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Economic Evaluation of Rapid Prototyping in the Development of New Products

by G. Zhang, M. Richardson,
R. Surana

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Guangming Zhang, Mark Richardson and Rena Surana
Department of Mechanical Engineering & Institute for Systems Research
University of Maryland, College Park, 20742 U.S.A.

ABSTRACT

This paper presents results obtained from a study of cost structure and cost estimation for applying the rapid prototyping technology in the process of developing new products. The laser-based rapid prototyping technology is creating a unique platform for the production of physical models using the solid free form fabrication technology. However, the high initial equipment investment calls for a careful balance between economic gains and losses. In this study a cost hierarchical structure is proposed using a combined industrial and engineering approach, which decomposes the process of rapid prototyping into four stages: 3D solid modeling, data preparation for free-form fabrication, part building, and quality inspection. A case study utilizing the stereolithography process to build physical prototypes for constructing 3D tactile graphics, is presented to demonstrate the cost structure and to justify the economical feasibility of using rapid prototyping in the process of developing new products.

I. Introduction

In the globally competitive market place, innovative technologies play a unique role in the development of new products. The laser-based rapid prototyping technology provides a platform for the production of physical models using the solid free form fabrication technology. The availability of physical prototype offers great opportunities to evaluate the product design. The enhancement of manufacturability in the early stage of product development improves product quality, shortens the time to market, and signifies great potential to increase profitability.

Traditional methods to produce prototypes include method of wood making fabrication, rubber molding, vacuum casting, etc. However, machining has been one of the major fabrication processes of making prototypes. The versatility of computer numerically controlled (CNC) machine tools in producing geometrically complicated features offers industry a unique tool to fabricate prototypes for design verification and cost evaluation. The accuracy of numerically controlled (NC) machining stands out. The disadvantage associated with the method of NC machining is the lead time. The time needed to complete the machining operation starts from preparing cutting tools and selecting fixtures. In addition, NC machining has limited capability of dealing with geometrical complexity characterized by a wide range of surface curvatures.

Attempts to generate physical objects directly from CAD data without part-specific tooling or human intervention led to the development of solid freeform fabrication in 1980s. First, with the advancement of computers and CAD systems, 2D design drawings have been gradually replaced by solid modeling in three-dimensional space. The designed object is uniquely characterized by fully-closed and water-tight surfaces using STL data representation. With the rapid advancement of laser technology, the layer manufacturing method is introduced. A designated laser traces the slice geometry on a photosensitive liquid polymer or on sheet material. By solidifying each layer, a physical prototype of the designed solid model is built without any additional tooling. As a result, the time needed to produce physical prototypes is thus reduced from weeks and/or months to days. With innovative technologies and expanding applications, rapid prototyping is now revolutionizing the process of product development in almost every sector of industry.

There has been a significant number of success stories concerning applications of rapid prototyping, such as revenue increase due to early introduction of products to market, and the strengthening of concurrent engineering of design and manufacturing. Although rapid prototyping is a fast-growing industry, its acceptance by industry in the product development cycle has been slow. High initial capital investment in equipment raises the issue of affordability for companies to purchase rapid prototyping equipment for in-house applications. Most small and medium sized companies are shied away by high prices charged by engineering service bureaus for rapid prototyping. The uncertainty and high risk on the rate of investment and capital return have built barriers between the technology providers and the technology users. To promote the emerging technology in industrial applications, there is a pressing need to provide a procedure to perform cost estimating and cost analysis of the rapid prototyping technology.

This paper presents a study which aims at enhancing the potential for efficient utilization of the rapid prototyping technology. The complexity of rapid prototyping is characterized by the requirement for special skills, methods, and equipment. Recognizing the interaction between CAD solid modeling and the process of rapid prototyping, the study begins with meeting the requirement of 3D solid modeling. As there are very few texts or high technical treatises on the mathematical and statistical aspects of estimating cost items which are directly associated with the rapid prototyping technology, a logical methodology is employed in this study. First, a top-down approach is used to define the major steps involved in applying the rapid prototyping process. Then, a decomposition approach is used to itemize individual engineering steps involved in each stage. The approach calls for estimating labor-hours, material consumption, equipment depreciation, pricing of other work related to the rapid prototyping process, and the accumulation of the total cost. Integration of these two approaches signifies economic evaluation of applying the rapid prototyping technology from the unique systems engineering perspective.

