Lecture Notes on

CAD-CIM

III B. Tech VI semester

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SYLLABUS

UNIT-I INTRODUCTION

Computers in industrial manufacturing , product cycle, CAD/CAM hardware, basic structure, CPU, memory types, input devices, display devices, hard copy devices, and storage devices, computer graphics, raster scan graphics coordinate system, database structure for graphics modeling, transformation of geometry, three dimensional transformations, mathematics of projections, clipping, hidden surface removal.

UNIT-II GEOMETRICAL MODELLING

Requirements, geometric models, geometric construction models, curve representation methods, surface representation methods, modeling facilities desired, drafting and modeling systems, basic geometric commands, layers, display control commands, editing, dimensioning and solid modeling.

UNIT-III GROUP TECHNOLGY COMPUTER AIDED PROCESS PLANNING

History of group technology, role of G.T in CAD/CAM integration, part families, classification and coding, DCLASS and MCLASS and OPTIZ coding systems, facility design using G.T, benefits of G.T, cellular manufacturing. Process planning, role of process planning in CAD/CAM integration, approaches to computer aided process planning, variant approach and generative approaches, CAPP and CMPP systems.

UNIT-IV COMPUTER AIDED PLANNING AND CONTROL, SHOP FLOOR CONTROL AND INTRODUCTION TO FMS

Production planning and control, cost planning and control, inventory management, material requirements planning (ERP), control, phases, factory data collection system, automatic identification methods, bar code technology, automated data collection system; FMS, components of FMS, types, FMS workstation, material handling and storage system, FMS layout, computer control systems, applications and benefits.

UNIT-V COMPUTER AIDED PLANNING AND CONTROL AND COMPUTER MONITORING

Production planning and control, cost planning and control, inventory management, material requirements planning (MRP), shop floor control, lean and agile manufacturing, types of production monitoring systems, structure model of manufacturing, process control and strategies, direct digital control.

Text Books:

1. A. Zimmers, P. Groover, ―CAD/ CAM‖, Prentice- Hall India, 2008.
2. Zeid, Ibrahim, ―CAD / CAM Theory and Practice‖, Tata McGraw-Hill, 1997.
3. Mikell. P.Groover ―Automation, Production Systems and Computer Integrated Manufacturing‖, Pearson Education 2001.
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1. P. Groover, Automation, ―Production Systems & Computer Integrated Manufacturing‖, Pearson Education.2nd Edition 1989.
2. Lalit Narayan, ―Computer Aided Design and Manufacturing‖, Prentice-Hall India.3rd Edition 2002.
3. Radhakrishnan, Subramanian, ―CAD / CAM / CIM‖, New Age.4th Edition 2016.
4. Jami J Shah, Martti Mantyla, ―Parametric and Feature-Based CAD/CAM: Concepts, Techniques, and Applications‖, John Wiley & Sons Inc, 1995.
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6. W. S. Seames,- Computer Numerical Control Concepts and Programming‖, 4th Edition 1999.

UNIT 1

INTRODUCTION

CAD/CAM

CAD/CAM is a term which means computer-aided design and computer- aided manufacturing. It is the technology concerned with the use of digital computers to perform certain functions in design and production. This technology is moving in the direction of greater integration of design and manufacturing, two activities which have traditionally been treated as distinct and separate functions in a production firm. Ultimately, CAD/CAM will provide the technology base for the computer-integrated factory of the future.

Computer-aided design (CAD) can be defined as the use of computer systems to assist in the creation, modification, analysis, or optimization of a design. The computer systems consist of the hardware and software to perform the specialized design functions required by the particular user firm. The CAD hardware typically includes the computer, one or more graphics display terminals, keyboards, and other peripheral equipment. The CAD software consists of the computer programs to implement computer graphics on the system plus application programs to facilitate the engineering functions of the user company. Examples of these application programs include stress-strain analysis of components, dynamic response of mechanisms, heat-transfer calculations, and numerical control part programming. The collection of application programs will vary from one user firm to the next because their product lines, manufacturing processes, and customer markets are different. These factors give rise to differences in CAD system requirements.

Computer-aided manufacturing (CAM) can be defined as the use of computer systems to plan, manage, and control the operations of a manufacturing plant through either direct or indirect computer interface with the plant's production resources. As indicated by the definition, the applications of computer-aided manufacturing fall into two broad categories:

1. **Computer monitoring and control.** These are the direct applications in which the computer is connected directly to the manufacturing process for the purpose of monitoring or controlling the process.

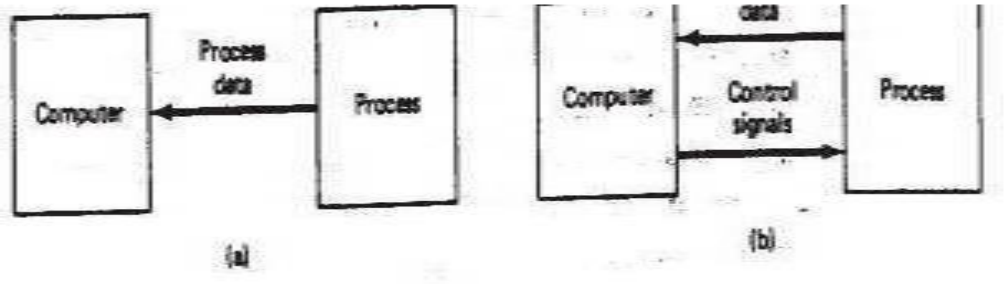
2. **Manufacturing support applications.** These are the indirect applications in which the computer is used in support of the production operations in the plant, but there is no direct interface between the computer and the manufacturing process.

The distinction between the two categories is fundamental to an understanding of computer-aided manufacturing. It seems appropriate to elaborate on our brief definitions of the two types.

Computer monitoring and control can be separated into monitoring applications and control applications. Computer process monitoring involves a direct computer interface with the manufacturing process for the purpose of observing the process and associated equipment and collecting data from the process. The computer is not used to control the operation directly. The control of the process remains in the hands of human operators, who may be guided by the information compiled by the computer.

Computer process control goes one step further than monitoring by not only observing the process but also controlling it based on the observations. The distinction between monitoring and control is displayed in Figure. With computer monitoring the flow of data between the process and the computer is in one direction only, from the process to the computer. In control, the computer interface allows for a two-way flow of data. Signals are transmitted from the process to the computer, just as in the case of computer monitoring. In addition, the computer issues command signals directly to the manufacturing process based on control algorithms contained in its software.

In addition to the applications involving a direct computer-process interface for the purpose of process monitoring and control, computer-aided manufacturing also includes indirect applications in which the computer serves a support role in the manufacturing operations of the plant. In these applications, the computer is not linked directly to the manufacturing process.



(a) computer monitoring, (b) computer control.

Instead, the computer is used "off-line" to provide plans, schedules, forecasts, instructions, and information by which the firm's production resources can be managed more effectively. The form of the relationship between the computer and the process is represented symbolically in Figure. Dashed lines are used to indicate that the communication and control link is an off-line connection, with human beings often required to consumate the interface. Some examples of CAM for manufacturing support that are discussed in subsequent chapters of this book include:

Numerical control part programming by computers. Control programs are prepared for automated machine tools.

Computer-automated process planning. The computer prepares a listing of the operation sequence required to process a particular product or component.

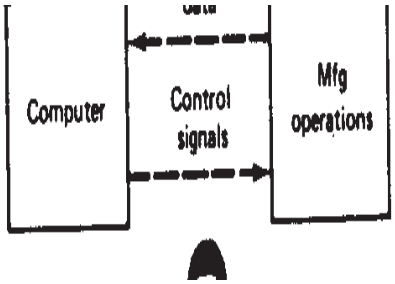
Computer-generate work standards. The computer determines the time standard for a particular production operation.

Production scheduling. The computer determines an appropriate schedule for meeting production requirements.

Material requirements planning. The computer is used to determine when to order raw materials and purchased components and how many should be ordered to achieve the production schedule.

Shop floor control. In this CAM application, data are collected from the factory to determine progress of the various production shop orders.

In all of these examples, human beings are presently required in the application either to provide input to the computer programs or to interpret the computer output and implement the required action.

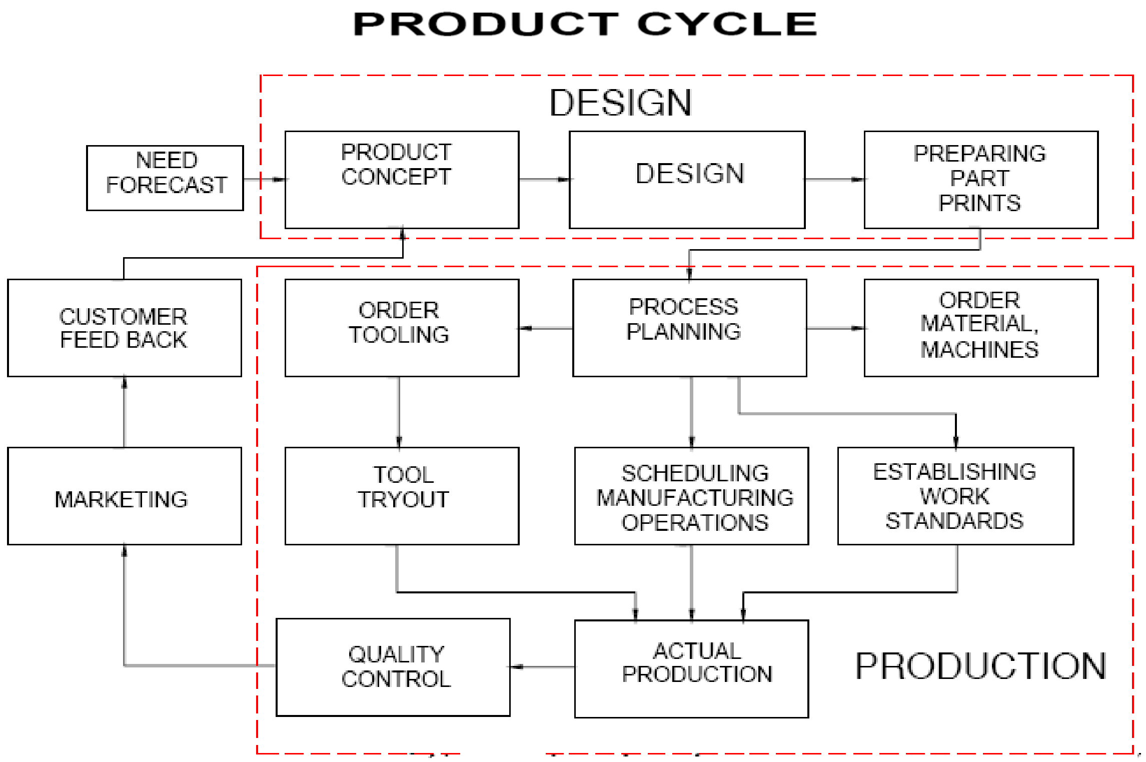


CAM for manufacturing support.

THE PRODUCT CYCLE AND CAD/CAM

For the reader to appreciate the scope of CAD/CAM in the operations of a manufacturing firm, it is appropriate to examine the various activities and functions that must be accomplished in the design and manufacture of a product. We will refer to these activities and functions as the product cycle.

A diagram showing the various steps in the product cycle is presented in Figure 1.1. The cycle is driven by customers and markets which demand the product. It is realistic to think of these as a large collection of diverse industrial and consumer markets rather than one monolithic market. Depending on the particular customer group, there will be differences in the way the product cycle is activated. In some cases, the design functions are performed by the customer and the product is manufactured by a different firm. In other cases, design and manufacturing is accomplished by the same firm. Whatever the case, the product cycle begins with a concept, an idea for a product. This concept is cultivated, refined, analyzed, improved, and translated into a plan for the product through the design engineering process. The plan is documented by drafting Ii set of engineering drawings showing how the product is made and providing a set of specifications indicating how the product should perform.



PRODUCT CYCLE IN CONVENTIONAL ENVIRONMENT

Except for engineering changes which typically follow the product throughout its life cycle, this completes the design activities in Figure. The next activities involve the manufacture of the product. A process plan is formulated which specifies the sequence of production operations required to make the product. New equipment and tools must sometimes be acquired to produce the new product. Scheduling provides a plan that commits the company to the manufacture of certain quantities of the product by certain dates. Once all of these plans are formulated, the product goes into production, followed by quality testing, and delivery to the customer.

Product cycle (design and manufacturing).

The impact of CAD/CAM is manifest in all of the different activities in the product cycle, as indicated in Figure. Computer-aided design and automated drafting are utilized in the conceptualization, design, and documentation of the product. Computers are used in process planning and scheduling to perform these functions more efficiently. Computers are used in production to monitor and control the manufacturing operations. In quality control, computers are used to perform inspections and performance tests on the product and its components.

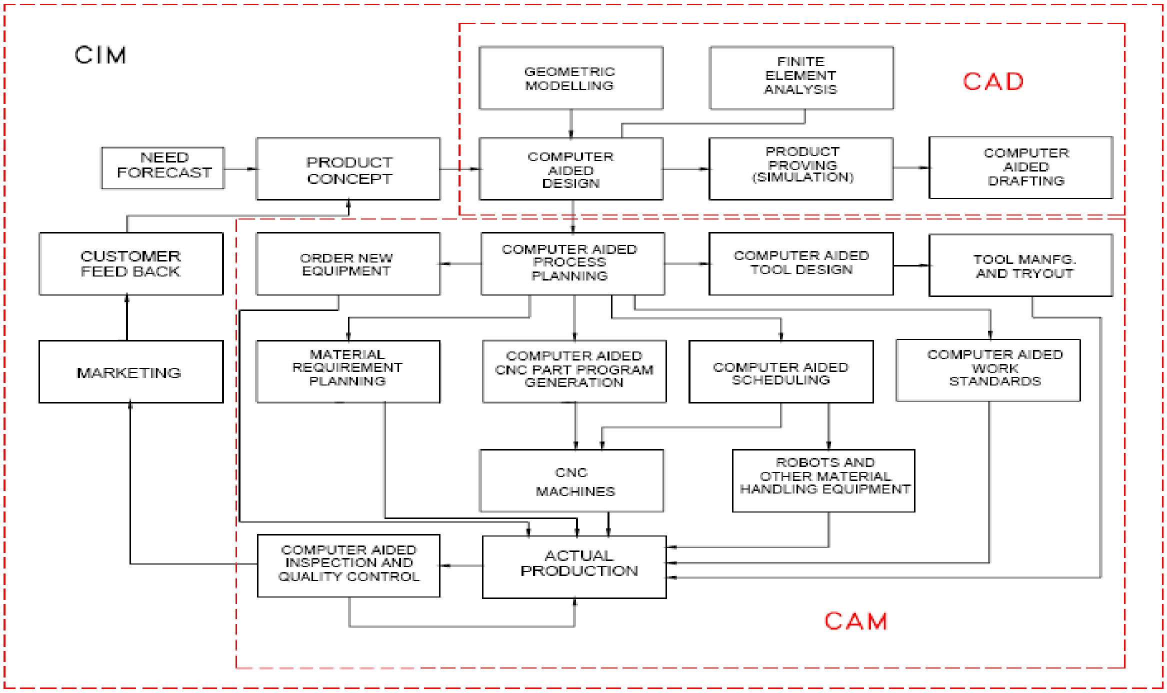


Fig 1.2: Product cycle in an computerised environment

As illustrated in Figure 1.2, CAD/CAM is overlaid on virtually all of the activities and functions of the product cycle. In the design and production operations of a modem manufacturing firm, the computer has become a pervasive, useful, and indispensable tool. It is strategically important and competitively imperative that manufacturing firms and the people who are employed by them understand CAD/CAM.

AUTOMATION AND CAD/CAM

Automation is defined as the technology concerned with the application of complex mechanical, electronic, and computer-based systems in the operation and control of production. It is the purpose of this section to establish the relationship between CAD/CAM and automation.

As indicated in previous Section, there are differences in the way the product cycle is implemented for different firms involved in production. Production activity can be divided into four main categories:

l. Continuous-flow processes
2. Mass production of discrete products
3. Batch production
4. Job shop production

The definitions of the four types are given in Table. The relationships among the four types in terms of product variety and production quantities can be conceptualized as shown in Figure. There is some overlapping of the categories as the figure indicates. Table provides a list of some of the notable achievements in automation technology for each of the four production types.

One fact that stands out from Table is the importance of computer technology in automation. Most of the automated production systems implemented today make use of computers. This connection between the digital computer and manufacturing automation may seem perfectly logical to the reader. However, this logical connection has not always existed. For one thing, automation technology

1.1: TABLE Four Types of Production

Category	Description
l. Continuous-flow processes	Continuous dedicated production of large amounts of bulk product. Examples include continuous chemical plants and oil refineries
2. Mass production of discrete products	Dedicated production of large quantities of one product (with perhaps limited model variations). Examples include automobiles, appliances, and engine blocks.
3. Batch production	Production of medium lot sizes of the same product or component. The lots may be produced once or repeated periodically. Examples include books, clothing, and certain industrial machinery.
4. Job shop production	Production of low quantities, often one of a kind, of specialized products. The products are often customized and technologically complex. Examples include prototypes, aircraft, machine tools, and other equipment

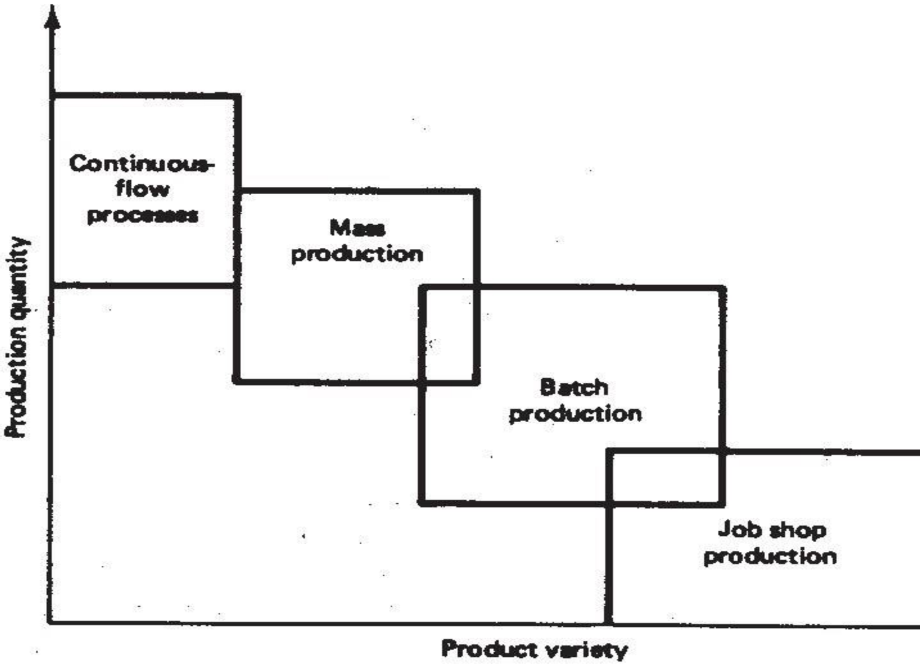


Fig: 1.3 Four production types related to quantity and product variation

TABLE Automation Achievements for the Four Types of Production

Category	Automation achievements
l. Continuous-flow processes	Flow process from beginning to end Sensor technology available to measure important process variables Use of sophisticated control and optimization strategies Fully computer-automated plants
2. Mass production of discrete products	Automated transfer machines Dial indexing machines Partially and fully automated assembly lines Industrial robots for spot welding, parts handling, machine loading, spray painting, etc.
	Automated materials handling systems Computer production monitoring
3. Batch production	Numerical control (NC), direct numerical control (DNC), computer numerical control (CNC) Adaptive control machining Robots for arc welding, parts handling, etc. Computer-integrated manufacturing systems
4. Job shop production	Numerical control, computer numerical control

FUNDAMENTALS OF CAD

INTRODUCTION

The computer has grown to become essential in the operations of business, government, the military, engineering, and research. It has also demonstrated itself, especially in recent years, to be a very powerful tool in design and manufacturing. In this and the following two chapters, we consider the application of computer technology to the design of a product. This secton provides an overview of computer-aided design.

The CAD system defined

As defined in previous section, computer-aided design involves any type of design activity which makes use of the computer to develop, analyze, or modify an engineering design. Modem CAD systems (also often called CAD/CAM systems) are based on interactive computer graphics (ICG).Interactive computer graphics denotes a user-oriented system in which the computer is employed to create, transform, and display data in the form of pictures or symbols. The user in the computer graphics design system is the designer, who communicates data and commands to the computer through any of several input devices. The computer communicates with the user via a cathode ray tube (CRT). The designer creates an image on the CRT screen by entering commands to call the desired software sub-routines stored in the computer. In most systems, the image is constructed out of basic geometric elements- points, lines, circles, and so on. It can be modified according to the commands of the designer-enlarged, reduced in size, moved to another location on the screen, rotated, and other transformations. Through these various manipulations, the required details of the image are formulated.

The typical ICG system is a combination of hardware and software. The hardware includes a central processing unit, one or more workstations (including the graphics display terminals), and peripheral devices such as printers. Plotters, and drafting equipment. Some of this hardware is shown in Figure. The software consists of the computer programs needed to implement graphics processing on the system. The software would also typically include additional specialized application programs to accomplish the particular engineering functions required by the user company.

It is important to note the fact that the ICG system is one component of a computer-aided design system. As illustrated in Figure, the other major component is the human designer. Interactive computer graphics is a tool used by the designer to solve a design problem. In effect, the ICG system magnifies the powers of the designer. This bas been referred to as the synergistic effect. The designer performs the portion of the design process that is most suitable to human intellectual skills (conceptualization, independent thinking); the computer performs the task: best suited to its capabilities (speed of calculations, visual display, storage of large data), and the resulting system exceeds the sum of its components.

There are several fundamental reasons for implementing a computer-aided design system.

l. To increase the productivity of the designer. This is accomplished by helping the designer to the product and its component subassemblies and parts; and by reducing the time required in synthesizing, analyzing, and documenting the design. This productivity improvement translates not only into lower design cost but also into shorter project completion times.

2. To improve the quality of design. A CAD system permits a more thorough engineering analysis and a larger number of design alternatives can be investigated. Design errors are also reduced through the greater accuracy provided by the system. These factors lead to a better design.
3. To improve communications. Use of a CAD system provides better engineering drawings, more standardization in the drawings, better documentation of the design, fewer drawing errors and greater legibility.
4. To create a database for manufacturing. In the process of creating the documentation for the product design (geometries and dimensions of the product and its components, material specifications for components, bill of materials, etc.), much of the required database to manufacture the product is also created.

THE DESIGN PROCESS

Before examining the several facets of computer-aided design, let us first consider the general design process. The process of designing something is characterized by Shigley as an iterative procedure, which consists of six identifiable steps or phases:-

l. Recognition of need
2. Definition of problem
3. Synthesis
4. Analysis and optimization
5. Evaluation
6. Presentation

Recognition of need involves the realization by someone that a problem exists for which some corrective action should be taken. This might be the identification of some defect in a current machine design by an engineer or the perception of a new product marketing opportunity by a salesperson. Definition of the problem involves a thorough specification of the item to be designed. This specification includes physical and functional characteristics, cost, quality, and operating performance.

Synthesis and analysis are closely related and highly interactive in the design process. A certain component or subsystem of the overall system is conceptualized by the designer, subjected to analysis, improved through this analysis procedure, and redesigned. The process is repeated until the design has been optimized within the constraints imposed on the designer. The components and subsystems are synthesized into the final overall system in a similar interactive manner.

Evaluation is concerned with measuring the design against the specifications established in the problem definition phase. This evaluation often requires the fabrication and testing of a prototype model to assess operating performance, quality, reliability, and other criteria. The final phase in the design process is the presentation of the design. This includes documentation of the design by means of drawings, material specifications, assembly lists, and so on. Essentially, the documentation requires that a design database be created. Figure illustrates the basic steps in the design process, indicating its iterative nature.

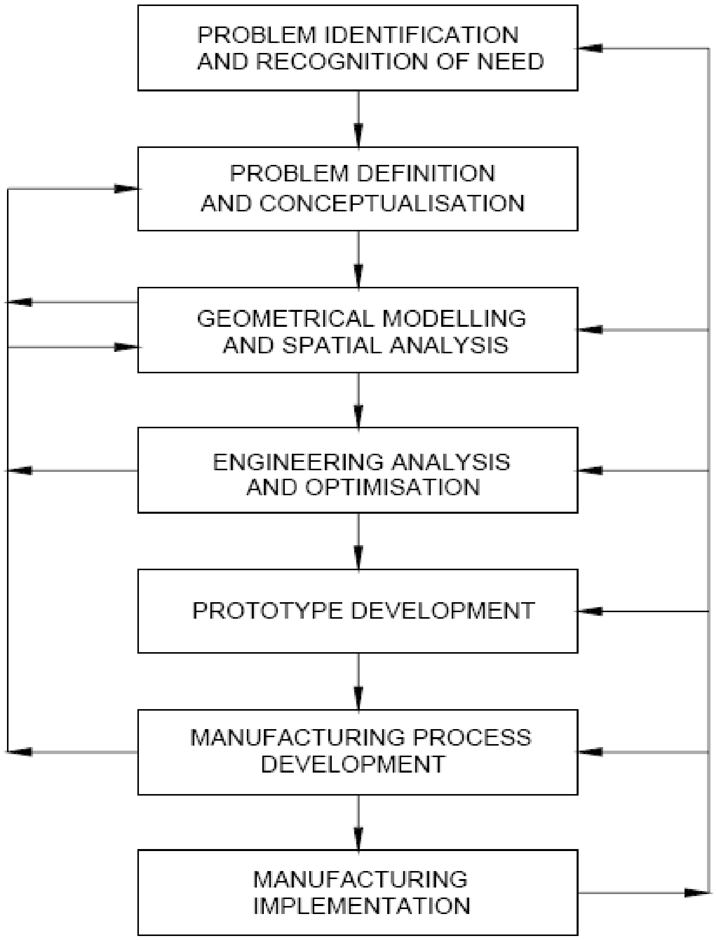


Fig 1.4: The general design process as defined by Shigley .

