most producers of rapid prototyping machines are protective of some of the more critical information. Because the time calculation for each of the machines is complex, several companies did not care to comment on estimated rate of build.

When asked how best this program could be used at Phoenix Analysis and Design Technologies, Mr. Chu says, "I could pick the best two choices and let the customer know these... and you (the customer) can make a choice." In fact, it is noted by Mr. Chu that "it (the RP Advisor) is a much better way to inform the customer what their options are."

When asked whether the RP Advisor could be used as a training tool for employees who are becoming involved with rapid prototyping, Mr. Chu is very positive. He states, "It's a great tool." Mr. Chu feels that it would be good to use the RP Advisor to help progress through the decision process to see how the selection is made and what variables play into the decision.

With respect to what could be added for functionality, Mr. Chu states, "I would like to see the materials in there." This is also an observation made by Mr. Foss in the previous interview and should definitely be addressed in any further versions of the RP Advisor.

The next question, "What are some strong points?," brings out an interesting idea. Mr. Chu says, "Especially for service companies, anybody can run this and they can help the customer much more quickly than to have to wait for the 'expert' to come back and talk to the customer."

As far as whether the program answers the questions that the user would want to know when they need to know the answers, Mr. Chu says that it answered most of his questions. However, the program needs to be updated frequently to keep pace with the changing industry.

Finally, when asked to rank the ease of use, Mr. Chu rates the RP Advisor between 8 and 9. He suggests a short, 5-10 page, users manual might be all that is needed. He says, "It (the RP Advisor) is pretty straight forward, very easy to use."

After the formal questions are discussed, Mr. Chu comments he feels that "it covers all the basics."

6.5 Discussion

This chapter validates the RP Advisor for both functionality and applicability. The most important customer requirements from the problem understanding form in chapter 4 are used to have a set of metrics to base the validation against. Throughout the case studies and interviews discussed in this chapter, all but two metrics are met. The two metrics which still need to be addressed are "Easily Updatable," and "Easily Expandable." The key to the satisfaction of these two requirements is in the selection of the platform used to implement the RP Advisor. As discussed in appendix E, a relational database allows the RP Advisor to meet these two criteria. For this reason, the RP Advisor is developed in Microsoft ACCESS, which is an easily accessible relational database developing tool.

To improve the accuracy of the RP Advisor, it is possible to develop more sophisticated time, cost and quality calculators and spawn those programs through the use of macros within the RP Advisor. This modularity allows the program to be updated with new calculator programs at any time and allows the program to be updated and expanded as needed. Also, to update any machine parameters, the user need only modify the machine data table, which can be modified independent of the program.

This shows the expandability and updatability of the RP Advisor (metric #11 and 12).

Through the test cases and interviews, it is apparent that the RP Advisor chooses a "best" machine for the job with respect to the specifications set by the user. Also, the RP Advisor suggests alternatives and allows the user to make a distinction between having a single part made and purchasing a rapid prototyping machine. Indeed, the RP Advisor "works as it should" and factors in costs, time and quality. The interviews show that the program is easy to use with help screens to explain what is required of the user. Tables 6.1 and 6.2 summarize the questions asked of the interviewees and their answers. Sections 6.4.1 and 6.4.2 contain quotes regarding the questions and other opinions volunteered by the interviewees.

Table 6.1 Robert Foss Interview Summary

Question #	Topic	Paraphrase
1	Major weaknesses	Needs to take into account material properties
2	Best use of program	Later versions could be used to justify equipment purchase
3	Training tool	Good tool for engineering during further education
4	Function improvements	Output results in table format
5	Strong points	The first program of its kind
6	Timely and informative	It is very helpful in answering questions It would give newcomers a real head start
7	Ease of use	You learn how to use it real fast

Table 6.2 Kou-Rey Chu Interview Summary

Question #	Topic	Paraphrase
1	Major weaknesses	Accuracy of the information in the database
2	Best use of program	To inform the customer of the top couple of choices
3	Training tool	"It's a great tool."
4	Function improvements	Need to show materials on data sheet
5	Strong points	Anybody can run the program, no need to wait for an expert
6	Timely and informative	Answers most questions
7	Ease of use	Straight forward and easy to use

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Introduction

As stated in section 1.7, the objective of this research is as follows:

1) Compile a comprehensive rapid prototyping database to be used within the RP Advisor;
2) Produce a quality function deployment (QFD) analysis for a rapid prototyping machine selector program called the RP Advisor;
3) Design and implement the RP Advisor to meet the customer and engineering requirements set forth in the QFD produced in objective two;
4) Validate the RP Advisors ability to satisfy the QFD;
5) Show the RP Advisor improves the design process.

Chapter 2 discusses previous work in the field of automated rapid prototyping system selection, and chapter 3 reviews the field of rapid prototyping, including a brief discussion of the largest players. Chapter 4 develops a quality function deployment analysis and benchmarks a program developed at Santa Clara University, California. Chapters 5 discusses the specific mathematical implementation of the RP Advisor, based on the QFD. And chapter 6 presents several case studies and interviews with members of industry to validate the RP Advisor. This chapter concludes the findings based on this research as reviews the limitations and recommendations for future.

7.2 Conclusions

The newly developing field of rapid prototyping is in need of a computer based rapid prototyping machine selector. This research gives insight toward the factors influencing the decision of the "best" rapid prototyping machine for any one situation. This research also results in a working computer program, based on that insight, capable of making decisions based on user defined criteria. The following paragraphs highlight the results and achievements of this research with respect to each of the goals stated above and in section 1.7. Each paragraph is numbered in accordance with those goals.

1) The author compiles the data available on the rapid prototyping machines produced by manufacturers who, combined, hold approximately 99% of the world wide rapid prototyping market (Wohlers, 1996). It should be noted that the manufacturers do not provide all values, which mandates the compilation to include expert opinion and estimations by people familiar with the processes. Because of this, the listed manufacturers should not be held to the standards reflected in the data table. Because "easily updatable" was a customer requirement met by the RP Advisor, updating the information in the database as more accurate information becomes available is a trivial task.

2) A QFD is performed on a program which advises the user of the "best" rapid prototyping machine for any one set of criteria. The results of the QFD are summarized in a problem understanding form.

3) This research is successful in developing a concept proof program called the RP Advisor. This program meets many of the customer and engineering requirements set forth in the QFD. However, as will be discussed in the following section of this report, the program has limitations.

4) Several test cases and interviews are performed in order to validate the RP Advisor. The RP Advisor is shown to be a functional and applicable implementation of the quality function deployment matrix.

5) Each step in the design process, regardless of the design process used, is an iterative process. Ideally, and most typically, this iteration directs the design of the product. Unfortunately, neophytes in rapid prototyping do not know which machine is "best" for the production of the prototype they want. The generic schematic of the design process, figure 1.6, does not show that the selection of the method of prototyping to develop a correct prototype is also iterative. However, it is also an iterative process. Figure 7.1 displays a portion of the generic design process, modified to represent this iteration.

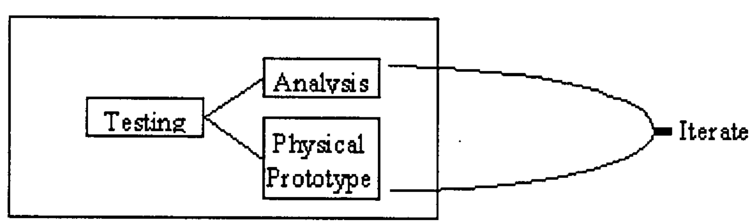


Figure 7.1 Prototype Production Method Iteration

Ideally, there would be no iteration here, because it takes away time that the design team could be using to improve the design. Also, when the wrong prototyping method is selected, the results of the testing could be incorrect, which may adversely affect the design. With the RP Advisor, a company without a rapid prototyping expert can make the decision of the "best" rapid prototyping machine and reasonable alternatives for each prototype to be built in a fast and efficient manner. The RP Advisor reduces time in the design process for all users of rapid prototyping, especially new users, thereby shortening the overall design process.

7.3 Limitations

The RP Advisor developed throughout this research is not as fully functional as it could be. Conceptually, this program would be beneficial to the development and implementation of rapid prototyping as well as improving the design process. The current version of the RP Advisor, as noted throughout the interviews in chapter 6, yields many strong points and could be used for many purposes. However, this version of the RP Advisor has limitations.

The main limitation of the RP Advisor is the dependability of the calculations. The time, cost and quality calculations are preliminary estimates. However, the current equations do not consider all the variables needed to provide a complete assessment of the available machines. The original concept involves graphing each machine in three dimensional space composed of time, cost and quality functions. For simplicity, disregard the quality rating at this time. The problem is two dimensional involving time and cost. The figure below represents the results of the RP Advisor's current version with respect to the two dimensional space.

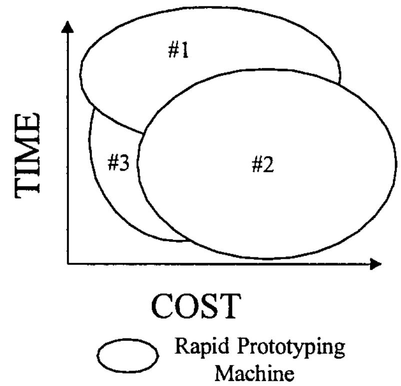


Figure 7.2 Current RP Advisor Comparison Example in Two-Dimensions

Because the time and cost ranges factor in only a few variables, the ranges are general. With this model, rapid prototyping design gaps can be found are on the fringes of cost and time. These places however, are the obvious places to look for new rapid prototyping ideas.

As the number of variables factored into time and cost increase, the area represented by each machine becomes more defined and probably smaller. The following figure demonstrates better RP Advisor results in this two dimensional space.

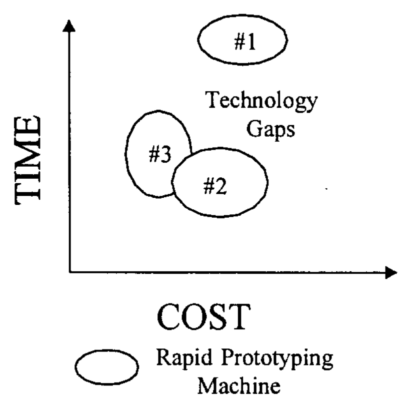


Figure 7.3 Ideal RP Advisor Comparison Example in Two-Dimensions

Each machine is well defined to reduce the area represented by each machine. Now it is easier for the user to locate design gaps in the technology. For example, using the graph above, if the user wanted to minimize the cost and maximize the time, a technology gap is identified. This indicates a machine that is cheap and very fast is needed. In order to develop a machine to fill this gap, the third dimension of quality would also need to be known.

Another limitation of the current RP Advisor is apparent by looking at the problem understanding form shown in figure 4.3. A number of engineering requirements are not satisfied. These requirements involve the inclusion of material properties in the decision between rapid prototyping machines. As noted in the interviews, the inclusion of the material properties is a necessary step in making the RP Advisor a robust program and will be discussed in the next section of this chapter. By factoring in these properties, the first major limitation will also be greatly reduced.

7.4 Future Work

The need for a fully robust rapid prototyping system selection program grows as the number and diversity of the rapid prototyping machines on the market continues to increase. Because this research involves a proof of concept program for rapid prototyping machine selection, future work needs to be directed at fulfilling all of the requirements of the quality function deployment developed in the research. By making the RP Advisor a fully robust program, the rapid prototyping community benefits from a program that would encourage more wide spread use of rapid prototyping, shorten the design process with respect to prototype production, and help in the development of tomorrow's rapid prototyping technology. The following sections of this report suggest possible areas of research and development.

7.4.1 Technology Gap Explanations

The current version of the RP Advisor does not make note of reasons for technology gaps. As discussed in case study III, future versions need to inform the user why the RP Advisor is unable to find a machine for the set criteria. For example, in case III, the automobile model is too large to be produced on any available machine. The RP Advisor should be able to recognize this and inform the user.

7.4.2 Materials Implementation

The most important improvement to the RP Advisor is the addition of materials and their properties to the decision process. Future work on the RP Advisor must include materials to lend more dependability to the program. The problem understanding form in chapter 4 outlines the most important factors with respect to materials.

7.4.3 Automatic Model Evaluator

Another research initiative improving the RP Advisor involves writing a program capable of reading an STL file of the part to be made. With this file, the new RP Advisor would extract much of the information needed to determine the "best" rapid prototyping machine for the job. Less input would be required by the user, which makes the program easier to use. Also, by extracting data directly from the part, the decision will be based on more accurate information than the current version of the RP Advisor. The program should also include the creation of support structures and options for part orientation.

7.4.4 World Wide Web Implementation

Finally, another possible research area is to implement the RP Advisor on the World Wide Web. Ideally, the RP Advisor can be a service provided by Arizona State University over the Internet queried from anywhere around the world. With the exposure the Internet provides, it would be in the best interest of rapid prototyping manufacturers, developers and service bureaus to continually update the information in the database. This would encourage close working relationships with Arizona State University.

REFERENCES

Standard References

Ashley, S., 1995, "Rapid Prototyping is Coming of Age," *Mechanical Engineering*, Vol. 117, No. 7, pp. 62-68.

Ashley, S., 1996, "Rapid Concept Modelers," *Mechanical Engineering*, Vol. 118, No. 1, pp. 64-66.

Ashley, S., 1996, "A New Dimension for Office Printers," *Mechanical Engineering*, Vol.118, No. 3, pp. 112-114.

ANSI/ASME, 1985, *An American National Standard: Surface Texture (Surface Roughness, Waviness, and Lay)*, The American Society of Mechanical Engineer's, New York.

Aubin, R. F., 1994, *A Worldwide Assessment of Rapid Prototyping Technologies. Initiated by the Intelligent Manufacturing Systems IMS Test Case on Rapid Product Development,* East Hartford, Connecticut.

Bedworth, B.D., Henderson, M.R., & Wolfe, P.M., 1991, *Computer-Integrated Design and Manufacturing,* McGraw-Hill, Inc., New York.

Chu, K., [Interview]. 1996, Director of Manufacturing Technology, Phoenix Analysis & Design, Gilbert, Arizona.

Clark, F.D. & Lorenzoni, A.B., 1985, *Applied Cost Engineering*, Marcel Dekker, Inc., New York.

Computer Aided Rapid Prototyping, 1996, *The CARP Project*, Produced by the CARP

Project Consortium.

Cross, N., 1994, *Engineering Design Methods: Strategies for Product Design,* John Wiley & Sons, Chichester.

Dym, C.L., 1994, *Engineering Design: A Synthesis of Views*, Cambridge Univeristy Press, New York.

Foss, R., [Interview]. 1996, Manager: Rapid Prototyping & Materials Sciences, Motorola, Scottsdale, Arizona.

Grabowski, H., Erb, J., & Geiger, K., 1994, *Choosing the Right Rapid Prototyping Technology for Each Phase of Product Development,* Institute for Computer Applications in Planning and Design, Karlsruhe.

Grabowski, H., Erb, J., & Geiger, K., 1994, *The Role of CAD in Rapid Product Development,* Institute for Computer Applications in Planning and Design, Karlsruhe.

Hornberger, L.E., Hight, T., & Lawrence, E., 1993, *Rapid Prototyping Program*, [Computer software]. School of Engineering, Department of Mechanical Engineering, Santa Clara University, CA.

Jacobs, P.F., 1993, "StereoLithography: From Art to Part," *Cutting Tool Engineering*, Vol. 45, No. 3.

Jacobs, P.F., 1996, *StereoLithography and Other RP&M Technologies: From Rapid Prototyping to Rapid Tooling,* ASME Press, New York.

Jelley, C. & Thompson, C.P., 1995, "The Development and Application of a StereoLithography Build Simulator," *First National Conference on Rapid*

Prototyping and Tooling Research, Mechanical Engineering Publications Limited, London.

Johnson, J.L., 1994, *Principles of Computer Automated Fabrication: A Unified Description of All Free Form Fabricattion Technologies Based on Fundamental Principles,* Palatino Press, Irvine.

Kanlpakjian, S., 1995, *Manufacturing Process for Engineering Materials,* Addison-Wesley Publishing Company, New York.

"New technology: Conveyed-adherent autofab", 1996, *Rapid Prototyping Report,* August, CAD/CAM Publishing, Inc.

Ostwald, P.F., 1984, *Cost Estimating,* Prentice-Hall, Inc., New Jersey.

Pugh, S., 1991, *Total Design,* Addison-Wesley Publishing Company, New York.

Roozenberg, N.F.M. & Eekels, J., 1995, *Product Design: Fundamentals and Methods,* John Wiley & Sons, Inc., Chichester.

Stewart, R.D., Wyskida, R.M., & Johannes, J.D., 1995, *Cost Estimator's Reference Manual,* John Wiley & Sons, Inc., New York.

Thomas, C.L., 1995, *An Introduction to Rapid Prototyping,* United States of America.