II. Process Flow of Rapid Prototyping

During the past decades, several formats of the rapid prototyping technology have been developed. Representative methods are stereolithography, laminated object manufacturing, and laser sintering. Although these methods employ different approaches to produce prototypes, there are four fundamental steps in applying the rapid prototyping technology. These fundamental steps are 3D solid modeling, data preparation for solid freeform fabrication, the process of part building, and quality inspection of the built prototype(s). The four key steps and the process flow of rapid prototyping are illustrated in Fig. 1.

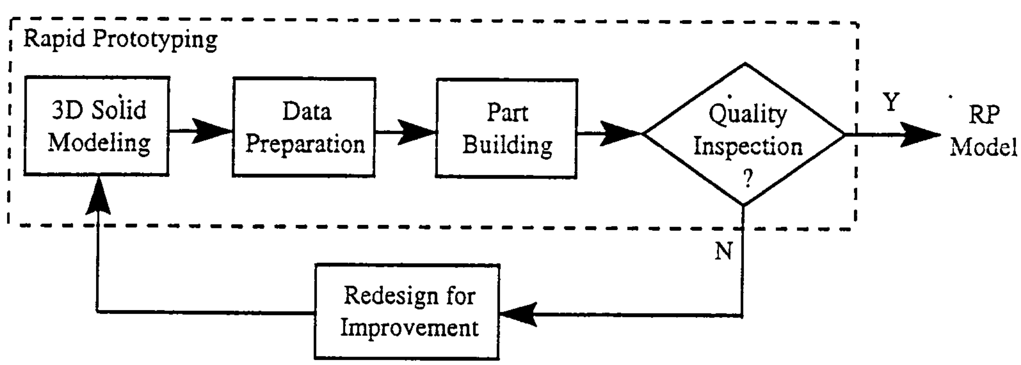


Figure 1 Process Flow of the Rapid Prototyping Application

The architecture of economic evaluation for rapid prototyping applications is built on the process flow. Cost estimation of each of these four fundamental steps is based on the requirement in terms of personnel, equipment and facilities, which are the three main resources that provide companies with the capability of carrying out business activities.

III. Cost Structure and Cost Estimates

Based on the process flow of the rapid prototyping application, an industrial engineering approach to cost estimating is used in this study. Cost elements are identified through the engineering activities involved in each of the four fundamental steps of the rapid prototyping application. Cost analysis is performed to justify the presence of cost elements, and data obtained from an industry survey of fifteen engineering service bureaus are used to calibrate the entire cost structure of the rapid prototyping application.

1. Cost Estimates Related to 3D Solid Modeling

In analyzing the engineering process of 3D solid modeling, three important cost elements are evident. They are the costs of converting 2D drawing to 3D solid models, recreation of cosmetic features, and adjustment of the dimensions associated with tolerances.

(1) Cost Related to Conversion of 2D Drawings to 3D Solid Models

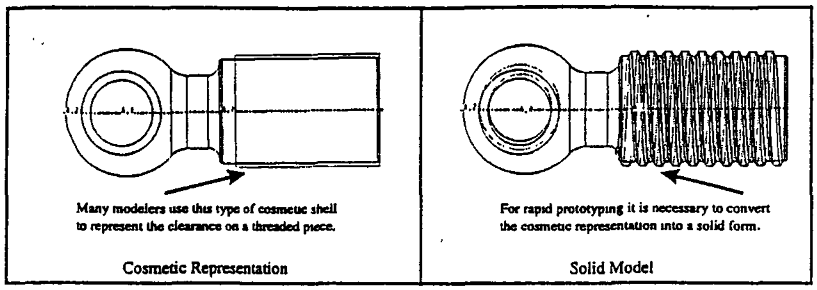
The method of solid free form fabrication requires the contour of a layer to be in a closed format to drive the building process. In this respect, CAD solid modeling plays a critical role when applying rapid prototyping. A significant number of companies have adopted 3D solid modeling in their product development because they recognize the importance of concurrent engineering. Solid modeling allows them to model and prototype a new design - a design which may not even work - long before documenting and implementing it. For those companies, there is no cost involved because engineering designs begin with the process of 3D solid modeling. However, cost related to 3D solid modeling will be added to the new product development for those companies where 2D drawings are the documenting format. The two cost elements for converting 2D drawings to 3D solid models are:

<u>Equipment Costs</u>: They are related to the purchase of computer(s) and CAD software which can be very high and should be entered into the overall cost estimate of a rapid prototyping application. In general, these purchased items are also used for supporting other engineering tasks in the company. It would be appropriate to account these equipment costs as one of the important elements in overhead costs, which also include the expenses related to maintaining and operating these purchased items.
<u>Labor Cost.</u> It has been one of the major cost elements in doing any type of work. Solid modeling requires the special skills of operating computer(s) and utilizing software. Additional expenses to pay for design engineers with high wages are expected.

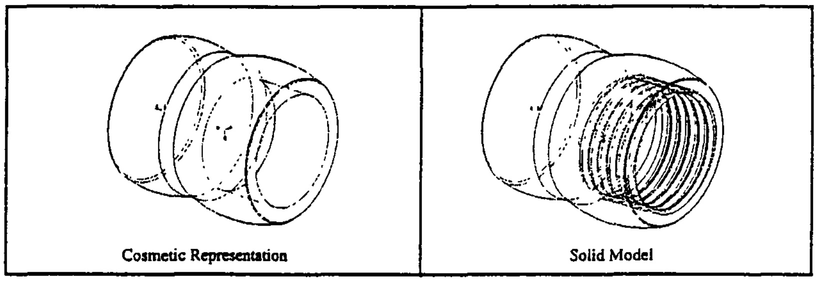
A survey of 15 engineering service bureaus in the Eastern region of the United States indicates that an average charge rate for converting 2D drawings to 3D solid models is $40 per hour with an overhead rate of 35%. Thus, for 10 hours of work, a total cost of $540 is expected.

(2) Recreation of True Geometric Shape(s) as Replacement of Cosmetic Feature(s)

For those companies where engineering designs begin with 3D solid modeling, there would be no need to convert 2D drawings to 3D solid models. However, cost related to the rapid prototyping application often occurs. A typical cost item would be the cost related to recreating cosmetic features of certain components in the design stage. One of the representative examples would be designs with threads. Based on the ISO 6410 and ANSI standard, threads are drawn in dashed lines and specialized symbols, respectively. It has become a convention in engineering design and has been implemented in most of the commercial CAD systems. However, such a cosmetic feature representation does not fit the requirement of solid modeling for the rapid prototyping application. Replacement of the cosmetic feature representation by true geometric shape(s) of the thread on the designed object is required. Figures 2a and 2b present a pair of two components coupled with external and internal threads. True geometrical shapes of these threads, in terms of thread form, thread pitch, location of starting surface, and the total thread length, have to be created accurately.



(a) External Threads



(b) Internal Threads

Figure 2 Cosmetic Features Versus Solid Models

(3) Dimension Adjustment to Accommodate Tolerance Requirement.

Additional costs may also be needed for adjusting dimensions related to assembly. When prototypes of two or more parts are being made, dimensions associated with tolerances have to be adjusted to reflect the design intent. The two components with threads shown in Figs. 2a and 2b serve as an example. Without adjustments of the thread diameters, additional work may be required to ensure the assembling of the two prototypes of these components together.

Equipment costs and labor costs are involved in recreation of true geometrical shape(s) and dimension adjustment. Cost estimating should follow the same procedure as stated in cost estimating for converting 2D drawings to 3D solid models. For 3 hours of replacement work and 2 hours of adjustment work, the cost can be high as much as $270, including the overhead cost involved.