Engineering design has traditionally been accomplished on drawing boards, with the design being documented in the form of a detailed engineering drawing. Mechanical design includes the drawing of the complete product as well as its components and subassemblies, and the tools and fixtures required to manufacture the product. Electrical design is concerned with the preparation of circuit diagrams, specification of electronic components, and so on. Similar manual documentation is required in other engineering design fields (structural design, aircraft design, chemical engineering design, etc.). In each engineering discipline, the approach has traditionally been to synthesize a preliminary design manually and then to subject that design to some form of analysis. The analysis may involve sophisticated engineering calculations or it may involve a very subjective judgment of the aesthete appeal possessed by the design. The analysis procedure identifies certain improvements that can he made in the design. As stated previously, the process is iterative. Each iteration yields an improvement in the design. The trouble with this iterative process is that it is time consuming. Many engineering labor hours are required to complete the design project.

THE APPLICATION OF COMPUTERS FOR DESIGN

The various design-related tasks which are performed by a modem computer-aided design-system can be grouped into four functional areas:

l. Geometric modeling

2. Engineering analysis

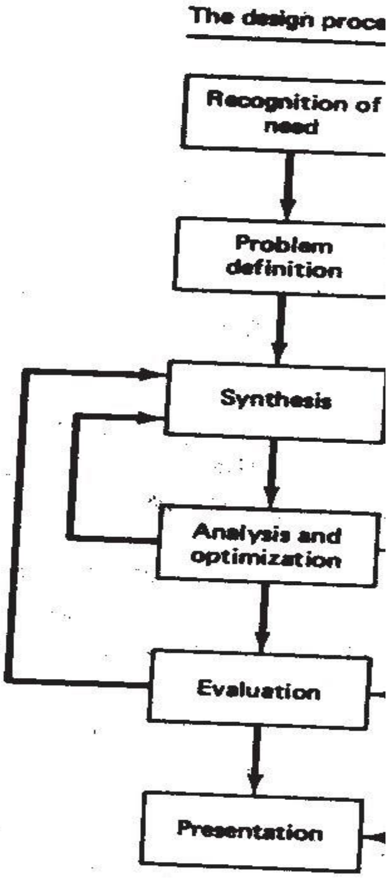
3. Design review and evaluation

4. Automated drafting

These four areas correspond to the final four phases in Shigley's general design process, illustrated in Figure. Geometric modeling corresponds to the synthesis phase in which the physical design project takes form on the ICG system. Engineering analysis corresponds to phase 4, dealing with analysis and optimization. Design review and evaluation is the fifth step in the general design procedure. Automated drafting involves a procedure for converting the design image data residing in computer memory into a hard-copy document. It represents an important method for presentation (phase 6) of the design. The following four sections explore each of these four CAD functions.

Geometric modeling

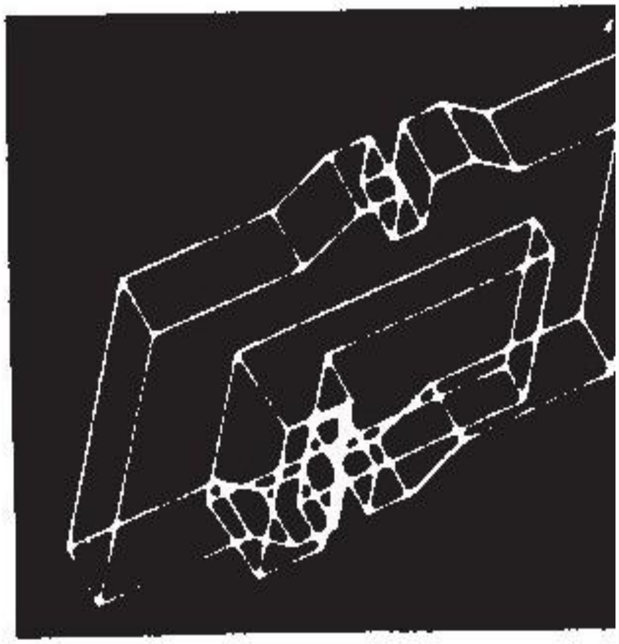
In computer-aided design, geometric modeling is concerned with the computer-compatible mathematical description of the geometry of an object. The mathematical description allows the image of the object to be displayed and manipulated on a graphics terminal through signals from the CPU of the CAD system. The software that provides geometric modeling capabilities must be designed for efficient use both by the computer and the human designer.



To use geometric modeling, the designer constructs, the graphical image of the object on the CRT screen of the ICG system by inputting three types of commands to the computer. The first type of command generates basic geometric elements such as points, lines, and circles. The second command type is used to accomplish scaling, rotating, or other transformations of these elements. The third type of command causes the various elements to be joined into the desired shape of the object being creaed on the ICG system. During the geometric modeling process, the computer converts the commands into a mathematical model, stores it in the computer data files, and displays it as an image on the CRT screen. The model can subsequently be called from the data files for review, analysis, or alteration.

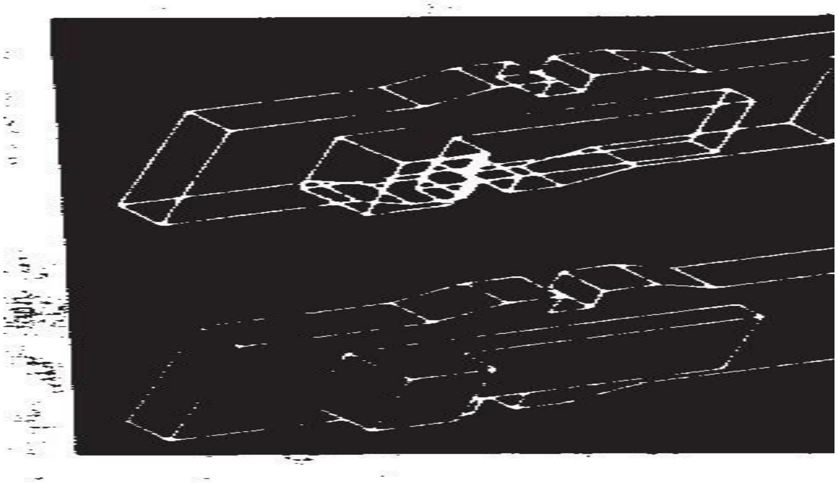
There are several different methods of representing the object in geometric modeling. The basic form uses wire frames to represent the object. In this form, the object is displayed by interconnecting lines as shown in Figure. Wire frame geometric modeling is classified into three types depending on the capabilities of the ICG system.
The three types are:

1. 2D. Two-dimensional representation is used for a flat object.
2. 2½D. This goes somewhat beyond the 2D capability by permitting a three-dimensional object to be represented as long as it has no side-wall details.
3. 3D. This allows for full three-dimensional modeling of a more complex geometry.



Example of wire-frame drawing of a part.

Even three-dimensional wire-frame representations of an object are sometimes inadequate for complicated shapes. Wire-frame models can be enhanced by several different methods. Figure shows the same object shown in the previous figure but with two possible improvements. lbe first uses dashed lines to portray the rear edges of the object, those which would be invisible from the front. lbe second enhancement removes the hidden lines completely, thus providing a less cluttered picture of the object for the viewer. Some CAD systems have an automatic "hidden- line removal feature," while other systems require the user to identify the lines that are to be removed from view. Another enhancement of the wire-frame model involves providing a surface representation which makes the object appear solid to the viewer. However, the object is still stored in the computer as a wire-frame model.



Same workpart as shown in Figure 4.4 but with (a) dashed lines lO show rear edges of part, and (b) hidden-line removal. (Courtesy of Computervision Corp.)

Solid model of yoke part as displayed on a computer graphics system. (Courtesy of Computervision Corp.)

The most advanced method of geometric modeling is solid modeling in three dimensions. This method, illustrated in Figure, typically uses solid geometry shapes called primitives to construct the object.

Another feature of some CAD systems is color graphics capability. By means of colour, it is possible to display more information on the graphics screen. Colored images help to clarify components in an assembly, or highlight dimensions, or a host of other purposes.

Engineering analysis

In the formulation of nearly any engineering design project, some type of analysis is required. The analysis may involve stress-strain calculations, heat-transfer computations, or the use of differential equations to describe the dynamic behavior of the system being designed. The computer can be used to aid in this analysis work. It is often necessary that specific programs be developed internally by the engineering analysis group to solve a particular design problem. In other situations, commercially available general-purpose programs can be used to perform the engineering analysis.

Turnkey CAD/CAM systems often include or can be interfaced to engineering analysis software which can be called to operate on the current design model.

Two important examples of this type:

1. Analysis of mass properties
2. Finite-element analysis

The analysis of mass properties is the analysis feature of a CAD system that has probably the widest application. It provides properties of a solid object being analyzed, such as the surface area, weight, volume, center of gravity, and moment of inertia. For a plane surface (or a cross section of a solid object) the corresponding computations include the perimeter, area, and inertia properties.

Probably the most powerful analysis feature of a CAD system is the finite-element method. With this technique, the object is divided into a large number of finite elements (usually rectangular or triangular shapes) which form an interconnecting network of concentrated nodes. By using a computer with significant computational capabilities, the entire Object can be analyzed for stress-strain, heat transfer, and other characteristics by calculating the behavior of each node. By determining the interrelating behaviors of all the nodes in the system, the behavior of the entire object can be assessed.

Some CAD systems have the capability to define automatically the nodes and the network structure for the given object. lbe user simply defines certain parameters for the finite-element model, and the CAD system proceeds with the computations.

The output of the finite-element analysis is often best presented by the system in graphical format on the CRT screen for easy visualization by the user, For example, in stress-strain analysis of an object, the output may be shown in the form of a deflected shape superimposed over the unstressed object. This is illustrated in Figure. Color graphics can also be used to accentuate the comparison before and after deflection of the object. This is illustrated in Figure for the same image as that shown in Figure . If the finite-element analysis indicates behavior of the design which is undesirable, the designer can modify the shape and recompute the finite-element analysis for the revised design.

Finite-element modeling for stress-strain analysis. Graphics display shows strained part superimposed on unstrained part for comparison.

Design review and evaluation

Checking the accuracy of the design can be accomplished conveniently on the graphics terminal. Semiautomatic dimensioning and tolerancing routines which assign size specifications to surfaces indicated by the user help to reduce the possibility of dimensioning errors. The designer can zoom in on part design details and magnify the image on the graphics screen for close scrutiny.

A procedure called layering is often helpful in design review. For example, a good application of layering involves overlaying the geometric image of the final shape of the machined part on top of the image of the rough casting. This ensures that sufficient material is available on the casting to acccomplish the final machined dimensions. This procedure can be performed in stages to check each successive step in the processing of the part.

Another related procedure for design review is interference checking. This involves the analysis of an assembled structure in which there is a risk that the components of the assembly may occupy the same space. This risk occurs in the design of large chemical plants, air-separation cold boxes, and other complicated piping structures.

One of the most interesting evaluation features available on some computer-aided design systems is kinematics. The available kinematics packages provide the capability to animate the motion of simple designed mechanisms such as hinged components and linkages. This capability enhances the designer‘s visualization of the operation of the mechanism and helps to ensure against interference with other components. Without graphical kinematics on a CAD system, designers must often resort to the use of pin-and-cardboard models to represent the mechanism. commercial software packages are available to perform kinematic analysis. Among these are programs such as ADAMS (Automatic Dynamic Analysis of Mechanical Systems), developed at the University of Michigan. This type of program can be very useful to the designer in constructing the required mechanism to accomplish a specified motion and/or force.

Automated drafting

Automated drafting involves the creation of hard-copy engineering drawings directly from the CAD data base. In some early computer-aided design departments, automation of the drafting process represented the principal justification for investing in the CAD system. Indeed, CAD systems can increase productivity in the drafting function by roughly five times over manual drafting.

Some of the graphics features of computer-aided design systems lend themselves especially well to the drafting process. These features include automatic dimensioning, generation of crosshatched areas, scaling of the drawing, and the capability to develop sectional views and enlarged views of particular path details. The ability to rotate the part or to perform other transformations of the image (e.g., oblique, isometric, or perspective views), as illustrated in Figure, can be of significant assistance in drafting. Most CAD systems are capable of generating as many as six views of the part. Engineering drawings can be made to adhere to company drafting standards by programming the standards into the CAD system. Figure shows an engineering drawing with four views displayed. This drawing was produced automatically by a CAD system. Note how much the isometric view promotes a higher level of understanding of the object for the user than the three orthographic views.

Parts classification and coding

In addition to the four CAD functions described above, another feature of the CAD data base is that it can be used to develop a parts classification and coding system. Parts classification and coding involves the grouping of similar part designs into classes, and relating the similarities by mean of a coding scheme. Designers can use the classification and coding system to retrieve existing part designs rather than always redesigning new parts.

CREATING THE MANUFACTURING DATA BASE

Another important reason for using a CAD system is that it offers the opportunity to develop the data base needed to manufacture the product. In the conventional manufacturing cycle practiced for so many years in industry, engineering drawings were prepared by design draftsmen and then used by manufacturing engineers to develop the process plan (i.e., the "route sheets"). The activities involved in designing the product were separated from the activities associated with process planning. Essentially, a two-step procedure was employed. This was both time consuming and involved duplication of effort by design and manufacturing personnel. In an integrated CAD/CAM system, a direct link is established between product design and manufacturing: It" is the goal of CAD/CAM not only to automate certain phases of design and certain phases of manufacturing, but also to automate the transition from design to manufacturing. Computer-based systems have been developed which create much of the data and documentation required to plan and manage the manufacturing operations for the product.

The manufacturing data base is an integrated CAD/CAM data base. It includes all the data on the product generated during design (geometry data, bill of materials and parts lists, material specifications, etc.) as well as additional data required for manufacturing much of which is based Oll the product design. Figure

4.lO shows how the CAD/CAM data base is related to design and manufacturing in a typical production-oriented company.

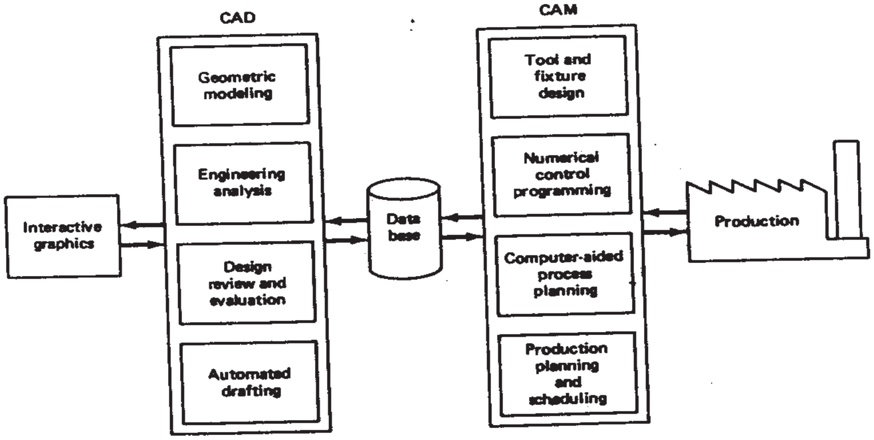


FIGURE Desirable relationship of CAD/CAM data base to CAD and CAM.

BENERTS OF COMPUTER-AIDED DESIGN

There are many benefits of computer-aided design, only some of which can be easily measured. Some of the benefits are intangible, reflected in improved work quality, more pertinent and usable information, and improved control, all of which are difficult to quantify. Other benefits are tangible, but the savings from them show up far downstream in the production process, so that it is difficult to assign a dollar figure to them in the design phase. Some of the benefits that derive from implementing CAD/CAM can be directly measured. Table provides a checklist of potential benefits of an integrated CAD/CAM system. In the subsections that follow, we elaborate on some of these advantages.

Productivity improvement in design

Increased productivity translates into a more competitive position for the firm because it will reduce staff requirements on a given project. This leads to lower costs in addition to improving response time on projects with tight schedules.

Surveying some of the larger CAD/CAM vendors, one finds that the Productivity improvement ratio for a designer/draftsman is usually given as a range, typically from a low end of 3: 1 to a high end in excess of lO: 1 (often far in excess of that figure). There are individual cases in which productivity has been increased by a factor of lOO, but it would be inaccurate to represent that figure as typical.

TABLE Potential Benefits That May Result from implementing CAD as Part of an Integrated CAD/CAM System.

l. Improved engineering productivity
2. Shorter lead times
3. Reduced engineering personnel requirements
4. Customer modifications are easier to make
5. Faster response to requests for quotations
6. Avoidance of subcontracting to meet schedules
7. Minimized transcription errors
8. Improved accuracy of design
9. In analysis, easier recognition of component interactions
lO. Provides better functional analysis to reduce prototype testing
ll. Assistance in preparation of documentation
l2. Designs have more standardization
l3. Better designs provided
l4. Improved productivity in tool design
l5. Better knowledge of costs provided
l6. Reduced training time for routine drafting tasks and NC part programming
l7. Fewer errors in NC part programming
l8. Provides the potential for using more existing parts and tooling
l9. Helps ensure designs are appropriate to existing manufacturing techniques
20. Saves materials and machining time by optimization algorithms
21. Provides operational results on the status of work in progress
22. Makes the management of design personnel on projects more effective
23. Assistance in inspection of complicated parts
24. Better communication interfaces and greater understanding among engineers, designers, drafters, management, and different project groups.

Productivity improvement in computer-aided design as compared to the traditional design process is dependent on such factors as:

Complexity of the engineering drawing

Level of detail required in the drawing

Degree of repetitiveness in the designed parts

Degree of symmetry in the parts

Extensiveness of library of commonly used entities

As each of these factors is increased. the productivity advantage of CAD will tend to increase

Shorter lead times

Interactive computer-aided design is inherently faster than the traditional design. It also speeds up the task of preparing reports and lists (e.g., the assembly lists) which are normally accomplished manually. Accordingly, it is possible with a CAD system to produce a finished set of component drawings and the associated reports in a relatively short time. Shorter lead times in design translate into shorter elapsed time between receipt of a customer order and delivery of the final product. The enhanced productivity of designers working with CAD systems will tend to reduce the prominence of design, engineering analysis, and drafting as critical time elements in the overall manufacturing lead time.

Design analysis

The design analysis routines available in a CAD system help to consolidate the design process into a more logical work pattern. Rather than having a back- and-forth exchange between design and analysis groups, the same person can perform the analysis while remaining at a CAD workstation. This helps to improve the concentration of designers, since they are interacting with their designs in a real-time sense. Because of this analysis capability, designs can be created which are closer to optimum. There is a time saving to be derived from the computerized analysis routines, both in designer time and in elapsed time. This saving results from the rapid response of the design analysis and from the tune no longer lost while the design finds its way from the designer's drawing board to the design analyst's queue and back again.

Fewer design errors

Interactive CAD systems provide an intrinsic capability for avoiding design, drafting, and documentation errors. Data entry, transposition, and extension errors that occur quite naturally during manual data compilation for preparation of a bill of materials are virtually eliminated. One key reason for such accuracy is simply that

No manual handling of information is required once the initial drawing has been developed. Errors are further avoided because interactive CAD systems perform time-consuming repetitive duties such as multiple symbol placement, and sorts by area and by like item, at high speeds with consistent and accurate results. Still more errors can be avoided because a CAD system, with its interactive capabilities, can be programmed to question input that may be erroneous. For example, the system might question a tolerance of O.OOOO2 in. It is likely that the user specified too many zeros. The success of this checking would depend on the ability of the CAD system designers to determine what input is likely to be incorrect and hence, what to question.

Greater accuracy in design calculations

There is also a high level of dimensional control, far beyond the levels of accuracy attainable manually. Mathematical accuracy is often to l4 significant decimal places. The accuracy delivered by interactive CAD systems in three-dimensional curved space designs is so far behind that provided by manual calculation methods that there is no real comparison.

Computer-based accuracy pays off in many ways. Parts are labeled by the same recognizable nomenclature and number throughout all drawings. In some CAD systems, a change entered on a single item can appear throughout the entire documentation package, effecting the change on all drawings which utilize that part. The accuracy also shows up in the form of more accurate material and cost estimates and tighter procurement scheduling. These items are especially important in such cases as long-lead-time material purchases.

Standardization of design, drafting, and documentation procedures

The single data base and operating system is common to all workstations in the CAD system: Consequently, the system provides a natural standard for design/drafting procedure -With interactive computer-aided design, drawings are standardized as they are drawn; there is no confusion as to proper procedures because the entire format is "built into" the system program.

Drawings are more understandable

Interactive CAD is equally adept at creating and maintaining isometrics and oblique drawings as well as the simpler orthographies. All drawings can he generated and updated with equal ease. Thus an up-to-date version of any drawing type can always he made available.

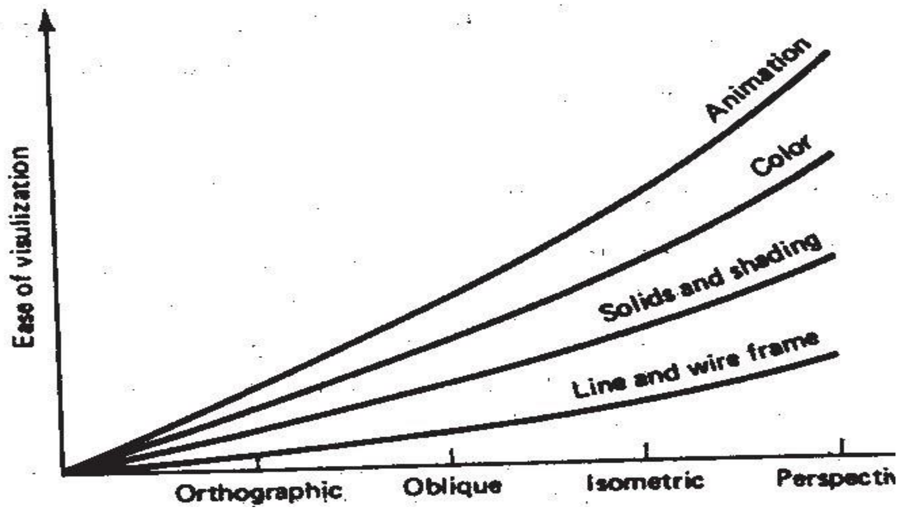


FIGURE Improvement in visualization of images for various drawing types and computer graphics features.

In general, ease of visualization of a drawing relates directly to the projection used. Orthographic views are less comprehensible than isometrics. An isometric view is usually less understandable than a perspective view. Most actual construction drawings are "line drawings." The addition of shading increases comprehension. Different colors further enhance understanding. Finally, animation of the images on the CRT screen allows for even greater visualization capability. The various relationships are illustrated in Figure..

Improved procedures for engineering changes

Control and implementation of engineering changes is significantly improved with computer-aided design. Original drawings and reports are stored in the data base of the CAD system. This makes them more accessible than documents kept in a drawing vault. They can be quickly checked against new information. Since data storage is extremely compact, historical information from previous drawings can be easily retained in the system's data base, for easy comparison with current design/drafting needs.

Benefits in manufacturing

The benefits of computer-aided design carry over into manufacturing. As indicated previously, the same CAD/CAM data base is used for manufacturing planning and control, as well as for design. These manufacturing benefits are found in the following areas:

Tool and fixture design for manufacturing

Numerical control part programming

Computer-aided process planning

Assembly lists (generated by CAD) for production

Computer-aided inspection

Robotics planning

Group technology

Shorter manufacturing lead times through better scheduling

These benefits are derived largely from the CAD/CAM data base, whose initial framework is established during computer-aided design. We will discuss the many facets of computer-aided manufacturing in later chapters. In the remainder of this chapter, let us explore several applications that utilize computer graphics technology to solve various problems in engineering and related fields.

HARDWARE IN COMPUTER-AIDED DESIGN

INTRODUCTION

Hardware components for computer-aided design are available in a variety of sizes, configurations, and capabilities. Hence it is possible to select a CAD system that meets the particular computational and graphics requirements of the user firm. Engineering firms that are not involved in production would choose a system exclusively for drafting and design-related functions. Manufacturing firms would choose a system to be part of a company-wide CAD/CAM system. Of course, the CAD hardware is of little value without the supporting software for the system, and we shall discuss the software for computer-aided design in the following chapter.

a modem computer-aided design system is based on interactive computer graphics (ICG). However, the scope of computer-aided design includes other computer systems as well. For example, computerized design has also been accomplished in a batch mode, rather than interactively. Batch design means that data are supplied to the system (a deck of computer cards is traditionally used for this purpose) and then the system proceeds to develop the details of the design. The disadvantage of the batch operation is that there is a time lag between when the data are submitted and when the answer is received back as output. With interactive graphics, the system provides an immediate response to inputs by the user. The user and the system are in direct communication with each other, the user entering commands and responding to questions generated by the system.

Computer-aided design also includes nongraphic applications of the computer in design work. These consist of engineering results which are best displayed in other than graphical form. Nongraphic hardware (e.g., line printers) can be employed to create rough images on a piece of paper by appropriate combinations of characters and symbols. However, the resulting pictures, while they may create interesting wall posters, are not suitable for design purposes.

The hardware we discuss in this chapter is restricted to CAD systems that utilize interactive computer graphics. Typically, a stand-alone CAD system would include the following hardware components:

One or more design workstations. These would consist of:

A graphics terminal

Operator input devices

One or more plotters and other output devices

Central processing unit (CPU)

Secondary storage

These hardware components would be arranged in a configuration as illustrated in Figure. The following sections discuss these various hardware components and the alternatives and options that can be obtained in each category.

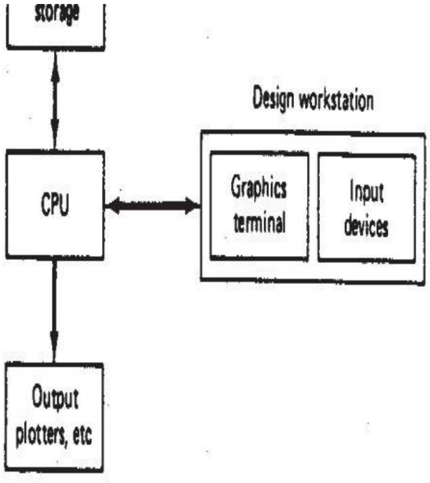


Figure 3: Typical configuration of hardware components in a stand-alone CAD system.