Trispectives, [Computer software]. (1995). 3D Eye, Ithica, New York.

Trudeau, N., 1995, *Professional Modelmaking: A Handbook of Techniques and Materials for Architects and Designers,* Watson-Guptill Publications, New York.

Ullman, D.G., 1992, *The Mechanical Design Process*, McGraw-Hill, Inc., New York.

Ulrich, K.T. & Eppinger, S.D., 1995, *Product Design and Development,* McGraw-Hill, Inc., New York.

Wohlers, T., 1996, *Rapid Prototyping State of the Industry: 1995-96 Worldwide Progress Report*, Wohlers Associates.

Wohlers, T., 1996, *RP Direct: 1997 Directory,* ConnectPress Ltd., USA.

Wood, L., 1993, *Rapid Automated Prototyping: An Introduction,* Industrial Press, Inc., New York.

Company marketing brochures

Actua 2100, 1996, Company marketing brochure. 3D Systems.

A Process with Material Advantages, 1996, Company marketing brochure. DTM Corporation.

DTM's SLS Selective Laser Sintering Process and the Sinterstation 2000 System, 1996, Company marketing brochure. DTM Corporation.

Model-Maker 3D Modeling System, 1996, Company marketing brochure. Sanders Prototype, Inc.

FDM 1650: The Versitile Modeler, 1996, Company marketing brochure. Stratasys Inc.

SLA-250/30, 1993, Company marketing brochure. 3D Systems.

SLA-350 Series, 1996, Company marketing brochure. 3D Systems.

SLA-500 Series, 1996, Company marketing brochure. 3D Systems.

World wide web sites

3D Systems, Accessed 1996, [http://www.3d.com].

Arizona CADD, Accessed 1996, [http://www.primenet.com/~azcadd].

Bowen, L., Accessed 1996, *Helisys Laminated Object Manufacturing,* Helisys, [http://www.cranfield.ac.uk/aero/rapid/PROCEEDING/bowman.html].

Crump, L.H., Accessed 1996, *Rapid Prototyping Using FDM: A Fast, Precise, Safe Technology*, Stratasys, Inc. [http.cranfield.ac.uk/aero/rapid/PROCEEDING/crump.html].

Digital Prototyping Services, Accessed 1996, [http://www.industry.net/dps].

Jacobs, P.F., Accessed 1996, *Fundamentals of StereoLithography,* 3D Systems, Inc. [http.cranfield.ac.uk/aero/rapid/PROCEEDING/jacobs1.html].

Laminated Objects Manufacturing - Helisys, Accessed 1996, [http://www.cranfield.ac.uk/aero/rapid/systems/explanation.html].

Muller, H., Bauer, J., & Klingenberg, H.H., Accessed 1996*, Computer Based Rapid Prototyping System Selection and Support*, [http://www.biba.uni-bremen.de/groups/rp/rptsel_e.html].

Nutt, K.L., Accessed 1996, *The SLSTM Selective Laser Sintering Process: An Update on the Technology, Materials, and Applications,* DTM Corporation, [http.cranfield.ac.uk/aero/rapid/PROCEEDING/nutt.html].

Proceedings of the 1st European Conference on Rapid Prototyping, Accessed 1996, http://www.cranfield.ac.uk/aero/rapid/rapid_prot.html].

RP and Manufacturing 96, Accessed 1996, [http://www.sme.org/conf/rpconf.html].

RP Directory, Accessed 1996, [http://mtiac.hq.iitri.com/mtiac/rp6.htm].

RP FFF, Accessed 1996, [http://www.cadcam.kth.se/public/computer/fff/RP.html].

RP Home Page, Accessed 1996, [http://stress.mech.utah.edu/home/novac/rapid.html].

RP Resource, Accessed 1996,
[http://cadserv.cadlab.vt.edu/bohn/RP.html/#BIBLIOGRAPHY].

Schroff Development Corporation, Accessed 1996, [http://www.jpsystem5.com].

Solid Concepts, Accessed 1996, [http://solidconcepts.com].

StereoLithography - 3D Systems Inc, Accessed 1996,
[http://www.cranfield.ac.uk/aero/rapid/systems/explanation.html].

Virginia Tech, Accessed 1996, *RP Laboratory,* [http://cadserv.cadlab.vt.edu/bohn/rp].

Wohlers, T., Accessed 1996, *Wohlers Web World,*
[http://lamar.ColoState.EDU/~wohlers].

APPENDIX A

RAPID PROTOTYPING POINTS OF CONTACT

AAROFLEX, Inc.
Kaisha Halcli
8550 Lee Hwy
Suite 650
Fairfax, VA 22031
(707) 573 - 0690

Ballistic Particle Manufacturing (BPM)
1200 Woodruff Rd. A-19
Greenville, SC 29607
(803) 297 - 7700

CGI
Graig Crump
15161 Technology Dr.
Minneapolis, MN 55344
(612) 937 - 2005

CMET Inc.
Japan 81-3-3739-6680

Cubital America, Inc.:
http://www.iquest.net/cubital/
Curtis Peel
1307 F Allen Dr.
Troy, MI 48083
(313) 585 - 7880
FAX: (810) 585 - 7884

D-MEC Ltd.
Japan 81-3-5565-6661

DTM Corporation:
http://www.dtm-corp.com/index.html
Kent Nutt
1611 Headway Circle
Bldg. 2
Austin, TX 78754
(512) 339 - 2922
FAX: (512) 832 - 6753

DuPont Somos
2 Penn's Wy.
Suite 401
New Castle, DE 19720
(302) 328 - 5435

Electrosetting
(301) 337 - 8702

Ennex Fabrication Technologies
Marshall Burns
549 Landfair Ave.
Los Angeles, CA 90024
(310) 891 - 0600

EOS GmbH
Germany 49-89-899131-14

Formigraphic
(415) 868 - 1283

Helisys: http://helisys.com/
Michael Feygin

Incremental Fabrication
(541) 745 - 7739

24015 Garnier St.
Torrance, CA 90505
(310) 891 - 0600
FAX: (310) 891 - 0626

Landfoam
(617) 444 - 6910

Light Sculpting
(414) 964 - 9860

MIT
Andrew Kelley III
(513) 634 - 7379
FAX: (513) 634 - 1509

Sanders Inc.
Rolf Hubert
PO Box 540
Pine Valley Mill
Wilton, NH 03086
(603) 654 - 5100
FAX: (603) 654 - 2616

Soligen Inc.:
http://www.partsnow.com/
Yehoram Uziel
19408 Londelius St.
Northridge, CA 91324
(818) 718 - 1221

Sparx AB
Sweden 46-31-277100

Stratasys:
http://www.stratasys.com/
William Camuel
14950 Martin Dr.
Eden Prairie, MN 55344
(612) 937 - 3000
FAX: (612) 937 - 0070

Schroff:
http://www.jpsystem5.com
(913) 262 - 2664
FAX: (913) 722 - 4936

3D Systems: http://www.3d.com
Tom Camp
Methods West
(602) 437-2220
FAX: (602) 437-2362

Jouni Paranen
26081 Avenue Hall
Valencia, CA 91355
(805) 295 - 5600 x - 2443
FAX: (805) 295 - 0249

APPENDIX B

RP ADVISOR INFORMATION TABLES

Table B.1 RP Advisor Machine Data

Machine	Technology	Manufacturer	Min Z	Max Z	Speed Catagory	Miniumum Speed	Maximum Speed
SLA-190/20	StereoLithography	3D Systems	0.004	0.02	1	10	10
SLA-250/30	StereoLithography	3D Systems	0.004	0.02	1	30	30
SLA-250/40	StereoLithography	3D Systems	0.004	0.02	1	30	30
SLA-350/10	StereoLithography	3D Systems	0.002	0.02	1	200	200
SLA-400	StereoLithography	3D Systems	0.004	0.02	1	200	200
SLA-500/40	StereoLithography	3D Systems	0.004	0.02	1	200	200
SLA-500/20	StereoLithography	3D Systems	0.004	0.02	1	200	200
SLA-500/30	StereoLithography	3D Systems	0.004	0.02	1	200	200
FDM 1650	Fused Deposition Modeling	Stratasys	0.005	0.02	2	0.00016	0.0002
STRATASYS 8000	Fused Deposition Modeling	Stratasys	0.005	0.02	2	0.002	0.002
GENISYS	Fused Deposition Modeling	Stratasys	0.014	0.014	2	0.005	0.005
LOM-1015	Laminated Object Manufacturing	Helisys	0.002	0.015	4	15	15
LOM-2030	Laminated Object Manufacturing	Helisys	0.002	0.015	4	24	24
Sinterstation 2000	Selective Laser Sintering	DTM	0.003	0.02	3	50	100
MM-6PRO	Inkjet Technology	Sanders	0.002	0.003	5	0.69	0.69
X-1 (ASU)	StereoLithography	ASU	0.0045	0.02	1	300	350
X-2 (ASU)	StereoLithography	ASU	0.0045	0.02	1	100	150
X-3 (ASU)	StereoLithography	ASU	0.001	0.02	1	100	150
X-4 (ASU)	StereoLithography	ASU	0.001	0.02	1	300	350
X-5 (ASU)	StereoLithography	ASU	0.001	0.02	1	300	350
X-6 (ASU)	StereoLithography	ASU	0.001	0.02	1	100	150
X-7 (ASU)	StereoLithography	ASU	0.0045	0.02	1	300	350
X-8 (ASU)	StereoLithography	ASU	0.0045	0.02	1	100	150
JP-SYSTEM5	Laminated Object Manufacturing	Schroff Corporation	0.002	0.015	4	800	800

Table B.1 cont.

Machine	Speed Units	Pre-Cost	Post-Cost	Machinetime cost	X	Y	Z	Purchase Cost	Overall Accuracy	Min Beam Diameter
SLA-190/20	in/sec	65	65	55	7.5	7.5	9	135000	0.0028	0.008
SLA-250/30	in/sec	65	65	55	10	10	10	215000	0.0028	0.008
SLA-250/40	in/sec	65	65	55	10	10	10	250000	0.0028	0.008
SLA-350/10	in/sec	65	65	65	13.8	13.8	15.7	425000	0.0028	0.01
SLA-400	in/sec	65	65	85	15	15	15	450000	0.0028	0.008
SLA-500/40	in/sec	65	65	95	20	20	23.75	560000	0.0028	0.008
SLA-500/20	in/sec	65	65	95	20	20	23.75	495000	0.0028	0.008
SLA-500/30	in/sec	65	65	95	20	20	23.75	540000	0.0028	0.008
FDM 1650	in^3/hour	65	65	50	10	10	10	107000	0.005	0.02
STRATASYS 8000	in^3/hour	65	65	65	17	20	24	250000	0.005	0.02
GENISYS	in^3/hour	35	35	10	8	8	8	55500	0.014	0.02
LOM-1015	in/sec	65	65	60	15	10	14	95000	0.01	0.01
LOM-2030	in/sec	65	65	85	32	22	20	180000	0.01	0.001
Sinterstation 2000	in/sec	65	65	100	12	12	15	397000	0.015	0.018
MM-6PRO	in^3/hour	65	65	50	6	6	6	50000	0.005	0.02
X-1 (ASU)	in/sec	85	85	100	24	24	24	100000	0.015	0.015
X-2 (ASU)	in/sec	85	85	100	24	24	24	100000	0.015	0.013
X-3 (ASU)	in/sec	85	85	100	24	24	24	100000	0.002	0.005
X-4 (ASU)	in/sec	85	85	100	50	50	50	100000	0.002	0.007
X-5 (ASU)	in/sec	55	55	80	24	24	24	50000	0.002	0.007
X-6 (ASU)	in/sec	55	55	80	24	24	24	100000	0.002	0.005
X-7 (ASU)	in/sec	55	55	80	24	24	24	100000	0.015	0.015
X-8 (ASU)	in/sec	55	55	80	50	50	50	100000	0.015	0.013
JP-SYSTEM5	in/sec	4.25	4.25	1	100	100	100	7500	0.018	0.001

Table B.1 cont.

Machine	Maximum Beam Diameter	Hazards	Computer	Operating System
SLA-190/20	0.011	Material Sensitivity	486/66 MHz	Ms-Dos
SLA-250/30	0.011	Material Sensitivity	486/66 MHz	Ms-Dos
SLA-250/40	0.011	Material Sensitivity	486/66 MHz	Ms-Dos
SLA-350/10	0.01	Material Sensitivity	486/66 MHz	Windows NT
SLA-400	0.01	Material Sensitivity	486/66 MHz	Windows NT
SLA-500/40	0.01	Material Sensitivity	486/66 MHz	Windows NT
SLA-500/20	0.01	Material Sensitivity	486/66 MHz	Windows NT
SLA-500/30	0.01	Material Sensitivity	486/66 MHz	Windows NT
FDM 1650	0.03	60 db	Silicon Graphics, Sun, HP, NT	UNIX/Windows NT
STRATASYS 8000	0.03	60 db	Silicon Graphics, Sun, HP, NT	UNIX/Windows NT
GENISYS	0.03	60 db	Silicon Graphics, Sun, HP, NT	UNIX/Windows NT
LOM-1015	0.015	Vent 500 CFM	486/33Mhz/16MB RAM/240MB HD/VGA	MS Windows NT, MS-Dos
LOM-2030	0.015	Vent 500 CFM	486/33Mhz/16MB RAM/240MB HD/VGA	MS Windows NT, MS-Dos
Sinterstation 2000	0.018	O2 monitor	486/66 MHz	UNIX
MM-6PRO	0.03	Post-Process Ventilation	486/66 MHz	Windows
X-1 (ASU)	0.015	Material Sensitivity	486/66 MHz	Windows NT
X-2 (ASU)	0.013	Material Sensitivity	486/66 MHz	Windows NT
X-3 (ASU)	0.01	Material Sensitivity	486/66 MHz	Windows NT
X-4 (ASU)	0.01	Material Sensitivity	486/66 MHz	Windows NT
X-5 (ASU)	0.01	Material Sensitivity	486/66 MHz	Windows NT
X-6 (ASU)	0.01	Material Sensitivity	486/66 MHz	Windows NT
X-7 (ASU)	0.015	Material Sensitivity	486/66 MHz	Windows NT
X-8 (ASU)	0.015	Material Sensitivity	486/66 MHz	Windows NT
JP-SYSTEM5	0.001	NONE	486/66 MHz	Ms-Dos

Table B.1 cont.

Machine	Input File Format	Network	Footprint	Build Materials	Casting	Weight	Warrantee	Maintanence Cost
SLA-190/20	STL	Yes	27X49X64.5	ThermoPlastic	Quickcast	650	Yes	Several Plans
SLA-250/30	STL	Yes	27X49X64.5	ThermoPlastic	Quickcast	650	Yes	Several Plans
SLA-250/40	STL	Yes	27X49X64.5	ThermoPlastic	Quickcast	Unknown	Yes	Several Plans
SLA-350/10	STL	Yes	W10ft x D 11.5ft	ThermoPlastic	Quickcast	1800	Yes	Several Plans
SLA-400	STL	Yes	W10ft x D 11.5ft	ThermoPlastic	Quickcast	Unknown	Yes	Several Plans
SLA-500/40	STL	Yes	W12ft x D14.8ft	ThermoPlastic	Quickcast	2612	Yes	Several Plans
SLA-500/20	STL	Yes	W12ft x D14.8ft	ThermoPlastic	Quickcast	Unknown	Yes	Several Plans
SLA-500/30	STL	Yes	W12ft x D14.8ft	ThermoPlastic	Quickcast	2612	Yes	Several Plans
FDM 1650	STL	Yes	9 ft^2	Polyester	Investment	350	Yes	7000
STRATASYS 8000	STL	Yes	15 ft^2	Polyester	Investment	500	Yes	12000
GENISYS	STL	Yes	7.5 ft^2	Polyester	Unknown	225	Yes	5500
LOM-1015	STL	Yes	19ft^2+11ft^2+15ft^2	Paper	Unknown	Unknown	Yes	Several Plans
LOM-2030	STL	Yes	4X4X5	Paper	Unknown	Unknown	Yes	Several Plans
Sinterstation 2000	STL	Yes	Large(6 parts)	Powder	Unknown	9300	Yes	Several Plans
MM-6PRO	STL	Yes	Desktop	Wax/plastic	Investment	136	Yes	Several Plans
X-1 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-2 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-3 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-4 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-5 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-6 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-7 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
X-8 (ASU)	STL	Yes	4X4X5	ThermoPlastic	Quickcast	Unknown	Yes	Free
JP-SYSTEM5	STL	No	3X1X1	Laminated Paper	No	15 lb	None	None

Table B.1 cont.

