Chapter 1
INTRODUCTION

The competition in the world market for manufactured products has intensified tremendously in recent years. It has become important, if not vital, for new products to reach the market as early as possible, before the competitors [1]. To bring products to the market swiftly, many of the processes involved in the design, test, manufacture and market of the products have been squeezed, both in terms of time and material resources. The efficient use of such valuable resources calls for new tools and approaches in dealing with them, and many of these tools and approaches have evolved. They are mainly technology-driven, usually involving the computer. This is mainly a result of the rapid development and advancement in such technologies over the last few decades.

In product development [2], time pressure has been a major factor in determining the direction of the development and success of new methodologies and technologies for enhancing its performance. These also have a direct impact on the age-old practice of prototyping in the product development process. This book will introduce and examine, in a clear and detailed way, one such development, namely, that of Rapid Prototyping (RP).

1.1 PROTOTYPE FUNDAMENTALS

1.1.1 Definition of a Prototype

A prototype is an important and vital part of the product development process. In any design practice, the word "prototype" is often not far from the things that the designers will be involved in. In most dictionaries, it is defined as a noun, e.g. the Oxford Advanced Learner's Dictionary of Current English [3] defines it as (see Figure 1.1):

A prototype is the first or original example of something that has been or will be copied or developed; it is a model or preliminary version; e.g.: A prototype supersonic aircraft.

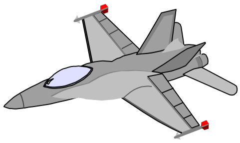

Figure 1.1: A general definition of a prototype

However, in design, it often means more than just an artefact. It has often been used as a verb, e.g. prototype an engine design for engineering evaluation, or as an adjective, e.g. build a prototype printed circuit board (PCB). To be general enough to be able to cover all aspects of the meaning of the word prototype for use in design, it is very loosely defined here as:

An approximation of a product (or system) or its components in some form for a definite purpose in its implementation.

This very general definition departs from the usual accepted concept of the prototype being physical. It covers all kinds of prototypes used in the product development process, including objects like mathematical models, pencil sketches, foam models, and of course the functional physical approximation of the product. Prototyping is the process of realizing these prototypes. Here, the process can range from just an execution of a computer program to the actual building of a functional prototype.

1.1.2 Types of Prototypes

The general definition of the prototype contains three aspects of interests:

(1) the implementation of the prototype; from the entire product (or system) itself to its sub-assemblies and components,
(2) the form of the prototype; from a virtual prototype to a physical prototype, and

RAPID PROTOTYPING - Principles and Applications (2nd Edition) (with Companion CD-ROM)

http://www.worldscibooks.com/engineering/5064.html

(3) the degree of the approximation of the prototype; from a very rough representation to an exact replication of the product.

The implementation aspect of the prototype covers the range of prototyping the complete product (or system) to prototyping part of, or a sub-assembly or a component of the product. The complete prototype, as its name suggests, models most, if not all, the characteristics of the product. It is usually implemented full-scale as well as being fully functional. One example of such prototype is one that is given to a group of carefully selected people with special interest, often called a focus group, to examine and identify outstanding problems before the product is committed to its final design. On the other hand, there are prototypes that are needed to study or investigate special problems associated with one component, sub-assemblies or simply a particular concept of the product that requires close attention. An example of such a prototype is a test platform that is used to find the comfortable rest angles of an office chair that will reduce the risk of spinal injuries after prolonged sitting on such a chair. Most of the time, sub-assemblies and components are tested in conjunction with some kind of test rigs or experimental platform.

The second aspect of the form of the prototype takes into account how the prototype is being implemented. On one end, virtual prototypes that refers to prototypes that are nontangible, usually represented in some form other than physical, e.g. mathematical model of a control system [4]. Such prototypes are usually studied and analyzed. The conclusions drawn are purely based upon the assumed principles or science that has been understood up to that point in time. An example is the visualization of airflow over an aircraft wing to ascertain lift and drag on the wing during supersonic flight. Such prototype is often used when either the physical prototype is too large and therefore takes too long to build, or the building of such a prototype is exorbitantly expensive. The main drawback of these kinds of prototypes is that they are based on current understanding and thus they will not be able to predict any unexpected phenomenon. It is very poor or totally unsuitable for solving unanticipated problems. The physical model, on the other hand, is the tangible manifestation of the product, usually built for testing and experimentation. Examples of such prototypes include a mock-up of a cellular telephone that looks and feels very much like the real product but without its intended functions. Such a prototype may be used purely for aesthetic and human factors evaluation.