THE DESIGN WORKSTATION

The CAD workstation is the system interface with the outside world. It represents a significant factor in determining how convenient and efficient it is for a designer to use the CAD system. The workstation must accomplish five functions:

l. It must interface with the central processing unit.
2. It must generate a steady graphic image for the user.
3. It must provide digital descriptions of the graphic image.
4. It must translate computer commands into operating functions.
5. It must facilitate communication between the user and the system

The use of interactive graphics has been found to be the best approach to accomplish these functions. A typical interactive graphics workstation would consist of the following hardware Components:

A graphics terminal
Operator input device

A graphics design workstation showing these components is illustrated in figure

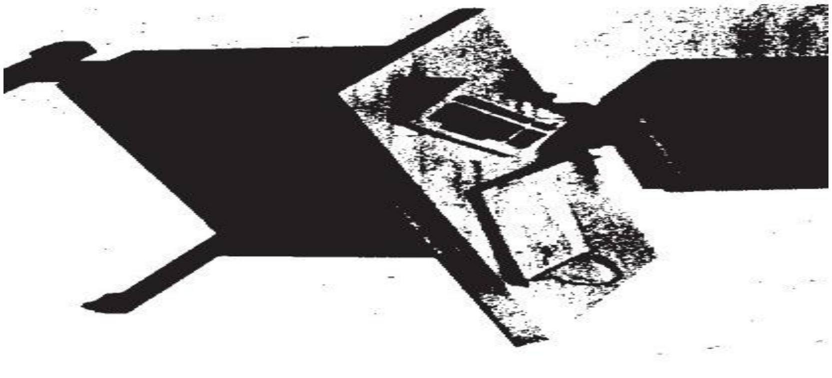


Figure: Interactive graphics design workstation showing graphics terminal and two input devices: alphanumeric keyboard and electronic tablet and pen.

THE GRAPHICS TERMINAL

'There are various technological approaches which have been applied to the development of graphics terminals. The technology continues to evolve as CAD system manufactures attempt to improve their products and reduce their costs. In this section we present a discussion of the current technology in interactive computer graphics terminals.

Image generation in computer graphics

Nearly all computer graphics terminals available today use the cathode ray tube (CRT) as the display device. Television sets use a form of the same device as the picture tube. 'The operation of the CRT is illustrated in Figure. A heated cathode emits a high-speed electron beam onto a phosphor-coated glass screen. 'The electrons energize the phosphor coating, causing it to glow at the points where the beam makes contact. By focusing the electron beam, changing its intensity, and controlling its point of contact against the phosphor coating through the use of a deflector system, the beam can be made to generate a picture on the CRT screen.

There are two basic techniques used in current computer graphics terminals for generating the image on the CRT screen. They are:

l. Stroke writing

2. Raster scan

Other names for the stroke-writing technique include line drawing, random position, vector writing, stroke writing, and directed beam. Other names for the raster scan technique include digital TV and scan graphics.

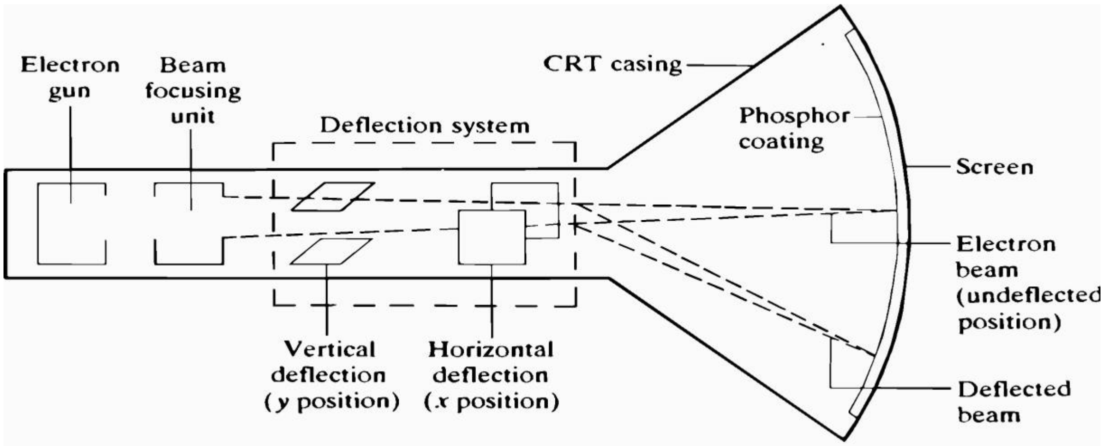


Figure : Diagram of cathode ray tube (CRT).

The stroke-writing system uses an electron beam which operates like a pencil to create a line image on the CRT screen. The image is constructed out of a sequence of straight-line segments. Each line segment is drawn on the screen by directing the beam to move from one point on the screen to the next, where each point is defined by its x and y coordinates. The process is portrayed in Figure . Although the procedure results in images composed of only straight lines, smooth curves can be approximated by making the connecting line segments short enough.

In the raster scan approach, the viewing screen is divided into a large number of discrete phosphor picture elements, called pixels. The matrix of pixels constitutes the raster. The number of separate pixels in the raster display might typically range from 256 × 256 (a total of over 65,(OO) to lO24 × lO24 (a total of over l,OOO,OOO points). Each pixel on the screen can be made to glow with a different brightness. Color screens provide for the pixels to have different colors as well as brightness. During operation, an electron beam creates the image by sweeping along a horizontal line on the screen from left to right and energizing the pixels in that line during the sweep. When the sweep of one line is completed, the electron beam moves to the next line below and proceeds in a fixed pattern as indicated in Figure. After sweeping the entire screen the process is repeated at a rate of 3O to 6O entire scans of the screen per second:

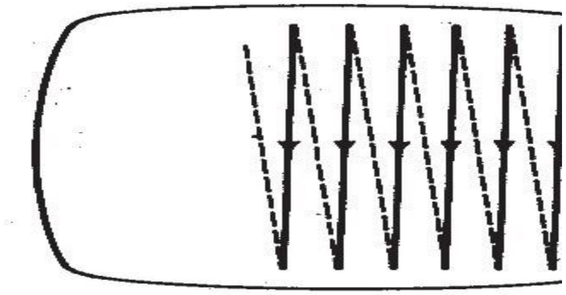


Figure : Raster scan approach for generating images in computer graphics.

Graphics terminals for computer-aided design

The two approaches described above are used in the overwhelming majority of current-day CAD graphics terminals. There are also a variety of other technical factors which result in different types of graphics terminals. These factors include the type of phosphor coating on the screen, whether color is required, the pixel density, and the amount of computer memory available to generate the picture. We will discuss three types of graphics terminals, which seem to be the most important today in commercially available CAD systems. The three types are:

l. Directed-beam refresh

2. Direct-view storage tube (DVST)

3. Raster scan (digital TV)

The following paragraphs describe the three basic types. We then discuss some of the possible enhancements, such as color and animation.

DIRECTED-BEAM REFRESH. The directed-beam refresh terminal utilizes the stroke-writing approach to generate the image on the CRT screen. The term refresh in the name refers to the fact that the image must be regenerated many times per second in order to avoid noticeable flicker of the image. The phosphor elements on the screen surface are capable of maintaining their brightness for only a short time (sometimes measured in microseconds). In order for the image to be continued, these picture tubes must be refreshed by causing the directed beam to retrace the image repeatedly. On densely filled screens (very detailed line images or many characters of text), it is difficult to avoid flickering of the image with this process. On the other hand, there are several advantages associated with the directed- beam refresh systems. Because the image is being continually refreshed, selective erasure and alteration of the image is readily accomplished. It is also possible to provide animation of the image with a refresh tube.

The directed-beam refresh system is the oldest of the modem graphics display technologies. Other names sometimes used to identify this system include vector refresh and stroke-writing refresh. Early refresh tubes were very expensive. but the steadily decreasing cost of solid-state circuitry has brought the price of these graphics systems down to a level which is competitive with other types.

DIRECT-VIEW STORAGE TUBE (DVST). DVST terminals also use the stroke-writing approach to generate the image on the CRT screen. The term storage tube refers to the ability of the screen to retain the image which has been projected against it, thus avoiding the need to rewrite the image which has been projected against it, thus avoiding the need to rewrite the image constantly. What makes this possible is the use of an electron flood gun directed at the phosphor coated screen which keeps the phosphor elements illuminated once they have been energized by the stroke-writing electron beam. The resulting image on the CRT screen is flicker- free. Lines may be readily added to the image without concern over their effect on image density or refresh rates. However, the penalty associated with the storage tube is that individual lines cannot be selectively removed from the image.

Storage tubes have historically been the lowest-cost terminals and are capable of displaying large amounts of data, either graphical or textual. Because of these features, there are probably more storage tube terminals in service in industry at the time of this writing than any other graphics display terminal. The principal disadvantage of a storage CRT is that selective erasure is not possible. Instead, if the user wants to change the picture, the change will not be manifested on the screen until the entire picture is regenerated. Other disadvantages include its lack of color capability, the inability to use a light pen as a data entry, and its lack of animation capability.

RASTER SCAN TERMINALS. Raster scan terminals operate by causing an electron beam to trace a zigzag pattern across the viewing screen, as described earlier. The operation is similar to that of a commercial television set. The difference is that a TV set uses analog signals originally generated by a video camera to construct the image on the CRT screen, while the raster scan ICG terminal uses digital signals generated by a computer. For this reason, the raster scan terminals used in computer graphics are sometimes called digital TVs.

The introduction of the raster scan graphics terminal using a refresh tube had been limited by the cost of computer memory. For example, the simplest and lowest-cost terminal in this category uses only two beam intensity levels, on or off. This means that each pixel in the viewing screen is either illuminated or dark. A picture tube with 256 lines of resolution and 256 addressable points per line to form the image would require 256 × 256 or over 65,OOO bits of storage. Each bit of memory contains the on/off status of the corresponding pixel on the CRT screen. This memory is called the frame buffer or refresh buffer. The picture quality can be improved in two ways: by increasing the pixel density or adding a gray scale (or color). Increasing pixel density for the same size screen means adding more lines of resolution and more addressable points per line. A lO24 × lO24 raster screen would require more than 1 million bits of storage in the frame buffer. A gray scale is accomplished by expanding the number of intensity levels which can be displayed on each pixel. This requires additional bits for each pixel to store the intensity level. Two bits are required for four levels, three bits for eight levels, and so forth. Five or six bits would be needed to achieve an approximation of a continuous gray scale. For a color display, three times as many bits are required to get various intensity levels for each of the three primary colors: red, blue, and green. (We discuss color in the following section.) A raster scan graphics terminal with high resolution and gray scale can require a very large capacity refresh buffer. Until recent developments in memory technology, the cost of this storage capacity was prohibitive for a terminal with good picture quality. The capability to achieve color and animation was notpossible except for very low resolution levels.

Table Comparison of Graphics Terminal Features

Type	**Directed-beam refresh**	**DVST**	**Raster scan**
Image generation	Stroke writing	Stroke writing	Raster scan
Picture quality	Excellent	Excellent	Moderate to good
Data content	Limited	High	High
Selective erase	Yes	No	Yes
Gray scale	Yes	No	Yes
Color capability	Moderate	No	Yes
Animation capability	Yes	No	Moderate

It is now possible to manufacture digital TV systems for interactive computer graphics at prices which are competitive with the other two types. The advantages of the present raster scan terminals include the feasibility to use low-cost TV monitors, color capability, and the capability for animation of the image. These features, plus the continuing improvements being made in raster scan technology, make it the fastest-growing segment of the graphics display market.

The typical color CRT uses three electron beams and a triad of color dots an the phosphor screen to provide each of the three colors, red, green, and blue. By combining the three colors at different intensity levels, a variety of colors can be created on the screen. It is mare difficult to fabricate a stroke-writing tube which is precise enough far color because of the technical problem of getting the three beams to. converge properly against the screen .

The raster scan approach has superior color graphics capabilities because of the developments which have been made over the years in the color television industry. Color raster scan terminals with lO24 × lO24 resolution are commercially available for computer graphics. The problem in the raster terminals is the memory requirements of the refresh buffer. Each pixel on the viewing screen' may require up to 24 bits of memory in the refresh buffer in order to display the full range of color tones. When multiplied by the number of pixels in the display screen, this translates into a very large storage buffer.

The capability for animation in computer graphics is limited to display methods in which the image can be quickly redrawn. This limitation excludes the storage tube terminals Both the directed-beam refresh and the raster scan systems are capable of animation. However, this capability is not automatically acquired .with these systems. It must be accomplished by means of a powerful and fast CPU interfaced to the graphics terminal to process the large volumes of data required for animated images In computer-aided design, animation would be a powerful feature in applications where kinematic simulation is required. The analysis of linkage mechanisms and other mechanical behavior would be examples. In computer-aided manufacturing, the planning of a robotic work cycle would be improved through the use of an animated image of the robot simulating the motion of the arm during the cycle. The popular video games marketed by Atari and other manufacturers for use with home TV sets are primitive examples of animation in computer graphics. Animation in these TV games is made possible by sacrificing the quality of the picture. This keeps the price of these games within an affordable range.

OPERATOR INPUT DEVICES

Operator input devices are provided at the graphics workstation to facilitate convenient communication between the user and the system. Workstations generally have several types of input devices to allow the operator to select the various preprogrammed input functions. These functions permit the operator to create or modify an image on the CRT screen or to enter alphanumeric data into the system. This results in a complete part on the CRT screen as well as complete geometric description of the part m the CAD data base.

Different CAG system vendors offer different types of operator input devices. These devices can be divided into three general categories:

l. Cursor control devices
2. Digitizers
3. Alphanumeric and other keyboard terminals

Of the three, cursor control devices and digitizers are both used for graphical interaction with the system. Keyboard terminals are used as input devices for commands and numerical data.

There are two basic types of graphical interaction accomplished by means of cursor control and digitizing: Creating and positioning new items on the CRT screen Pointing at or otherwise identifying locations on the screen, usually associated with existing images. Ideally, a graphical input device should lend itself to both of these functions. However, this is difficult to accomplish with a single unit and that is why most workstations have several different input devices.

Cursor control

The cursor normally takes the form of a bright spot on the CRT screen that, indicates where lettering or drawing will occur. The computer is capable of reading the current position of the cursor. Hence the user's capability to control the cursor position allows locational data to be entered into the CAD system data base. A typical example would be for the user to locate the cursor to identify the starting point of a line. Another, more sophisticated case, would be for the user to position the cursor to select an item from a menu of functions displayed on the screen. For instance, the screen might be divided into two sections, one of which is an array of blocks which correspond to operator input functions. The user simply moves the cursor to the desired block to execute the particular function.

There are a variety of cursor control devices which have been employed in CAD systems. These include:

Thumbwheels
Direction keys on a keyboard terminal
Joysticks
Tracker ball
Light pen
Electronic
tablet/pen

The first four items in the list provide control over the cursor without any direct physical contact of the screen by the user. The last two devices in the list require the user to control the cursor by touching the screen (or some other flat surface which is related to the screen) with a pen-type device.

The thumbwheel device uses two thumbwheels, one to control the horizontal position of the cursor, the other to control the vertical position. This type of device is often mounted as an integral part of the CRT terminal. The cursor in this arrangement is often represented by the intersection of a vertical line and a horizontal line displayed on the CRT screen. The two lines are like crosshairs in a gunsight which span the height and width of the screen.

Direction keys on the keyboard are another basic form of cursor control used not only for graphics terminals but also for CRT terminals without graphics capabilities. Four keys are used for each of the four directions in which the cursor can be moved (right or left, and up or down).

The joystick apparatus is pictured in Figure. It consists of a box with a vertical toggle stick that can be pushed in any direction to cause the cursor to be moved in that direction. The joystick gets its name from the control stick that was used lO old airplanes.

The tracker ball is pictured in Figure. Its operation is similar to that of the joystick except that an operator-controlled ball is rotated to move the cursor in the desired direction on the screen.

The light pen is a pointing device in which the computer seeks to identify position where the light pen is in contact with the screen. Contrary to what its name suggests, the light pen does not project light. Instead, it is a detector of light on the CRT screen and uses a photodiode, phototransistor, or some other form of light sensor. The light pen can be utilized with a refresh-type CRT but not with a storage tube. This is because the image on the refresh tube is being generated in time sequence. The time sequence is so short that the image appears continuous to the human eye.

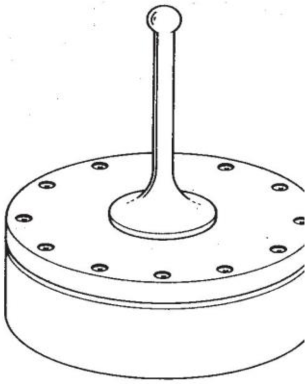


FIGURE Joystick input device for interactive computer graphics

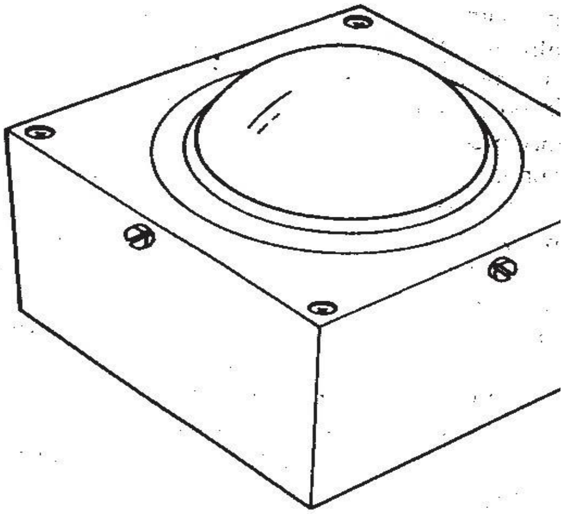


Figure: Tracker ball input device for interactive computer graphics.

However, the computer is capable of discerning the time sequence and it coordinates this timing with the position of the pen against the screen. In essence, the system is performing as an optical tracking loop to locate the cursor or to execute some other input function. The tablet and pen in computer graphics describes an electronically sensitive tablet used in conjunction with an electronic stylus. The tablet is a flat surface, separate from the CRT screen, on which the user draws with the penlike stylus to input instructions or to control the cursor

It should be noted that thumbwheels, direction keys, joysticks, and tracker balls are generally limited in their functions to cursor control. The light pen and tablet/pen are typically used for other input functions as well as cursor control. Some of these functions are:

Selecting from a function menu

Drawing on the screen or making strokes on the screen or tablet which indicate what image is to be drawn

Selecting a portion of the screen for enlargement of an existing image

Digitizers

The digitizer is an operator input device which consists of a large, smooth board (the appearance is similar to a mechanical drawing board) and an electronic tracking device which can be moved over the surface to follow existing lines. It is a common technique in CAD systems for taking x, y coordinates from a paper drawing. The electronic tracking device contains a switch for the user to record the desired x and y coordinate positions. The coordinates can be entered into the computer memory or stored on an off-line storage medium such as magnetic tape. High-resolution digitizers, typically with a large board (e.g., 42 in by 6O in.) can provide resolution and accuracy on the order of O.OOl in. It should be mentioned that the electronic tablet and pen, previously discussed as a cursor control device, can be considered to be a small, low-resolution digitizer.

Not all CAD systems would include a digitizer as part of its core of operator input devices. It would be inadequate, for example, in three-dimensional mechanical design work since the digitizer is limited to two dimensions. For two-dimensional drawings, drafters can readily adapt to the digitizer because it is similar to their drafting boards. It can be tilted, raised, or lowered to assume a comfortable position for the drafter.

The digitizer can be used to digitize line drawings. The user can input data from a rough schematic or large layout drawing and edit the drawings to the desired level of accuracy and detail. The digitizer can also be used to freehand a new design with subsequent editing to finalize the drawing.

Keyboard terminals

Several forms of keyboard terminals are available as CAD input devices. The most familiar type is the alphanumeric terminal which is available with nearly all interactive graphics systems. The alphanumeric terminal can be either a CRT or a hard copy terminal, which prints on paper. For graphics, the CRT has the advantage because of its faster speed, the ability to easily edit, and the avoidance of large volumes of paper. On the other hand, a permanent record is sometimes desirable and this is most easily created with a hard-copy terminal. Many CAD systems use the graphics screen to display the alphanumeric data, but there is an advantage in having a separate CRT terminal so that the alphanumeric messages can be created without disturbing or overwriting the image on the graphics screen.

The alphanumeric terminal is used to enter commands, functions, and supplemental data to the CAD system. This information is displayed for verification on the CRT or typed on paper. The system also communicates back to the user in a similar manner. Menu listings, program listings, error messages, and so forth, can be displayed by the computer as part of the interactive procedure.

These function keyboards are provided to eliminate extensive typing of commands, or calculate coordinate positions, and other functions. The number of function keys varies from about 8 to 8O. The particular function corresponding with each button is generally under computer control so that the button function can be changed as the user proceeds from one phase of the design to the next. In this way the number of alternative functions can easily exceed the number of but tons on the keyboard.

Also, lighted buttons are used on the keyboards to indicate which functions are possible in the current phase of design activity. A menu of the various function alternatives is typically displayed on the CRT screen for the user to select the desired function.

PLOTTERS AND OTHER OUTPUT DEV CES

There are various types of output devices used in conjunction with a computer-aided design system. These output devices include:

Pen plotters

Hard-copy units

Electrostatic plotters Computer-output-to-microfilm (COM) units

We discuss these devices in the following sections.

Pen plotters

The accuracy and quality of the hard-copy plot produced by a pen plotter is considerably greater than the apparent accuracy and quality of the corresponding image on the CRT screen. In the case of the CRT image, the quality of the picture is degraded because of lack of resolution and because of losses in the digital-to-analog conversion through: the display generators. On the other hand, a high-precision pen plotter is capable of achieving a hard-copy drawing whose accuracy is nearly consistent with the digital definitions in the CAD data base.

The pen plotter uses a mechanical ink pen (either wet ink or ballpoint) to write on paper through relative movement of the pen and paper. There are two basic types of pen plotters currently in use:

Drum plotters

Fiat-bed plotters

Hard-copy unit

A hard-copy unit is a machine that can make copies from the same image data layed on the CRT screen. The image on the screen can be duplicated in a matter of seconds. The copies can be used as records of intermediate steps in the design process or when rough hard copies of the screen are needed quickly. The hard copies produced from these units are not suitable as final drawings because the accuracy and quality of the reproduction is not nearly as good as the output of a pen plotter.

Most hard-copy units are dry silver copiers that use light-sensitive paper exposed through a narrow CRT window inside the copier. The window is typically 8½ in. (2l6 mm), corresponding to the width of the paper, by about ½ in. (l2 mm) wide. The paper is exposed by moving it past the window and coordinating the CRT beam to gradually transfer the image. A heated roller inside the copier is used to develop the exposed paper. The size of the paper is usually limited on these hard- copy units to 8½ by II in. Another drawback is that the dry silver copies will darken with time when they are left exposed to normal light.

Electrostatic plotters

Hard-copy units are relatively fast but their accuracy and resolution are poor. Pen plotters are highly accurate but plotting time can take many minutes (up to a half-hour or longer for complicated drawings). The electrostatic plotter offers a compromise between these two types in terms of speed and accuracy. It is almost as fast as the hard-copy unit and almost as accurate as the pen plotter.

The electrostatic copier consists of a series of wire styli mounted on a bar which spans the width of the charge-sensitive paper. The styli have a density of up to 2OO per linear inch. The paper is gradually moved past the bar and certain styli are activated to place dots on the paper. By coordinating the generation of the dots with the paper travel, the image is progressively transferred from the data base into hard- copy form. The dots overlap each other slightly to achieve continuity. For example, a series of adjacent dots gives the appearance of a continuous line.

A limitation of the electrostatic plotter is that the data must be in the raster format (i.e., in the same format used to drive the raster-type CRT) in order to be readily converted into hard copy using the electrostatic method. If the data are not in raster format, some type of conversion is required to change them into the required format. The conversion mechanism is usually based on a combination of software and hardware.

An advantage of the electrostatic plotter which is shared with the drum-type pen plotter is that the length of the paper is virtually unlimited. Typical plotting widths might be up to 6 ft (l.83 m). Another advantage is that the electrostatic plotter can be utilized as a high-speed line printer, capable of up to l2OO lines of text per minute.

Memory Types

- ROM - Read only memory
- PROM - Programmable ROM
- EPROM - Erasable programmable ROM
- EEPROM - Electrically erasable and programmable ROM
- RAM - Random access memory
- Flash memory

THE CENTRAL PROCESSING UNIT

The CPU operates as the central "brain" of the computer-aided design system. It is typically a minicomputer. It executes all the mathematical computations needed to accomplish graphics and other functions, and it directs the various activities within the system.

THE SOFTWARE CONFIGURATION OF A GRAPHICS SYSTEM

In the operation of the graphics system by the user, a variety of activities take place, which can be divided into three categories:

l. Interact with the graphics terminal to create and alter images on the screen

2 Construct a model of something physical out of the images on the screen. the models are sometimes called application models.

3. Enter the model into computer memory and/or secondary storage.

In working with the graphics system the user performs these various activities in combination rather than sequentially. The user constructs a physical model and inputs it to memory by interactively describing images to the system. This is done without any thought about whether the activity falls into category l, 2, or 3.

The reason for separating these activities in this fashion is that they correspond to the general configuration of the software package used with the interactive computer graphics (ICG) system. The graphics software can be divided into three modules according to a conceptual model suggested by Foley and Van Dam:

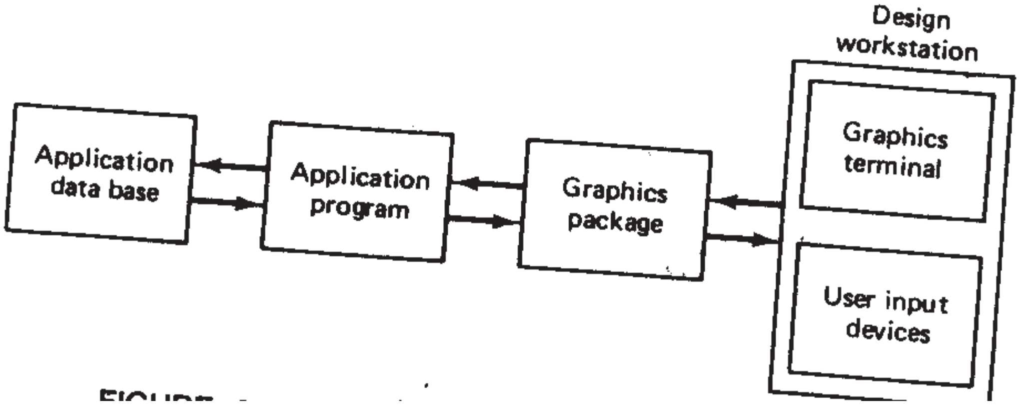
l. The graphics package (Foley and Van Dam called this the graphics systems

2. The application program

3. The application data bas

This software configuration is illustrated in Figure. The central module is the application program. It controls the storage of data into and retrieves data out of the application data base. The application program is driven by the user through the graphics package.