Machine	Power	Imaging
SLA-190/20	200-240 VAC	Helium Cadmium Laser
SLA-250/30	200-240 VAC	Helium Cadmium Laser
SLA-250/40	200-240 VAC	Helium Cadmium Laser
SLA-350/10	200-240 VAC	Neodymium Yttrium Vanadate
SLA-400	200-240 VAC	Solid State
SLA-500/40	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
SLA-500/20	200-240 VAC	Argon Laser
SLA-500/30	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 132 mW
FDM 1650	110V @ 20A or 220V @ 10A	Extrude Head
STRATASYS 8000	110V @ 20A or 220V @ 10A	Extrude Head
GENISYS	110V @ 20A or 220V @ 10A	Extrude Head
LOM-1015	110V / 25W	25W CO2 Laser
LOM-2030	110/220V / 50W	50W CO2 Laser
Sinterstation 2000	208 or 240V/70A 60 Hz single phase	CO2 Laser (50W)
MM-6PRO	115/230VAC, 50-60Hz	Inkjet Technology
X-1 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-2 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-3 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-4 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-5 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-6 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-7 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
X-8 (ASU)	200-240 VAC, 4wire, 3 phase 100amp/phase	Argon Laser 264 mW
JP-SYSTEM5	110V	Razer Blade

Table B.2 Machine Table

MACHINES
SLA-190/20
SLA-250/30
SLA-250/40
SLA-350/10
SLA-400
SLA-500/40
SLA-500/20
SLA-500/30
FDM 1650
STRATASYS 8000
GENISYS
LOM-1015
LOM-2030
Sinterstation 2000
MM-6PRO
X-1 (ASU)
X-2 (ASU)
X-3 (ASU)
X-4 (ASU)
X-5 (ASU)
X-6 (ASU)
X-7 (ASU)
X-8 (ASU)
JP-SYSTEM5

Table B.3 Manufacturer Table

MANUFACTURER
3D Systems
Stratasys
Helisys
Sanders
DTM
ASU

Table B.4 Technology Table

TECHNOLOGY
StereoLithography
Fused Deposition Modeling
Laminate Object Manufacturing
Selective Laser Sintering
Inkjet Technology

APPENDIX C

RP ADVISOR MACROS

AUTOEXEC
Open Start Form (Normal)
Maximize
Open Priorities Form (Hidden)
Open Machine Selection Form (Hidden)
Open Budget Form (Hidden)
Open Select a Technology Form (Hidden)
Open Select a Manufacturer Form (Hidden)
Open Part Parameter Form (Hidden)
Open Preliminary Calculations Query*
Close Preliminary Calculations Query

CALC GET MAX NON-DIM
Open form: FIND MAX NON-DIM

CALC GET MAX QUALITY
Open form: FIND MAX QUALITY

CALC GET MAX TCQ VALUES
Open form: FIND MAX NUMBERS

CALC NORM NON-DIM
Open Query: NON-DIM NORMALIZING
Close Query: NON-DIM NORMALIZING
Close Form: FIND MAX NON-DIM

CALC NORMALIZE QUALITY
Open Query: CALC NORMALIZE QUALITY
Close Query: CALC NORMALIZE QUALITY
Close Form: FIND MAX QUALITY

CALC NORMALIZE TCQ
Open Query: NORMALIZING
Open Query: NORMALIZING
Close Query: NORMALIZING
Close Form: FIND MAX NUMBERS

CALC RUN_TIMES
For Cat I & III
    Open Query: CAT I
    Open Query: CAT I
    Open Query: CAT I

Open Query: CAT I
Close Query: CAT I
For Cat II
Open Query: CAT II
Close Query: CAT II
For Cat IV
Open Query: CAT IV
Open Query: CAT IV
Open Query: CAT IV
Close Query: CAT IV
For Cat V
Open Query: CAT V
Close Query: CAT V

CALC SOLVE FOR NON-DIM
Open Query: MAKE CHOICE
Close Query: MAKE CHOICE

CALC SUM TIMES
For Cat I:
Open Query: SUM TIMES CAT I
Open Query: SUM TIMES CAT I
Open Query: SUM TIMES CAT I
Close Query: SUM TIMES CAT I
For Cat II:
Open Query: SUM TIMES CAT II
Open Query: SUM TIMES CAT II
Open Query: SUM TIMES CAT II
Close Query: SUM TIMES CAT II
For Cat III:
Open Query: SUM TIMES CAT III
Open Query: SUM TIMES CAT III
Open Query: SUM TIMES CAT III
Close Query: SUM TIMES CAT III
For Cat IV:
Open Query: SUM TIMES CAT IV
Open Query: SUM TIMES CAT IV
Open Query: SUM TIMES CAT IV
Close Query: SUM TIMES CAT IV
For Cat V:
Open Query: SUM TIMES CAT V
Open Query: SUM TIMES CAT V

Open Query: SUM TIMES CAT V
Close Query: SUM TIMES CAT V

CALC TOTAL COST AND QUALITY
Open Query: Total Cost
Open Query: Total Cost
Close Query: Total Cost

Change Available Machines
Close View Available Machines Form
Open Machine Selection Form (Normal)

close CRITERIA SUMMARY
Close CRITERIA SUMMARY Report
Close CRITERIA SUMMARY Form

CLOSE ALL
Closes every form and query

Close Criteria summary and open start
Open Form: START
Close Form: CRITERIA SUMMARY

Close Main Run and go back to Main
Close MAIN RUN Form
Open MAIN Form (Normal)

Go to Budget
Open Budget Form (Normal)

HELP - BACK TO START
Message box (Beep)

HELP - MACHINE PURCHASE
Message box (Beep)

HELP - MAIN FORM
Message box (Beep)

HELP - ONE
Message box (Beep)

HELP - PART DIMENSIONS
Message box (Beep)

HELP - PRIORITIES
Message box (Beep)

HELP - PURPOSE OF SEARCH
Message box (Beep)

HELP - RP ADVISOR
Message box (Beep)

HELP - RUN MAIN
Message box (Beep)

HELP - SELECT AVAILABLE MACHINES
Message box (Beep)

HELP - SET PART PARAMETERS
Message box (Beep)

HELP - SINGLE PART ANALYSIS
Message box (Beep)

HELP - VIEW CRITERIA
Message box (Beep)

IN^2 per layer
Open IN^2 Per layer Query*

OPEN CALCULATIONS PAGE
Open CALCULATIONS PAGE Form (Hidden)
Run CALCULATIONS Macro*
Run In^2 per layer Macro*
Run UPDATE CAT1 Macro*
Open MAIN Form (Normal)

Open SORRY Form
Open SORRY Form (Normal)

PRINT - SUMMARY
Open CRITERIA SUMMARY Report (Print)

Close CRITERIA SUMMARY Report

Purchase Info Visible
(Settings are all on MAIN RUN Form)

ACTION	CRITERIA
Set Visible Value Yes (purchse info label)	Running Machine Purchase Search
Set Visible Value Yes (P - Line)	""
Set Visible Value Yes (P - 1)	""
Set Visible Value Yes (P - 2)	""
Set Visible Value Yes (P - 3)	""
Set Visible Value Yes (P - 4)	""
Set Visible Value Yes (P - 5)	""
Set Visible Value Yes (P - 6)	""
Set Visible Value Yes (P - 7)	""
Set Visible Value Yes (P - 8)	""
Set Visible Value Yes (P - 9)	""
Set Visible Value Yes (P - 10)	""
Set Visible Value Yes (P - 11)	""
Set Visible Value Yes (Purchase Cost)	""
Set Visible Value Yes (Imaging)	""
Set Visible Value Yes (Footprint)	""
Set Visible Value Yes (Weight)	""
Set Visible Value Yes (Computer)	""
Set Visible Value Yes (Operating System)	""
Set Visible Value Yes (Network)	""
Set Visible Value Yes (Power)	""
Set Visible Value Yes (Maintanence Cost)	""
Set Visible Value Yes (Hazards)	""
Set Visible Value Yes (Warrantee)	""

Reset selection
Set Value of Machine Selection = 1 on Machine Selection Form
Open Machine Selection Form (Normal)

Run CALCULATIONS

If dim accuracy is general:	Set DA Gen From Specific = value of general selection
If dim accuracy is specific:	Specific value > 0.0125, Set = 1
	Specific value between 0.004 and 0.0125, Set = 2
	Specific value < 0.004, Set = 3
If surface finish is general:	Set SF Gen From Specific = value of general selection
If surface finish is specific:	Specific value > 266, Set = 1
	Specific value between 16 and 266, Set = 2

	Specific value < 16, Set = 3
If (DA+SF) = 2:	Set Quality Rating = 1
If 2 < (DA+SF) < 6:	Set Quality Rating = 2
If (DA+SF) = 6:	Set Quality Rating = 3
If volume is general:	Set bounding volume = X*Y*Z
If volume is specific:	Set volume = value entered
Open #LAYERS Query	
Open #LAYERS Query	
If Plastic part:	If complexity = simple, Set % volume = 0.06
	If complexity = medium, Set % volume = 0.1
	If complexity = complex, Set % volume = 0.15
If Metal part:	If complexity = simple, Set % volume = 0.15
	If complexity = medium, Set % volume = 0.2
	If complexity = complex, Set % volume = 0.25
If volume is general:	Set volume = bounding volume * % volume
If general Dim Accuracy:	If = 1, Set Accuracy = 0.02
	If = 2, Set Accuracy = 0.005
	If = 3, Set Accuracy = 0.003
If specific Dim Accuracy:	Set Accuracy to value entered

RUN MAIN QUERY
Run Macro: OPEN CALCULATION PAGE
Run Macro: CALC RUN_TIMES
Run Macro: CALC SUM TIMES
Run Macro: CALC TOTAL COST AND QUALITY
Run Macro: CALC GET MAX TCQ VALUES
Run Macro: CALC NORMALIZE TCQ
Run Macro: CALC GET MAX QUALITY
Run Macro: CALC NORMALIZE QUALITY
Run Macro: CALC SOLVE FOR NON-DIM
Run Macro: CALC GET MAX NON-DIM
Run Macro: CALC NORM NON-DIM
Open MAIN RUN Form
Run Purchase Info Visible Macro*

Select a Technology
Open Select a Technology Form (Normal)

Select Manufacturer
Open Select Manufacturer Form (Normal)

update CRITERIA SUMMARY

Open CRITERIA SUMMARY Form
Open CRITERIA SUMMARY Report
(all of setting of values are performed on the form and the report)

If using all machines:	Set machines to "All Machines"
If using one manufacturer:	Set machines to "Manufacturer"
	Set manufacturer to Manufacturer selected
	Set manufacturer to visible
	Set manufacterer label to visible
If using one technology:	Set technology to "Technology"
	Set technology to Technology selected
	Set technology to visible
	Set technology label to visible
If using all service company:	Set machines to "Service Company"
If using specific machines:	Set machines to "Specific Machines"
If single part analysis:	Set Type of Analysis to "Single Part Analysis"
If machine purchase:	Set Type of Analysis to "Machine Purchase"
	Set budget label to visible
	Set minimum budget value to visible
	Set dash to visible
	Set maximum budget value to visible
If dim accuracy is general:	Set DA - Type of value to "General"
	If general value = 1, Set DA - Value = 0.02
	If general value = 2, Sete DA - Value = 0.005
	If general value = 3, Sete DA - Value = 0.003
If dim accuracy is specific:	Set DA - Type of value to "Specific"
	Set DA - Value equal to the specific dimesional accuracy
If surface finish is general:	Set SF - Type of value to "General"
	If general value = 1, Set SF - Value = 500
	If general value = 2, Sete SF - Value = 32
	If general value = 3, Sete SF - Value = 1
If surface finish is specific:	Set SF - Type of value to "Specific"
	Set SF - Value equal to the specific surface finish
If volume is general:	Set VOL - Type of value to "General"
	If general value = 1, Set VOL - Value = "Plastic Part"
	If general value = 2, Sete VOL - Value = "Metal Part"
If volume is specific:	Set VOL - Type of value to "Specific"
	Set VOL - Value equal to the specific volume
If complexity value = 1:	Set COMPLEXITY = "Simple"
If complexity value = 2:	Set COMPLEXITY = "Medium"
If complexity value = 3:	Set COMPLEXITY = "Complex"

Open CRITERIA SUMMARY Form

Use these Machines
Close View Available Machines Form
Open MAIN Form

View Available Machines
Open View Available Machines Form

APPENDIX D

RP ADVISOR QUERIES

#LAYERS
(Update Query)
- effective Z thickness
- # of layers

CALC NORMALIZE QUALITY
(Update Query)
- calculates the normalized value of quality

Cat I
(Update Query)
*Calculates the following values only if Speed Catagory = 1 or 3
- effective beam diameter
- travel distance per layer
- seconds per layer
- run time

Cat II
(Update Query)
*run time if speed catagory = 2

Cat IV
(Update Query)
*Calculates the following values only if speed catagory = 4
- run time
- travel per layer
- seconds per layer

Cat V
(Update Query)
*run time if speed catagory = 5

FIND MAX NON DIM
(Select Query)
finds the maximum of the non-dimensional ratings

FIND MAX NUMBERS
(Select Query)
*Finds maximum values of the following
- Total Time
- Total Cost

FIND MAX QUALITY

(Select Query)
*Finds maximum values of the following
- Total Quality

Find ONE machine
(Select Query)
*Displays All available information on machine, which matches
the machine selected on the "Selection of ONE machine" Form

IN^2 Per layer
(Update Query)
- calculates number of inches of travel per layer

MAIN RUN
(Select Query)
*Displays all available information on machines that fit the following criteria
*Displays in decending Non-Dimensional Rating order
*If only one manufacturer, query only runs on those machines made by that manufacturer.
*If only one technology, query only runs on those machines made by that technology.
- Model X-Value <= Machine max X-Value
- Model Y-Value <= Machine max Y-Value
- Model Z-Value <= Machine max Z-Value
- Model Accuracy >= Machine Accuracy
- Cost of machine falls between budget amounts

MAKE CHOICE
(Update Query)
- calculates non-dimensional rating

NON DIM NORMALIZING
If the maximum non-dimensional rating is greater than zero
Normalizes all of the non-dimensional ratings

NORMALIZING
(Update Query)
Calculates the following
- normalized total time
- normalized total cost

SUM TIMES CAT I
*If speed catagory = 1

- calculate pre-processing time
- calculate post-processing time
- sum the times

SUM TIMES CAT II
*If speed catagory = 2
- calculate pre-processing time
- calculate post-processing time
- sum the times

SUM TIMES CAT III
*If speed catagory = 3
- calculate pre-processing time
- calculate post-processing time
- sum the times

SUM TIMES CAT IV
*If speed catagory = 4
- calculate pre-processing time
- calculate post-processing time
- sum the times

SUM TIMES CAT V
*If speed catagory = 5
- calculate pre-processing time
- calculate post-processing time
- sum the times

Preliminary Calculations
(Update Query)
Calculates the following
- incremental Z value
- base z value
- average speed
- base diameter
- incremental diameter

Total Cost
(Update Query)
- calculates total cost
- calculates total quality

View Available Machines
(Select Query)
Displays - Machine
Manufacturer
Technology

APPENDIX E

RP ADVISOR USER MANUAL

TABLE OF CONTENTS

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CHAPTER E1

INTRODUCTION

The user manual outlines the implementation and organization of the RP Advisor. This manual is a reference for users navigating the program and developers modifying the program. While running the RP Advisor, the user is able to access help by selecting the question mark button after the item in question.

CHAPTER E2

DETERMINING THE IMPLEMENTATION TOOLS

The first step in developing the RP Advisor is to determine the program platform. By consulting the customer requirements, the following were determined to be directly related to the system platform:

1) easy to install
2) easy to use
3) inexpensive
4) latest technology

Possible platforms were compared to these requirements. After doing this, it was decided to develop the RP Advisor on a personal computer running Windows 95. Because most people are familiar with using personal computers, a personal computer fulfills the easy to install and easy to use criteria. Also, a personal computer is, for the most part, less expensive than a Unix workstation. To take advantage of the latest technology, it was decided to develop the RP Advisor in a Windows 95 environment.

The next decision was to determine the program or programming language to be used. To meet the following requirements, it was determined that a relational database would be the best way to set up the RP Advisor.

1) lets user define what is "best"
2) easy to use
3) easily updatable
4) easily expandable
5) allow for customization

The latest relational database program available on a personal computer, running Windows 95, is Microsoft ACCESS. This program allows the RP Advisor to fulfill all of the requirements listed above.

CHAPTER E3

RP ADVISOR SYSTEM STRUCTURE

Once the computer system and program are determined, it is possible to set up a structure for the flow of the program. Figure E.1, E.2, E.3 and E.4 are schematic representations of the flow for the RP Advisor.