The third aspect covers the degree of approximation or representativeness of the prototype. On one hand, the model can be a very rough representation of the intended product, like a foam model, used primarily to study the general form and enveloping dimensions of the product in its initial stage of development. Some rough prototypes may not even look like the final product, but are used to test and study certain problems of the product development. An example of this is the building of catches with different material to find the right "clicking" sound for a cassette player door. On the other hand, the prototype can be an exact full scale exact replication of the product that models every aspects of the product, e.g. the pre-production prototype that is used not only to satisfy customer needs evaluation but also addressing manufacturing issues and concerns. Such "exact" prototypes are especially important towards the end-stage of the product development process.

Figure 1.2 shows the various kinds of prototypes placed over the three aspects of describing the prototype. Each of the three axes represents one aspect of the description of the prototype. Note that this illustration is not meant to provide an exact scale to describe a prototype, but serves to demonstrate that prototypes can be described along these three aspects.

Rapid prototyping typically falls in the range of a physical prototype, usually are fairly accurate and can be implemented on a component level or at a system level. This is shown as the shaded volume shown in Figure 1.2. The versatility and range of different prototypes, from complete systems to individual components, that can be produced by RP at varying degrees of approximation makes it an important tool for prototyping in the product development process. Adding the major advantage of speed in delivery, it has become an important component in the prototyping arsenal not to be ignored.

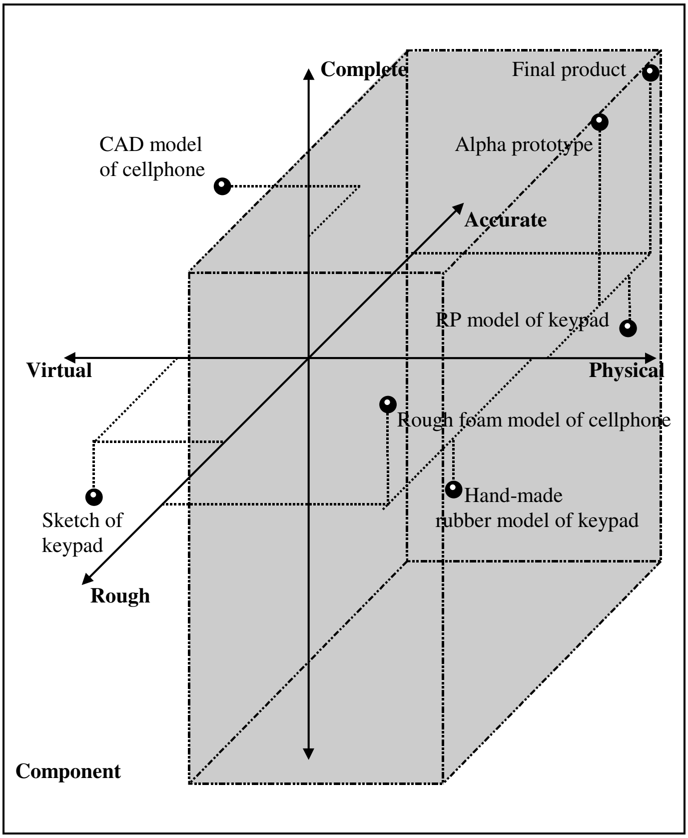

Figure 1.2: Types of prototypes described along the three aspects of implementation, form and approximation

1.1.3 Roles of the Prototypes

The roles that prototypes play in the product development process are several. They include the following:

(1) Experimentation and learning
(2) Testing and proofing
(3) Communication and interaction
(4) Synthesis and integration
(5) Scheduling and markers

To the product development team, prototypes can be used to help the thinking, planning, experimenting and learning processes whilst designing the product. Questions and doubts regarding certain issues of the design can be addressed by building and studying the prototype. For example, in designing the appropriate elbow-support of an office chair, several physical prototypes of such elbow supports can be built to learn about the "feel" of the elbow support when performing typical tasks on the office chair.

Prototypes can also be used for testing and proofing of ideas and concepts relating to the development of the product. For example, in the early design of folding reading glasses for the elderly, concepts and ideas of folding mechanism can be tested by building rough physical prototypes to test and prove these ideas to see if they work as intended.

The prototype also serves the purpose of communicating information and demonstrating ideas, not just within the product development team, but also to management and client (whether in-house or external). Nothing is clearer for explanation or communication of an idea than a physical prototype where the intended audience can have the full experience of the visual and tactile feel of the product. A three-dimensional representation is often more superior than that of a two-dimensional sketch of the product. For example, a physical prototype of a cellular phone can be presented to carefully selected customers. Customers can handle and experiment with the phone and give feedback to the development team on the features of and interactions with the phone, thus providing valuable information for the team to improve its design.

A prototype can also be used to synthesize the entire product concept by bringing the various components and sub-assemblies together to ensure that they will work together. This will greatly help in the integration of the product and surface any problems that are related to putting the product together. An example is a complete or comprehensive functional prototype of personal digital assistant (PDA). When putting the prototype together, all aspects of the design, including manufacturing and assembly issues will have to be addressed, thus enabling the different functional members of the product development team to understand the various problems associated with putting the product together.