2. Cost Related to Data Preparation for Solid Free Form Fabrication

Solid freeform fabrication is characterized by building a solid part layer by layer. There are several critical requirements in solid freeform fabrication. To minimize the trapped volume of liquid during fabrication, selection of part orientation for the building process is critical. Deflection of a thin, solidified layer without sufficient supports causes distortion of the geometrical shape required to build. To ensure accuracy, a support structure has to be designed and added to the part geometry before the process of building the prototype. A software tool is also needed to generate slicing files of horizontal cross sections for part building. All these requirements call for special skills and, thus, additional labor costs. On the other hand, special and designated software tools are needed to assist the design of support structures and the generation of slicing files. As these software tools come with the rapid prototyping equipment, and they are specialized only in rapid prototyping applications. Relatively high charge fees are enforced by most engineering service bureaus, ranging from $60 to $80 per hour for labor cost with 35% overhead rate. Thus, 3 hours of service in the rapid prototyping application can cost as high as $324.

3. Cost Related to the Process of Part Building

Costs related to the process of part building are determined by the specific rapid prototyping technique used. In this paper, cost estimating of the rapid prototyping technology is focused on applications of stereolithography, a process for building a solid plastic part out of a photosensitive liquid polymer using a directed laser beam to solidify the polymer. Figure 3 illustrates a general setup for the stereolithography process where part fabrication is accomplished as a series of layers in which one layer is added onto the previous layer to gradually build the desired 3D geometry.

The stereolithography process is a slow building process as the rate of the solidification process limits the rate of energy absorption, or the size of the laser spot, to ensure the part accuracy. The initial investment of equipment is relatively high. A machine capable of building a 250 x 250 x 250 mm solid is priced at $200,000. At present, the maintenance cost charged by the equipment manufacturer accounts for 10 - 15% of the equipment purchasing price. The cost of laser replacement adds another important element to the equipment costs. Although a fully automatic and unattended stereolithography operation is claimed by the equipment manufacturer to signify low labor cost, the operational expense is relatively high. Results obtained from the 15 engineering service bureaus indicate an hourly charge rate with a mean of $130 per hour, and the charge rate can be as high as $200 per hour.

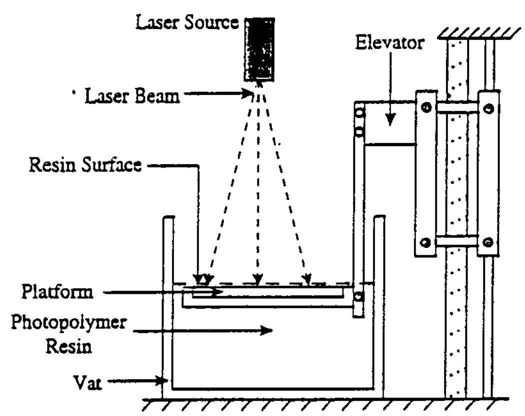


Figure 3 Stereolithography Process

Cost of the photosensitive resin stands for a variable cost item to cover the material consumption not only for the built solid, but also the support structure. The charge fee for a built solid weighing 1000 grams ranges from $100 to $200.

A surcharge fee is generally enforced to cover the labor cost for setting up the machine, cleaning the supports from the built solid, the post-process curing to complete the liquid solidification, and surface smoothing, such as light sanding. Survey data indicate the average surcharge fee is $150 per part. By summing the equipment cost, material cost and labor cost, a part to be built weighing 500 grams and needing 12 building hours may cost as high as $400 + $2,400 + $150 = $2,950.

To summarize the discussion of cost structure of applying the rapid prototyping technology, and to quantify each of the cost estimates, we present an example. It is making a prototype of the fan used in a sander for dust collection. . As illustrated in Fig. 4, the part weighs approximately 200 grams. As the geometry and size of the designed fan imply, building a prototype using the stereolithography process requires 10 hours of work for converting a 2D drawing to a 3D solid model, 4 hours for data preparation, and 10 building hours. The itemized cost elements and the total cost, as expected and without overhead rate charge, are listed below:

2D to 3D conversion:	$40 x 10	$400
Data Preparation:	$70 x 4	$280
Material Cost:	$150 x 0.5	$75
Building Hours:	$130 x 10	$1300
Surcharge Fee:	$150	$150
	Total:	$2,205