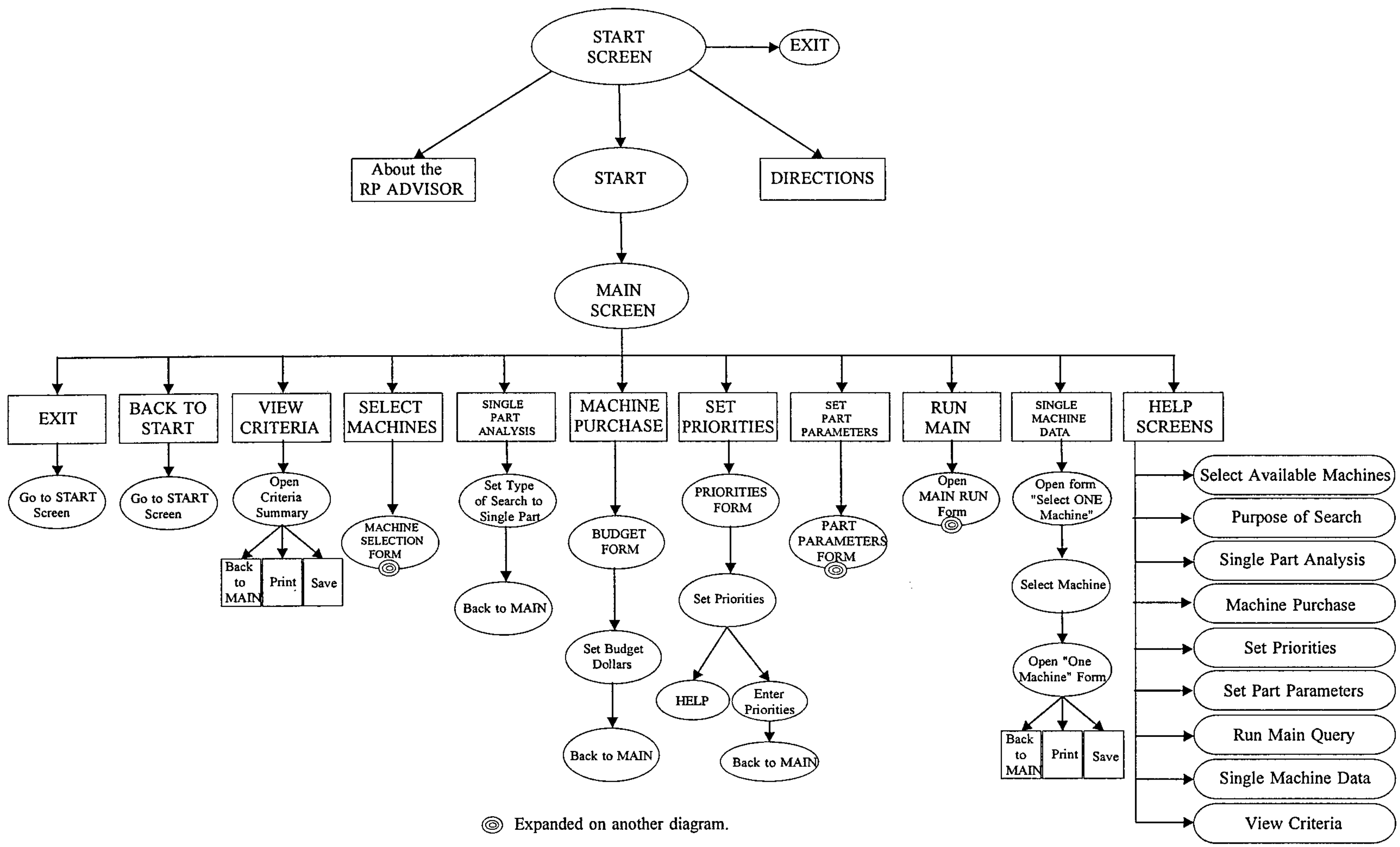


Figure E.1 Start and Main Form Schematic

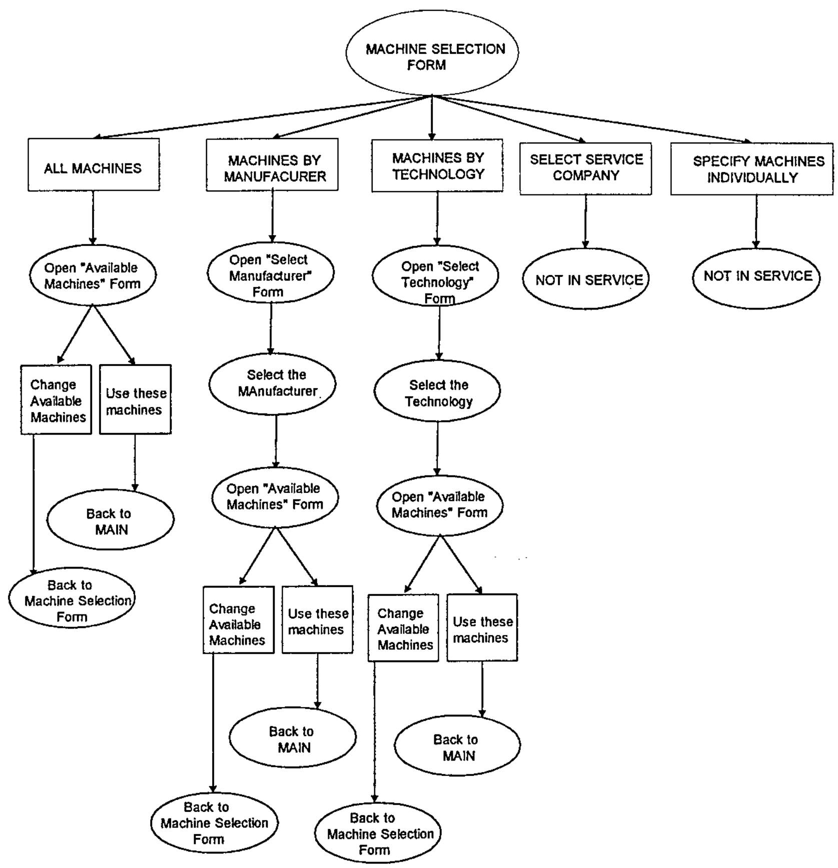


Figure E.2 Machine Selection Form Schematic

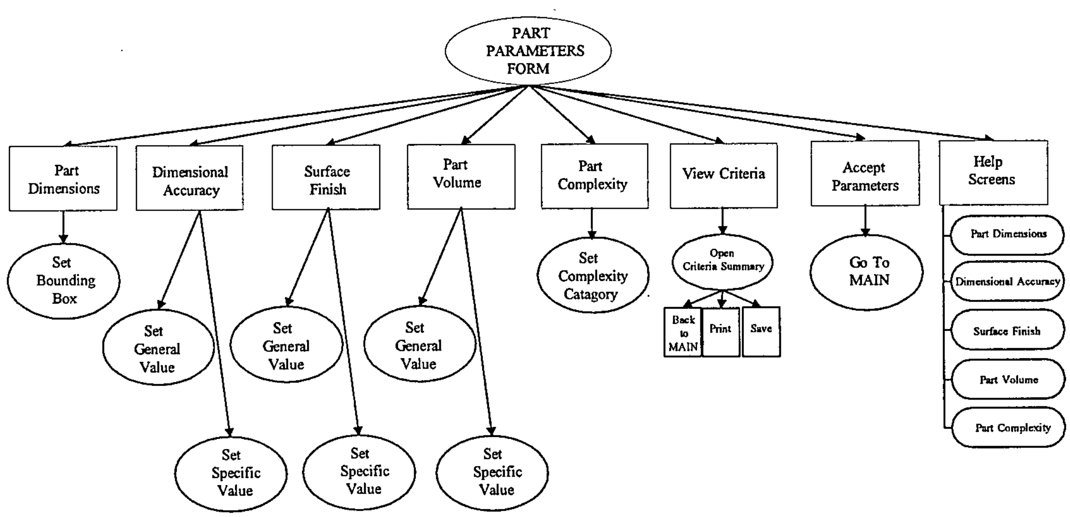


Figure E.3 Part Parameters Form Schematic

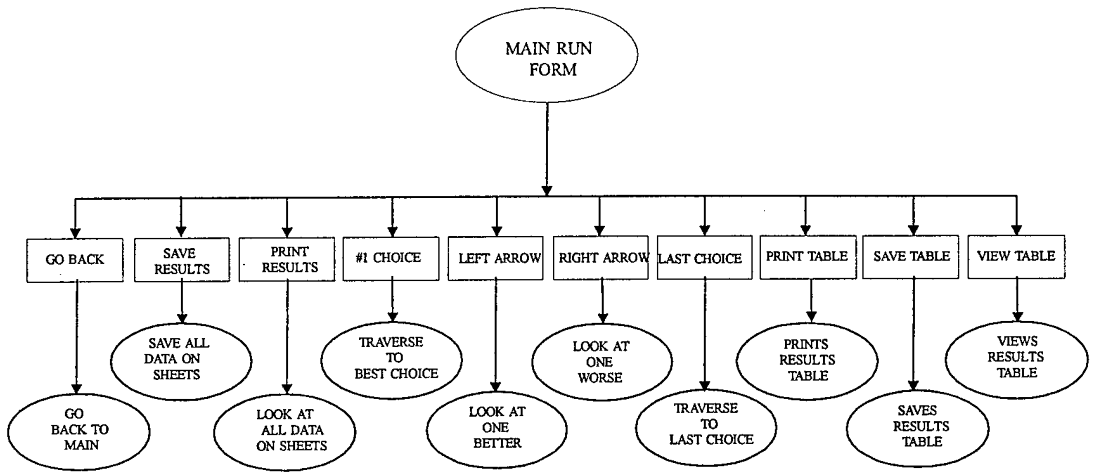


Figure E.4 Main Run Form Schematic

The following sections use screen dumps from the RP Advisor to help the reader understand the organization of the program.

CHAPTER E4

START FORM

The first screen the user is presented with is the start form, shown in figure E.5.

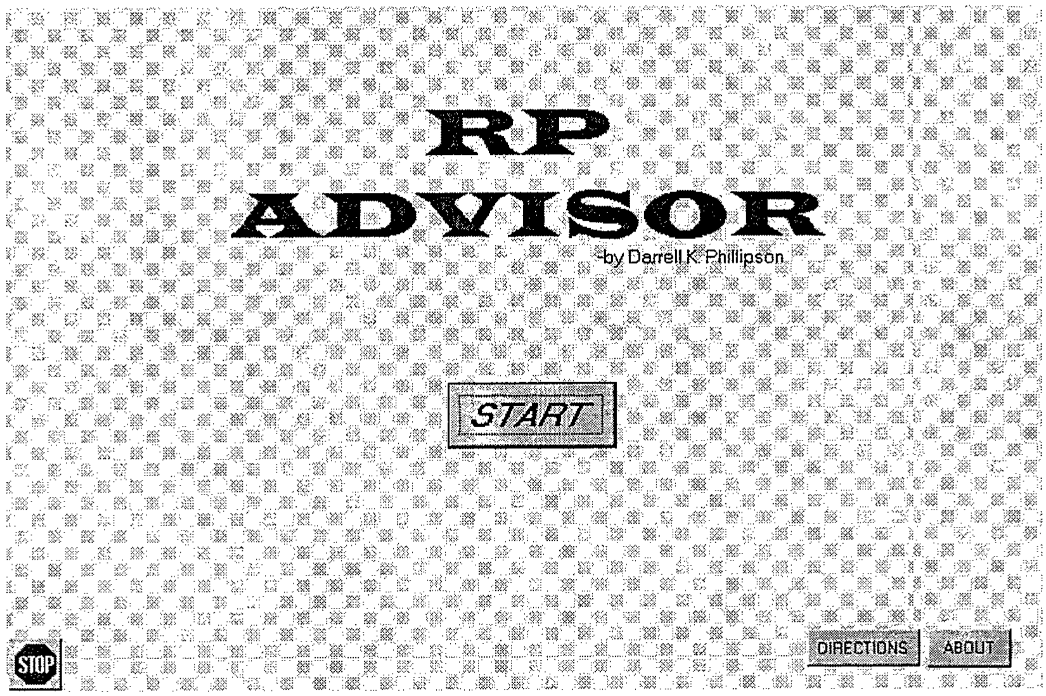


Figure E.5 Start Form

The standard user has four options from this screen. However, to allow a more advanced user the ability to modify the program, a double click on the words "RP Advisor" will cause another button to appear. When this button is selected the program closes without closing Microsoft Access. This allows editing of all tables, forms, reports, queries and macros.

The four options for standard users are represented by the following buttons:

1) Stop
2) Directions
3) About

4) Start

The following sections detail the selection of each of these four options.

E4.1 Stop

When the user selects the stop button from the start screen, the program automatically closes. Microsoft Access also completely closes, restricting the users ability to edit the RP Advisor.

E4.2 Directions

When the user selects the directions button, the form shown in figure E.6 is displayed.

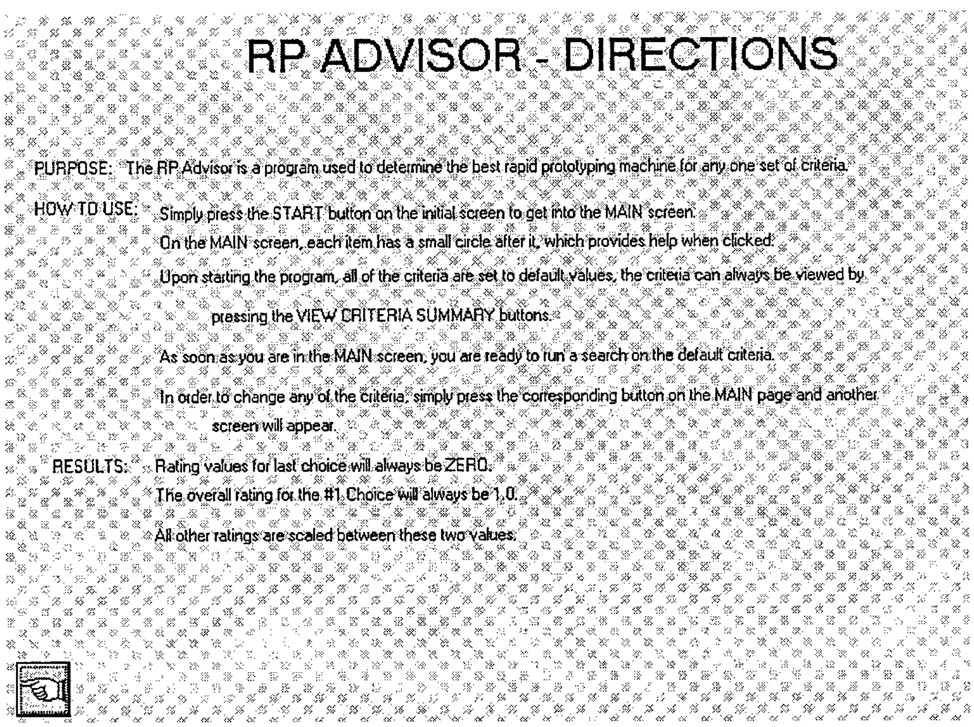


Figure E.6 Directions Form

This form provides an explanation of the purpose of the RP Advisor, how to use the program, and how to interpret the results. To back out of this screen, as can be done from within most screens, the user selects the back up button. The back up button is always a picture of a hand pointing left.

E4.3 About

When the about button is selected a message box is displayed. This message box reads, "Automated RP Machine Selection Program: VERSION 3.0." Selecting OK takes the user back to the start form.

E4.4 Start

Selecting the start button takes the user into the main form for the RP Advisor. This form will be outlined in section E5. Figure E.7 shows the main form.

CHAPTER E5

MAIN FORM

Upon selecting the start button from the start form, the user is presented with the form shown in figure E.7. A schematic of the options and paths available from the main form are shown in figure E.1.