Prototyping also serves to help in the scheduling of the product development process and is usually used as markers for the end or start of the various phases of the development effort. Each prototype usually marks a completion of a particular development phase, and with proper planning, the development schedule can be enforced. Typically in many companies, the continuation of a development project often hinges on the success of the prototypes to provide impetus to management to forge ahead with it.

It should be noted that in many companies, prototypes do not necessary serve all these roles concurrently, but they are certainly a necessity in any product development project.

The prototypes created with Rapid Prototyping technologies will serve most if not all of these roles. Being accurate physical prototypes that can be built with speed, many of these roles can be accomplished quickly and effectively, and together with other productivity tools, e.g. CAD, repeatedly with precision.

1.2 HISTORICAL DEVELOPMENT

The development of Rapid Prototyping is closely tied in with the development of applications of computers in the industry. The declining cost of computers, especially of personal and mini computers, has changed the way a factory works. The increase in the use of computers has spurred the advancement in many computer-related areas including Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer Numerical Control (CNC) machine tools. In particular, the emergence of RP systems could not have been possible without the existence of CAD. However, from careful examinations of the numerous RP systems in existence today, it can be easily deduced that other than CAD, many other technologies and advancements in other fields such as manufacturing systems and materials have also been crucial in the development of RP systems. Table 1.1 traces the historical development of relevant technologies related to RP from the estimated date of inception.

Table 1.1: Historical development of Rapid Prototyping and related technologies

Year of Inception	Technology
1770	Mechanization [4]
1946	First Computer
1952	First Numerical Control (NC) Machine Tool
1960	First commercial Laser [5]
1961	First commercial Robot
1963	First Interactive Graphics System (early version of Computer-Aided Design) [6]
1988	First commercial Rapid Prototyping System

1.2.1 Three Phases of Development Leading to Rapid Prototyping

Prototyping or model making in the traditional sense is an age-old practice. The intention of having a *physical* prototype is to realize the conceptualization of a design. Thus, a prototype is usually required before the start of the full production of the product. The fabrication of prototypes is experimented in many forms — material removal, castings, moulds, joining with adhesives etc. and with many material types — aluminium, zinc, urethanes, wood, etc.

Prototyping processes have gone through three phases of development, the last two of which have emerged only in the last 20 years [7]. Like the modeling process in computer graphics [8], the prototyping of physical models is growing through its third phase. Parallels between the computer modeling process and prototyping process can be drawn as seen in Table 1.2. The three phases are described as follows.

1.2.2 First Phase: Manual Prototyping

Prototyping had began as early as humans began to develop tools to help them live. However, prototyping as applied to products in what is

Table 1.2: Parallels between geometric modeling and prototyping

Geometric Modeling	Prototyping

❶ **First Phase: 2D Wireframe**
• Started in mid-1960s
• Few straight lines on display may be:
  • circuit path on a PCB
  • plan view of a mechanical component
• "Natural" drafting technique
	❶ **First Phase: Manual Prototyping**
	• Traditional practice for many centuries
	• Prototyping as a skilled crafts is:
	  • traditional and manual
	  • based on material of prototype
	• "Natural" prototyping technique

❷ **Second Phase: 3D Curve and Surface Modeling** • Mid-1970s • Increasing complexity • Representing more information about precise shape, size and surface contour of parts	❷ **Second Phase: Soft or Virtual Prototyping** • Mid-1970s • Increasing complexity • Virtual prototype can be stressed, simulated and tested, with exact mechanical and other properties
❸ **Third Phase: Solid Modeling** • Early 1980s • Edges, surfaces and holes are knitted together to form a cohesive whole • Computer can determine the inside of an object from the outside. Perhaps, more importantly, it can trace across the object and readily find all intersecting surfaces and edges • No longer ambiguous but exact	❸ **Third Phase: Rapid Prototyping** • Mid-1980s • Benefit of a hard prototype made in a very short turnaround time is its main strong point (relies on CAD modeling) • Hard prototype can also be used for limited testing • Prototype can also assist in the manufacturing of the products

considered to be the first phase of prototype development began several centuries ago. In this early phase, prototypes typically are not very sophisticated and fabrication of prototypes takes on average about four weeks, depending on the level of complexity and representativeness [9]. The techniques used in making these prototypes tend to be craft-based and are usually extremely labor intensive.

1.2.3 Second Phase: Soft or Virtual Prototyping

As application of CAD/CAE/CAM become more widespread, the early 1980s saw the evolution of the second phase of prototyping — *Soft or Virtual Prototyping*. Virtual prototyping takes on a new meaning as more computer tools become available — computer models can now be stressed, tested, analyzed and modified as if they were physical prototypes. For example, analysis of stress and strain can be accurately predicted on the product because of the ability to specify exact material attributes and properties. With such tools on the computer, several iterations of designs can be easily carried out by changing the parameters of the computer models.