The application program is implemented by the user to construct the model of a physical entity whose image 'is to be viewed on the graphics-screen. Application programs are written for particular problem areas. Problem areas in engineering design would include architecture, construction, mechanical components, electronics, chemical engineering, and aerospace engineering. Problem areas other than design would include flight simulators, graphical display of data, mathematical analysis, and even artwork. In each case, the application software is developed to deal with images and conventions which are appropriate for that field.



The graphics package is the software support between the user and the graphics terminal. It manages the graphical interaction between the user and the system. It also serves as the interface between the user and the application software. The graphics package consists of input subroutines and output subroutines. The input routines accept input commands and data from the user and forward them to the application program. The output subroutines control the display terminal (or other output device) and converts the application models into two-dimensional or three- dimensional graphical pictures.

The third module in the ICG software is the data base. The data base contains mathematical, numerical, and logical definitions of the application models, such as electronic circuits, mechanical components, automobile bodies, and so forth. It also includes alphanumeric information associated with the models, such as bills of materials, mass properties, and other data. The contents of the data base can be readily displayed on the CRT or plotted out in hard-copy form. Section

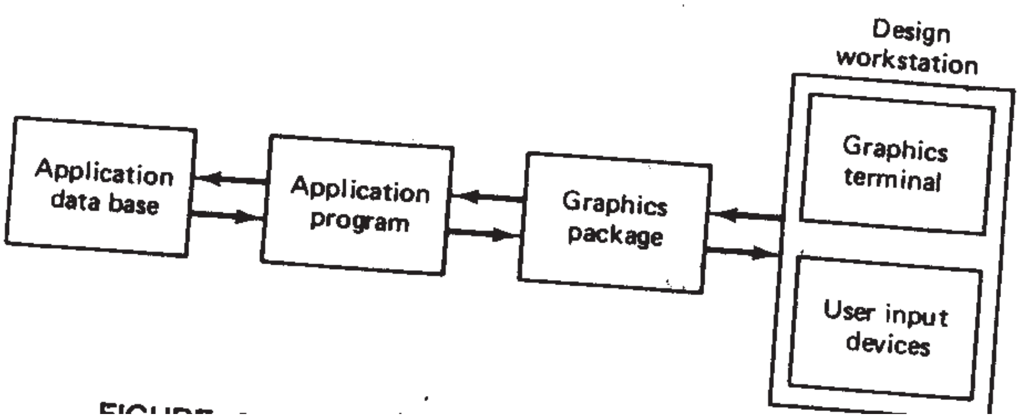


FIGURE Model of graphics software configuration .

FUNCTIONS OF A GRAPHICS PACKAGE

To fulfill its role in the software configuration, the graphics package must perform a variety of different functions. these functions can be grouped into function sets. Each set accomplishes a certain kind of interaction between the user and the system. Some of the common function sets are:

Generation of graphic elements

Transformations

Display control and windowing functions

Segmenting functions

User input functions

TRANSFORMATIONS

Many of the editing features involve transformations of the graphics elements or cells composed of elements or even the entire model. In this section we discuss the mathematics of these transformations. Two-dimensional transformations are considered first to illustrate concepts. Then we deal with three dimensions.

Two-dimensional transformations

To locate a point in a two-axis cartesian system, the x and y coordinates are specified. These coordinates can be treated together as a lxl matrix: (x,y). For example, the matrix (2, 5) would be interpreted to be a point which is 2 units from the origin in the x-direction and 5 units from the origin in the y-direction.

This method of representation can be conveniently extended to define a line as a 2 x 2 matrix by giving the x and y coordinates of the two end points of the line.

The notation would be

$$L = \begin{matrix} x_l & y_l \\ x_2 & y_2 \end{matrix}$$

Using the rules of matrix algebra, a point or line (or other geometric element represented in matrix notation) can be operated on by a transformation matrix to yield a new element.

There are several common transformations used in computer graphics. We will discuss three transformations: translation, scaling, and rotation.

TRANSLATION.

Translation involves moving the element from one location to another. In the case of a point, the operation would be

$$x' = x + m, \qquad y' = y + n$$

where x', y' = coordinates of the translated point

x, y = coordinates of the original point

m, n = movements in the x and y directions, respectively

In matrix notation this can be represented as

$$(x', y') = (x, y) + T$$

where

T = (m,n), the translation matrix

Any geometric element can be translated in space by applying Eq. to each point that defines the element. For a line, the transformation matrix would be applied to its two end points.

SCALING.

Scaling of an element is used to enlarge it or reduce its size. The scaling need not necessarily be done equally in the x and y directions. For example, a circle could be transformed into an ellipse by using unequal x and y scaling factors.

The points of an element can be scaled by the scaling matrix as follows:

$$(x' ,y') = (x,y)S$$

where

$$s \quad \begin{matrix} m & 0 \\ O & n \end{matrix} \qquad \text{the scaling matrix}$$

This would produce an alteration in the size of the element by the factor m in the x-direction and by the factor n in the y direction. It also has the effect of repositioning the element with respect to the cartesian system origin. If the scaling factors are less than I, the size of the element is reduced and it is moved closer to the origin. If the scaling factors are larger than I, the element is enlarged and removed farther from the origin.

ROTATION.

In this transformation, the points of an object are rotated about the origin by an angle O. For a positive angle, this rotation is in the counterclockwise direction. This accomplishes rotation of the object by the same angle, but it also moves the object. In matrix notation, the procedure would be as follows:

$$(x',y') = (x,y)R$$

where

$$R = \begin{matrix} \cos O & \sin O \\ \sin O & \cos O \end{matrix} \qquad \text{the rotation matrix}$$

EXAMPLE 1: As an illustration of these transformations in two dimensions, consider the line defined by

$$L = \begin{matrix} 1 & 1 \\ 2 & 4 \end{matrix}$$

Let us suppose that it is desired to translate the line in space by 2 units in the x direction and 3 units in the y direction. This would involve adding 2 to the current x value and 3 to the current y value of the end points defining the line. That is,

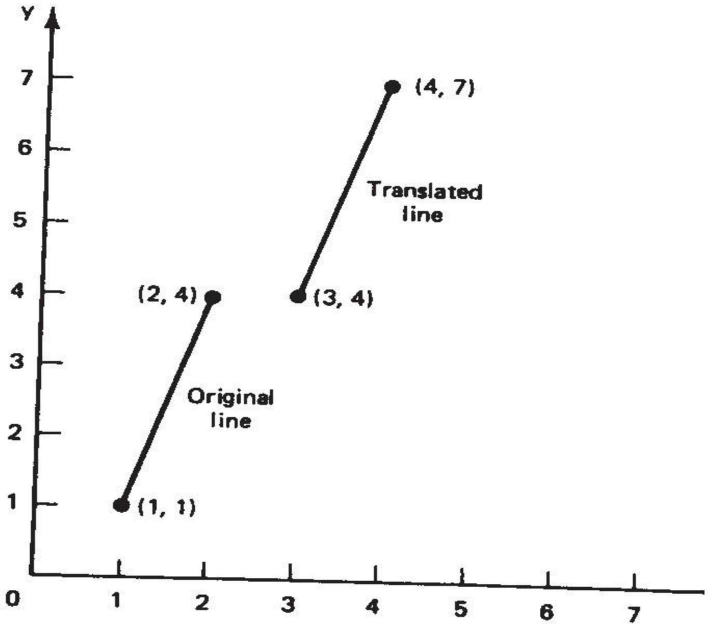


FIGURE. Results of translation in Example 6.1.

$$\begin{matrix} 1 & 1 & 2 & 3 & 3 & 4 \\ 2 & 4 & 2 & 3 & 4 & 7 \end{matrix}$$

The new line would have end points at (3, 4) and (4, 7). The effect of the transformation is illustrated in Figure 6.3.

Example 2: For the same original line as in Example 6.l, let us apply the scaling factor of 2 to the line. The scaling matrix for the 2 x 2 line definition would therefore be

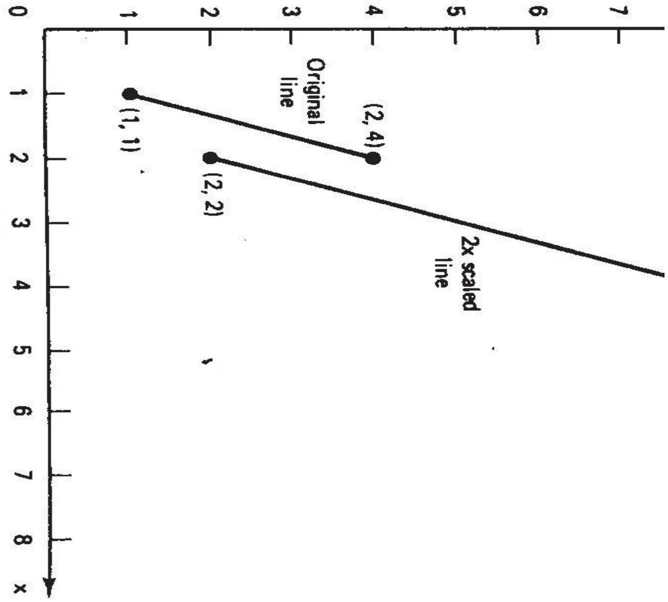
$$T = \begin{matrix} 2 & O \\ O & 2 \end{matrix}$$

The resulting line would be determined by Eq. as follows:

$$\begin{matrix} l & l & 2 & O & 2 & 4 \\ 2 & 4 & O & 2 & 4 & 8 \end{matrix}$$

The new line is pictured in Figure .

Example 3: We will again use our same line and rotate the line about the origin by 3O°. Equation would be used to determine the transformed line where the rotation matrix would be:



FigureResults of scaling in Example .

$$R = \begin{matrix} \cos 3O & \sin 3O & O.866 & O.5OO \\ \sin 3O & \cos 3O & O.5OO & O.866 \end{matrix}$$

The new line would be defined as:

1 1 0.866 0.500 0.366 1.366
2 4 0.500 0.866 0.268 4.464

The effect of applying the rotation matrix to the line is shown in Figure.

Three-dimensional transformations

Transformations by matrix methods can be extended to three-dimensional space. We consider the same three general categories defined in the preceding section. The same general procedures are applied to use these transformations that were defined for the three cases by Eqs. translation. The translation matrix for a point defined in three dimensions would be

T = (m. n, p)

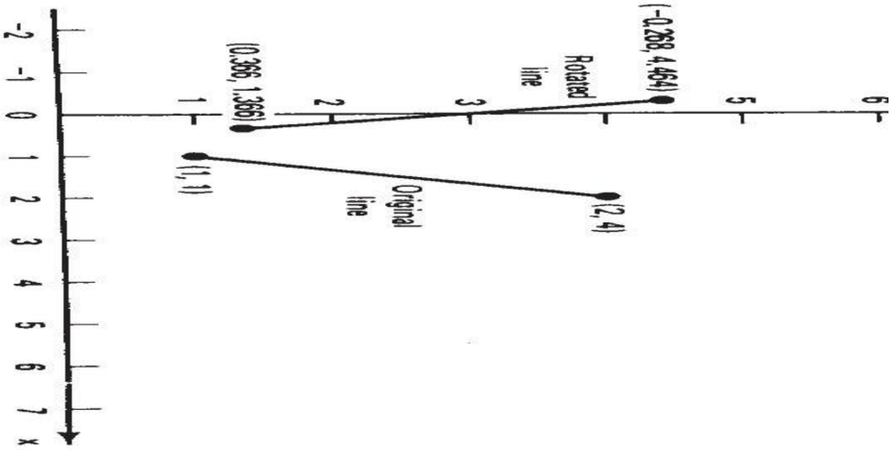


FIGURE Results of rotation in Example

and would be applied by adding the increments m, n, and p to the respective coordinates of each of the points defining the three-dimensional geometry element.

SCALING.

The scaling transformation is given by

$$S = \begin{matrix} m & O & O \\ O & n & O \\ 0 & 0 & p \end{matrix}$$

For equal values of m, n, and p, the scaling is linear.

ROTATION. Rotation in three dimensions can be defined for each of the axes

Rotation about the z axis by an angle is accomplished by the matrix

$$R_z = \begin{matrix} \cos & \sin & O \\ \sin & \cos & O \\ 0 & 0 & 1 \end{matrix}$$

Rotation about the y axis by the angle 6 is accomplished similarly.

$$R_y = \begin{matrix} \cos & 0 & \sin \\ O & 1 & O \\ \sin & 0 & \cos \end{matrix}$$

Rotation about the x axis by the angle is done with an analogous transformation matrix.

$$R_x = \begin{matrix} l & O & O \\ O & \cos & \sin \\ 0 & \sin & \cos \end{matrix}$$

Concatenation

The previous single transformations can be combined as a sequence of transformations. This is called concatenation, and the combined transformations are called concatenated transformations.

During the editing process when a graphic model is being developed. the use of concatenated transformations is quite common. It would be unusual that only a single transformation would be needed to accomplish a desired manipulation of the image. Two examples of where combinations of transformations would be required would be: -

Rotation of the element about an arbitrary point in the element

Magnifying the element but maintaining the location of one of its points in the same location

In the first case, the sequence of transformations would be' translation to the origin, then rotation about the origin, then translation back to the original location. In the second case, the element would be scaled (magnified) followed by a translation to locate the desired point as needed:-

The objective of concatenation is to accomplish a series of image manipulations as a single-transformation. This allows the concatenated transformation to be defined more concisely and the computation can generally be accomplished more efficiently.

Determining the concatenation of a sequence of single transformations can be fairly straightforward if the transformations are expressed in matrix form as we have done. For example. if we wanted to scale a point by the factor of 2 in a two dimensional system and then rotate it about the origin by 45°, the concatenation would simply be the product of the two transformation matrices. It is important that the order of matrix multiplication be the same as the order in which the transformations are to be carried out. Concatenation of a series of transformations becomes more complicated when a translation is involved, and we will not consider this case.

MODELLING

WIRE-FRAME VERSUS SOLID MODELING

The importance of three-dimensional geometry

Early CAD systems were basically automated drafting board systems which displayed a two-dimensional representation of the object being designed. Operators (e.g., the designer or drafter) could use these graphics systems to develop the line drawing the way they wanted it and then obtain a very high quality paper plot of the drawing. By using these systems, the drafting process could be accomplished in less time, and the productivity of the designers could be improved.

However, there was a fundamental shortcoming of these early systems. Although they were able to reproduce high-quality engineering drawings efficiently and quickly, these systems stored in their data files a two-dimensional record of the drawings. The drawings were usually of three-dimensional objects and it was left to the human beings who read these drawings to interpret the three-dimensional shape from the two-dimensional representation. The early CAD systems were not capable of interpreting the three-dimensionality of the object. It was left to the user of the system to make certain that the two-dimensional representation was correct (e.g., hidden lines removed or dashed, etc.), as stored in the data files.

More recent computer-aided design systems possess the capability to define objects in three dimensions. This is a powerful feature because it allows the designer to develop a full three-dimensional model of an object in the computer rather than a two-dimensional illustration. The computer can then generate the orthogonal views, perspective drawings, and close-ups of details in the object.

The importance of this three-dimensional capability in interactive computer graphics should not be underestimated.

Wire-Frame models

Most current day graphics systems use a form of modeling called wire- frame modeling. In the construction of the wire-frame model the edges of the objects are shown as lines. For objects in which there are curved surfaces, contour lines can be added; as shown in Figure, to indicate the contour. The image assumes the appearance of a frame constructed out of wire - hence the name wire frame model.

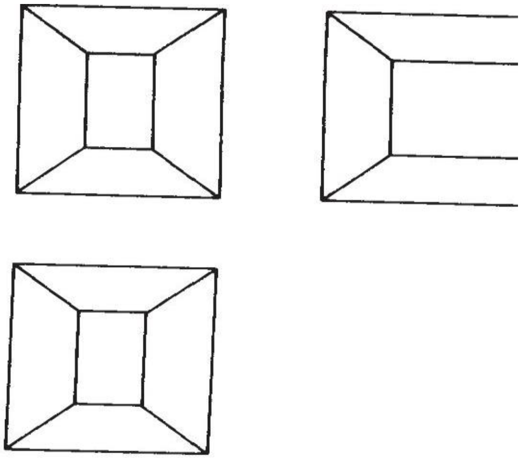


Figure : Orthographic views of three-dimensional object without hidden- ine removal.

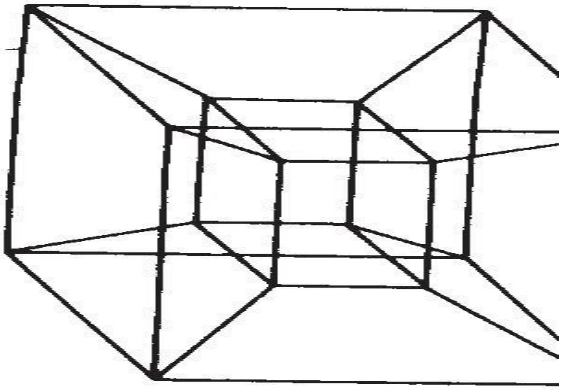


Figure : Perspective view of three-dimensional object of Figure without hidden line removal.

There are limitations to the models which use the wire-frame approach to form the image. These limitations are, of course, especially pronounced in the case of three-dimensional objects. In many cases, wire-frame models are quite adequate for two-dimensional representation. The most conspicuous limitation is that all of the lines that define the edges (and contoured surfaces) of the model are shown in the image. Many three-dimensional wire-frame systems in use today do not possess an automatic hidden-line removal feature. Consequently, the lines that indicate the edges at the rear of the model show right through the foreground surfaces. This can cause the image to be somewhat confusing to the viewer, and in some cases the image might be interpretable in several different ways. This interpretation problem can be alleviated to some extent through human intervention in removing the hidden background lines in the image.

There are also limitations with the wire-frame models in the way many CAD systems define the model in their data bases. For example, there might be ambiguity in the case of a surface definition as to which side of the surface is solid. This type of limitation prevents the computer system from achieving a comprehensive and unambiguous definition of the object.

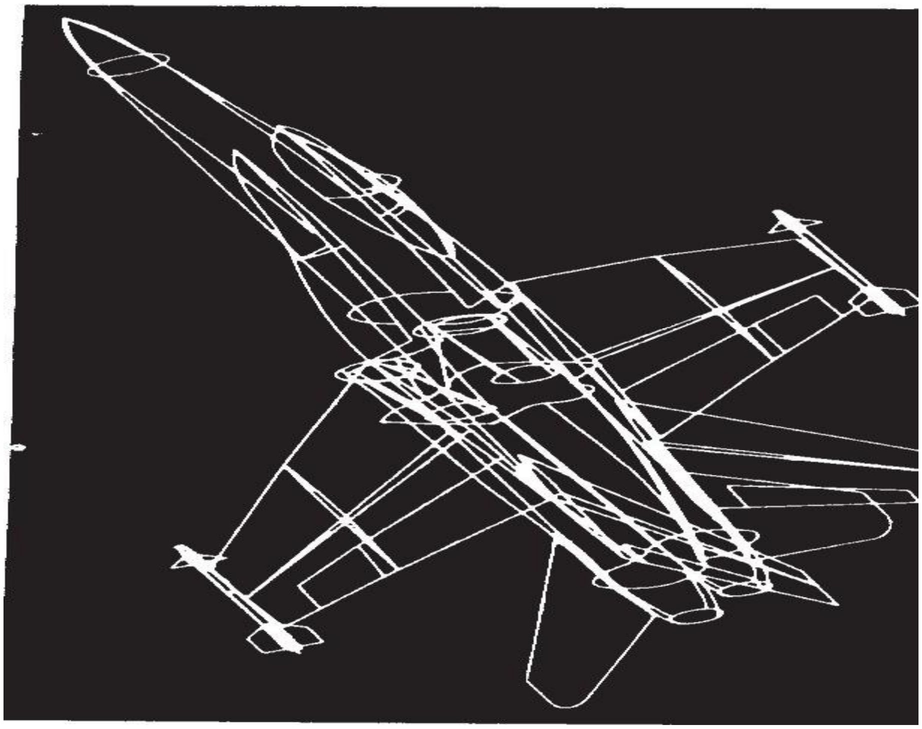


Figure : Wireframe model of F/A-l8 fighter aircraft, showing primary control curves.

Solid models

An improvement over wire-frame models, both in terms of realism to the user and definition to the computer, is the solid modeling approach. In this approach, the models are displayed as solid objects to the viewer, with very little risk of misinterpretation. When color is added to the image, the resulting picture becomes strikingly realistic. It is anticipated that graphics systems with this capability will find a wide range of applications outside computer-aided design and manufacturing. These applications will include' color illustrations in magazines and technical publications, animation in movie films, and training simulators (e.g., aircraft pilot training).

There are two factors which promote future widespread use of solid modelers (i.e., graphics systems with the capability for solid modeling). The first is the increasing awareness among users of the limitations of wire-frame systems. As powerful as today's wire-frame-based CAD systems have become, solid model systems represent a dramatic improvement in graphics technology. The second reason is the continuing development of computer hardware and software which make solid modeling possible. Solid modelers require a great deal of computational power, in terms of both speed and memory, in order to operate.

The advent of powerful, low-cost minicomputers has supplied the needed capacity to meet this requirement. Developments in software will provide application programs which take advantage of the opportunities offered by solid modelers. Among the possibilities are more highly automated model building and design systems, more complete three-dimensional engineering analysis of the models, including interference checking, automated manufacturing planning, and more realistic production simulation models.

Two basic approaches to the problem of solid modeling have been developed:

l. Constructive solid geometry (CSG or C-rep), also called the building-block approach

2. Boundary representation (B-rep)

The CSG systems allow the user to build the model out of solid graphic primitives, such as rectangular blocks, cubes, spheres, cylinders, and pyramids. This building-block approach is similar to the methods described in Section 6.4 except that a solid three-dimensional representation of the object is produced. The most common method of structuring the solid model in the graphics data base is to use Boolean operations, described in the preceding section and pictured in Figure.

The boundary representation approach requires the user to draw the outline or boundary of the object on the CRT screen using an electronic tablet and pen or analogous procedure. The user would sketch the various views of the object (front, side, and top, more views if needed), drawing interconnecting lines among the views to establish their relationship. Various transformations and other specialized editing procedures are used to refine the model to the desired shape. The general scheme is illustrated in Figure

The two approaches have their relative advantages and disadvantages. The C-rep systems usually have a significant procedural advantage in the initial formulation of the model. It is relatively easy to construct a precise solid model out of regular solid primitives by adding, subtracting, and intersecting the components. The building-block approach also results in a more compact file of the model in the database.

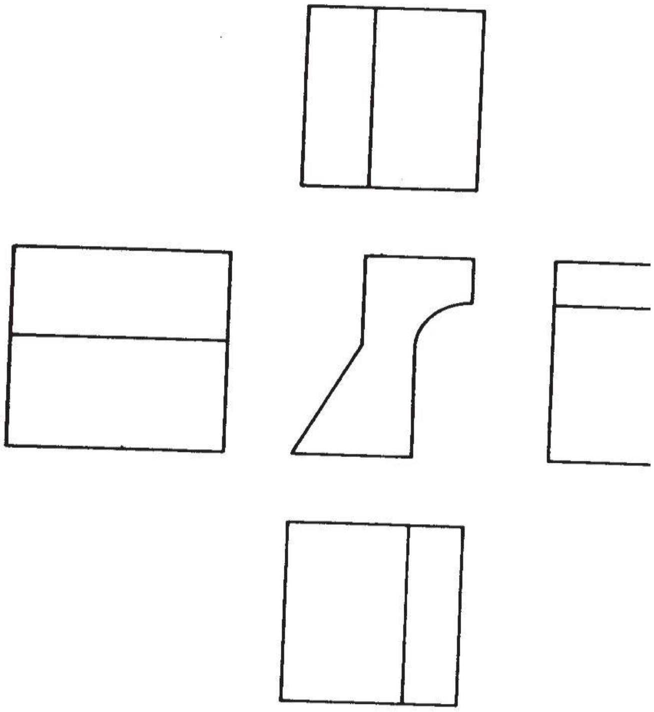


Figure 2.4: Input views of the types required for boundary representation (B-rep) .

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On the other hand, B-rep systems have their relative advantages. One of them becomes evident when unusual shapes are encountered that would not be included within the available repertoire of the CSG systems. This kind of situation is exemplified by aircraft fuselage and wing shapes and by automobile body styling. Such shapes would be quite difficult to develop with the building-block approach, but the boundary representation method is very feasible for this sort of problem.

Another point of comparison between the two approaches is the difference in the way the model is stored in the data base for the two systems. The CSG approach stores the model by a combination of data and logical procedures (the Boolean model). This generally requires less storage but more computation to reproduce the model and its image. By contrast, the B-rep system stores an explicit definition of the model boundaries. This requires more storage space but does not necessitate nearly the same computation effort to reconstruct the image. A related benefit of the B-rep systems is that it is relatively simple to convert back and forth between a boundary representation and a corresponding wire-frame model. The reason is that the model's boundary definition is similar to the wire-frame definition, which facilitates conversion of one form to the other. This makes the newer solid B-rep systems compatible with existing CAD systems out in the field.

Because of the relative benefits and weaknesses of the two approaches, hybrid systems have been developed which combine the CSG and B-rep approaches. With these systems, users have the capability to construct the geometric model by either approach, whichever is more appropriate to the particular problem.