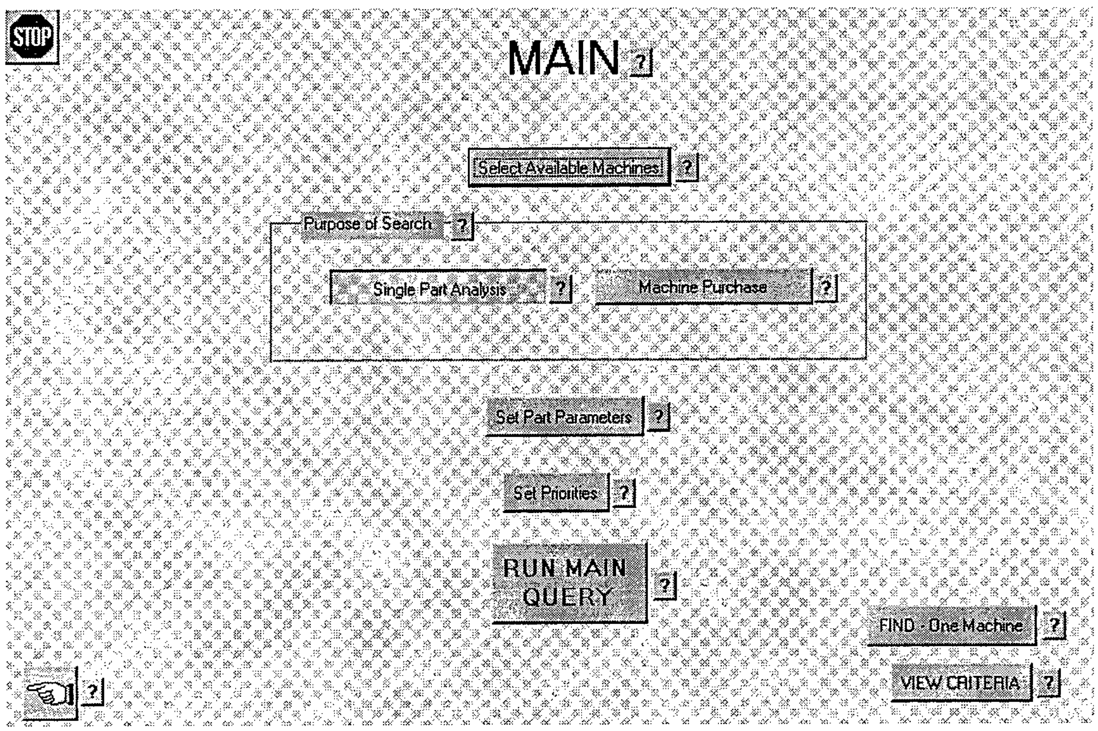


Figure E.7 Main Form

The main form is the focal point of the RP Advisor. From this screen, the user has eleven options, not counting help buttons. These options include criteria input screens, specific function screens, and the main results screen. The following is a complete list of the available options, depicted as buttons on the form:

1) Stop
2) Left Arrow

3) Select Available Machines
4) Single Part Analysis
5) Machine Purchase
6) Set Part Parameters
7) Set Priorities Question Mark
8) Set Priorities
9) Run Main Query
10) Find One Machine
11) View Criteria

The following sections detail the results of selecting each of the options listed above.

E5.1 Stop

When the user selects the stop button from this screen or any other screen, besides the start screen, the user is taken back to the start screen. The purpose of this is to allow the user a second chance to start without shutting the program down. This safety measure takes the place of asking the user if he/she is sure they want to exit.

E5.2 Left Arrow

By selecting this button on any screen, the program goes back one screen. This button is not an option on every screen, because at times it is necessary for the user to make a decision.

E5.3 Select Available Machines

The purpose of this button is to take the user to a screen where he/she is allowed to narrow the search of the "best" machine to a subset of machines. The form that appears when this button is selected is shown in figure E.14. Figure E.2 outlines the options available from this form and what happens when those options are selected.

E5.4 Single Part Analysis Button

If the user wants to have one part built, he/she selects this button. When this is done, a variable within the program is set to identify the search as a single part analysis. This is the default for the program.

E5.5 Machine Purchase

If the user decides to query the database as a machine purchase, he/she selects the machine purchase button. Upon selecting this button, the budget form, shown in figure E.8, is presented to the user.

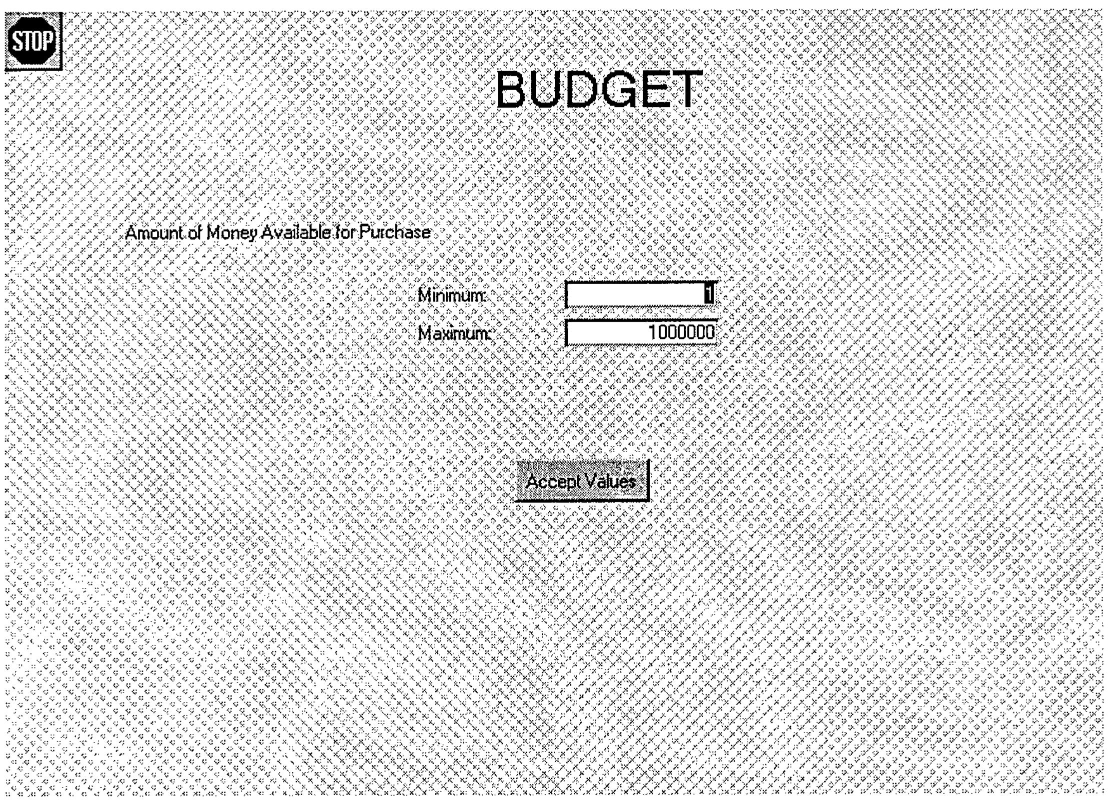


Figure E.8 Budget Form

The decision now takes into account the purchase of a machine. The default values for the budget are a minimum of one dollar and a maximum of one million dollars. This is a non-restrictive set of values, because all machines in the database cost more than one dollar and less than one million dollars. Enter the new values to change the range.

From this screen, the user has only two options, stopping the program and accepting the values. Upon selecting the stop button, the program will return to the start screen. Otherwise, the user must accept the values of the budget range once they have been set. If the user decides not to use the budget values he/she re-selects the single machine analysis button on the main form. Upon selecting the accept values button on the budget form, the user is again shown the main form. It is notable that the machine purchase button is now selected.

E5.6 Set Part Parameters

Selecting this button takes the user to a form which allows him/her to define the variables of the part in question. An expanded explanation of this form is covered in chapter E7. Figure E.19 is a picture of the set part parameters form.

E5.7 Set Priorities

Once the parameters are set and the user has defined the type of search, the remaining information needed is the users determination of priorities. By selecting the set priorities button, the user is shown the form in figure E.9.

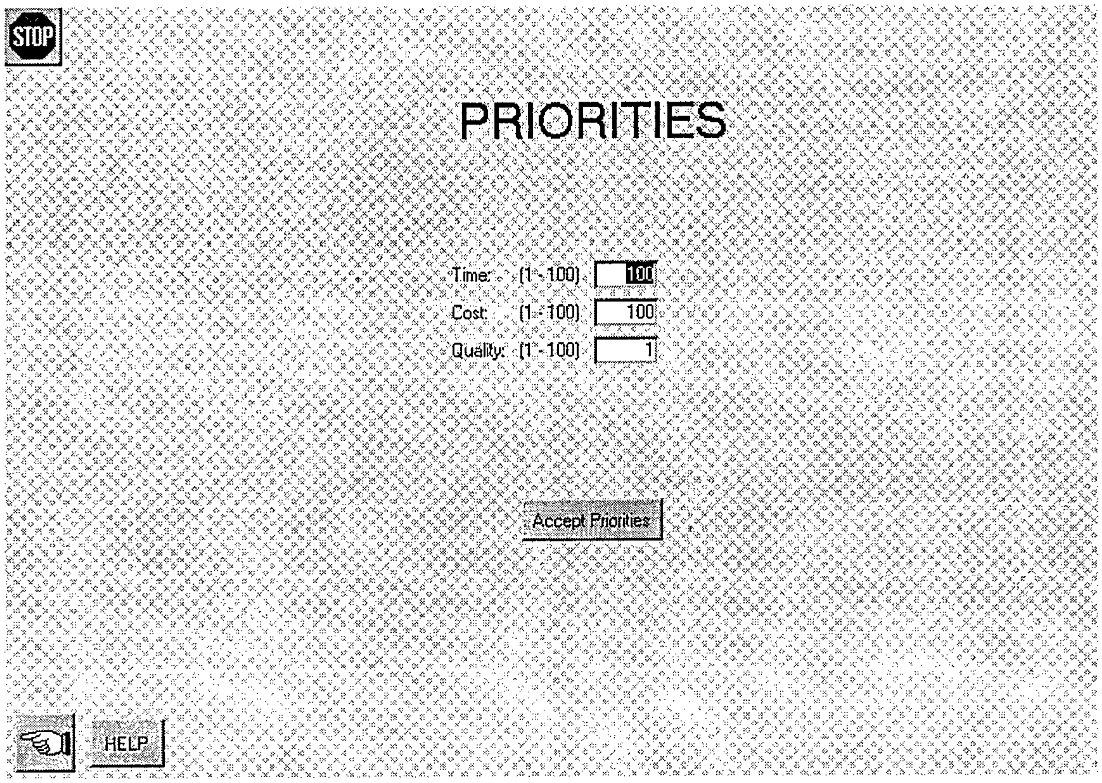


Figure E.9 Set Priorities Form

On this form, the user is allowed to set the importance of keeping time to a minimum, keeping cost to a minimum, and keeping quality high. The help page discussed in section E5.7 describes this decision in detail. The defaults for the priorities are Time = 100, Cost = 100 and Quality = 1. This infers that getting a fast inexpensive part is most important and the user is not concerned with quality.

Once the priorities are determined, the user selects the accept priorities button to return to the main screen. However, the user also has the option of exiting to the start form by selecting the stop button. Also, the user may go back to the main form without accepting the priorities by selecting the back up button. Viewing the help screen about the priorities which is shown in figure E.10 is the final option.

E5.8 Set Priorities Question Mark

Upon selecting this question mark a help screen is displayed which describes what priorities are, what they mean, and shows examples. Figure E.10 is a picture of this help screen.

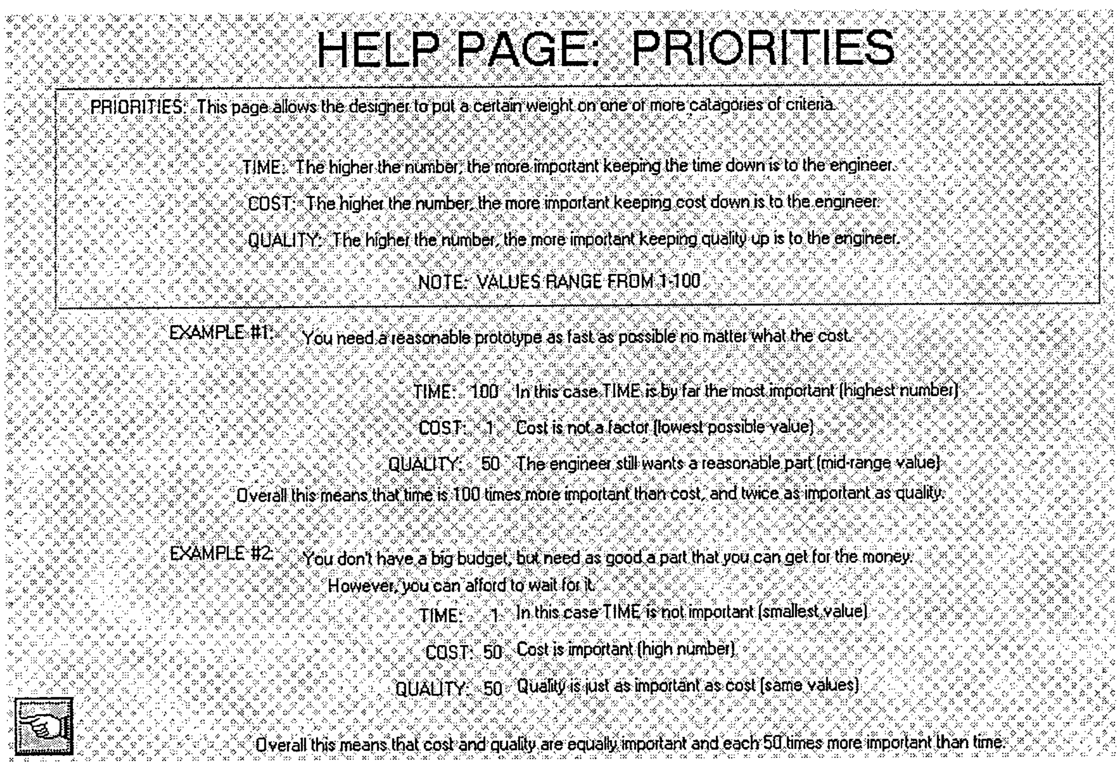


Figure E.10 Set Priorities Help Screen

It is necessary to provide the user with more than a simple message box because of the complexity of setting priorities. Selecting the back up button takes the user back to either the main form or the set priorities form, depending on how this form was accessed.

E5.9 Run Main Query

The system now has all the information needed to make a decision. By selecting this button, the user initiates the calculations necessary to order the machines and recommend the "best" machine. After the system is through calculating, the user is presented with the "RP Advisor Results" form. This form will be reviewed in greater detail in section E8. A picture of this form can be seen in figure E.23.

To return to the main form, the user selects the back up button.

E5.10 Find One Machine

This button does not effect the search for the "best" machine. However, it does add functionality to the program. Many times, a user of the RP Advisor may already know which machine he/she wants information about. By setting the criteria just right, the user is able to pull up the machine they want to view. However, this is a crude way to look at the information on a machine for which the user already knows the name. To avoid the need to trick the program into selecting that machine, the find one machine button gives the user the ability to quickly look up any one machine by name. Upon selecting this button, the form shown in figure E.11 is presented to the user.

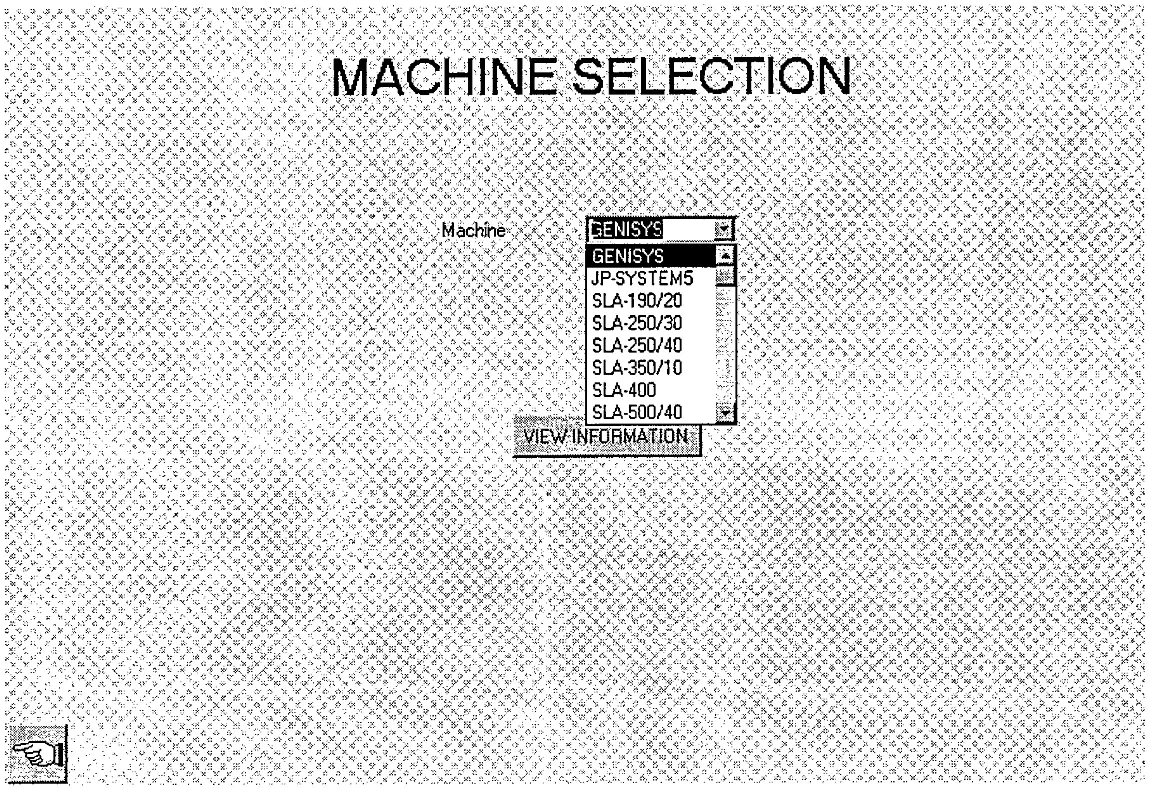


Figure E.11 Single Machine Selection Form

This form is composed of a combination box containing the names of all the machines in the database, a view information button, and a back up button. The combination box is a list of machines that can be selected one at a time. The user moves down the list of machines until he/she finds the machine of interest and highlights it. By selecting the view information button now, the user is shown a data form on the chosen machine. An example of this form is given in figure E.12.