Also, products and as such prototypes tend to become relatively more complex — about twice the complexity as before [9]. Correspondingly, the time required to make the physical model tends to increase tremendously to about that of 16 weeks as building of physical prototypes is still dependent on craft-based methods though introduction of better precision machines like CNC machines helps.

Even with the advent of Rapid Prototyping in the third phase, there is still strong support for virtual prototyping. Lee [10] argues that there are still unavoidable limitations with rapid prototyping. These include material limitations (either because of expense or through the use of materials dissimilar to that of the intended part), the inability to perform endless what-if scenarios and the likelihood that little or no reliable data can be gathered from the rapid prototype to perform finite element analysis (FEA). Specifically in the application of kinematic/dynamic analysis, he described a program which can assign physical properties of many different materials, such as steel, ice, plastic, clay or any custom material imaginable and perform kinematics and motion analysis as if a working prototype existed. Despite such strengths of virtual prototyping, there is one inherent weakness that such soft prototypes cannot be tested for phenomena that is not anticipated or accounted for in the computer program. As such there is no guarantee that the virtual prototype is really problem free.

1.2.4 Third Phase: Rapid Prototyping

Rapid Prototyping of physical parts, or otherwise known as solid freeform fabrication or desktop manufacturing or layer manufacturing technology, represents the third phase in the evolution of prototyping. The invention of this series of rapid prototyping methodologies is described as a "watershed event" [11] because of the tremendous time savings, especially for complicated models. Though the parts (individual components) are relatively three times as complex as parts made in 1970s, the time required to make such a part now averages only three weeks [9]. Since 1988, more than twenty different rapid prototyping techniques have emerged.

1.3 FUNDAMENTALS OF RAPID PROTOTYPING

Common to all the different techniques of RP is the basic approach they adopt, which can be described as follows:

(1) A model or component is modeled on a Computer-Aided Design/ Computer-Aided Manufacturing (CAD/CAM) system. The model which represents the physical part to be built must be represented as closed surfaces which unambiguously define an enclosed volume. This means that the data must specify the inside, outside and boundary of the model. This requirement will become redundant if the modeling technique used is solid modeling. This is by virtue of the technique used, as a valid solid model will automatically be an enclosed volume. This requirement ensures that all horizontal cross sections that are essential to RP are closed curves to create the solid object.

(2) The solid or surface model to be built is next converted into a format dubbed the "STL" (STereoLithography) file format which originates from 3D Systems. The STL file format approximates the surfaces of the model by polygons. Highly curved surfaces must employ many polygons, which means that STL files for curved parts can be very large. However, there are some rapid prototyping systems which also accept IGES (Initial Graphics Exchange Specifications) data, provided it is of the correct "flavor".

(3) A computer program analyzes a STL file that defines the model to be fabricated and "slices" the model into cross sections. The cross sections are systematically recreated through the solidification of either liquids or powders and then combined to form a 3D model. Another possibility is that the cross sections are already thin, solid laminations and these thin laminations are glued together with adhesives to form a 3D model. Other similar methods may also be employed to build the model.

Fundamentally, the development of RP can be seen in four primary areas. The Rapid Prototyping Wheel in Figure 1.3 depicts these four key aspects of Rapid Prototyping. They are: Input, Method, Material and Applications.