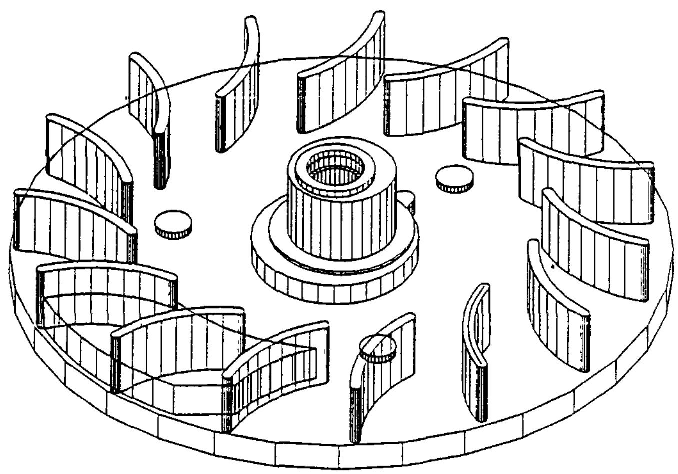


Figure 4 Isometric View of a Dust Collection Fan

IV. Case Study - Production of a Mold Pattern of Tactile Graphics

To demonstrate the procedure used for cost estimating preparation, a case study is presented in this section. The study deals with the production of a mold pattern for tactile graphics using the stereolithography process. Figure 4 is a picture of human heart. The picture contains features, such as arteries, ventricles, and blood flow, depicting the function of a human heart in the study of human biology science. Note that these features are created in the process of 3D solid modeling. On the picture, Braille characters are embedded. Therefore, the picture is also called tactile graphics, which specifically fits the educational need for blind children.

Tactile graphics learning aids are produced using a thermal forming process where a mold pattern is needed. Figure 6 illustrates the process flow of tactile graphics production. The product starts with the creation of geometrical features, then the production of a mold pattern, and finally the

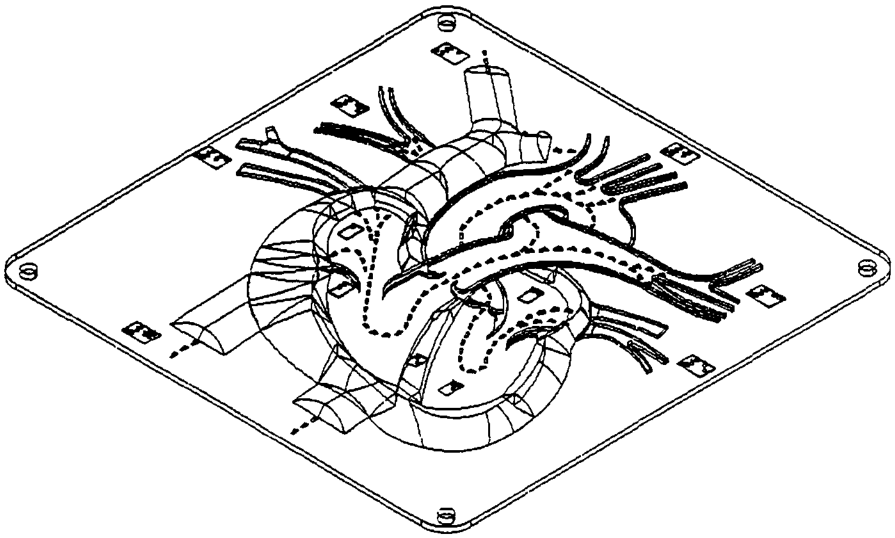


Figure 5 3-Dimensional Representation of the Human Heart

production of duplicates made from the mold pattern using a thermal forming process. Traditionally, mold patterns are made by hand. NC machining has recently been introduced to automate the task of mold creation. However, it also requires a significant amount of time to machine the geometrically complicated surfaces. The associated tooling cost is extremely high to ensure accuracy of the mold pattern. Breakage of Braille dots on the mold pattern often occurs during machining. Quality assurance is a real challenge. Table 1 lists cost estimates of the major operations involved in applying NC machining.