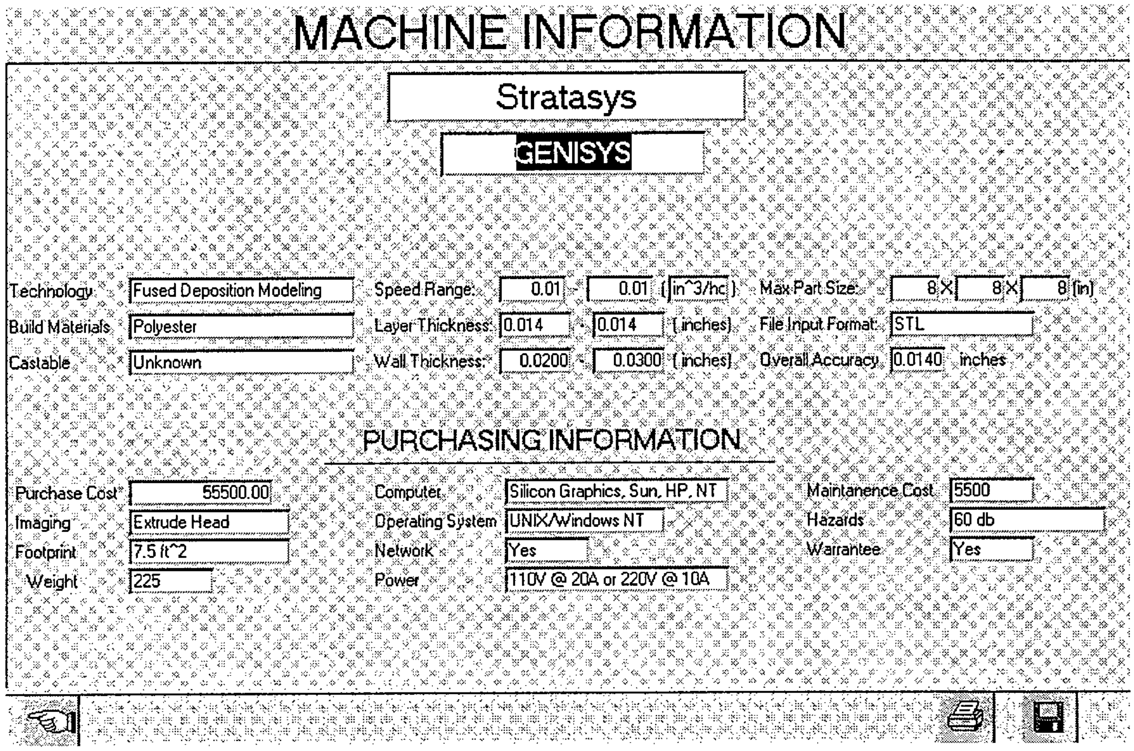


Figure E.12 Single Machine Information Form

This form displays information with regard to the machine of interest. The user is now able to print or save the information by selecting the printer or the diskette. If the user chooses to save the information, he/she will have the option of saving it in excel, text, or rich text format. After the user is done viewing, saving, or printing the machine information, selecting the back up button takes the user back to the single machine selection form shown in figure E.11. The user can now view information for another machine or select the back up button to go the main form.

E5.11 View Criteria

The view criteria button presents a summary of all user defined criteria. A sample of this summary form is shown in figure E.13.

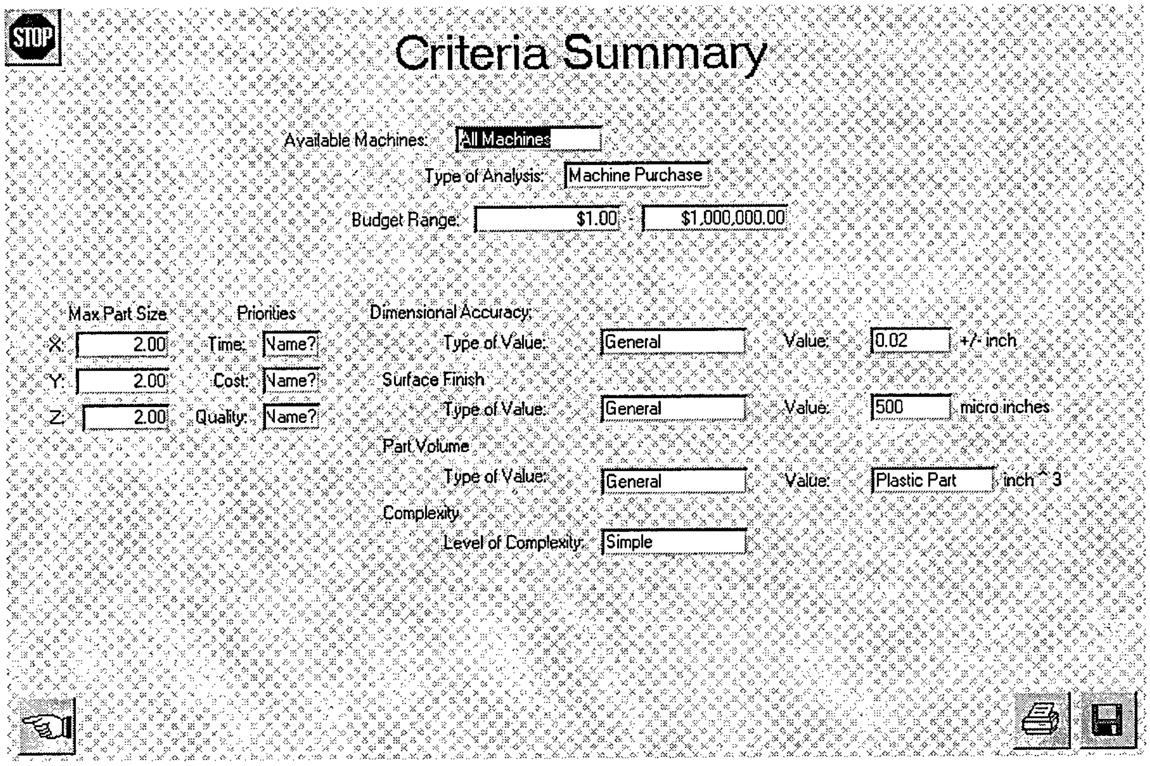


Figure E.13 Criteria Summary Form

As the criteria change, this page reflects the changes. From this form, the user has the option to print or save the summary form. The user can also select the stop button to return to the start screen. Finally, when the user has completed viewing, printing and saving the criteria summary form, he/she can select the back up button to return to the main page.

CHAPTER E6

MACHINE SELECTION FORM

The machine selection form is used to assist the user in defining a list of machines to be compared in the search. Figure E.14 is a picture of the machine selection form.

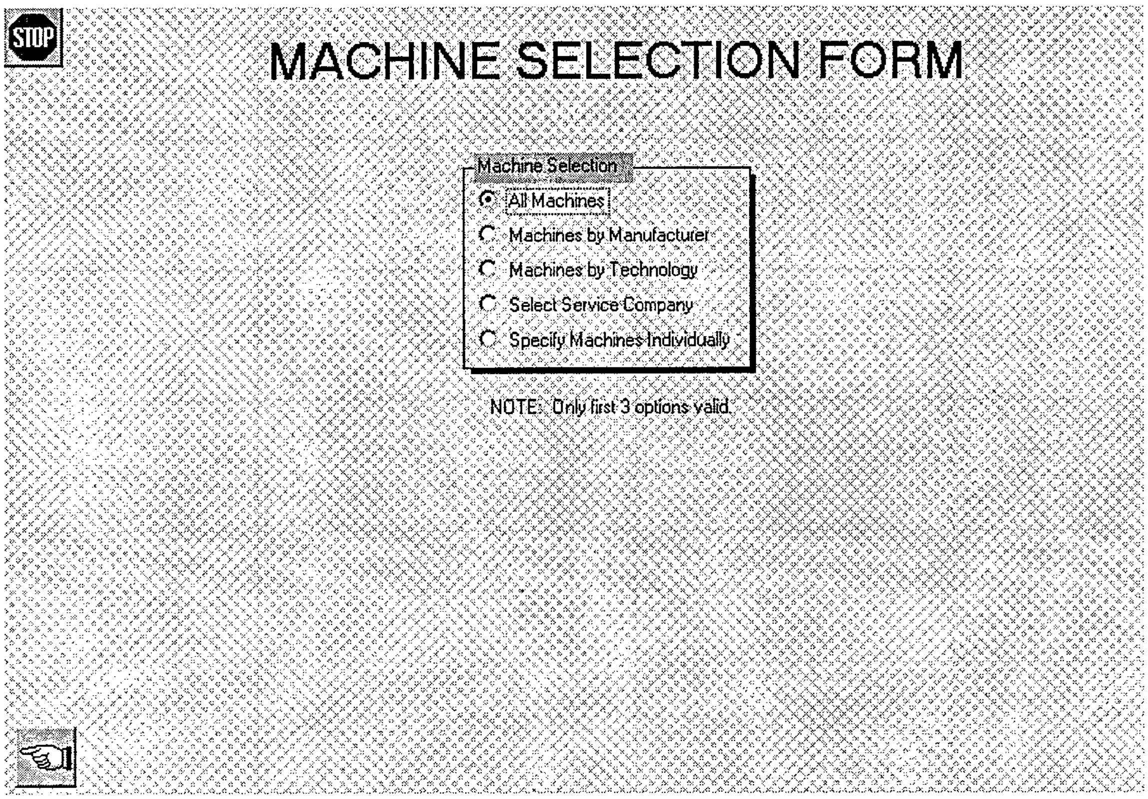


Figure E.14 Machine Selection Form

It may seem that the user would always want to search through all the machines in the database to find the "best" machine for the job. However, the following sections will describe why this may not be true. The following is a list of options that are available on the machine selection form:

1) Stop
2) Left Arrow

3) All Machines
4) Machines by Manufacturer
5) Machines by Technology
6) Select Service Company
7) Select Machines Individually

Figure E.2 is a schematic representation of this form and the path taken by selecting any of the options listed above. The following sections will describe in detail each of these options, presenting figures where necessary to help the reader follow the progression.

E6.1 Stop

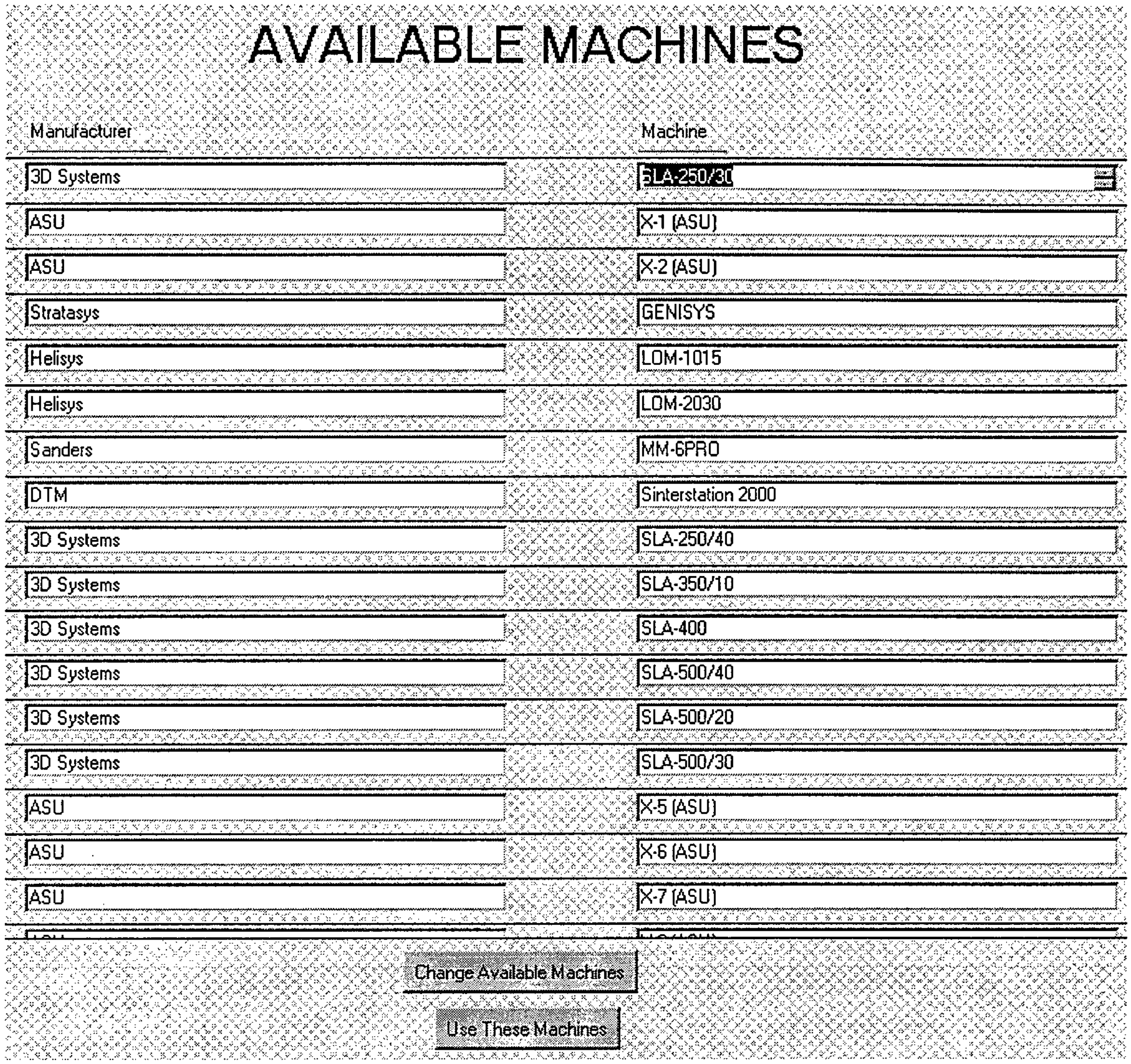
By selecting this button, the user is taken back to the start screen. The function of this button has been discussed in previous sections.

E6.2 Left Arrow

When the user selects this button he/she is taken back to the main form. This button has a similar function on every screen where it is available, as discussed earlier.

E6.3 All Machines

If the user is interested in running the search with respect to all of the machines in the database, this option is selected. Upon making this selection, the user is shown a form listing the available machines. This list consists of all of the machines in the database. Figure E.15 shows an example of this form.



AVAILABLE MACHINES

Manufacturer	Machine
3D Systems	SLA-250/30
ASU	X-1 (ASU)
ASU	X-2 (ASU)
Stratasys	GENISYS
Helisys	LOM-1015
Helisys	LOM-2030
Sanders	MM-6PRO
DTM	Sinterstation 2000
3D Systems	SLA-250/40
3D Systems	SLA-350/10
3D Systems	SLA-400
3D Systems	SLA-500/40
3D Systems	SLA-500/20
3D Systems	SLA-500/30
ASU	X-5 (ASU)
ASU	X-6 (ASU)
ASU	X-7 (ASU)

Change Available Machines

Use These Machines

Figure E.15 Available Machines Form

This form displays the manufacturer and machine name. It also has two options at the bottom. The first option, change available machines, allows the user to return to the select available machines form and select a different category of machines. The second option, use these machines, is selected if the user is satisfied with the list of machines presented. Upon selecting the use these machines option, the user is taken back to the main form and the RP Advisor is set to search all machines.

E6.4 Machines by Manufacturer

The user may have a good working relationship with a machine manufacturer and want to see what that manufacturer has to offer. In this scenario, the user runs the search on only those machines made by that manufacturer. To do this, the user selects the machines by manufacturer option from the machine selection form. The user is now presented the form, shown in figure E.16, which allows him/her to select a manufacturer.