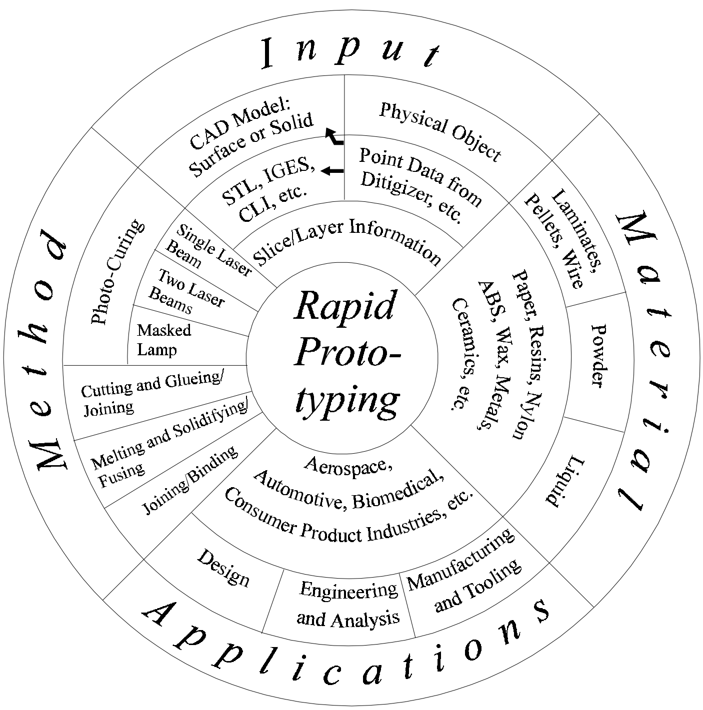

Figure 1.3: The Rapid Prototyping Wheel depicting the four major aspects of RP

1.3.1 Input

Input refers to the electronic information required to describe the physical object with 3D data. There are two possible starting points — a computer model or a physical model. The computer model created by a CAD system can be either a surface model or a solid model. On the other hand, 3D data from the physical model is not at all straightforward. It requires data acquisition through a method known as reverse engineering. In reverse engineering, a wide range of equipment can be used, such as CMM (coordinate measuring machine) or a laser digitizer, to capture data points of the physical model and "reconstruct" it in a CAD system.

1.3.2 Method

While they are currently more than 20 vendors for RP systems, the method employed by each vendor can be generally classified into the following categories: photo-curing, cutting and glueing/joining, melting and solidifying/fusing and joining/binding. Photo-curing can be further divided into categories of single laser beam, double laser beams and masked lamp.

1.3.3 Material

The initial state of material can come in either solid, liquid or powder state. In solid state, it can come in various forms such as pellets, wire or laminates. The current range materials include paper, nylon, wax, resins, metals and ceramics.

1.3.4 Applications

Most of the RP parts are finished or touched up before they are used for their intended applications. Applications can be grouped into (1) Design (2) Engineering, Analysis, and Planning and (3) Tooling and Manufacturing. A wide range of industries can benefit from RP and these include, but are not limited to, aerospace, automotive, biomedical, consumer, electrical and electronics products.

1.4 ADVANTAGES OF RAPID PROTOTYPING

Today's automated, toolless, patternless RP systems can directly produce functional parts in small production quantities. Parts produced in this way usually have an accuracy and surface finish inferior to those made by machining. However, some advanced systems are able to produce near tooling quality parts that are close to or are the final shape. The parts produced, with appropriate post processing, will have material qualities and properties close to the final product. More fundamentally, the time to produce any part — once the design data are available — will be fast, and can be in a matter of hours.

The benefits of RP systems are immense and can be categorized into direct and indirect benefits.

1.4.1 Direct Benefits

The benefits to the company using RP systems are many. One would be the ability to experiment with physical objects of any complexity in a relatively short period of time. It is observed that over the last 25 years, products realized to the market place have increased in complexity in shape and form [9]. For instance, compare the aesthetically beautiful car body of today with that of the 1970s. On a relative complexity scale of 1 to 3 as seen in Figure 1.4, it is noted that from a base of 1 in 1970, this relative complexity index has increased to about 2 in 1980 and close to 3 in the 1990s. More interestingly and ironically, the relative project completion times have not been drastically increased. Initially, from a base of about 4 weeks' project completion time in 1970, it increased to 16 weeks in 1980. However, with the use of CAD/CAM and CNC technologies, project completion time reduces to 8 weeks. Eventually, RP systems allowed the project manager to further cut the completion time to 3 weeks in 1995.

To the individual in the company, the benefits can be varied and have different impacts. It depends on the role in which they play in the