UNIT -II
GEOMETRIC MODELING

Geometry
Topology
Spatial addressability

Geometry Vs Topology

For wire frame- geometrical data
For surface model- geometrical data
For solid model- topology and geometry

Geometry is the acual dimensions that defines entities of a object

Geometry is visible to users
The geometry that defines the object shown below
Length of lines L1, L2, L3
Angle between lines
The center point P1 of semi circle

Topology or Combinational structure

It is the connectivity and association of the object entity
It determines relational information between object entities

Topology of object can be stated as below

L1 shares a vertex point with L2 & C1
L2 shares a vertex point with L1 & L3
L3 shares a ertex point with L2 & C1
L1 & L3 do not overlap
P1 lies outside the object

Example for better understanding

a) Same geometry but different topology
b) Same topology but different geometry

Spatial Addresability

A complete geometric data representation of an object is one that enables points in space to be classified relative to the object, if it is inside or outside or on the object

Addresability

A complete geometric data representation of an object is one that enables points in space to be classified relative to the object, if it is inside or outside or on the object This classification is called spatial addressability.

3D modeling	Point location			Spatial addresability
	On object	Inside object	Outside Object	
Wire frame				Incapable of handling spatial address
Surface				Incapable of handling spatial address
Solid				Capable of handling spatial address

Free form surfaces

These are the surfaces which cannot be defined by any analytical techniques

Ex: Sculpture surface Surface is controlled by series of control points and boundaries

These are large number of numerical techniques available such as Brazier, Curves, Spline surfaces and NURBS, etc

Classification of surfaces

I. Planar surfaces: a flat 2Dsurface

II. Curved surfaces :

Single curved surfaces :It s a simple curved surface obtained by rotating straight lines around an axis Ex: cylindrical, conical, pyramid surfaces, prisms and -Double curved surfaces: They are complex surfaces generated by complex curved lines/ surfaces

Ex: Spherical, Torous, Ellipsoid, Parabaloid, Fuselage, Automobiles, etc

A ruled surface: constructed by transiting between two or more curves by using linear bending between each section OF SURFACE. Curve fittingmethods

For geometrical modeling curve fitting methods are generally used which are broadly classified as: Interpolation techniques

Between interpolation & approximation

Interpolation	Best fit/ Approximate
Curve can be made to pass through all the control data points for	The curve does not pass through all the points for designing curves and surfaces
Actual shape between points depends on degree of polynomial & boundary condition	Used in computer graphics to design curves that look good and aesthetic goal. It can also be used to design free form surfaces, sculptures, surface of automobiles, aerodynamic profile
Used to reconstruct the shape of degitized curved object Ex: cubic spline	These techniques are preferred over interpolation in curve design due to the added flexibility and additional initiative fuel Ex: Bazier curve, B- Spline
Cubic spline & Lagrange	Regression & least square matrix are used

The shape of curve is affected greatly by manipulating a single data point. The nature	It is possible to have local modification by tweaking a single point where the behavior is more predictable

Important properties for designing curves

Control points : data points

1. start from 0 to n
2. total n+1 points
3. Multiple values: parametric formation of a curve allows it to represent multiple valued shapes. A curve is multi valued with respect to all coordinate systems
4. Axis of independence: - curves must be independent of coordinate systems
   if any point on curve is moved by x0 then the curve rotates x0 but shape does not change.
5. Control :- Global control: moving any control point on curve , this leads o entire curve moves.
   Ex:Bazier curve
   Local control: moving control point on curve results only that point move on curve.
   Ex: B- spline
6. Variation Diminishing properties : Curve should not oscillate widely away from it is defined control pairs.
   Ex: Brazier curves.
7. Versactality : depends on the number of control points. Ex: complex curve more control points
8. Order of continuity: Continuity at joints between curves. ex:
   c^0, c^1, c^2

Parametric continuity condition

Data points are called control points to construct a smooth curve that passes through the given data points, various continuity requirements can be specified at the data points to impose various degree of smoothness of the resulting curve.

The order f continuity becomes more important where a complex curve is modeled by several curved segments pieced together end to end. If each set of curve is described with parametric coordinate functions of the form x=f(u), y=g(u), & l= h(u)

Whereumin$\leq$ u $\leq$ umax

To ensure a smooth transition from one section of segment to the next we can impose the following continuity condition at the joint of connecting points. Therefore, - Zero order parametric continuity (c0)

- First order parametric continuity (c1)
- Second order parametric continuity (c2)

C0 continuity: zero order parametric continuity describes as c0 continuity means simply that the curves meet i.e. values of x,y,z evaluated t umax of first curve section are equal respectively to the values of x,y,z evaluated at uminfor the next curve section.

C1 continuity: the first order parametric continuity referred as c1 continuity means that the first parametric derivatives (tangent lines/ vectors) of coordinate function is function for two successive curve sections are equal after joining points. Curves are same as the intersection. First order continuity is often sufficient for digitizing drawings and for some design applications.

C2 continuity: second order parametric continuity c2 continuity means that the both first order and second order parametric derivates of line segment sections (i.e. end points of firs segment sections 2nd order parametric derivatives= start point of 2nd segment, 1st and 2nd order parametric derivatives.) are same at the intersection.

First derivative of parametric equations of segment – end point = first order derivative parametric equation of start point of 2nd segment.

Similarly End point of 2nd order derivative of 1st segment= start point of 2nd order derivative of 2nd Segment 2nd order continuity is useful for setting approximation path for camera motion for many precisions CAD requirements.

Blending function

When modeling a curve f(x) by using curve segments, we try to represent the curve as a sum of smaller segments Ǿi(x) called blending function or basis function.

Analytical curves

Analytical curves are defined as those that can be described by analytical equations such as lines, circles and conics. Analytical curves provide very compact forms to represent shapes and simplify the computation of related properties such as areas and volumes

Analytical curves are not attractive to deal with interactively

Analytical curves are points, lines, arcs and circles, fillets and chambers and also conics like parabola, hyperbola, ellipse, etc.

Synthetic curves

A synthetic curve is defined as that can be described by a set of data points(control points) such as splines and bazier curves. Synthetic curves provide designers with greater flexibility and control of curve shapes by changing the positions of control points. Global and local control of a curve is possible. Synthetic curves are attractive to deal with interactively

Synthetic curves include various types of splines like cubic spline, B- spline, NURBS and Bazier curves.

Curves

A 3D curve is an object in space that the direction only much like a thread A curve has one degree of freedom. This means that a point on a curve can be moved in only one independent direction Curve representation: is represented by an equation or group of equations that has only one free variable or parameter (i.e. u)

The x,y,z coordinates of any point on the curve are determined by this free variable or parameter

Mathematically there are 2 types of curve representatons

a) Non parameteric form: - explicit -implicit

b) Parameteric form:

-analytical

-synthetical

Parametric curve description

A parametric form curve is described by an equation or group of equations that has only one free variable or parameter.

Surface

A surface is a 3D space in an object that has breadth and width much like a piece of cloth A surface has two degrees of freedom. This means that a point on surface can be moved in 2independent directions The x,y,z coordinates of any point on the surface are determined by these free variables or parameters(i.e. u & v) Mathematically there are two types of surface description

Non parametric surface description: - implicit -explicit

Parametric surface description: -analytical -synthetic

PARAMETERIC REPRESENTATION OF SYNTHETIC CURVES

-Analytical curves are insufficient to meet the requirement of mechanical points having complex curve shapes such as Propeller blades Aircraft wings Ship nuts Automobile bodies

The composite require free form or synthetic curve -Design of curved boundaries and surfaces require curve representations that can be manipulated by changing data points which will create bends and sharp turns in the shape of the curve These curves are called Synthetic curve and data points are called control points.

-If curve passes through all the data points it is called as interpolated curve.

-The smoothness of curve is mere important requirement of synthetic curve. Most popular synthetic curves are

- Hermit cube
- Bezier curve
- B- spline
- NURBS (Non- Uniform Rotation B- Spline)

1) Hermit cube curve (HCC)

- HCC is defined by defining 2position vectors and 2 tangent vectors at data points
- Hermit cube curve is also called as parametric cube curve and cubic spline
- The curve is used to interpolate given data points but not free form curve
- The most commonly used, cubic spline is a 3D planer curve
- It is represented by cubic polynomial
- Several splines can be joined together by imposing slope continuity at the corner points.
- The parametric equation for a cubic spline is given by

  $P\ u = {}_{=0}^{3}\ a_i u_i \qquad 0<u<1$

(1)

Where $a_i$are polynomial coefficients and u is the parameter.

Expand (1)

$P(u)= a_0+a_1u+a_2u^2+a_3u^3$

------(2)

If x,y,z are coordinates of P equation be

$X(u) = a_{0x}+a_{1x}u+ a_{2x}u^2+a_{3x}u^3$

$Y(u) = a_{0y}+a_{1y}u+ a_{2x}u^2+a_{3y}u^3$

$Z(u) = a_{0x}+a_{1x}u+ a_{2x}u^2+a_{3z}u^3$

Tangent vector to the curve at any point is obtained by differentiating equation (1) wrt u

Now $P'(u) = {}^{3}_{=0}\ ai.i.u^{i-1}$

Where $0<u<1$

-- (3)

(i) Tangent vector at point P can be defined as

$X'(u)= a_{1x}+ 2a_{2x}u+3a_{3x}u^2$

$Y'(u)= a_{1x}+ 2a_{2x}u+3a_{3y}u^2$

$Z'(u)= a_{1x}+ 2a_{2x}u+3a_{3z}u^2$

The coefficients can be evaluated by applying the boundary conditions at the end points.

Substituting boundary conditions at u=0, u=1 in equation (2) & (3) we get

$P_0= P(0)= a_0$

$P_1 = P(1) = a_0 + a_1 + a_2 + a_3$
$P'_0 = P'(0) = a_1$
$P'_1 = P'(1) = a_1 + 2a_2 + 3a_3$
Solving these equations simultaneously for coefficients, we get
$a_0 = P_0$,
$a_1 = P_0$
$a_2 = 3(P_1 - P_0) - (2P'_0 + P'_1)$

$a_3 = -2(P_1 - P_0) + P'_0 + P'_1$

Parametric Cubic Curves

In order to assure C1 continuity at two extremities, our functions must be of at least degree

$$x = a_x t^3 + b_x t^2 + c_x t + d_x$$

$$y = a_y t^3 + b_y t^2 + c_y t + d_y$$

Here's what a parametric cubic spline function looks like: Alternatively, it can be written in matrix form:

$$[x \quad y] = [t^3 \quad t^2 \quad t \quad 1] \begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix}$$

Solving for Coefficients

An Illustrative Example

Cubic Hermite Splines:

Hermite Specification

The Gradient of The Gradient of a Cubic Spline

$$\begin{bmatrix} \frac{dx}{dt} & \frac{dy}{dt} \end{bmatrix} = \begin{bmatrix} 3t^2 & 2t & 1 & 0 \end{bmatrix} \begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix}$$

The Hermite Specification as a Matrix Equation

$$\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \frac{dx_1}{dt} & \frac{dy_1}{dt} \\ \frac{dx_2}{dt} & \frac{dy_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 3 & 2 & 1 & 0 \end{bmatrix} \begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix}$$

Solve for the Hermite Coefficients

$$\begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 3 & 2 & 1 & 0 \end{bmatrix}^{-1} \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \frac{dx_1}{dt} & \frac{dy_1}{dt} \\ \frac{dx_2}{dt} & \frac{dy_2}{dt} \end{bmatrix} = \begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix}$$

The Hermite Specification as a Matrix Equation

$$\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \frac{dx_1}{dt} & \frac{dy_1}{dt} \\ \frac{dx_2}{dt} & \frac{dy_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 3 & 2 & 1 & 0 \end{bmatrix} \begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix}$$

Spline Basis and Geometry Matrices

$$\underbrace{\begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{M}_{Hermite}} \underbrace{\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \frac{dx_1}{dt} & \frac{dy_1}{dt} \\ \frac{dx_2}{dt} & \frac{dy_2}{dt} \end{bmatrix}}_{\mathbf{G}_{Hermite}} = \begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix}$$

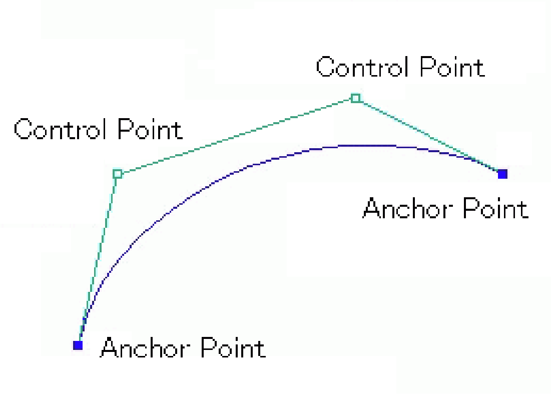
Resulting Cubic Hermite Spline Equation

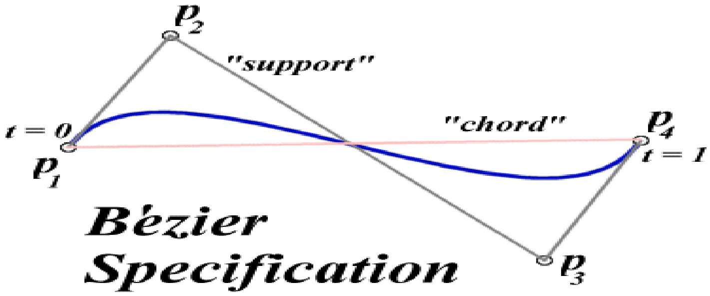
$$[x \quad y] = [t^3 \quad t^2 \quad t \quad 1] \underbrace{\begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{M}_{Hermite}} \underbrace{\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \frac{dx_1}{dt} & \frac{dy_1}{dt} \\ \frac{dx_2}{dt} & \frac{dy_2}{dt} \end{bmatrix}}_{\mathbf{G}_{Hermite}}$$

Bézier Curves

Another Spline class that has more intuitive controls

A Cubic Bézier Spine has four control points, two of which are knots.





Bezier spline is a way to define a curve by sequence of two end points and one or more control points which control the curve.
Two end points are called Anchor Points.
The bezier splines with two control points are called Cubic Bezier Spline.

Coefficients for Cubic Bezier Splines

It just so happens that the knot gradients of a Bezier Spline can be expressed in terms of

the adjacent control points: $\begin{aligned} \nabla p_1 &= 3(p_2 - p_1) \\ \nabla p_4 &= 3(p_4 - p_3) \end{aligned}$

$$\underbrace{\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \frac{dx_1}{dt} & \frac{dy_1}{dt} \\ \frac{dx_2}{dt} & \frac{dy_2}{dt} \end{bmatrix}}_{\mathbf{G}_{Hermite}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -3 & 3 & 0 & 0 \\ 0 & 0 & -3 & 3 \end{bmatrix} \underbrace{\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \end{bmatrix}}_{\mathbf{G}_{Bezier}}$$

$$\begin{bmatrix} a_x & a_y \\ b_x & b_y \\ c_x & c_y \\ d_x & d_y \end{bmatrix} = \underbrace{\begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{M}_{Bezier}} \underbrace{\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \end{bmatrix}}_{\mathbf{G}_{Bezier}}$$

Bezier Blending Functions

The reasonable justification for Bezier spline basis can only be approached by considering its blending functions:

$$p(t) = \begin{bmatrix} (1-t)^3 \\ 3t(1-t)^2 \\ 3t^2(1-t) \\ t^3 \end{bmatrix}^{\mathbf{T}} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix}$$

This family of polynomials (called
properties:

They are all positive in the interval

B-spl

formulation

$Q_i(u) = \Sigma\, P_{i-3+k}\, B_{i-3+k}$

i is segment number, k is

$Q_i(u) = U\, B_S\, [\, P_{i-3}\, P_{i-2}$

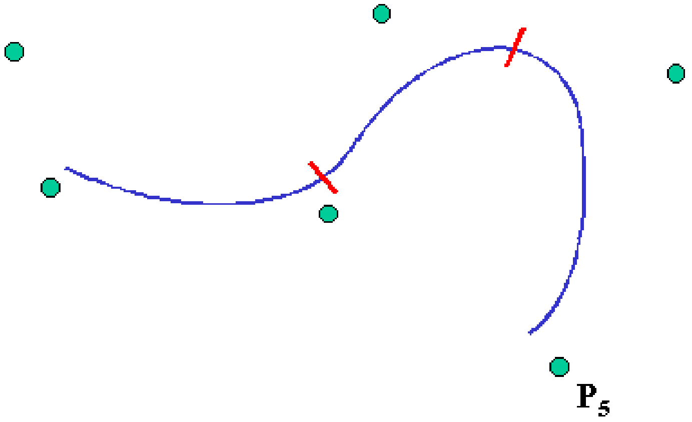
$= [u^3\ u^2\ u\ 1]\ 1/6\ \lceil -1$

3

-3

$\lfloor\ 1$

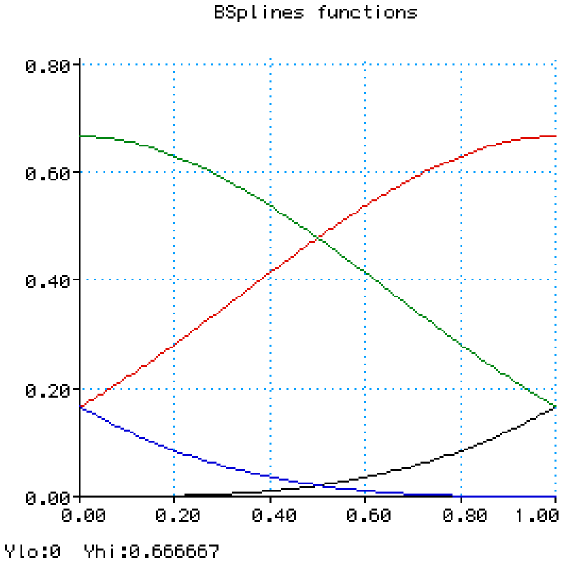
B-spline Segments



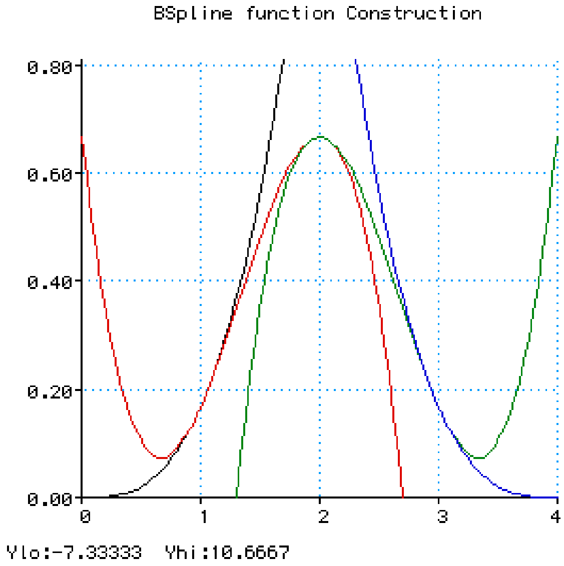
B Spline functions

Bi(u) = (u^3)/6Bi-1(u) = (-3*(u^3) + 3*(u^2) + 3*u +1)/6
Bi-2(u) = (3*(u^3) - 6*(u^2) +4)/6

Bi-3(u) = (1 - u)^3/6

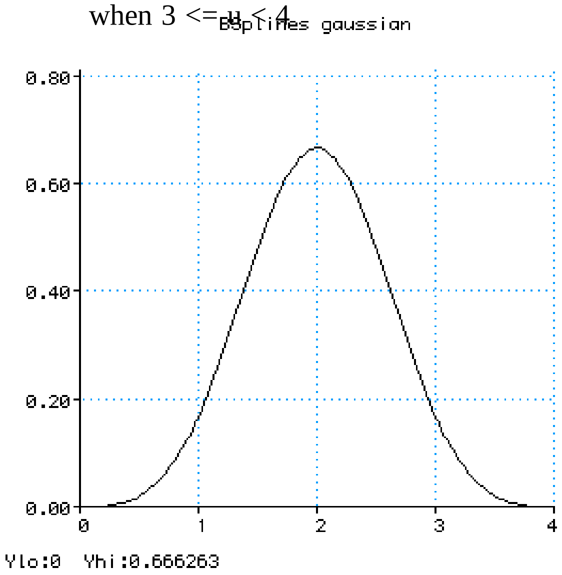


Bi(u) = (u^3)/6Bi-1(u) = (-3*((u-1)^3) + 3*((u-1)^2) + 3*(u-1) +1)/6
Bi-2(u) = (3*((u-2)^3) - 6*((u-2)^2) +4)/6
Bi-3(u) = (1 - (u-3))^3/6



Bi(u) = (u^3)/6
Bi-1(u) = (-3*((u-1)^3) + 3*((u-1)^2) + 3*(u-1) +1)/6
Bi-2(u) = (3*((u-2)^3) - 6*((u-2)^2) +4)/6
Bi-3(u) = (1 - (u-3))^3/6

B(u) = Bi(u) when 0 <= u < 1, Bi-1(u) when 1 <= u < 2, Bi-2(u) when 2 <= u < 3, Bi-3(u) when 3 <= u < 4

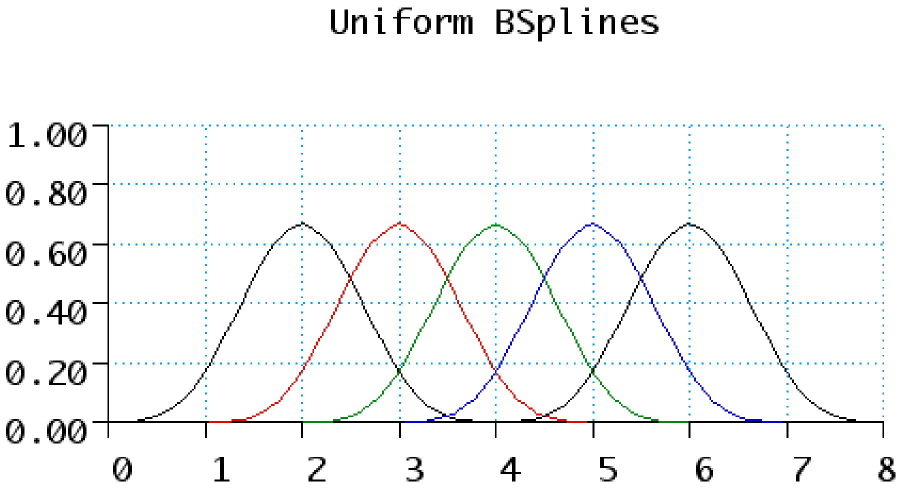


Bi(u) = (u^3)/6
Bi1(u) = (-3*((u-1)^3) + 3*((u-1)^2) + 3*(u-1) +1)/6
Bi2(u) = (3*((u-2)^3) - 6*((u-2)^2) +4)/6
Bi3(u) = (1 - (u-3))^3/6

B(u) = Bi(u) when 0 <= u < 1, Bi1(u) when 1 <= u < 2,

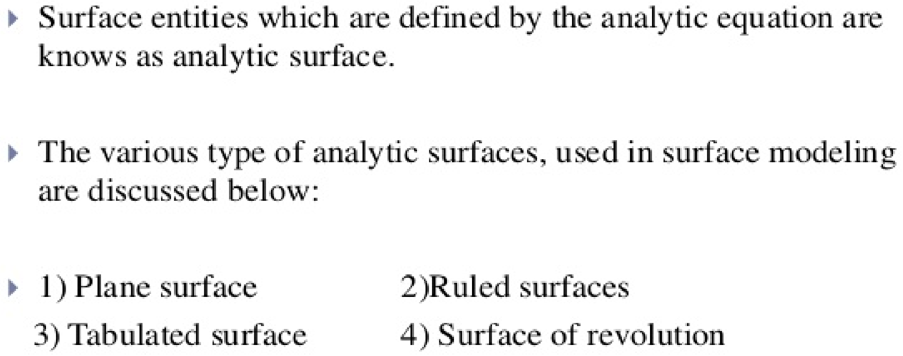
Bi2(u) when 2 <= u < 3,
Bi3(u) when 3 <= u < 4

B1(u) = B(u-1)
B2(u) = B(u-2)
B3(u) = B(u-3)
B4(u) = B(u-4)



Algebraic and geometric form:

Surface entities:



- Surface entities which are defined by the analytic equation are knows as analytic surface.

- The various type of analytic surfaces, used in surface modeling are discussed below:

- 1) Plane surface 2)Ruled surfaces
  3) Tabulated surface 4) Surface of revolution

Parametric space of surface , subdividing:

A **parametric surface** is a surface in the Euclidean space which is defined by a parametric equation with two parameters Parametric representation is a very general way to specify a surface, as well as implicit representation. Surfaces that occur in two of the main theorems of vector calculus, Stokes' theorem and the divergence theorem, are frequently given in a parametric form. The curvature and arc length of curves on the surface, surface area, differential geometric invariants such as the first and second fundamental forms, Gaussian, mean, and principal curvatures can all be computed from a given parameterization.

We can represent a surface as a series of grid points inside its bounding curves. Surfaces can be in two-dimensional space (planar) or in three-dimensional space (general surfaces). Surface can be described using non-parametric or parametric equations Surfaces can be represented by equations to pass through all the data points (fitting) or have patches of them connected at the data points.

Geometric Shape:

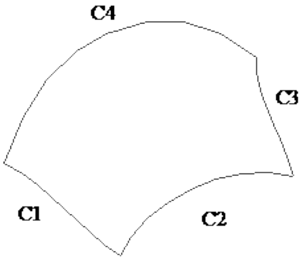
A geometric shape is the geometric information which remains when location, scale, orientation and reflection are removed from the description of a geometric object. That is, the result of moving a shape around, enlarging it, rotating it, or reflecting it in a mirror is the same shape as the original, and not a distinct shape.

Objects that have the same shape as each other are said to be similar. If they also have the same scale as each other, they are said to be congruent.