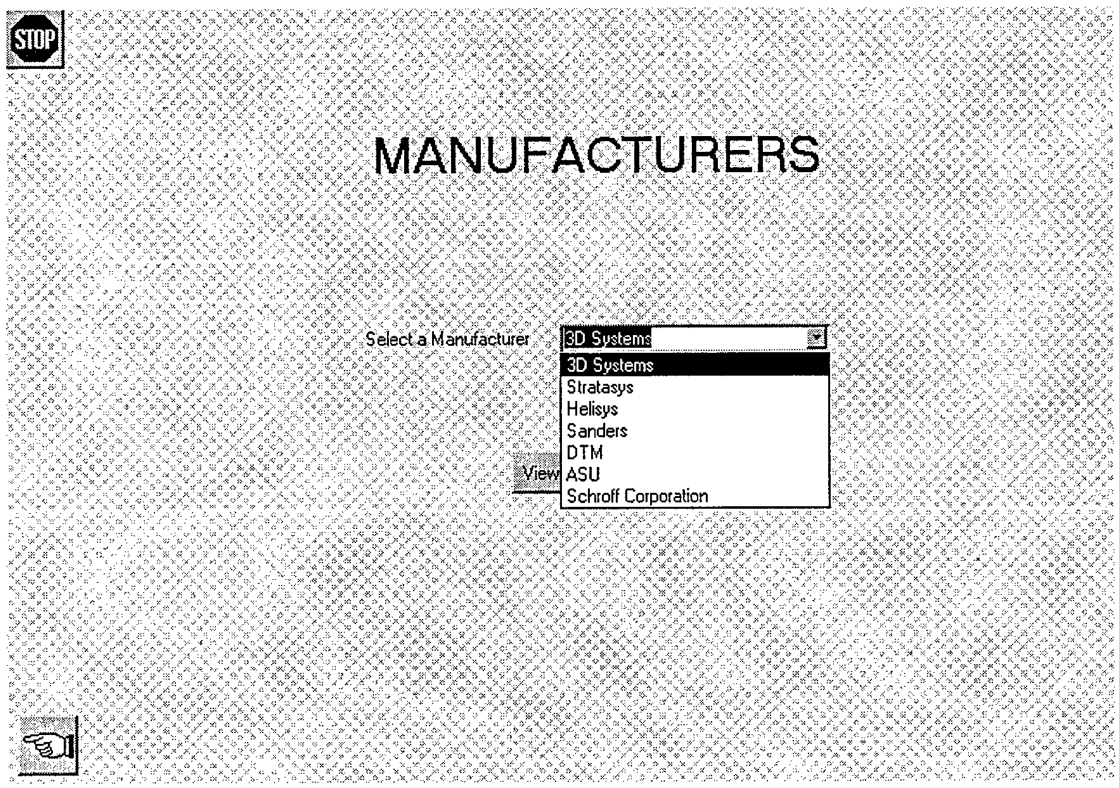


Figure E.16 Manufacturer Selection Form

At this point, the user can scroll down the combination box, which contains all manufacturer names contained in the database, and select the manufacturer of choice. After the manufacturer is specified, selecting the view available machines button will take to the user to the available machines form shown in figure E.15. Now the user has the same options described in section E6.3. The only difference is the machine list now consists of only those machines produced by the manufacturer designated in the manufacturer selection form.

E6.5 Machines by Technology

In many cases, the user has a preference of technology or has a request to make a prototype with a specific technology. Now the user is interested in finding the "best" machine available that utilizes the chosen technology. To do this, the user selects the machines by technology option from the machine selection form. The user is now shown the form in figure E.17, which allows him/her to specify a technology.

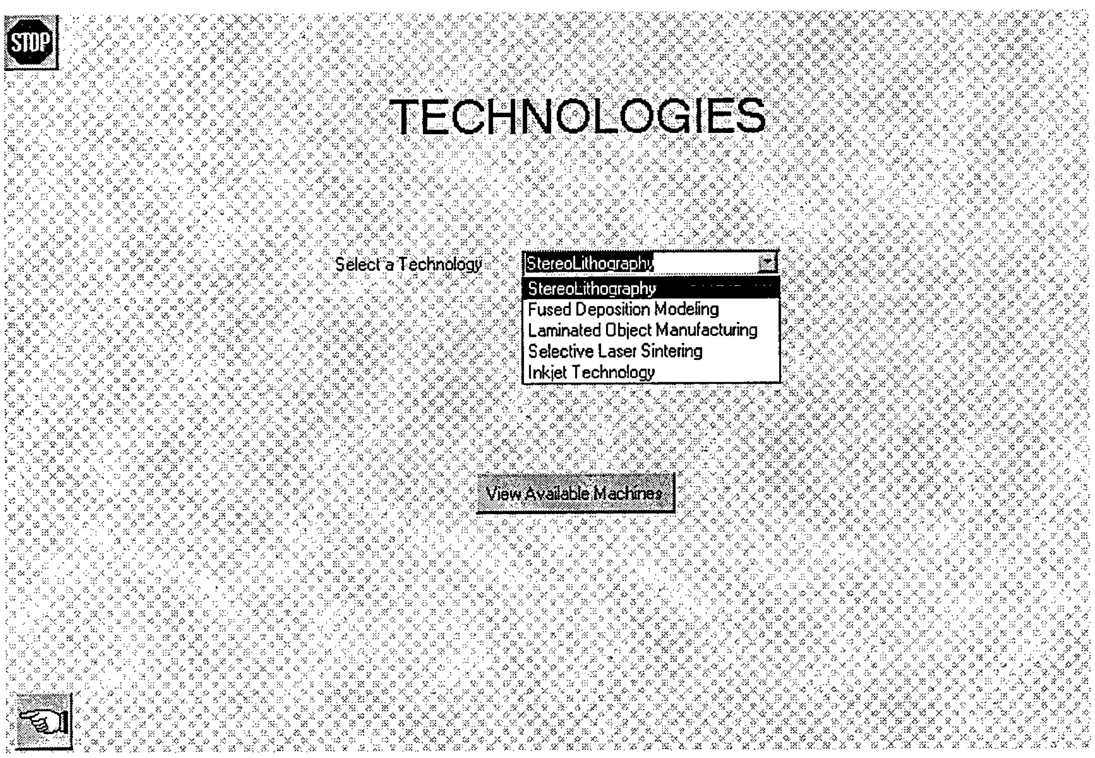


Figure E.17 Technology Selection Form

The user can now scroll down the combination box and select a technology. Selecting the view available machines button now takes to the user to the available machines form shown in figure E.15. The user will have the same options as described in section E6.3. The only difference is that the machine list now consists of only those machines which employ the chosen technology.

E6.6 Select Service Company

Many service companies are being formed that provide the service of rapid prototype production. With this program, each of these companies can submit the names of the machines they own. Once this information is implemented, the user will be able to select any one service company and perform the search on the machines owned by that company.

This option has not been implemented in version 3.0 of the RP Advisor. Selecting this option takes the user to the error screen shown in figure E.18.

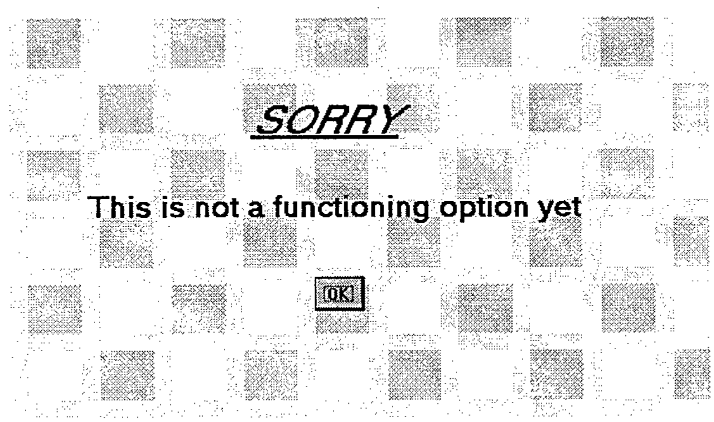


Figure E.18 Non-Functioning Option Form

When implemented, the select service company button will take the user to a form similar to the select manufacturer and select technology forms where the user will specify the service company and view the available machines.

E6.7 Select Machines Individually

The final option, select machines individually, will allow the user to select any combination of machines from the database. This allows the user to compare only the machines that he/she is interested in looking at. However, this option is not yet available in the RP Advisor version 3.0. If this option is selected, the user will be presented with the error screen shown in figure E.18.

CHAPTER E7

SET PART PARAMETERS FORM

As discussed in section E5.6, the set part parameters form provides the user with an interface to specify the variables used in the "best" machine selection. Figure E.19 is a picture of the machine selection form.

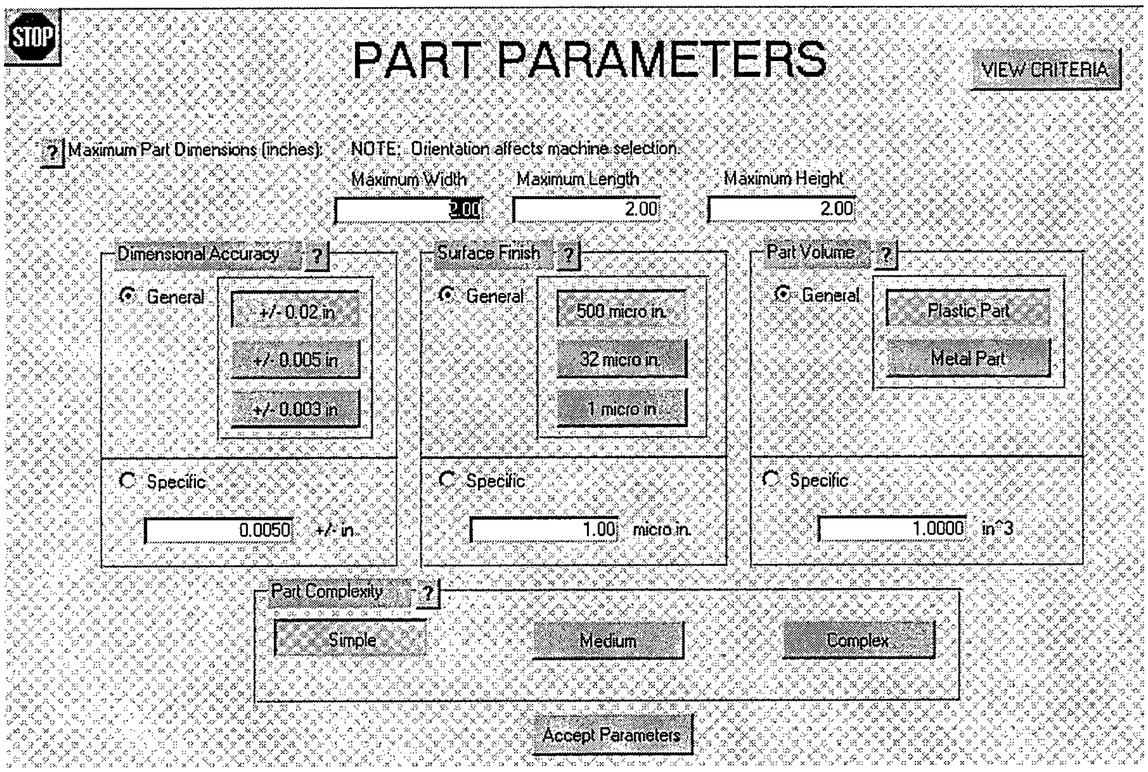


Figure E.19 Part Parameters Form

The following is a list of options made available to the user on the part parameters form:

1) Stop
2) Maximum Part Dimension Values
3) Dimensional Accuracy Value
4) Dimensional Accuracy Question Mark
5) Surface Finish Value

6) Surface Finish Question Mark
7) Part Volume Value
8) Part Volume Question Mark
9) Part Complexity Value
10) Part Complexity Question Mark
11) View Criteria

Figure E.3 is a schematic representation of this form and the path taken by selecting any of the options listed above. The following sections discuss each of these options, using figures to help the reader follow the progression.

E7.1 Stop

As discussed in previous sections, when the user selects the stop button the start screen is displayed. If the user selects the stop button again, he/she will exit the program.

E7.2 Maximum Part Dimension Values

The maximum part dimension values consist of a width, length and height value. The user is required to enter the minimum dimensions of a bounding box that can contain the part being made. The orientation of the part may affect the output of the RP Advisor. All dimensions are in inches.

E7.3 Dimensional Accuracy Value

Specifying the dimensional accuracy can be done in two different ways. The first method is a general method, used when the exact dimensional accuracy is unknown. To use this method, the user ensures that the marker in front of "General" is selected. Then the user is required to select the button that most closely matches the dimensional accuracy he/she is looking to attain. The options are +/-0.02, +/-0.005, or +/-0.003 inches.

The second method of specifying the dimensional accuracy involves typing in the specific dimensional accuracy. To do this, the user selects the marker in front of "Specific" and enters the exact value.

E7.4 Dimensional Accuracy Question Mark

When the user selects the question mark to the right of the words "Dimensional Accuracy," the program displays a help screen. Figure E.20 is a picture of this help screen.

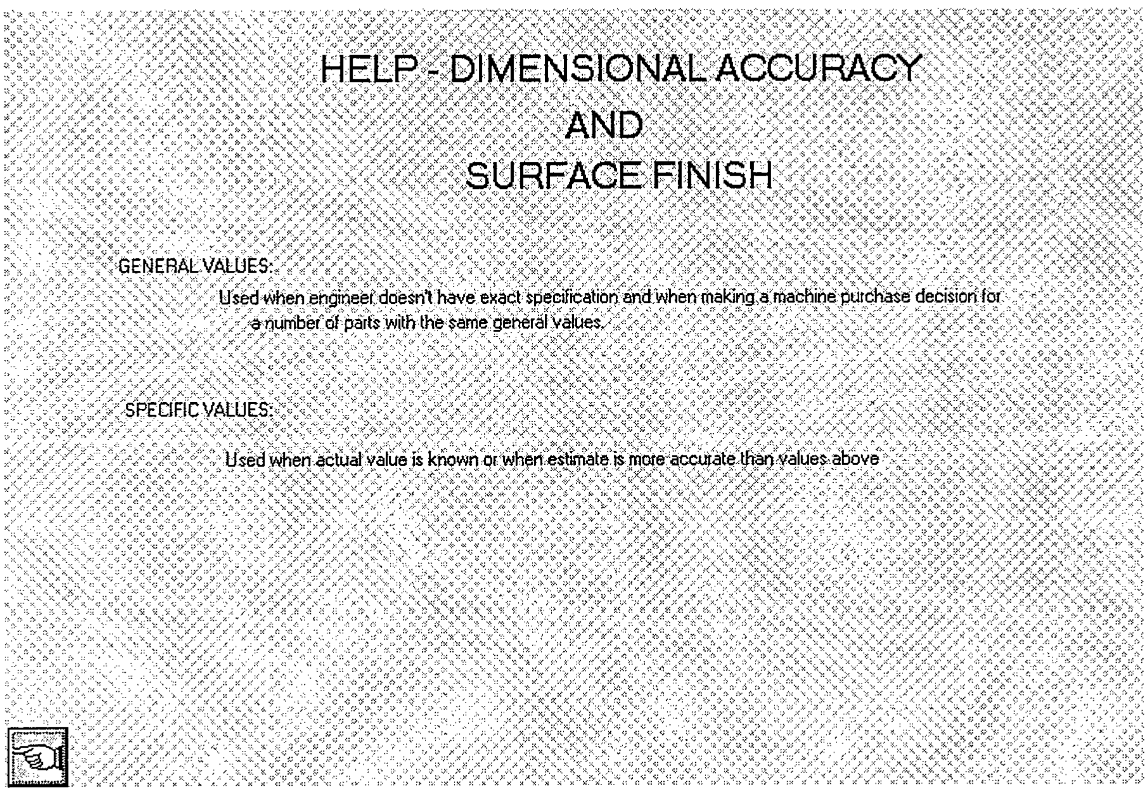


Figure E.20 Dimensional Accuracy and Surface Finish Help Screen

This screen defines when to use general values or specific values for both the dimensional accuracy and the surface finish. To return to the part parameters page the user selects the back up button.

E7.5 Surface Finish Value

Specifying the surface finish can also be done in two ways. The first method is a general method, used when the exact surface finish is unknown. The user ensures the marker in front of "General" is selected. Then the user selects the button that most closely matches the surface finish he/she is looking to attain. The options are 500, 32 and 1 micro inch.

The second method is to enter the exact surface finish. This option is used when the specific value is known. To do this, the user selects the marker in front of "Specific" and enters the exact value.

E7.6 Surface Finish Question Mark

When the user selects the question mark to the right of the words "Surface Finish," the program displays a help screen for the user. Figure E.20 is a picture of this help screen, which is also used for the dimensional accuracy. To return to the part parameters page the user selects the back up button.

E7.7 Part Volume Value

Specifying the part volume can also be done in two different ways. The first method is a general method, used when the exact part volume is unknown. The user ensures the marker in front of "General" is selected and specifies whether the final product is a metal or plastic part.

The second method is to enter the exact volume. This option is used when the user can obtain the volume from some other software. The user selects the marker in front of "Specific" and enters the exact value in the input field.

E7.8 Part Volume Question Mark

When the user selects the question mark to the right of the words "Part Volume," the program displays a help screen for the user. Figure E.21 is a picture of this help screen.