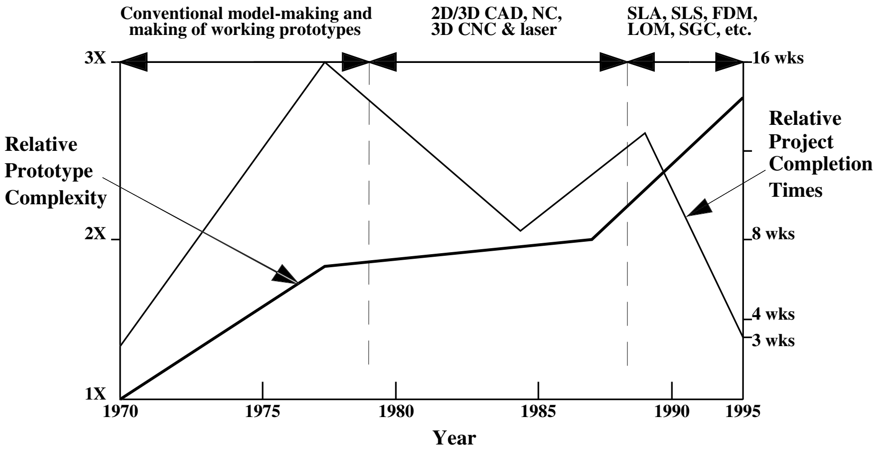

Figure 1.4: Project time and product complexity in 25 years' time frame

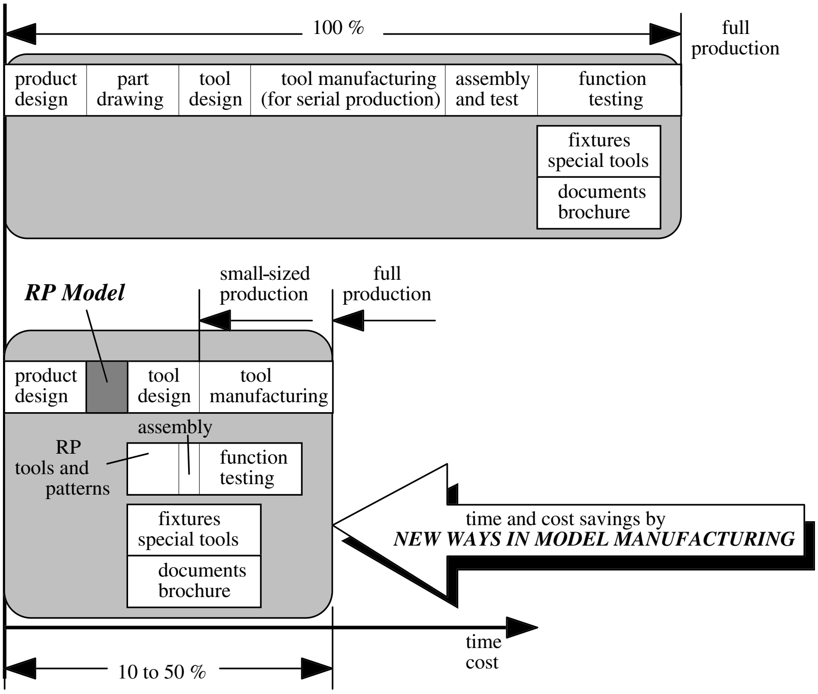

Figure 1.5: Results of the integration of RP technologies

company. The full production of any product encompasses a wide spectrum of activities. Kochan and Chua [12] describe the impact of RP technologies on the entire spectrum of product development and process realization. In Figure 1.5, the activities required for full production in a conventional model are depicted at the top. At the bottom of Figure 1.5 is the RP model. Depending on the size of production, savings on time and cost could range from 50% up to 90%!

1.4.1.1 *Benefits to Product Designers*

The product designers can increase part complexity with little significant effects on lead time and cost. More organic, sculptured shapes for functional or aesthetic reasons can be accommodated. They can optimize part design to meet customer requirements, with little restrictions by manufacturing. In addition, they can reduce parts count by combining features in single-piece parts that are previously made from several because of poor tool accessibility or the need to minimize machining and waste. With fewer parts, time spent on tolerance analysis, selecting fasteners, detailing screw holes and assembly drawings is greatly reduced.

There will also be fewer constraints in the form of parts design without regard to draft angles, parting lines or other such constraints. Parts which cannot easily be set up for machining, or have accurate, large thin walls, or do not use stock shapes to minimize machining and waste can now be designed. They can minimize material and optimize strength/weight ratios without regard to the cost of machining. Finally, they can minimize time-consuming discussions and evaluations of manufacturing possibilities.

1.4.1.2 *Benefits to the Tooling and Manufacturing Engineer*

The main savings are in costs. The manufacturing engineer can minimize design, manufacturing and verification of tooling. He can realize profits earlier on new products, since fixed costs are lower. He can also reduce parts count and, therefore, assembly, purchasing and inventory expenses.

The manufacturer can reduce the labor content of manufacturing, since part-specific setting up and programming are eliminated, machining/casting labor is reduced, and inspection and assembly are also consequently reduced as well. Reducing material waste, waste disposal costs, material transportation costs, inventory cost for raw stock and finished parts (making only as many as required, therefore, reducing storage requirements) can contribute to low overheads. Less inventory is scrapped because of design changes or disappointing sales.

In addition, the manufacturer can simplify purchasing since unit price is almost independent of quantity, therefore, only as many as are needed for the short-term need be ordered. Quotations vary little among supplies, since fabrication is automatic and standardized. One can purchase one general purpose machine rather than many special purpose machines and therefore, reduce capital equipment and maintenance expenses, need fewer specialized operators and less training. A smaller production facility will also result in less effort in scheduling production. Furthermore, one can reduce the inspection reject rate since the number of tight tolerances required when parts must mate can be reduced. One can avoid design misinterpretations (instead, "what you design is what you get"), quickly change design dimensions to deal with tighter tolerances and achieve higher part repeatability, since tool wear is eliminated. Lastly, one can reduce spare parts inventories (produce spare on demand, even for obsolete products).

1.4.2 Indirect Benefits

Outside the design and production departments, indirect benefits can also be derived. Marketing as well as the customers will also benefit from the utilization of RP technologies.