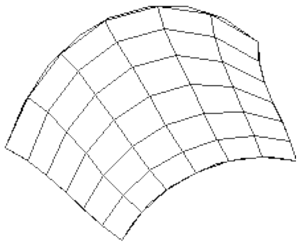
Many two-dimensional geometric shapes can be defined by a set of points or vertices and lines connecting the points in a closed chain, as well as the resulting interior points. Such shapes are called polygons and include triangles, squares, and pentagons. Other shapes may be bounded by curves such as the circle or the ellipse.

Subdividing:

A **parametric surface** is a **surface** in the Euclidean **space** which is defined by a**parametric** equation with two parameters. **Parametric** representation is a very general way to specify a **surface**, as well as implicit representation.



(a) Closed boundary



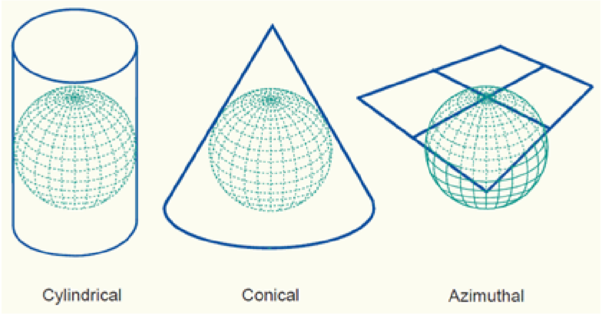
(b) Coons patch

Cylindrical Surface:

A cylindrical surface whose generatrix is parallel to one of the coordinate axes and whose directrix is a curve in the coordinate plane that is perpendicular to the generatrix, has the same equation as the directrix. For example, if the directrix is the ellipse. in the x-y plane, the equation of the ellipse as

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$$

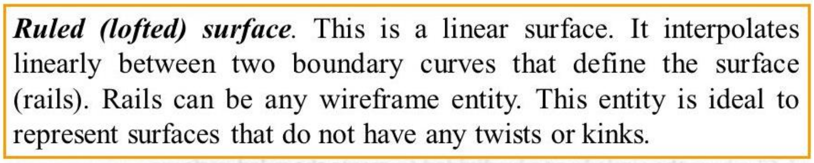
In the x-y plane, the equation of the cylinder is Cylinder. (1) A cylindrical surface (2) Suppose we are given two parallel planes and two simple closed curves C1 and C2 in these planes for which lines joining corresponding points of C1 and C2 are parallel to a given line L. A cylinder is a closed surface consisting of two bases which are plane regions bounded by such curves C1 and C2 and a lateral surface which is the union of all line segments joining corresponding points of C1 and C2. Each of the curves C1 and C2 is a directrix of the cylinder and the line segments joining corresponding points of C1 and C2 are elements (or generators or rulings). The cylinder is circular or elliptic if a directrix is a circle or an ellipse, respectively. Sometimes a circular cylinder is defined to be a cylinder whose intersections with planes perpendicular to the elements are circles. The cylinder is a right cylinder or an oblique cylinder according as L is perpendicular to the planes or not perpendicular to the planes. The altitude of a cylinder is the perpendicular distance between the planes containing the bases and a right section is the intersection of the cylinder and a plane perpendicular to the elements that crosses the cylinder between the bases.



Ruled surface

Ruled Surfaces are surfaces that are generated using two curves with a straight line connecting each curve. The two driving curves can be 3D Curves or existing edges of parts or other surfaces. Ruled Surface, Ruled Surface to Point, and Ruled Surface to Face Examples.

A ruled surface can be described as the set of points swept by a moving straight line. For example, a cone is formed by keeping one point of a line fixed whilst moving another point along a circle. A surface is doubly ruled if through every one of its points there are two distinct lines that lie on the surface.


Ruled (lofted) surface. This is a linear surface. It interpolates linearly between two boundary curves that define the surface (rails). Rails can be any wireframe entity. This entity is ideal to represent surfaces that do not have any twists or kinks.

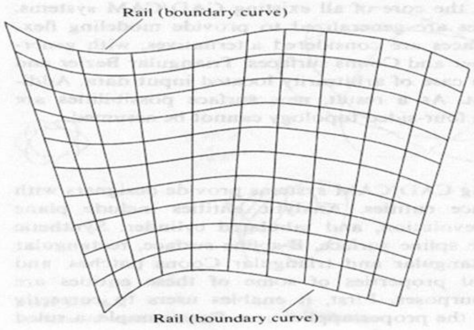
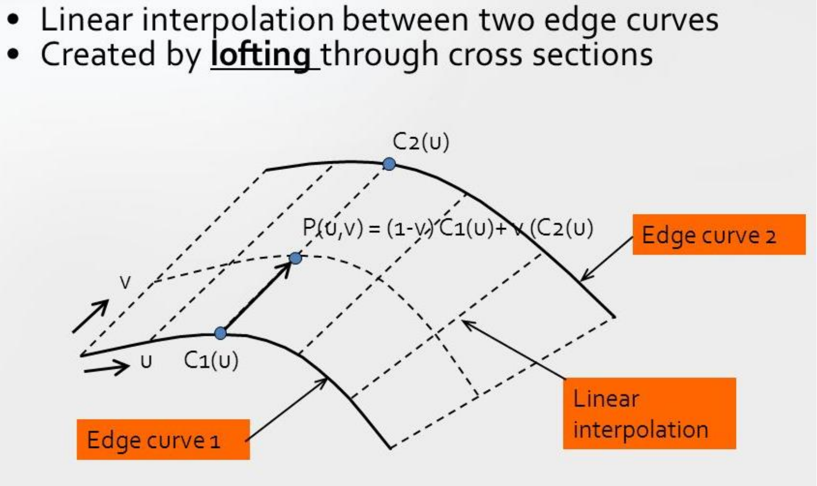


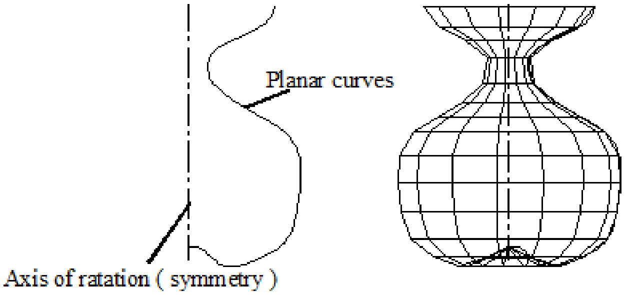
FIGURE 6-5
Ruled surface.



- Linear interpolation between two edge curves
- Created by **lofting** through cross sections

Surface of revolution spherical surface:

A surface of revolution is generated by revolving a given curve about an axis. The given curve is a ***profile curve*** while the axis is the ***axis of revolution.***.



Many commonly seen and useful surfaces are surfaces of revolution (e.g., spheres, cylinders, cones and tori).

Sphere:

A sphere is obtained by revolving a sei-circle about the axis of revolution. In the curve system, this semi-circle must be in the xz-plane and the axis of revolution must be the z-axis.

UNIT III

GROUP TECHNOLOGY

INTRODUCTION

Group technology (abbreviated GT) is a manufacturing philosophy in which similar parts are identified and grouped together to take advantage of their similarities in manufacturing and design. Similar parts are arranged into part families. For example, a plant producing lO,OOO different part numbers may be able to group the vast majority of these parts into 5O or 6O distinct families. Each family would possess similar design and manufacturing characteristics. Hence, the processing of each member of a given family would be similar, and this results in manufacturing efficiencies. These efficiencies are achieved in the form of reduced setup times, lower in-process inventories, better scheduling, improved tool control, and the use of standardized process plans. In some plants where GT has been implemented, the production equipment is arranged into machine groups, or cells, in order to facilitate work flow and parts handling.

In product design, there are also advantages obtained by grouping parts into families. For example, a design engineer faced with the task of developing a new part design must either start from scratch or pull an existing drawing from the files and make the necessary changes to conform to the requirements of the new part.

The problem is that finding a similar design may be quite difficult and time consuming. For a large engineering department, there may be thousands of drawings in the files, with no systematic way to locate the desired drawing. As a consequence, the designer may decide that it is easier to start from scratch in developing the new part. This decision is replicated many times over in the company, thus consuming valuable time creating duplicate or near-duplicate part designs. If an effective design- retrieval system were available, this waste could be avoided by permitting the engineer to determine quickly if a similar part already exists. A simple change in an existing design would be much less time consuming than starting from scratch. This design-retrieval system is a manifestation of the group technology principle applied to the design function. To implement such a system, some form of parts classification and coding is required.

Parts classification and coding is concerned with identifying the similarities among parts and relating these similarities to a coding system. Part similarities are of two types: design attributes (such as geometric shape and size), and manufacturing attributes (the sequence of processing steps required to make the part). While the processing steps required to manufacture a part are usually correlated with the part's design attributes, this is not always the case. Accordingly, classification and coding systems are often devised to allow for differences between a part's design and its manufacture.

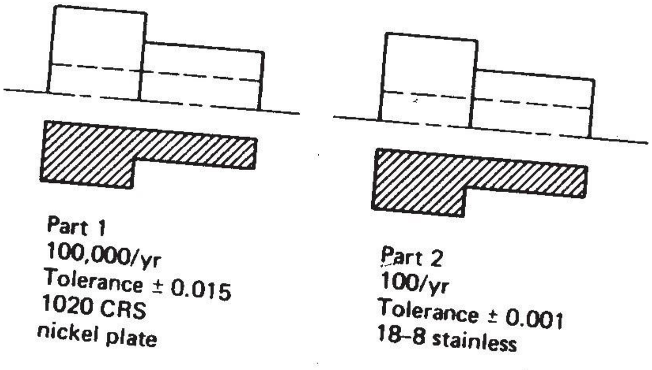
Whereas a parts classification and coding system is required in a design- retrieval system, it can also be used in computer-aided process planning (CAPP). Computer-aided process planning involves the automatic generation of a process plan (or route sheet) to manufacture the part. lbe process routing is developed by recognizing the specific attributes of the part in question and relating these attributes to the corresponding manufacturing operations.

In the present chapter we develop the topics of group technology and p classification and coding. In the following chapter we present a discussion of computer-aided process planning and several related issues. Group technology and parts classification and coding are based on the concept of a part family.

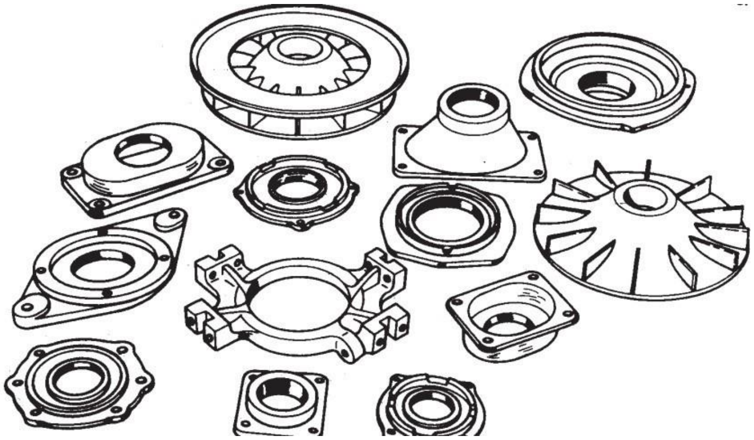
3.2 PART FAMILIES

A part family is a collection of parts which are similar either because of geometric shape and size or because similar processing steps are required in their manufacture. The parts within a family are different, but their similarities are close enough to merit their identification as members of the part family. Figures show two part families. The two parts shown in Figure are similar from design viewpoint but quite different in terms of manufacturing. The parts shown in Figure might constitute a part family in manufacturing, but their geometry characteristics do Dot permit them to be grouped as a design part family.

The part family concept is central to design-retrieval systems and modify current computer-aided process planning schemes. Another important manufacturing

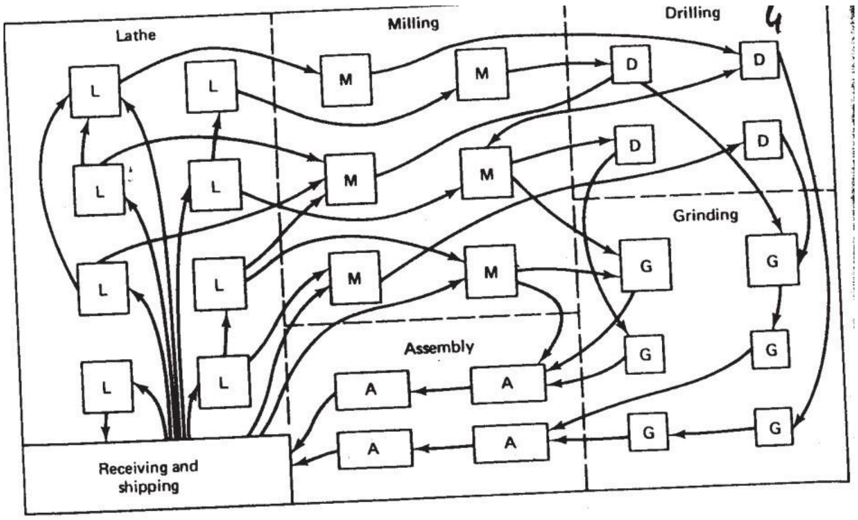


Two parts of identical shape and size but different manufacturing requirements.

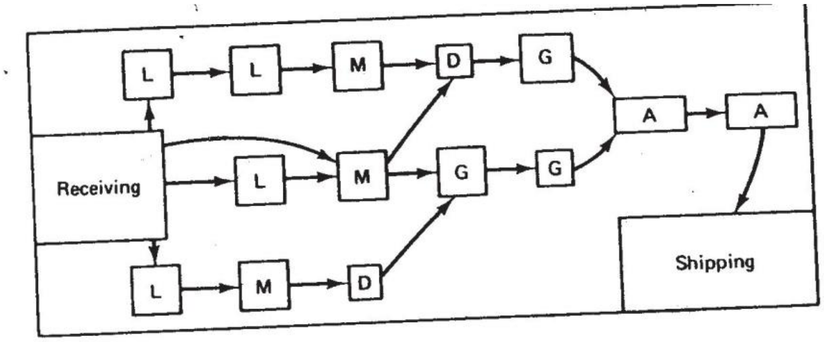


Thirteen parts with similar manufacturing process requirements but different design attributes.

Advantage derived from grouping workparts into families can be explained with reference to Figures. Figure shows a process-type layout for batch production in a machine shop. The various machine tools are arranged by function. There is a lathe section, milling machine section, drill press section, and so on. During the machining of a given part, the workpiece must be moved between sections, with perhaps the same section being visited several times. This results in a significant amount of material handling, a large in-process inventory, usually more setups than necessary, long manufacturing lead times, and high cost. Figure shows a production shop of supposedly equivalent capacity, but with the machines arranged into cells. Each cell is organized to specialize in the manufacture of a particular part family. Advantages are gained in the form of



Process-type layout.



Group technology layout.

reduced workpiece handling, lower setup times, less in-process inventory, less floor space, and shorter lead times. Some of the manufacturing cells can be designed to form production flow lines, with conveyors used to transport workparts between machines in the cell. The biggest single obstacle in changing over to group technology from a traditional production shop is the problem of grouping parts into families. There are three general methods for solving this problem. All three methods are time consuming and involve the analysis of much data by properly trained personnel. The three methods are:

2. Production flow analysis (PFA)
3. Parts classification and coding system

The visual inspection method is the least sophisticated and least expensive method. It involves the classification of parts into families by looking at either the physical parts or photographs and arranging them into similar groupings. This method is generally considered to be the least accurate of the three.

The second method, production flow analysis, was developed by J. L. Burbidge. PFA is a method of identifying part families and associated machine tool groupings by analyzing the route sheets for parts produced in a given shop. It groups together the parts that have similar operation sequences and machine routings. The disadvantage of PF A is that it accepts the validity of existing route sheets, with no consideration given to whether these process plans are logical or consistent. The production flow analysis approach does not seem to be used much at all in the United States.

The third method, parts classification and coding, is the most time consuming and complicated of the three methods. However, it is the most frequently applied method and is generally recognized to be the most powerful of the three.

3.3 PARTS CLASSIFICATION AND CODING

This method of grouping parts into families involves an examination of the individual design and/or manufacturing attributes of each part. The attributes of the part are uniquely identified by means of a code number. This classification and coding may be carried out on the entire list of active parts of the firm, or a sampling process may be used to establish the part families. For example, parts produced in the shop during a certain given time period could be examined to identify part family categories. The trouble with any sampling procedure is the risk that the sample may be unrepresentative of the entire population. However, this risk may be worth taking, when compared to the relatively enormous task of coding all the company's parts.

Many parts classification and coding systems have been developed throughout the world, and there are several commercially available packages being sold to industrial concerns. It should be noted that none of them has been universally adopted. One of the reasons for this is that a classification and coding system should be custom-engineered for a given company or industry. One system may be best for one company while a different system is more suited to another company.

TABLE Design and Manufacturing Part Attributes Typically Included in a Group Technology Classification System

Part design attributes

Basic external shape
Basic internal shape
Length/diameter ratio
type
Part function

Major dimensions
Minor dimensions
Tolerances Material
Surface finish

Part manufacturing attributes

Major process
Minor operations
Major dimensions
Length/diameter ratio
Surface finish
Machine tool

Operation sequence
Production time
Batch size
Annual production
Fixtures needed
Cutting tools

Design systems versus manufacturing systems

Parts classification and coding systems divide themselves into one of three general categories:

1. Systems based on part design attributes
2. Systems based on part manufacturing attributes
3. Systems based on both design and manufacturing attributes

Systems in the first category are useful for design retrieval and to promote design standardization. Systems in the second category are used for computer-aided process planning, tool design, and other production-related functions. The third category represents an attempt to combine the functions and advantages of the other two systems into a single classification scheme. The types of design and manufacturing parts attributes typically included in classification schemes are listed in Table. It is clear that there is a certain amount of overlap between the design and manufacturing attributes of a part.

Coding system structure

A parts coding scheme consists of a sequence of symbols that identify the part' design and/or manufacturing attributes. The symbols in the code can be al numeric, all alphabetic, or a combination of both types. However, most of the common classification and coding systems use number digits only. There are basic code structures used in group technology applications:

l. Hierarchical structure

2. Chain-type structure

3. Hybrid structure, a combination of hierarchical and chain-type structures

With the hierarchical structure, the interpretation of each succeeding symbol depends on the value of the preceding symbols. Other names commonly used for this structure are monocode and tree structure. The hierarchical code provides a relatively compact structure which conveys much information about the part in a limited number of digits.

In the chain-type structure, the interpretation of each symbol in the sequence is fixed and does not depend on the value of preceding digits. Another name commonly given to this structure is polycode. The problem associated with polycodes is that they tend to be relatively long . On the other hand, the use of a polycode allows for convenient identification of specific part attributes. This can be helpful in recognizing parts with similar processing requirements.

To illustrate the difference between the hierarchical structure and the chain type structure, consider a two-digit code, such as 15 or 25. Suppose that the first digit stands for the general part shape. The symbol 1 means round workpart and 2 means flat rectangular geometry. In a hierarchical code structure, the interpretation of the second digit would depend on the value of the first digit. If preceded by 1, the 5 might indicate some length/diameter ratio, and if preceded by 2, the 5 might be interpreted to specify some overall length. In the chain-type code structure, the symbol 5 would be interpreted the same way regardless of the value of the first digit. For example, it might indicate overall part length, or whether the part is rotational or rectangular.

Most of the commercial parts coding systems used in industry are a combination of the two pure structures. The hybrid structure is an attempt to achieve the best features of monocodes and polycodes. Hybrid codes are typically constructed as a series of short polycodes. Within each of these shorter chains, the digits are independent, but one or more symbols in the complete code number are used to classify the part population into groups, as in the hierarchical structure. This hybrid coding seems to best serve the needs of both design and production.

3.5 THREE PARTS CLASSIFICATION AND CODING SYSTEMS

When implementing a parts classification and coding system, most companies elect to purchase a commercially available package rather than develop their own. Inyong Ham recommends that the following factors be considered in selecting a parts coding and classification system:

Objective. The prospective user should first define the objective for the system. Will it be used for design retrieval or part-family manufacturing or both?

Scope and application. What departments in the company will use the system? What specific requirements do these departments have? What kinds of information must be coded? How wide a range of products must be coded? How complex are the parts, shapes, processes, tooling, and so forth?

Costs and time. The company must consider the costs of installation, training, and maintenance for their parts classification and coding system.

Will there be consulting fees, and how much? How much time will be required to install the system and train the staff to operate and maintain it? How long will it be before the benefits of the system are realized?

Adapability to other systems. Can the classification and coding system be readily adapted to the existing company computer systems and data bases? Can it be readily integrated with other existing company procedures, such as process planning, NC programming, and production scheduling?

Management problems. It is important that all involved management personnel be informed and supportive of the system. Also, will there be any problems with the union? Will cooperation and support for the system be obtained from the various departments involved?

In the sections below, we review three parts classification and coding systems which are widely recognized among people familiar with GT:

i . Opitz system, 2. MICLASS system and 3. CODE system

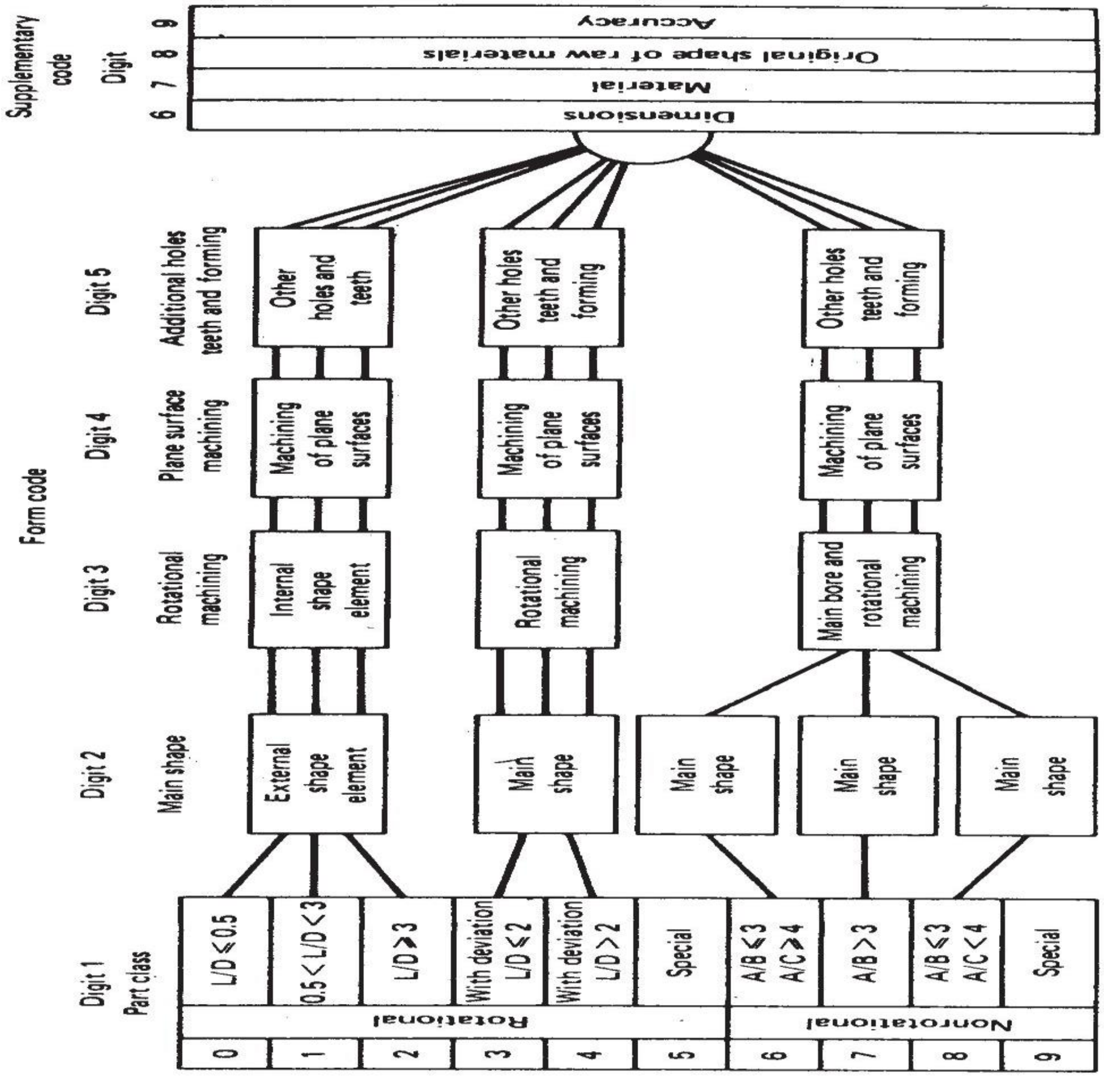
3.6.1 The Opitz classification system

This parts classification and coding system was developed by H. Opitz of the University of Aachen in West Germany. It represents one of the pioneering efforts in the group technology area and is perhaps the best known of the classification and coding schemes.