To meet this challenge, the stereolithography process is introduced to carve the complex surfaces covered on the mold pattern as well as to produce the Braille dots descriptions on the mold pattern. The versatility of the layer fabrication method has made the rapid prototyping application of making the mold pattern particularly attractive. For an area of size 125 x 125 mm, 10 building hours are sufficient to produce the mold patterns. The list below illustrates the cost estimates of the major operations involved in applying rapid prototyping. Comparing the two sets of data, economic benefits are evident for a reduced cost ($2,265 Vs. $2,880) and shortened time period (27 hours Vs. 47 hours) to produce the mold pattern using the rapid prototyping technology. Additional advantages gained by using rapid prototyping include the reliability of the building process with no risk of breakage occurring, and easy accommodation of a variety of surface texture patterns to improve the learning efficiency for blind children.

Rapid Prototyping Application		NC Machining Application	
3D Solid Modeling:	$40 x 15	3D Solid Modeling:	$40 x 15
Data Preparation:	$70 x 2	NC Path Preparation:	$70 x 2
Material Cost:	$150 x 0.5	Material Cost:	$40
Building Hours:	$130 x 10	Machining Hours	$60 x 30
Surcharge Fee:	$150	Tooling Cost:	$300
Total Cost:	$2,265	Total Cost:	$2,880

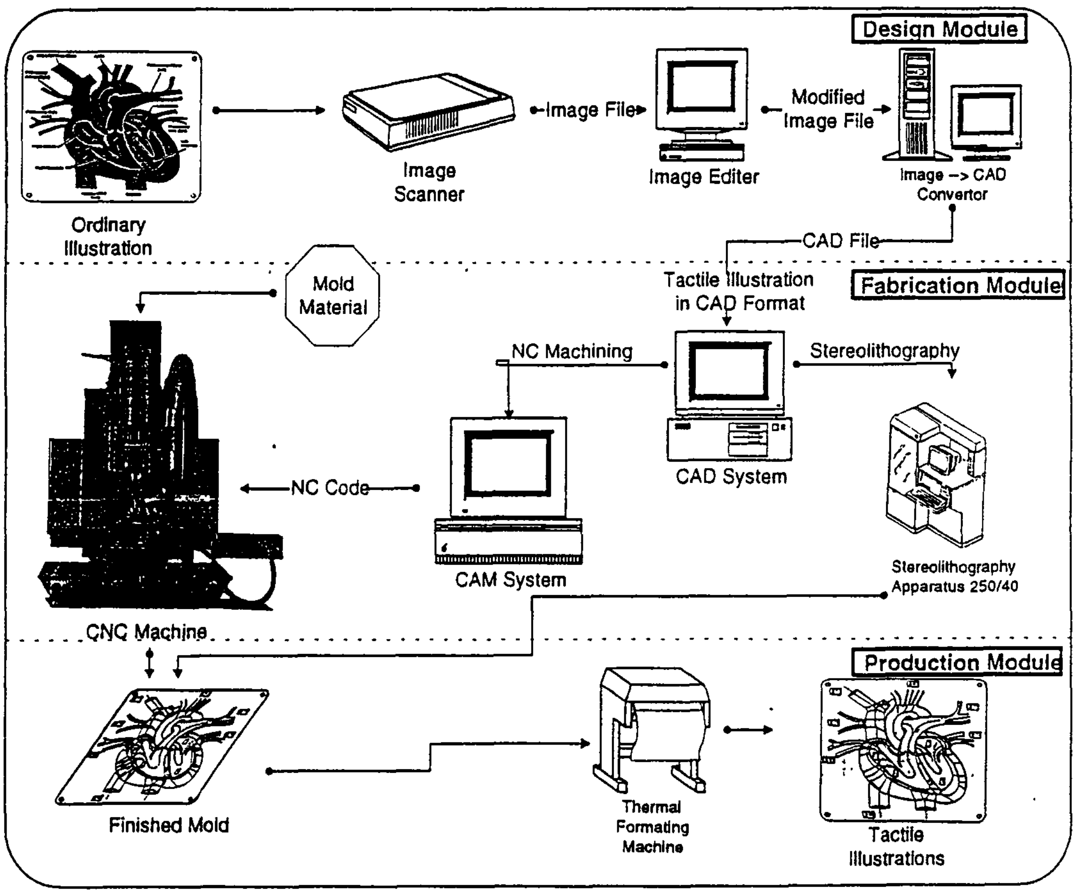


Figure 6 Process Flow of Tactile Graphics Production

V. Discussion of Results

The ultimate objective of a product development process is to produce products with superior quality and competitive prices for the functionality the products can offer. With global competition, companies are becoming leaner and getting their products to market faster by reformulating their business strategy. Rapid prototyping, as a tool in the product development process, is playing a unique role in speeding up product design, and assisting in identifying product improvements in the early design stage. Based on the cost estimating and cost analysis presented in this paper, the relatively high cost associated with rapid prototyping applications is mainly contributed by the following factors:

(1) High Initial Investment of the Rapid Prototyping Equipment. The 1995 market price of a representative stereolithography facility for building capacity 250 x 250 x 250 mm was $200,000 per unit. The rapid prototyping equipment industry is young, and has a history of less than a decade. The accumulated expenditure made by the industry in research and development has been high. Although the market growth rate of rapid prototyping is one of the highest among promising technologies, such as aerospace and computer chip manufacturing, the industry wealth has not accumulated sufficiently enough to offer low equipment prices to its customers. However, a significant price drop can be anticipated in the very near future as the rapid prototyping equipment industry is making tremendous progress to introduce new and innovative technologies with significantly lower costs.

(2) High Reliance on the Technical Support Provided by Engineering Service Bureaus. Based on a survey conducted in 1996, for United States alone, there are about 150 engineering service bureaus located all over the country. At present most of the companies are still in the process of accepting the 3D solid modeling approach in their product development process. As a result, a significant amount of drawings made today are in 2D format. When those companies try rapid prototyping, they have to seek needed technical support from engineering service bureaus. An investment of $200,000 for a five-year return comes up with an annual payment of $52,000 at an interest rate of 10%. An annual maintenance fee is in the order of $15,000 and the cost for laser replacement is about $10,000 for every 2000 hours. The sum of these three cost elements constitutes the major portion of the operational expense besides the labor cost. An hourly rate for building a part using the stereolithography equipment, calculated based on these estimates, may come up with $38 per hour. This number is significantly lower than what is actually charged by most of the engineering service bureaus. Such an inflated service charge puts companies at a disadvantage for maintaining the product development cost at a low level. However, corrections on the service charges are anticipated as the competition among service providers in the industrial neighborhood drives the price down. More important is the fact that most companies are in their final stage of implementing the 3D solid modeling approach in the product design. Due to this, the reliance on engineering service bureaus to provide technical support for rapid prototyping applications becomes less critical, and will eventually be limited to the narrower scope of building prototypes.

(3) Economic Potential of Applying Rapid Prototyping. Product innovation has come to be seen as a fundamental solution for companies to maintain their competitiveness. It has become very critical to develop their new products fast enough to keep up with the turbulent, shifting market. With the rapid prototyping technology, increasing the pace of developing products is not a dream. The benefits of a short development cycle are evident for extending the product's sales

life, strengthening customer loyalty, and gaining an extra time of revenue and profit. If a product profit model is introduced in the case study of producing a mold pattern for tactile graphics, and we assume that a one month earlier completion of producing the required number of learning aids would save one month labor cost for three operators, the expense of $2205 spent on using the rapid prototyping technology, instead of using NC machining, would be well justified. As rapid prototyping applications stretch out, it can be anticipated that companies will gradually create a culture of prototyping to guide the product design because of the compelling economic potential which can be gained from shortening the product development cycle.

VI. Conclusions

As an emerging technology, rapid prototyping is revolutionizing the engineering design approach. This paper presents a comprehensive and detailed coverage of the elements needed to embark on a cost estimating task for applying the rapid prototyping technology in the product development process. Using cost estimates of the work activities involved in rapid prototyping applications, this study points out a critical phenomenon, which has led to a slow acceptance of the rapid prototyping technology by industry. It is the combined effect of high equipment cost and a low volume of work load. Such an effect has led to an uneven distribution of the capital investment in rapid prototyping applications, and has positioned rapid prototyping applications as high-risk activities to gain short-term investment return. Price reduction of rapid prototyping equipment and the creation of a culture of prototyping are the two main challenges facing the design and manufacturing community in promoting the rapid prototyping technology.

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