1.4.2.1 *Benefits to Marketing*

To the market, it presents new capabilities and opportunities. It can greatly reduce time-to-market, resulting in (1) reduced risk as there is no need to project customer needs and market dynamics several years into the future, (2) products which fit customer needs much more closely, (3) products offering the price/performance of the latest technology, (4) new products being test-marketed economically.

Marketing can also change production capacity according to market demand, possibly in real time and with little impact on manufacturing. One can increase the diversity of product offerings and pursue market niches currently too small to justify due to tooling cost (including custom and semi-custom production). One can easily expand distribution and quickly enter foreign markets.

1.4.2.2 *Benefits to the Consumer*

The consumer can buy products which meet more closely individual needs and wants. Firstly, there is a much wider diversity of offerings to choose from. Secondly, one can buy (and even contribute to the design of) affordable products built-to-order. Furthermore, the consumer can buy products at lower prices, since the manufacturers' savings will ultimately be passed on.

1.5 COMMONLY USED TERMS

The number of terms used by the engineering communities around the world is alarmingly large. Perhaps, this is due to the newness of the technology. It certainly does not help as already there are so many buzz words used today. Worldwide, the most commonly used term is Rapid Prototyping. The term is apt as the key benefit of RP is its *rapid* creation of a physical model. However, prototyping is slowly growing to include other areas. Soon, *Rapid Prototyping, Tooling and Manufacturing* (RPTM) should be used to include the utilization of the prototype as a master pattern for tooling and manufacturing.

Some of the less commonly used terms include *Direct CAD Manufacturing*, *Desktop Manufacturing* and *Instant Manufacturing*. The rationale behind these terms are also speed and ease, though not exactly direct or instant! *CAD Oriented Manufacturing* is another term and provides an insight into the issue of orientation, often a key factor influencing the output of a prototype made by RP methods like SLA.

Another group of terms emphasizes on the unique characteristic of RP — layer by layer addition as opposed to traditional manufacturing methods such as machining which is material removal from a block. This group includes *Layer Manufacturing*, *Material Deposit Manufacturing*, *Material Addition Manufacturing* and *Material Incress Manufacturing*.

There is yet another group which chooses to focus on the words "solid" and "freeform" — *Solid Freeform Manufacturing* and *Solid Freeform Fabrication*. *Solid* is used because while the initial state may be liquid, powder, individual pellets or laminates, the end result is a solid, 3D object, while *freeform* stresses on the ability of RP to build complex shapes with little constraint on its form.

1.6 CLASSIFICATION OF RAPID PROTOTYPING SYSTEMS

While there are many ways in which one can classify the numerous RP systems in the market, one of the better ways is to classify RP systems broadly by the initial form of its material, i.e. the material that the prototype or part is built with. In this manner, all RP systems can be easily categorized into (1) liquid-based (2) solid-based and (3) powder-based.

1.6.1 Liquid-Based

Liquid-based RP systems have the initial form of its material in liquid state. Through a process commonly known as curing, the liquid is converted into the solid state. The following RP systems fall into this category:

(1) 3D Systems' Stereolithography Apparatus (SLA)
(2) Cubital's Solid Ground Curing (SGC)
(3) Sony's Solid Creation System (SCS)
(4) CMET's Solid Object Ultraviolet-Laser Printer (SOUP)
(5) Autostrade's E-Darts
(6) Teijin Seiki's Soliform System

(7) Meiko's Rapid Prototyping System for the Jewelry Industry
(8) Denken's SLP
(9) Mitsui's COLAMM
(10) Fockele & Schwarze's LMS
(11) Light Sculpting
(12) Aaroflex
(13) Rapid Freeze
(14) Two Laser Beams
(15) Microfabrication

As is illustrated in the RP Wheel in Figure 1.3, three methods are possible under the "*Photo-curing*" method. The *single laser beam* method is most widely used and include all the above RP systems with the exception of (2), (11), (13) and (14). Cubital (2) and Light Sculpting (11) use the *masked lamp* method, while the *two laser beam* method is still not commercialized. Rapid Freeze (13) involves the freezing of water droplets and deposit in a manner much like FDM to create the prototype. Each of these RP systems will be described in more detail in Chapter 3.

1.6.2 Solid-Based

Except for powder, solid-based RP systems are meant to encompass all forms of material in the solid state. In this context, the solid form can include the shape in the form of a wire, a roll, laminates and pellets. The following RP systems fall into this definition:

(1) Cubic Technologies' Laminated Object Manufacturing (LOM)
(2) Stratasys' Fused Deposition Modeling (FDM)
(3) Kira Corporation's Paper Lamination Technology (PLT)
(4) 3D Systems' Multi-Jet Modeling System (MJM)
(5) Solidscape's ModelMaker and PatternMaster
(6) Beijing Yinhua's Slicing Solid Manufacturing (SSM), Melted Extrusion Modeling (MEM) and Multi-Functional RPM Systems (M-RPM)

(7) CAM-LEM's CL 100
(8) Ennex Corporation's Offset Fabbers

Referring to the RP Wheel in Figure 1.3, two methods are possible for solid-based RP systems. RP systems (1), (3), (4) and (9) belong to the *Cutting and Glueing/Joining* method, while the *Melting and Solidifying/Fusing* method used RP systems (2), (5), (6), (7) and (8). The various RP systems will be described in more detail in Chapter 4.