The Opitz coding system uses the following digit sequence:

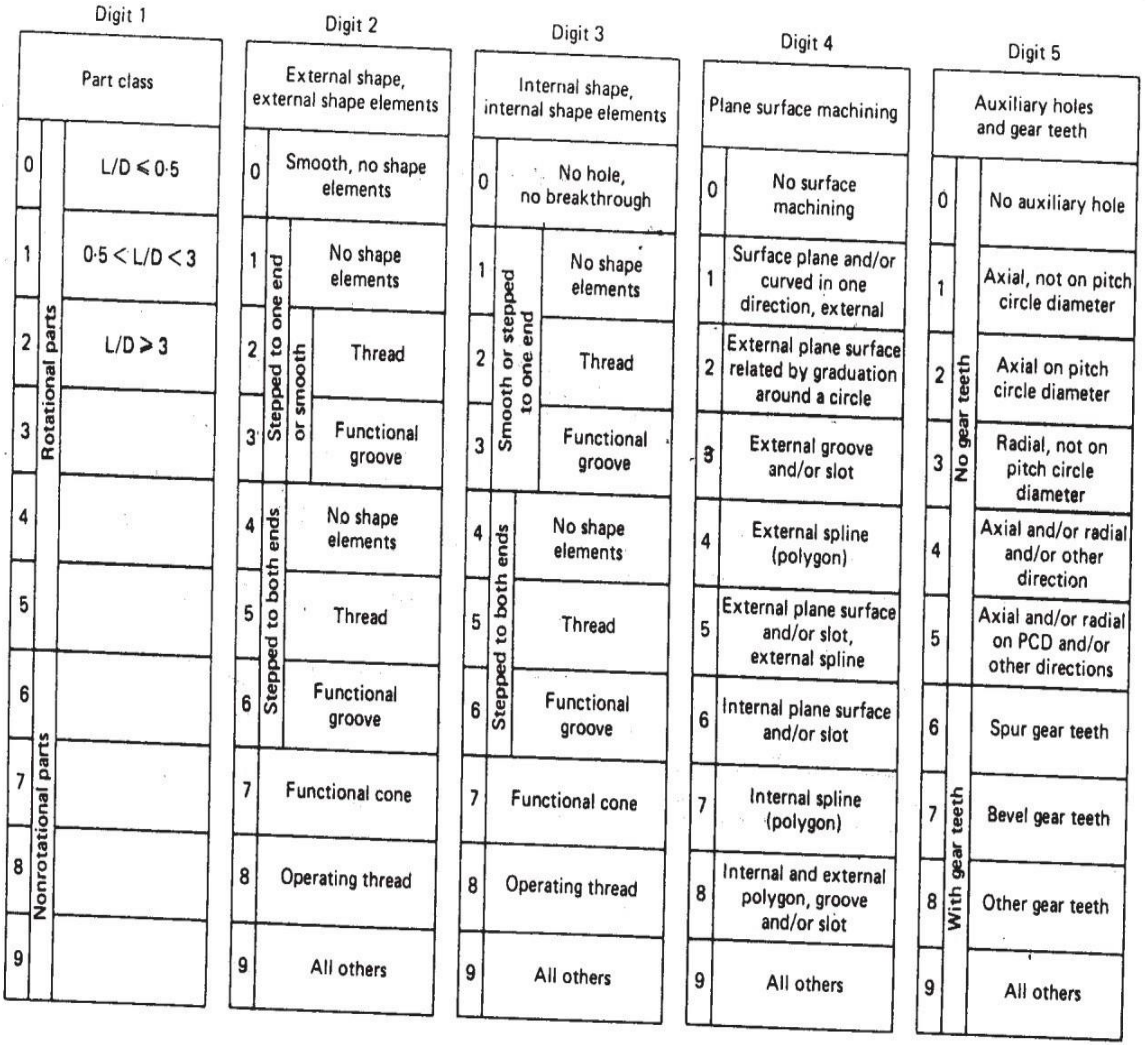
l2345 6789 ABCD

The basic code consists of nine digits, which can be extended by adding four more digits. The first nine digits are intended to convey both design and manufacturing data. The general interpretation of the nine digits is indicated in Figure. The first five digits, l2345, are called the "form code" and describe the primary design attributes of the part. The next four digits, 6789, constitute the supplementary code.



It indicates some of the attributes that would be of use to manufacturing (dimensions, work material, starting raw workpiece shape and accuracy). The extra four digits, ABCD, are referred to as the "secondary code" and are intended to identify the production operation type and sequence. The secondary code can be designed by the firm to serve its own particular needs.

The complete coding system is too complex to provide a comprehensive description here. Opitz wrote an entire book on his system [l2]. However, to obtain a general idea of how the Opitz system works, let us examine the first five digits of the code, the form code. The first digit identifies whether the part is a rotational or a non rotational part. It also describes the general shape and proportions of the part. We will limit our survey to rotational parts possessing no unusual features, those with code values O, l, or 2. See Figure for definitions. For this general class of workparts, the coding of the first five digits is given in Figure. An example will demonstrate the coding of a given part.



	Digit 1		Digit 2		Digit 3		Digit 4	Digit 5	
	Part class		External shape, external shape elements		Internal shape, internal shape elements		Plane surface machining	Auxiliary holes and gear teeth	
0	Rotational parts	$L/D \leqslant 0{\cdot}5$		Smooth, no shape elements		No hole, no breakthrough	No surface machining	No gear teeth	No auxiliary hole
1		$0{\cdot}5 < L/D < 3$	Stepped to one end or smooth	No shape elements	Smooth or stepped to one end	No shape elements	Surface plane and/or curved in one direction, external		Axial, not on pitch circle diameter
2		$L/D \geqslant 3$		Thread		Thread	External plane surface related by graduation around a circle		Axial on pitch circle diameter
3				Functional groove		Functional groove	External groove and/or slot		Radial, not on pitch circle diameter
4			Stepped to both ends	No shape elements	Stepped to both ends	No shape elements	External spline (polygon)		Axial and/or radial and/or other direction
5				Thread		Thread	External plane surface and/or slot, external spline		Axial and/or radial on PCD and/or other directions
6	Nonrotational parts			Functional groove		Functional groove	Internal plane surface and/or slot	With gear teeth	Spur gear teeth
7				Functional cone		Functional cone	Internal spline (polygon)		Bevel gear teeth
8				Operating thread		Operating thread	Internal and external polygon, groove and/or slot		Other gear teeth
9				All others		All others	All others		All others

3.6.2 The MICLASS System

MICLASS stands for Metal Institute Classification System and was developed by TNO, the Netherlands Organization for Applied Scientific Research. It was started in Europe about five years before being introduced in the United States in l974. Today, it is marketed in the United States by the Organization for Industrial Research in Waltham, Massachussets. The MICLASS system was developed to help automate and standardize a number of design, production, and management functions. These include:

Standardization of engineering drawings

Retrieval of drawings according to classification number

Standardization of process routing

Automated process planning

Selection of parts for processing on particular groups of machine tools

Machine tool investment analysis

The MICLASS classification number can range from l2 to 3O digits. The first l2 digits are a universal code that can be applied to any part. Up to l8 additional digits can be used to code data that are specific to the particular company or industry. For example, lot size, piece time, cost data, and operation sequence might be included in the l8 supplementary digits.

The workpart attributes coded in the first l2 digits of the MICLASS number are as follows:

lst digit	Main shape
2nd and 3rd digits	Shape elements
4th digit	Position of shape elements
5th and 6th digits	Main dimensions
7th digit	Dimension ratio
8th digit	Auxiliary dimension
9th and lOth digits	Tolerance codes
llth and l2th digits	Material codes

3.6.4 The CODE system

The CODE system is a parts classification and coding system developed and marketed by Manufacturing Data Systems, Inc. (MDSI), of Aim Arbor, Michigan. Its most universal application is in design engineering for retrieval of part design data, but it also has applications in manufacturing process planning, purchasing, tool design, and inventory control.

The CODE number has eight digits. For each digit there are l6 possible values (zero through 9 and A through F) which are used to describe the part's design and manufacturing characteristics. The initial digit position indicates the basic geometry of the part and is called the Major Division of the CODE system. This digit would be used to specify whether the shape was a cylinder, flat piece, block, or other. The interpretation of the remaining seven digits depends on the value of the first digit, but these remaining digits form a chain-type structure. Hence the CODE system possesses a hybrid structure.

BENEFITS OF GROUP TECHNOLOGY

Although group technology is expected to be an important principle in future production plants, it has not yet achieved the widespread application which might be expected. There are several reasons for this. First, as we have already indicated, there is the problem of rearranging the machines in the plant into GT cells. Many companies have been inhibited from adopting group technology because of the expense and disruption associated with this transition to GT machine cells. Second, there is the problem of identifying part families among the many components produced in the plant. Usually associated with this problem is the expense of parts classification and coding. Not only is this procedure expensive, but it also requires a considerable investment in time and personnel resources. Managers often feel that these limited resources can better be allocated to other projects than group technology with its uncertain future benefits. Finally, it is common for companies to encounter a general resistance among its operating personnel when changeover to a new system is contemplated.

When these problems are solved and group technology is applied, the company will typically realize benefits in the following areas:

Product design

Tooling and setups

Materials handling

Production and inventory control

Employee satisfaction

Process planning procedures

COMPUTER-AIDED PROCESS PLANNING

THE PLANNING FUNCTION

This chapter examines several process planning functions which can be implemented by computer systems. Process planning is conerned with determining the sequence of individual manufacturing operations needed to produce a given part or product. The resulting operation sequence is documented on a form typically referred to as a route sheet. The route sheet is a listing of the production operations and associated machine tools for a workpart or assembly.

Closely related to process planning are the functions of determining appropriate cutting conditions for the machining operations and setting the time standards for the operations. All three functions-planning the process, determining the cutting conditions, and setting the time standards-have traditionally been carried out as tasks with a very high manual and clerical content. They are also typically routine tasks in which similar or even identical decisions are repeated over and over. Today, these kinds of decisions are being made with the aid of computers. In the first four sections of this chapter we consider the process planning function and how computers can be used to perform this function.

Traditional process planning

There are variations in the level of detail found in route sheets among different companies and industries. In the one extreme, process planning is accomplished by releasing the part print to the production shop with the instructions make to drawing. Most firms provide a more detailed list of steps describing each operation and identifying each work center. In any case, it is traditionally the task of the manufacturing engineers or industrial engineers in an organization to write these process plans for new part designs to be produced by the shop. The process planning procedure is very much dependent on the experience and judgment of the planner. It is the manufacturing engineer's responsibility to determine an optimal routing for each new part design. However, individual engineers each have their own opinions about what constitutes the best routing. Accordingly, there are differences among the operation sequences developed by various planners. We can illustrate rather dramatically these differences by means of an example.

In one case cited, a total of 42 different routings were developed for various sizes of a relatively simple part called an "expander sleeve." There were a total of 64 different sizes and styles, each with its own part number. The 42 routings included 2O different machine tools in the shop. The reason for this absence of process standardization was that many different individuals had worked on the parts: 8 or 9 manufacturing engineers, 2 planners, and 25 NC part programmers. Upon analysis, it was determined that only two different routings through four machines were needed to process the 64 part numbers. It is clear that there are potentially great differences in the perceptions among process planners as to what constitutes the "optimal" method of production.

In addition to this problem of variability among planners, there are often difficulties in the conventional process planning procedure. New machine tools in the factory render old routings less than optimal. Machine breakdowns force shop personnel to use temporary routings, and these become the documented routings even after the machine is repaired. For these reasons and others, a significant proportion of the total number of process plans used in manufacturing are not optimal.

Automated process planning

Because of the problems encountered with manual process planning, attempts have been made in recent years to capture the logic, judgment, and experience required for this important function and incorporate them into computer programs. Based on the characteristics of a given part, the program automatically generates the manufacturing operation sequence. A computer-aided process planning (CAPP) system offers the potential for reducing the routine clerical work of manufacturing engineers. At the same time, it provides the opportunity to generate production routings which are rational, consistent, and perhaps even optimal. Two alternative approaches to computer-aided process planning have been developed. These are:

l. Retrieval-type CAPP systems (also called variant systems)

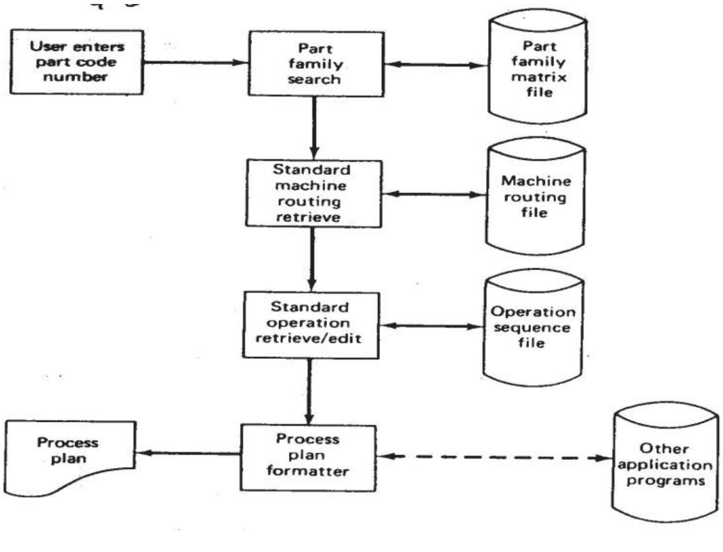
2. Generative CAPP systems

The two types are described in the following two sections.

RETRIEVAL - TYPE PROCESS PLANNING SYSTEMS

Retrieval-type CAPP systems use parts classification and coding and group technology as a foundation. In this approach, the parts produced in the plant are grouped into part families, distinguished according to their manufacturing characteristics. For each part family, a standard process plan is established. The standard process plan is stored in computer files and then retrieved for new workparts which belong to that family. Some form of parts classification and coding system is required to organize the computer files and to permit efficient retrieval of the appropriate process plan for a new workpart. For some new parts, editing of the existing process plan may be required. This is done when the manufacturing requirements of the new part are slightly different from the standard. The machine routing may be the same for the new part, but the specific operations required at each machine may be different. The complete process plan must document the operations as well as the sequence of machines through which the part must be routed. Because of the alterations that are made in the retrieved process plan, these CAPP systems are sometimes also called by the name' 'variant system." Figure will help to explain the procedure used in a retrieval process planning system. The user would initiate the procedure by entering the part code number at a computer terminal. The CAPP program then searches the part family matrix file to determine if a match exists. If the file contains an identical code number, the standard machine routing and operation sequence are retrieved from the respective computer files for display to the user. The standard process plan is examined by the user to permit any necessary editing of the plan to make it compatible with the new part design. After editing, the process plan formatter prepares the paper document in the proper form.

If an exact match cannot be found between the code numbers in the computer file and the code number for the new part, the user may search the machine routing file and the operation sequence file for similar parts that could be used to develop the plan for the new part. Once the process plan for a new part code number has been entered, it becomes the standard process for future parts of the same classification.



Information flow in a retrieval-type computer-aided process planning system.

In Figure the machine routing file is distinguished from the operation sequence file to emphasize that the machine routing may apply to a range of different part families and code numbers. It would be easier to find a match in the machine routing file than in the operation sequence file. Some CAPP retrieval sys• terns would use only one such file which would be a combination of operation sequence file and machine routing file.

The process plan formatter may use other application programs. These could include programs to compute machining conditions, work standards, and standard costs. Standard cost programs can be used to determine total product costs for pricing purposes.

A number of retrieval-type computer-aided process planning systems have been developed. These include MIPLAN, one of the MICLASS modules [6,2O] the CAPP system developed by Computer-Aided Manufacturing-International [l], COMCAPP V by MDSI, and systems by individual companies [lO]. We will use MIPLAN as an example to illustrate these industrial systems.

GENERATIVE PROCESS PLANNING SYSTEMS

Generative process planning involves the use of the computer to create an individual process plan from scratch, automatically and without human assistance. The computer would employ a set of algorithms to progress through the various technical and logical decisions toward a final plan for manufacturing. Inputs to the ~ tern would include a comprehensive description of the workpart. This may involve the use of some form of part code number to summarize the workpart data, but does not involve the retrieval of existing standard plans. Instead, the general CAPP system synthesizes the design of the optimum process sequence, based an analysis of part geometry, material, and other factors which would influence manufacturing decisions.

In the ideal generative process planning package, any part design could presented to the system for creation of the optimal plan. In practice, cu generative- type systems are far from universal in their applicability. They ter fall short of a truly generative capability, and they are developed for a some limited range of manufacturing processes. We will illustrate the generative process planning approach by means system called GENPLAN developed at Lockheed-Georgia Company

BENEFITS OF CAPP

Whether it is a retrieval system or a generative system, computer-aided process planning offers a number of potential advantages over manually oriented process planning.

l. *Process rationalization*. Computer-automated preparation of operation routings is more likely to be consistent, logical, and optimal than its manual counterpart. The process plans will be consistent because the same computer software is being used by all planners. We avoid the tendency for drastically different process plans from different planners. The process plans tend to be more logical and optimal because the company has presumably incorporated the experience and judgment of its best manufacturing people into the process planning computer software.

2. *Increased productivity of process planners*. With computer-aided process planning, there is reduced clerical effort, fewer errors are made, and the planners have immediate access to the process planning data base. These benefits translate into higher productivity of the process planners. One system was reported to increase productivity by 6OO% in the process planning function [lO].

3. *Reduced turnaround time*. Working with the CAPP system, the process planner is able to prepare a route sheet for a new part in less time compared to manual preparation. "Ibis leads to an overall reduction in manufacturing lead time.

4. *Improved legibility*. The computer-prepared document is neater and easier to read than manually written route sheets. CAPP systems employ standard text, which facilitates interpretation of the process plan in the factory.

5. *Incorporation* *of other application programs*. The process planning system can be designed to operate in conjunction with other software packages to automate many of the time-consuming manufacturing support functions.

Mono code or Hierarchical code

The structure of these codes is like a tree in which each symbol is qualified by the preceding characters. Figure 7.1 depicts the monocode generation scheme. The first digit (from 0 to 9) divides the set of parts into major groups such as sheet metal parts, machined parts, purchased parts, and raw materials, and so forth. The second subsequent digits further partition the set into subgroups for each of these groups. For example, the second digit partitions the machined parts into rotational (0) and nonrotational (1) parts. Consider a code 100 in figure 7.1. It represents a machined rotational part with a length to diameter ratio of less than 0.5. The digit 1 in the first place of code has different meaning and different information. Therefore, the digits in a monocode cannot be interpreted independently; the interpretation depends on the information contained in the preceding symbol.

Advantage:

It can represent a large amount of information with very few code positions. The hierarchical nature of the code makes it useful for storage and retrieval of design related information such as geometry, material, and size as depicts in figure7.1.

Disadvantage:

A drawback is related to the complexity of the coding system. The applicability of these codes in manufacturing is limited, as it is difficult to cover information on manufacturing sequences in hierarchical manner.

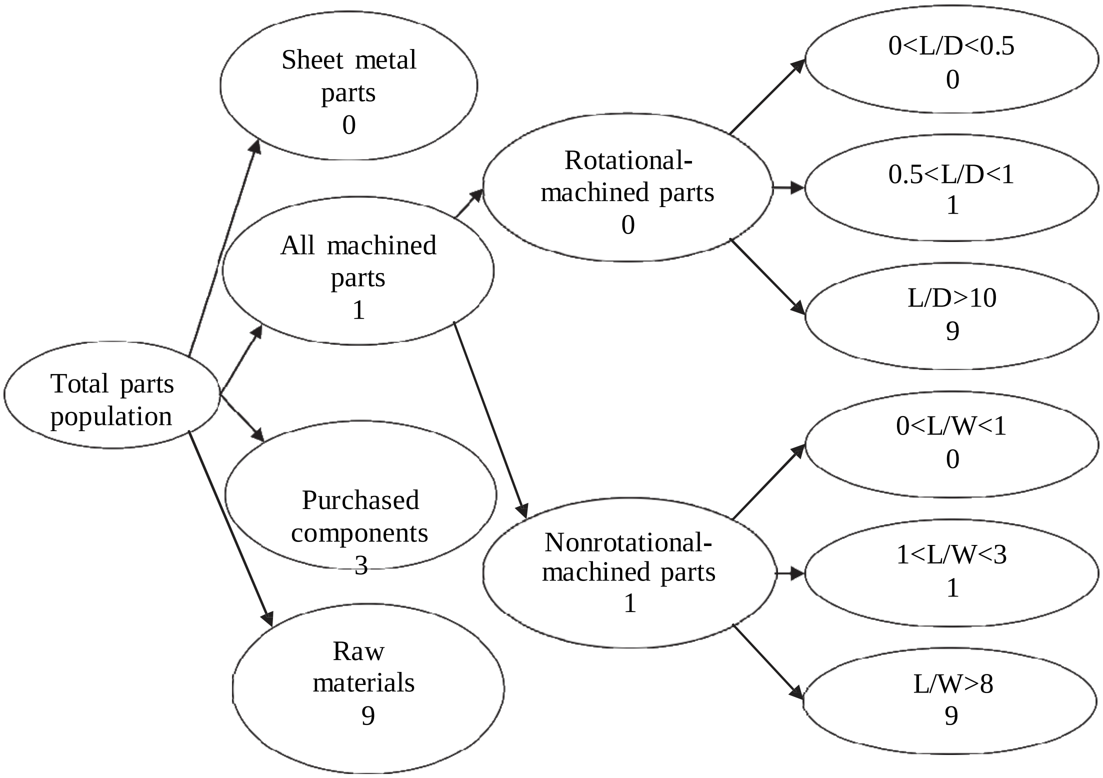


Figure Example of Monocode.

Chain code or Poly code

In polycode the code symbols are independent of each other. Each digit in specific location the code represents a distinct bit of information. A chain-structured coding scheme is presented. Numeral 3 in the third position always means axial and cross hole no matter what numbers are given to position 1 and 2.

Advantages:

Chain codes are compact and are much easier to construct and use.

Disadvantage:

They cannot be as detailed as hierarchical structures with the same number of coding digits.

Digit position	1	2	3	4
Class of features	External shape	Internal shape	Holes	…
Possible value				
1	Shape 1	Shape 1	Axial	…
2	Shape 1	Shape 1	cross	…
3	Shape 1	Shape 1	Axial and cross	…
.	.	.	.	.
.	.	.	.	.

Chain structure

Mixed code or Hybrid code

Mixed code is mixture of the hierarchical code and chain code (Figure 7.2). It retains the advantage of both mono and chain code. Therefore, most existing code system uses a mixed structure. One good example is widely used optiz code

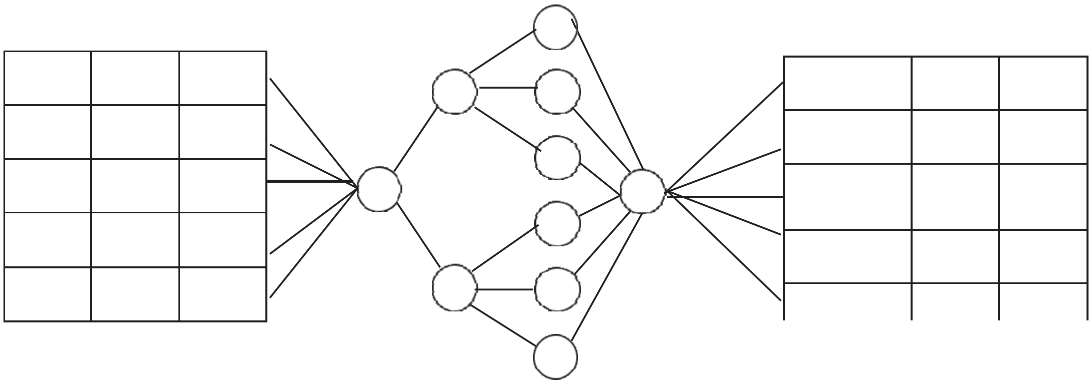


Figure: A hybrid structure

Group Technology Coding Systems

Too much information regarding the components sometimes makes the decision very difficult proposition. It would be better to provide a system with an abstract kind of thing, which can summarize the whole system with the necessary information without giving great details.

Group technology (GT) is a fitting tool for this purpose. Coding, a GT technique, can be used to model a component with necessary information. When constructing a coding system for a component‘s representation, there are several factors need to be considered. They include The population of components (i.e. rotational, prismatic, deep drawn, sheet metal, and so on) Detail in the code. The code structure. The digital representation (i.e. binary, octal, decimal, alphanumeric, hexadecimal, and so on).In component coding, only those features are included which are variant in nature. When a coding scheme is designed the two criteria need to be fulfilled (1) unambiguity (2) completeness. We can define coding as a function of F that maps components from a population space P into a coded space C (Figure 7.3). Unambiguity of a code can be defined (for component j) as

j P only one i C i = F (j)... (1)

Completeness can be defined as j P i C i = F (j)... (2)

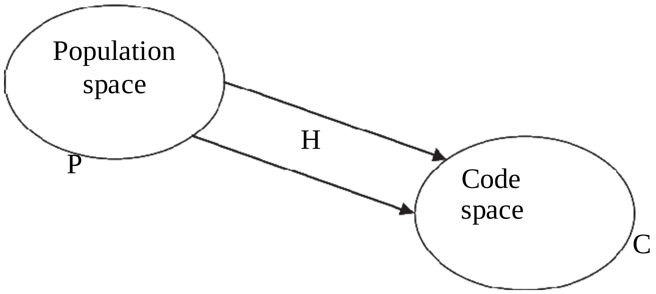


Figure: Mapping from a population space to a code space

The two properties suggest that each component in a population has its own unique code

However, if two codes are complete and unambiguous, the one having more conciseness is opted whereas a longer code is normally necessary whenever more detail is required e.g. in basic optiz code system and the KK-3, former one uses 5 digits to describe the shape of the component. 5 digits can represent 10^5 combinations. With this set, it is quite difficult to show all the details of a component. So, KK-3 of Japan (Japan society, 1980), which has 21 digits and contains multiple digits for single feature, and MICLASS of TNO (Houtzeel and Schilperoort, 1976), which has a 12-digit code, is used.

Code contents

When using a code to represent an engineering design, it is important that it represents the basic features of the design such as shape, size, tolerance, critical dimensions, material, and so on. For process planning, it is desired to have codes that can distinguish unique production families. Because a coding system transforms the properties and requirements of a design into a code, the aforementioned informations must be provided to the process planning system.

The length of a part code dictates the detail that is captured by the code. In general, the longer the code, the more detail that can be extracted. However, length and details of the code depend on the specific application, in industrial use for product mix.

