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
1946	First Computer
1952	First Numerical Control (NC) Machine Tool
1960	First commercial Laser
1961	First commercial Robot
1963	First Interactive Graphics System
1988	First commercial Rapid Prototyping System

First Phase: Manual Prototyping

Prototyping had begun as early as humans began to develop tools to help them live. However, prototyping as applied to products in what is 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. The techniques used in making these prototypes tend to be craft-based and are usually extremely labour intensive.

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. 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 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.

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.

FUNDAMENTALS OF RAPID PROTOTYPING

a) A model or component is modelled 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 mean that the data must specify the inside, outside and boundary of the model. This requirement will become redundant if the modelling technique used is solid modelling. This is by virtue of the technique used, as a valid solid model will automatically be enclosed volume. This requirement ensures that all horizontal cross sections that are essential to RP are enclosed curves to create the solid object.

b) 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 ten model by polygons. Highly curved surfaces must employ many polygons, which means that STL files for curved parts can be very large. However, these are some rapid prototyping systems which also accept IGES (Initial Graphics Exchange Specifications) data, provided it is of the correct "flavour".

c) 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 depicts these four key aspects of Rapid Prototyping. They are: Input, Method, Material and Applications.

INPUT

Input refers to the electronic information required to describe the physical object with 3D data. These 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 straight forward. 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.

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 gluing/joining, melting and solidifying/fusing and joining/binding. Photo-curing can be further divided into categories of single beam, double laser beams and masked lamp.

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.

APPLICATION:

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.

Applications of Rapid Prototyping

RAPID TOOLING

- Patterns for Sand Casting
- Patterns for Investment Casting
- Pattern for Injection mouldings

RAPID MANUFACTURING

- Short productions run
- Custom made parts
- On-Demand Manufacturing
- Manufacturing of very complex shapes

AEROSPACE & MARINE

- Wind tunnel models
- Functional prototypes
- Boeing’s On-Demand-Manufacturing

AUTOMOTIVE RP SERVICES

- Needed from concept to production level
- Reduced time to market

- Functional testing
- Dies & Moulds

BIOMEDICAL APPLICATIONS - I

- Prosthetic parts
- Use of data from MRI and CT scan to build 3D parts
- 3D visualization for education and training

BIOMEDICAL APPLICATIONS - II

- Customized surgical implants
- Mechanical bone replicas
- Anthropology
- Forensics

ARCHITECTURE

- 3D visualization of design space
- Iterations of shape
- Sectioned models

FASHION & JEWELRY

- Shoe Design
- Jewellery
- Pattern for lost wax
- Other castings

Classification of Rapid Prototyping Systems

LIQUID-BASED

- Stereo lithography (SLA)
- Solid Ground Curing (SGA)

SOLID-BASED

- Fused deposition modeling (FDM)
- Laminated object manufacturing (LOM)

POWDER-BASED

- 3D Printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)

Classification of Rapid Prototyping Systems

The professional literature in RP contains different ways of classifying RP processes. However, one representation based on German standard of production processes classifies RP processes according to state of aggregation of their original material and is given in figure

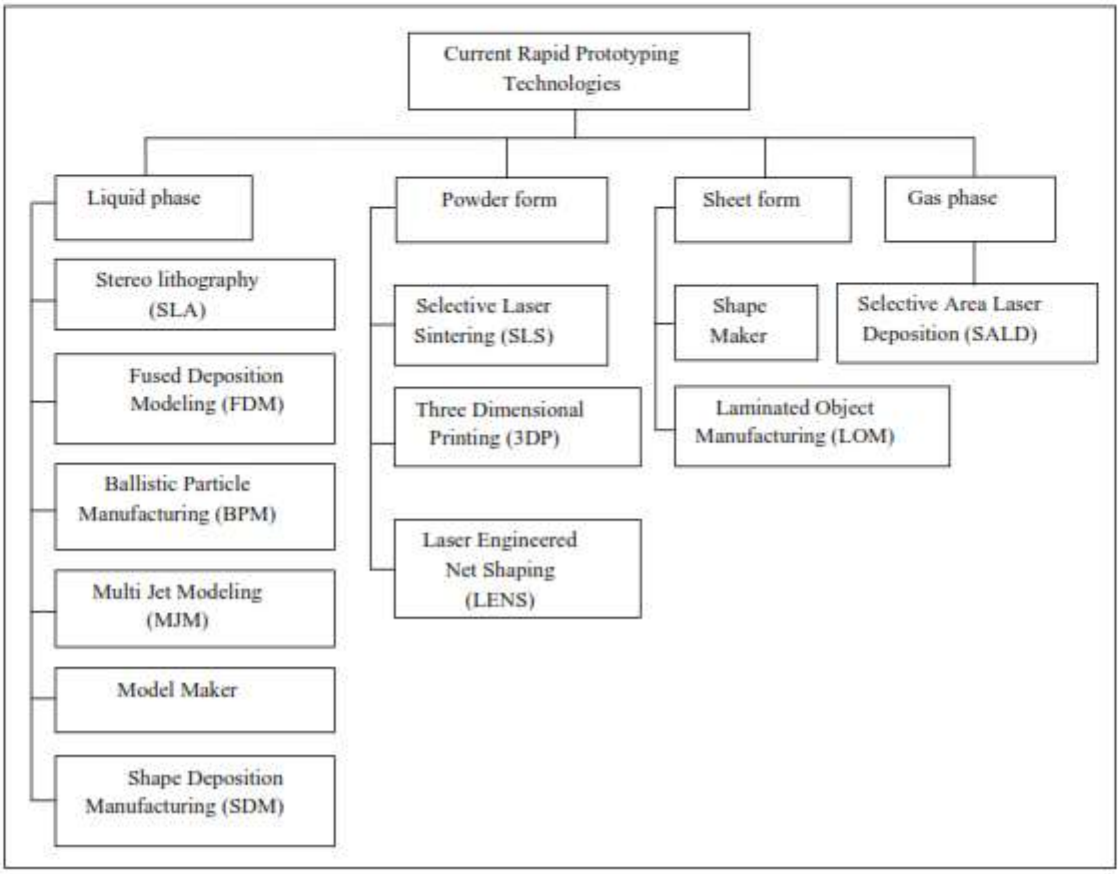

Fig 1.1: Classification of Rapid Prototyping Systems

a) Liquid-based
b) Solid-based
c) Powder-based

Liquid-Based

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

i) 3D systems' Stereolithography apparatus (SLA)
ii) Cubical's Solid Ground Curing (SGC)
iii) Sony's Solid reaction Systems (SCS)
iv) CMET's Solid Object Ultraviolet-Laser Printer (SOUP)
v) Autostrade's E-Darts
vi) Teijin Seiki's Soliform Systems
vii) Meiko's Rapid Prototyping systems for the jewellery Industry
viii) Denken's SLP
ix) Mitsui's COLAMN
x) Fockele & Schwarze's LMS
xi) Light Sculpting
xii) Aaroflex
xiii) Rapid Freeze
xiv) Two Laser Beams
xv) Microfabrication

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:

i) Cubic Technologies' Laminated Object Manufacturing (LOM)
ii) Stratasys's Fused Deposition Modelling (FDM)
iii) Kira Corporation's Paper Laminated Technology (PLT)
iv) 3D Systems's Multi-Jet Modelling Systems (MJM)
v) Solidscape's Modelmaker and PatternMaster
vi) Beijing Yinhua's Slicing Solid Manufacturing (SSM), Melted Extrusion Modelling (MEM) and Multi-Functional RPM Systems (M-RPM)
vii) CAM-LEM's CL 100
viii) Ennex Corporation's Offset Fabbers