1.6.3 Powder-Based

In a strict sense, powder is by-and-large in the solid state. However, it is intentionally created as a category outside the solid-based RP systems to mean powder in grain-like form. The following RP systems fall into this definition:

(1) 3D Systems's Selective Laser Sintering (SLS)
(2) EOS's EOSINT Systems
(3) Z Corporation's Three-Dimensional Printing (3DP)
(4) Optomec's Laser Engineered Net Shaping (LENS)
(5) Soligen's Direct Shell Production Casting (DSPC)
(6) Fraunhofer's Multiphase Jet Solidification (MJS)
(7) Acram's Electron Beam Melting (EBM)
(8) Aeromet Corporation's Lasform Technology
(9) Precision Optical Manufacturing's Direct Metal Deposition (DMD™)
(10) Generis' RP Systems (GS)
(11) Therics Inc.'s Theriform Technology
(12) Extrude Hone's Prometal™ 3D Printing Process

All the above RP systems employ the *Joining/Binding* method. The method of joining/binding differs for the above systems in that some employ a laser while others use a binder/glue to achieve the joining effect. Similarly, the above RP systems will be described in more detail in Chapter 5.

REFERENCES

[1] Wheelwright, S.C. and Clark, K.B., *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality*, The Free Press, New York, 1992.

[2] Ulrich, K.T. and Eppinger, S.D., *Product Design and Development*, 2nd edition, McGraw Hill, Boston, 2000.

[3] Hornby, A.S. and Wehmeier, S. (Editor), *Oxford Advanced Learner's Dictionary of Current English*, 6th edition, Oxford University Press, Oxford, 2000.

[4] Koren, Y., *Computer Control of Manufacturing Systems*, McGraw Hill, Singapore, 1983.

[5] Hecht, J., *The Laser Guidebook*, 2nd edition, McGraw Hill, New York, 1992.

[6] Taraman, K., *CAD/CAM: Meeting Today's Productivity Challenge*, Computer and Automated Systems Association of SME, Michigan, 1982.

[7] Chua, C.K., "Three-dimensional rapid prototyping technologies and key development areas," *Computing and Control Engineering Journal* **5**(4) (1994): 200–206.

[8] Chua, C.K., "Solid modeling — A state-of-the-art report," *Manufacturing Equipment News* (September 1987): 33–34.

[9] Metelnick, J., "How today's model/prototype shop helps designers use rapid prototyping to full advantage," *Society of Manufacturing Engineers Technical Paper* (1991): MS91-475.

[10] Lee, G., "Virtual prototyping on personal computers," *Mechanical Engineering* **117**(7) (1995): 70–73.

[11] Kochan, D., "Solid freeform manufacturing — Possibilities and restrictions," *Computers in Industry* **20** (1992): 133–140.

[12] Kochan, D. and Chua, C.K., "State-of-the-art and future trends in advanced rapid prototyping and manufacturing," *International Journal of Information Technology* **1**(2) (1995): 173–184.

PROBLEMS

1. How would you define prototype in the context of modern product development?
2. What are the three aspects of interest in describing a prototype? Describe them clearly.
3. What are the main roles and functions for prototypes? How do you think rapid prototyping satisfies these roles?
4. Describe the historical development of Rapid Prototyping and related technologies.
5. What are the three phases of prototyping? Contrasting these with those of geometric modeling, what similarities can be drawn?
6. Despite the increase in relative complexity of the shape and form of products, project times has been kept relatively shorter. Why?
7. What are the fundamentals of Rapid Prototyping?
8. What is the *Rapid Prototyping Wheel*? Describe its four primary aspects. Is the *Wheel* a static representation of what is Rapid Prototyping today? Why?
9. Describe the advantages of Rapid Prototyping in terms of its beneficiaries such as the product designers, tool designer, manufacturing engineer, marketeers and consumers?
10. Many terms have been used to mean Rapid Prototyping. Discuss three such terms and explain why they have been used in place of Rapid Prototyping.
11. Name three Rapid Prototyping Systems that are liquid-based.
12. How can the liquid form be converted to the solid form as in these liquid-based Rapid Prototyping Systems?
13. In what form of material can Rapid Prototyping Systems be classified as solid-based? Name three such systems.
14. What is the method used in powder-based Rapid Prototyping Systems?