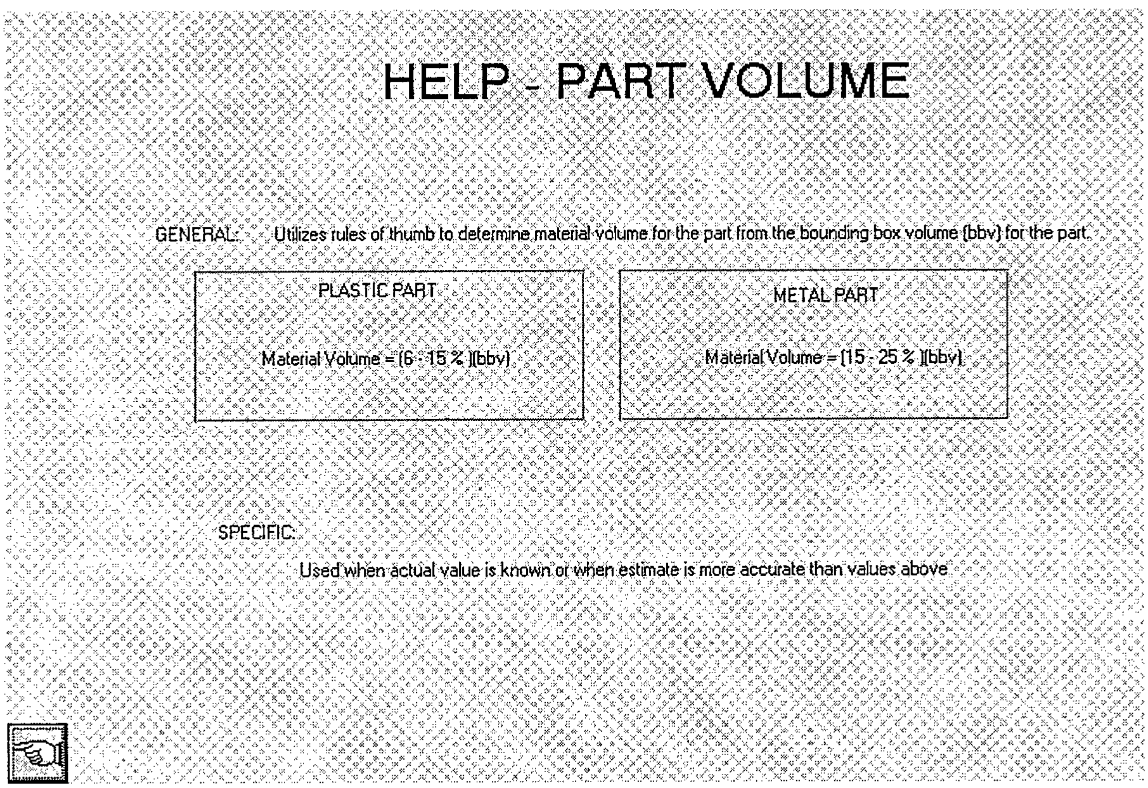


Figure E.21 Part Volume Help Screen

This screen explains the use of a rule of thumb in determining the part volume from the bounding box volume (Chu, 1996). To return to the part parameters page the user selects the back up button.

E7.9 Part Complexity Value

The part complexity value is a general measure of part geometry. By looking at the examples given on the part complexity help screen, shown in figure E.22, the user selects simple, medium or complex to describe the part.

E7.10 Part Complexity Question Mark

When the user selects the question mark to the right of the words "Part Complexity," the help screen shown in figure E.22 is presented.

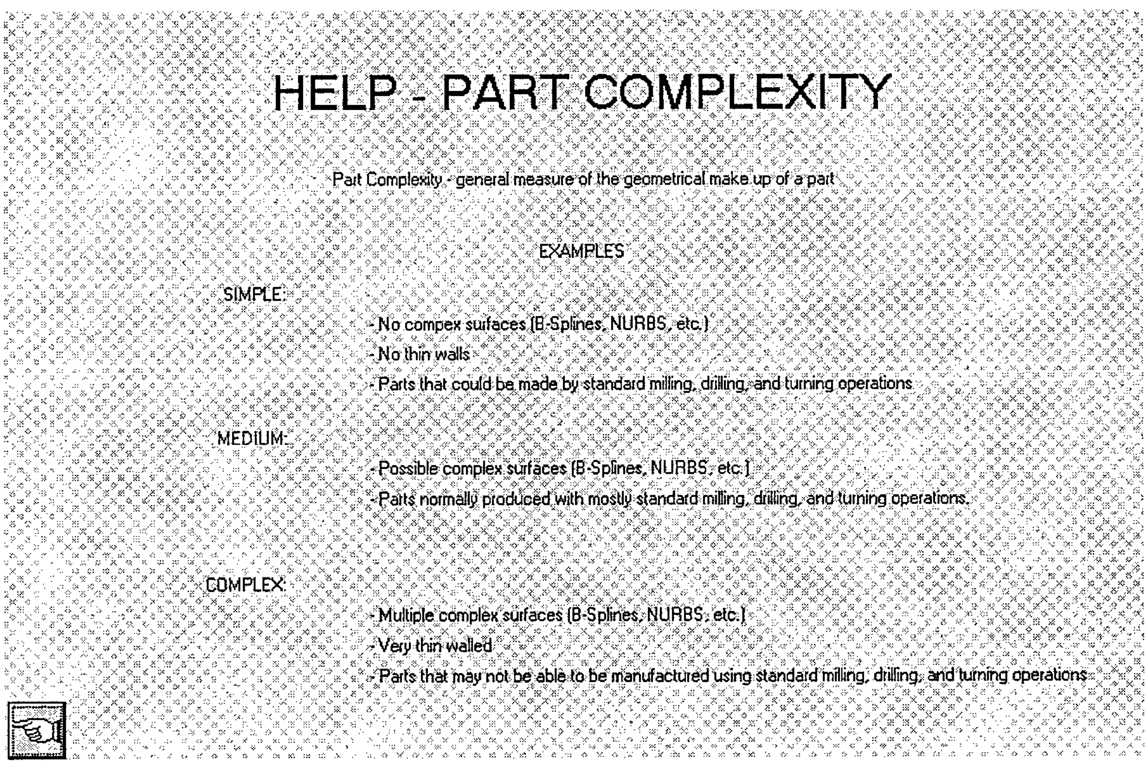


Figure E.22 Part Complexity Help Screen

This help screen defines what part complexity is and gives examples of simple, medium and complex parts. To return to the part parameters page, the user selects the back up button.

E7.11 View Criteria

This button allows the user to view a summary of all the user defined variables. For a full description of this form refer to section E5.11. Figure E.13 is a picture of this form.

CHAPTER E8

RP ADVISOR RESULTS FORM

The RP Advisor results form displays the final results of the RP Advisor and allows the manipulation of the data in several ways. Figure E.23 is a sample picture of the RP Advisor Results form.

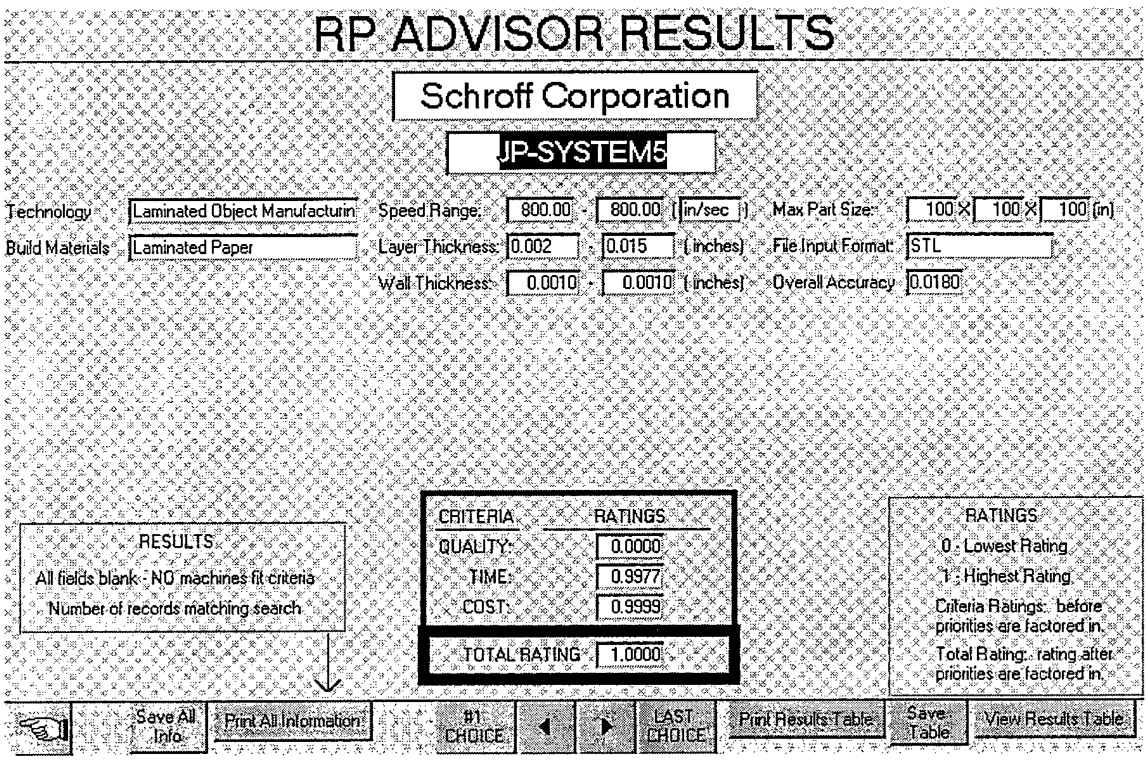


Figure E.23 RP Advisor Results Form

The following is a list of options that are made available to the user on the RP Advisor Results form:

1) Left Arrow
2) Save All Information
3) Print All Information
4) Navigation
5) Print Results Table

6) Save Table
7) View Results Table

Figure E.4 is a schematic representation of this form and the path taken by selecting any of the options listed above. The following sections detail the progression of this form, presenting figures where necessary.

E8.1 Left Arrow

Following the format of the back up buttons throughout this program, selecting this button takes the user back one screen. In this case the main form is presented to the user.

E8.2 Save All Information

The first screen of the RP Advisor results form is the information on the "best" choice. However, there is a full sheet of information on all machines that fit the criteria. The save all information button allows the user to save in excel, text, or rich text format. The user can now view the information at a later time.

E8.3 Print All Information

When this button is selected, the RP Advisor prints the data sheets for all machines that match the criteria. The machines are printed in order, from "best" to worst. Figure E.24 is an example of this printout.

RP ADVISOR RESULTS

JP-SYSTEM5 *BY:* Schroff Corporation

Technology	Laminated Object Manufacturin	*Speed:*	00.0000 _ 00.0000 (in/sec)
Purchase Cost	7500.00	*Max Part Size*	100 X 100 X 100 (in)
Overall Accuracy	0.0180 Inches	*Layer Thickness:*	0.002 - 0.015 (Inches)

Wall Thickness: 0.0010 - 0.0010 (Inches)

PURCHASE CONSIDERATIONS

Operating System	Ms-Dos	*Computer*	486/66 MHz
Input File Format	STL	*Hazards*	NONE
Network	No	*Imaging*	Razer Blade
Footprint	3X1X1	*Power*	110V
Build Materials	Laminated Paper	*Maintanence Cost*	None
Weight	15 lb	*Warrantee*	None

RATINGS

QUALITY	0.0000
TIME	0.9977
COST	0.9999
OVERALL RATING	1.0000

RATINGS
0 - Lowest Rating
1 - Highest Rating
Criteria Ratings: before priorities are factored in.
Total Rating: rating after priorities are factored in.

Figure E.24 Example "Best" Machine Printout

E8.4 Navigation

There are also four navigation keys on the form to assist the user in scrolling through the selected machines.

The first button is labeled “#1 CHOICE” and displays the "best" choice when selected. The second and third buttons are arrow buttons pointing in opposite directions. The left pointing arrow traverses the machines up the list toward the number one choice. The right pointing arrow traverses the machines down the list toward the lowest ranking machine. The last button reads, "LAST CHOICE" and takes the user to the lowest ranking machine.

E8.5 Print Results Table

It is difficult to compare the machines by looking at one machine at a time. Therefore, as per the request of industry representatives, this button allows the user the option of printing a summary table of chosen machines. Figure E.25 is a picture of the resulting printout for an example search.

RP ADVISOR RESULTS

Machine	*Manufacturer*	*TIME*	*COST*	*QUALITY*	*TOTAL*
JP-SYSTEM5	Schroff Corporation	0.9977	0.9999	0.0000	1.0000
GENISYS	Stratasys	0.9953	0.9988	0.2222	0.9994
STRATASYS 8000	Stratasys	0.9883	0.9853	0.7222	0.9916
X-7 (ASU)	ASU	0.9818	0.9733	0.1667	0.9795
X-1 (ASU)	ASU	0.9818	0.9656	0.1667	0.9757
X-5 (ASU)	ASU	0.9727	0.9599	0.8889	0.9719
X-4 (ASU)	ASU	0.9727	0.9484	0.8889	0.9661
SLA-350/10	3D Systems	0.9556	0.9441	0.8444	0.9552
SLA-400	3D Systems	0.9556	0.9299	0.8444	0.9481
SLA-500/20	3D Systems	0.9556	0.9227	0.8444	0.9445
SLA-500/30	3D Systems	0.9556	0.9227	0.8444	0.9445
SLA-500/40	3D Systems	0.9556	0.9227	0.8444	0.9445
X-8 (ASU)	ASU	0.9526	0.9306	0.1667	0.9435
X-2 (ASU)	ASU	0.9453	0.8969	0.1667	0.9230
X-6 (ASU)	ASU	0.9289	0.8958	0.8889	0.9179
Sinterstation 2000	DTM	0.9373	0.8842	0.1667	0.9127
LOM-2030	Helisys	0.9229	0.8766	0.4444	0.9030
X-3 (ASU)	ASU	0.9289	0.8660	0.8889	0.9030
FDM 1650	Stratasys	0.8700	0.8694	0.7222	0.8743
LOM-1015	Helisys	0.8766	0.8553	0.4444	0.8692
SLA-250/30	3D Systems	0.7308	0.7044	0.8444	0.7227
SLA-250/40	3D Systems	0.7308	0.7044	0.8444	0.7227
SLA-190/20	3D Systems	0.1923	0.1133	0.8444	0.1572
MM-6PRO	Sanders	0.0000	0.0000	0.7222	0.0036

Figure E.25 RP Advisor Results Table Printout

This table displays the machine name and manufacturer for each machine. The raw values for time, cost and quality are also given along with the weighted normalized non-dimensional rating. These values allow the user to determine how each machine is rated.

E8.6 Save Table

Selecting this button allows the user the ability to save the summary table in excel, text, or rich text format. Once saved, the table can be viewed at a later time.

E8.7 View Results Table

This button allows the user to view the table discussed in section E8.5 before deciding to save or print. Figure E.26 shows an example of the form that is displayed when the user selects this button.

RP ADVISOR RESULTS TABLE

Machine	Manufacturer	TIME	COST	QUALITY	TOTAL
JP-SYSTEM5	Schroff Corporation	0.9977	0.9999	0.0000	1.0000
GENISYS	Stratasys	0.9953	0.9988	0.2222	0.9994
STRATASYS 8000	Stratasys	0.9883	0.9853	0.7222	0.9916
X-7 (ASU)	ASU	0.9818	0.9733	0.1667	0.9795
X-1 (ASU)	ASU	0.9818	0.9656	0.1667	0.9757
X-5 (ASU)	ASU	0.9727	0.9599	0.8889	0.9719
X-4 (ASU)	ASU	0.9727	0.9484	0.8889	0.9661
SLA-350/10	3D Systems	0.9556	0.9441	0.8444	0.9552
SLA-400	3D Systems	0.9556	0.9299	0.8444	0.9481
SLA-500/20	3D Systems	0.9556	0.9227	0.8444	0.9445
SLA-500/30	3D Systems	0.9556	0.9227	0.8444	0.9445
SLA-500/40	3D Systems	0.9556	0.9227	0.8444	0.9445
X-8 (ASU)	ASU	0.9526	0.9306	0.1667	0.9435
X-2 (ASU)	ASU	0.9453	0.8969	0.1667	0.9230

Figure E.26 RP Advisor Results Table

The user is now allowed to save or print the table. These buttons accomplish the identical tasks described in sections E8.5 and E8.6. To return to the RP Advisor results form the user selects the back up button.

CHAPTER E9

SUMMARY

The purpose of this manual is to present the reader with a complete description of the program. After reading this manual, the user should have few questions regarding the flow of the RP Advisor. Also, by referring to this manual, a user can determine what will happen by selecting any button throughout the RP Advisor.