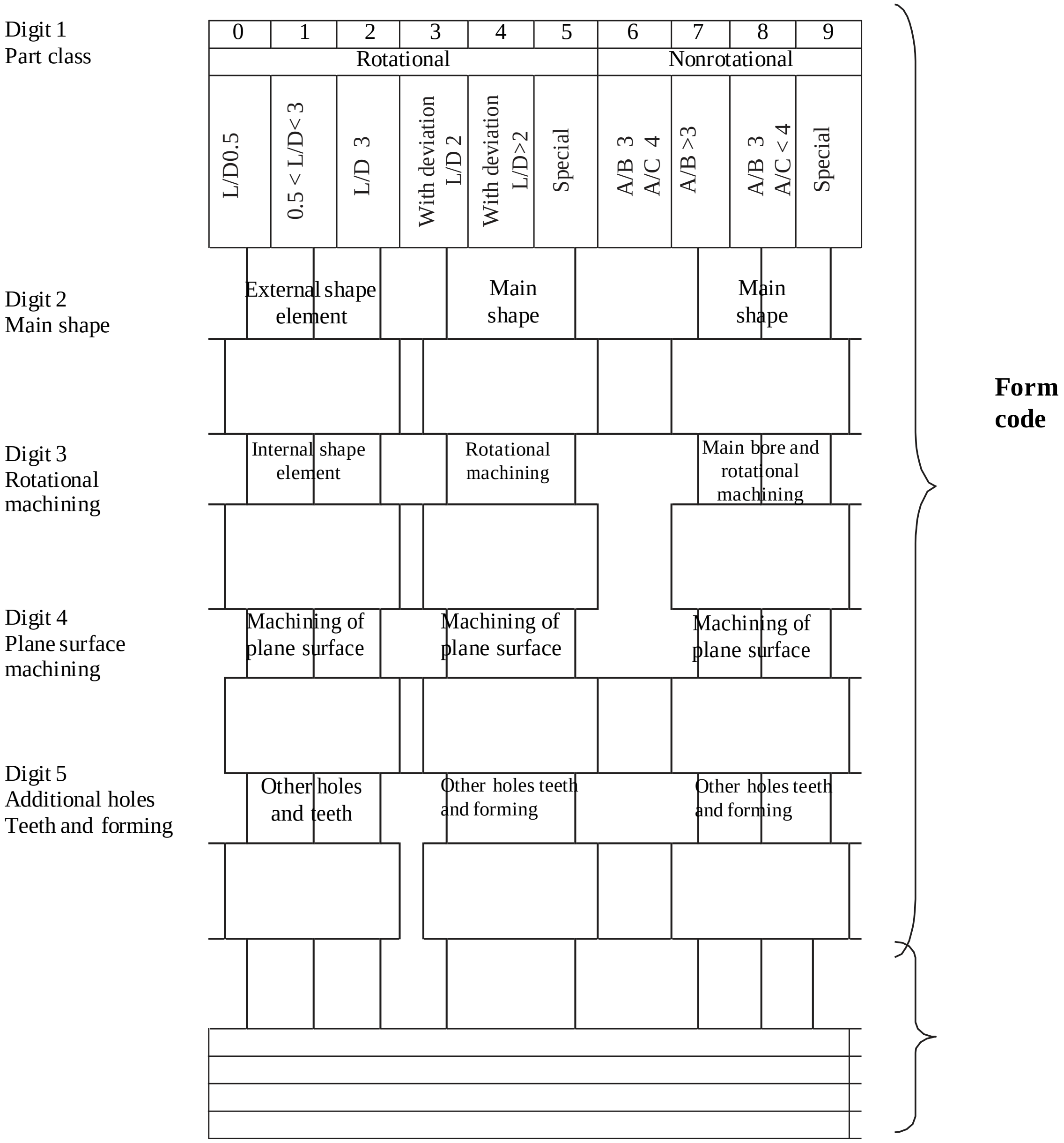
The optiz system

The Optiz coding is most likely the best-known coding system. It was developed by H. optiz of the Aachen Tech University in West Germany. The code uses a hybrid structure. However, except the first digit, it resembles a chain structure more closely.

It has following advantages over the existing system

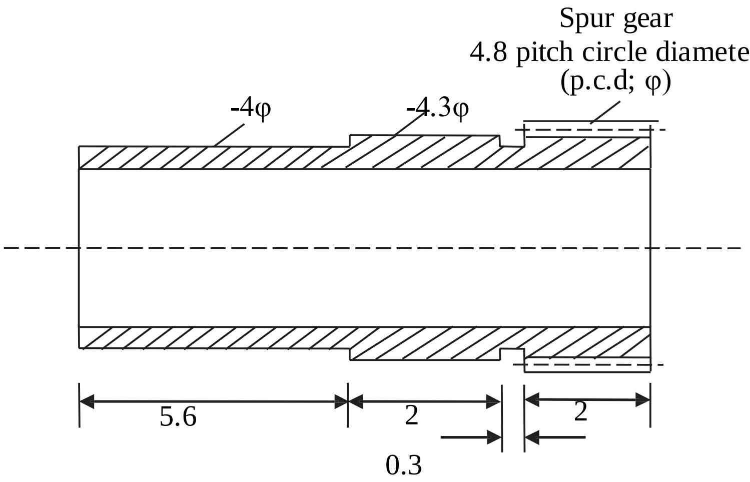
- It is nonproprietary.
- It is widely used.
- It provides a basic framework for understanding the classification and coding process.
- It can be applied to machined parts, non-machined parts, and purchased parts.
- It considers both design and manufacturing information.

The optiz code consists of a form code and supplementary code (Figure 7.4). The form code can represent parts of the following variety: long, short, cubic, flat, rotational etc. A dimension ratio is further used in classifying the geometry: the length/diameter ratio is used to classify the rotational components and the length/height ratios are used to classify Nonrotational components. The attributes of rotational parts are described as shown in table 7.2. The optiz form code uses five digits that focuse on 1) component class 2) basic shape 3) rotational-surface machining 4) plane surface machining 5) auxiliary holes, gear teeth, and forming. A supplementary code is a polycode consisting four digits is usually appended to the Optiz system.



Digit 6
Digit 7
Digit 8
Digit 9

Example: A part design is shown in figure. Develop an optiz code for that design



By using information from figure, the form code with explanation is given below
Part class:

Form code

Form code	1	3	1	0	6

Rotational part, L/D = 9.9/4.8 = 2.0 (nearly) based on the pitch circle diameter of the gear. Therefore, the first digit would be 1.

External shape:

The part is stepped in one side with a functional groove. Therefore, the second digit will be 3.

Internal shape:
Due to the hole the third digit code is one. Plain surface machining:
Since, there is no surface machining the fourth digit is 0. Auxiliary holes and gear teeth:

Because there are spur gear teeth on the part the fifth digit is 6.

The KK3 system

The KK3 system is one of the general-purpose classification and coding system for machined parts. It was developed by the Japanese society for the encouragement of the machined industry. KK-3 was first presented in 1976 and use a 21-digit decimal system. Tables show the code structure for rational component. It can represent more information than that of optiz code because of greater length. It includes two digits for component name or functional name classification. First digits classify the general function, such as gears, shafts, drive and moving parts, and fixing parts. The second digit describes more detailed function such as spur gears, bevel gears, worm gears, and so on.

KK-3 also classifies materials using two-code digit. The first digit classifies material type and second digit classifies shape of the raw material. Length, diameter, and length/diameter ratios are classified for rotational components. Shape details and types of processes are classified using 13 digits of code. At last one digit is required for accuracy presentation. An example of coding a component using KK-3 is illustrated in figure 7.6 and table 7.5.

Digit	Items (rotational component)		
1	Parts name	General classification	
2		Detail classification	
3	Materials	General classification	
4		Detail classification	
5	Chief dimension	Length	
6		Diameter	
7	Primary shapes and length diameter ratio		
8	Shape details and kinds of processes	External surface	External surface and outer primary shape
9			Concentric screw threaded parts
10			Functional cut-off parts
11			Extraordinary shaped parts
12			Forming
13			Cylindrical surface
14		Internal surface	Internal primary shape
15			Internal curved surface
16			Internal flat surface and cylindrical surface
17		End surface	
18		Nonconcentric holes	Regularly located holes
19			Special holes
20		Noncutting process	
21	Accuracy		

Table: Structure of the KK-3 coding system (rotational components)

The MICLASS system

Originally TNO of Holland developed MICLASS system, and is maintained in the United States by the organization for industrial research. It is a chain-structured code of 12 digits. It includes both design and manufacturing information. Information such as the main shape, shape elements, position of shape elements, main dimensions, ratio of dimensions, auxiliary dimension, tolerance, and the machinability of the material is included (Table 7.6). An additional 18 digits of code is also available for user-specified information (i.e. part function, lot size, major machining operation, etc). These supplementary digits provide flexibility expansion.

Code position	Item
1	Main shape
2	Shape elements
3	
4	Position of shape element
5	Main dimension
6	
7	Dimension ratio
8	Auxiliary dimension
9	Tolerance codes
10	
11	Material codes
12	

Table: MICLASS code structure

The DICLASS systems

Del Allen at Brigham Young University developed the DICLASS system. It is a tree-structured system that can generate codes for components, materials, processes, machines, and tools. For components, an eight-digit code is used.

Digits	Item
1-3	Basic shape
4	From feature
5	Size
6	Precision
7-8	Material

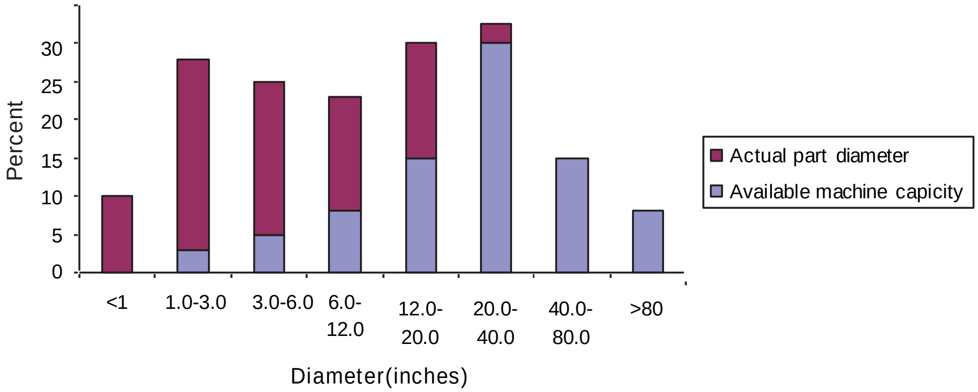
Table: Description of DICLASS code structure

In DICLASS, each branch represents a condition, and a code can be found at the terminal of each branch. This system is not only a coding system, but also a decision-support system.

Underutilization of expansive processing equipment is a common characteristic of big industries. The underutilization can have two forms.

1. Much of the machine time is idle and totally unproductive.
2. Many of the parts assigned to a specific machine are far below the capacity of the machine.

Machines can be more fully utilized from both by using effective scheduling as well as a capacity technique utilization by grouping closely matched parts into a part family. By using a part coding system, similar parts having similar feature dimension specification can be assigned to the part family, and machines corresponding to the minimum product specification can be selected rather than over specifying the processing. The phenomenon for lathe parts. In the figure it can be seen that only a few percent of the parts being machined required the full lathe swing or length. Further more, the speed and feed capacity of the lathe can also be over specified in



Actual vs Available Machine Capacity

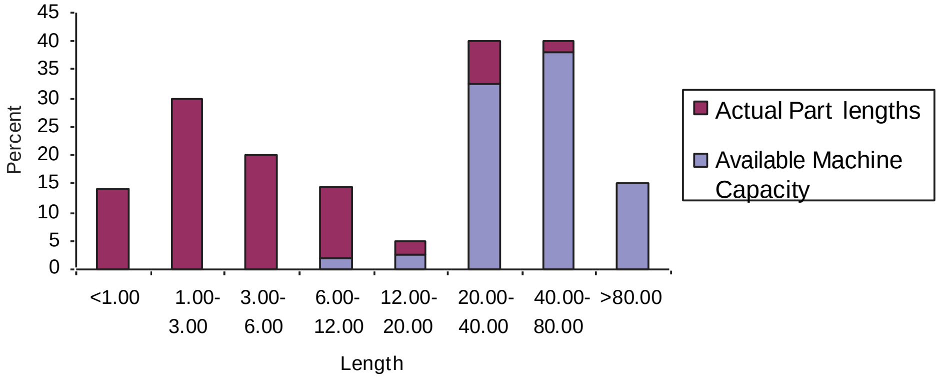


Figure 7.7 Comparision of a turned-part dimension as a function of machine capacity

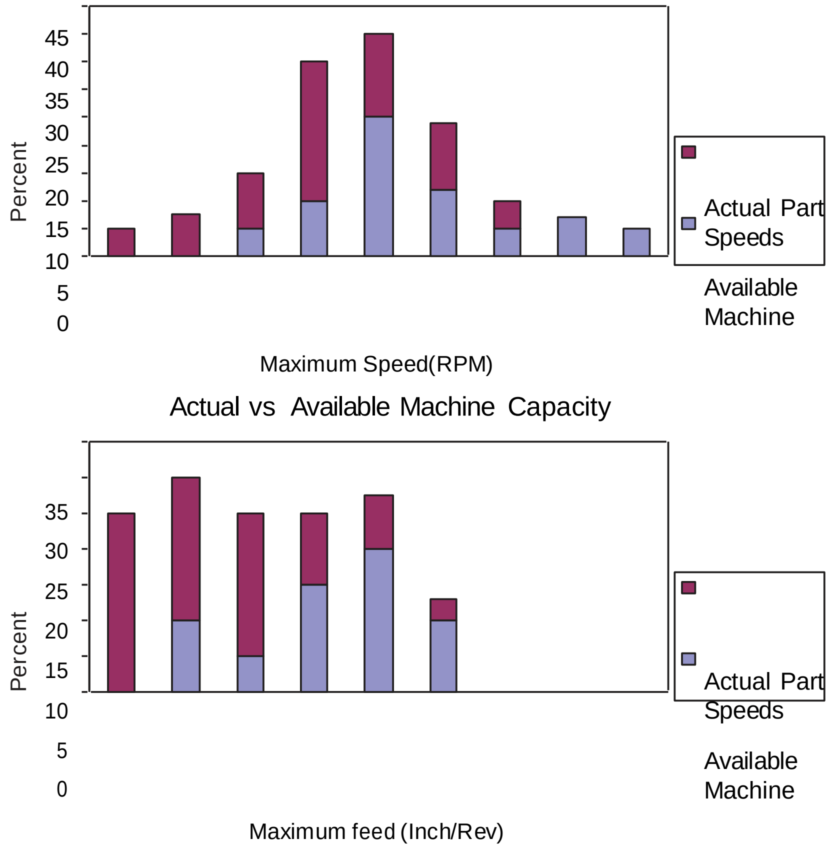


Figure 7.8 Comparision of maximum speeds and feeds with maximum used

MODELS FOR MACHINE CELL AND PART FAMILY FORMATION

One of the primary uses of coding system in manufacturing is to develop part families for efficient workflow. Efficient workflow can result from grouping machines logically so that material handling and setup can be minimized. The same tools and fixtures can be used by grouping parts having similar operations. Due to this, a major reduction in setup results and also material handling between machining operations is minimized.

Family formation is based on production parts or more specifically, their manufacturing feature. Components requiring similar processing are grouped into the same family. There is no rigid rule require similar routing. A user may want to put only those parts having exactly the same routing sequence into a family. Minimum modification on the standard route is required for such family members. Only, few parts will qualify for family membership. On the other hand, if one groups all the parts requiring a common machine into family, large part families will results.

Before grouping can start, information related to the design and processing of all existing components have to be collected from existing part and processing files. Each component is represented in a coded form, called an operation-plan code (operation plan code, Table 7.8). An OP code represents a series of operations on a machine and/or one workstation.

Operation code		Operation plan
01	SAW 01	Cut to size
02	LATHE 02	Face end
		Drill
		Center drill
		Ream
		Bore
		Turn straight
		Turn groove
		Chamfer
		Cutoff
		Face
03	GRIND 05	Grind
04	INSP 06	Inspect dimension
		Inspect finish

1. operation-plan code (OP code) and operation plan

1 SAW 01
2 LATHE 02
3 GRIND 05
4 INSP 06

2. OP-code sequence

Table: Operation plan, OP code, and Op-code sequence

For example, we can use GRIND05 to represent the sequence; load the work piece onto the grinding machine, attach the grinding wheel, grind the work piece, and unload the work piece from the grinding machine. Operations represented by the Op code are called an operation plan. It is not necessary that an OP code include all operations required on a machine for a component. It is used to represent a logical group of operations on a machine, so that a process plan can be represented in a much more concise manner. Such a representation is called an OP code sequence. The main aim of an OP code is to simplify the representation of process plans. This simplified process plan can be stored and retrieved

PRODUCTION FLOW ANALYSIS

problem for manufacturing cell design. This analysis uses the information contained on production route sheets. Work parts with identical or similar routing are classified into part families which can be used to form logical machine cells in a group technology layout. Since PFA uses manufacturing data rather than design data to identify part families, it can overcome two possible abnormalities that can occur in part classification and coding. First, parts whose basic geometries are quite different may nevertheless require similar or identical process routing. Second, parts whose geometries are quite similar may nevertheless require process routing that are quite different.

The procedure in PFA consists of the following steps.

> *Machine classification*. Classification of machines is based on the operation that can be performed on them. A machine type is assigned to machines capable of performing similar operations.
>
> *Checking part list and production route information*. For each parts, information on the operations to be taken and the machines required to perform each of these operations is checked carefully
>
> *Factory flow analysis.* This comprise a micro level examination of flow of components through machines. Thus, it allows the problem to be decomposed into a number of machine-component groups.
>
> *Machine-component group analysis.* This analysis recommended manipulating the matrix to form cells.

Many researchers have been subsequently developed algorithm to solve the family-formation problem for manufacturing cell design. In PFA, a large matrix generally termed as incidence is constructed. Each row represents an OP code, and each column represents a component. We can define the matrix as M_{ij}, where i indicates the optiz code and j indicates components for example M_{ij} = 1 if component j has OP code i; otherwise Mij = 0. The objective of PFA is to bring together those components that need the similar set of OP codes in clusters.

Rank order clustering

This method is based on sorting the rows and columns of machine part incidence matrix. The rank order clustering was developed by King (1980). Steps of this algorithm is given below

Step 1. For each row of the machine part incidence matrix, assign binary weight and calculate the decimal equivalent

Step 2. Sort rows of the binary matrix in decreasing order of the corresponding decimal weights.

Step 3. Repeat the preceding two steps for each column.

Step 4. Repeat the preceding steps until the position of each element in each row and column does not change.

A weight for each row i and column j are calculated as follows:

$$\text{Row } i: W_i = \sum_{k=1}^{n} a_{ik} 2^{n-k}$$

$$\text{Column } j: W_j = \sum_{k=1}^{m} a_{kj} 2^{n-k}$$

In the final matrix generated by the ROC algorithm, clusters are identified visually.

Example 7.3

Step 1. Assign binary equivalent to each row and calculate binary equivalent:

Part number

Part number	1 (2^4)	2 (2^3)	3 (2^2)	4 (2^1)	5 (2^0)	Decimal equivalent
		1		1	1	11
	1		1			20
		1		1		10
	1		1			20

Machine number

Step 2. Sorting the decimal weights in decreasing order results in the following matrix:

Part number

Machine number	1	2	3	4	5
2	1		1		
4	1		1		
1		1		1	1
3		1		1	

Step 3. Repeating the proceeding steps for each column produces the following matrix:

Part number

Machine number	1	3	2	4	5
2	1	1			
4	1	1			
1			1	1	1
3			1	1	

In this matrix two separate clusters are visible

Bond energy algorithm

McCormick, Schweitzer, and white (1972) developed an interchange-clustering algorithm called the bond energy algorithm (BEA). The BEA seeks to form by minimizing the measure of effectiveness. This is defined as follows:

$$ME = \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} \left[a_{i,j+1} + a_{i,j-1} + a_{i+1,j} + a_{i-1,j} \right] \quad \ldots (3)$$

BEA algorithm

Step 1. Set j=1. Select one of the columns arbitrarily.

Step 2. Place each of the remaining n-j columns, one at a time, for each of j+1 positions, and compute each column‘s contribution to the ME.

Place the column that gives the largest incremental contribution to the ME in its best location.

Increase j by 1 and repeat the preceding steps until j=n.

Step 3. When all the columns have been placed, repeat the procedure for the rows.

The BEA applied to the Example7.3 and is illustrated below in Example 7.4

Example 7.4

Step 1. Set j=1. Select column 2.

Step 2. Place each of the remaining columns in each of the j+1 position. The contribution to the ME value of the column 2 is computed next:

Position	J=1	J+1	ME value
Column number	2	1	0
	2	3	0
	2	4	2
	2	5	1

Column 4 is placed in the j+1 position.

Machine number

assemble these components into final product. Process planning acts as a bridge

UNIT IV

COMPUTER AIDED PLANNING AND CONTROL, SHOP FLOOR CONTROL AND INTRODUCTION TO FMS

1. Structure

INTRODUCTION

Before introduction to the role of computer aided process planning (CAPP), it is worthwhile to understand the role of process planning in the product cycle. Once the design of the product has been evolved from customer's views, its manufacturing necessitates careful planning and scheduling of the various processes of manufacture. So that, the product is made to right specifications and delivered at the right time at a minimal cost. The cycle from concept to design, planning, production, quality control and feedback to design goes on in which one can easily understand the crucial role of planning. In job/batch manufacture, as an enormous amount of data is needed for planning as well as other activities, data bases are required and the flow of information should be fast for a high performance of the total manufacturing system.

2. Objectives

After studying this unit, you should be able to

- understand what is process planning and CAPP,
- know the various steps involved in CAPP,
- classify the various methods of CAPP, and
- understand the feature recognition in CAPP.

INTRODUCTION TO PROCESS PLANNING

In manufacturing, the goal is to produce components that meet the design specifications. assemble these components into final product. Process planning acts as a bridge

The design specification ensures the functionality aspect. Next step to follow is to

assemble these components into final product. Process planning acts as a bridge between design and manufacturing by translating design specification into manufacturing process detail. Hence, in general, process planning is a production organization activity that transforms a product design into a set of instruction (sequence, machine tool setup etc.) to manufacture machined part economically and competitively. The information provided in design includes dimensional specification (geometric shape and its feature) and technical specification (tolerance, surface finish etc.)

Now-a-days, process planning is applied to many manufacturing industries like metal cutting, sheet metal forming, composite and ceramic fabrication and other manufacturing processes. Figure 9.1 represents the various steps involved in developing a process plan.

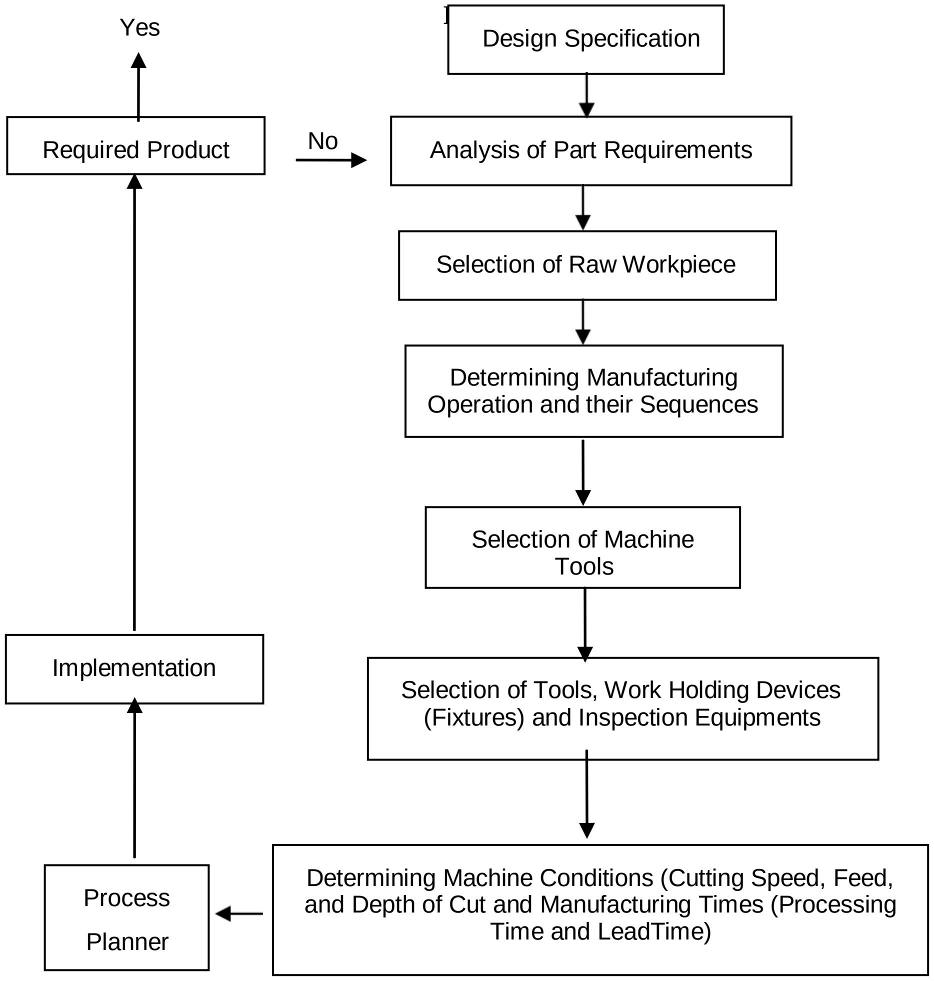


Figure 9.1

Various steps are discussed as follows :

The analysis of finished part requirement is the first step in process planning. Initially the features of parts are analyzed. Examples of geometric feature include plane, cylinder, cone step, edge and include fillet. These common features can be modified by the addition of slots, pockets, grooves, holes and others. The second step is the selection of raw work piece shape, size (dimensions and weight), material and other attributes are determined. Weight and material of the raw part are determined by the functional requirement of plan.

The next logical step in process planning is to determine the appropriate types of processing operations and their sequences to transform the features, dimensions and tolerances of a part from the raw to the finished state. There may be many ways to produce a design some times constraints are also considered like some feature be machined before or after other. Furthermore, the types of machine, available tools as well as batch size influence the process sequence.

Next step to be followed in process planning is the selection of machine tools on which these operations are made.

Some of the factors which influences the selection of machine tool are as follows :

(i) Attributes related to workpiece, such as desired features, dimensions of workpiece, dimensional tolerances and raw material form.

(ii) Attributes related to machine tools, e.g. process capability size, mode of operation, tooling capabilities and automatic tool changing capabilities.

(iii) Attribute related to production volume, e.g. production quantity and order frequency.

Unit cost of production, manufacture lead time and quality are three basic criteria for evaluating the suitability of a machine tool to accomplish an operation.

Next step to be followed is the selection of tools work holding devices and inspection equipments. Features on the workpieces are generated using a combination of machine tool and cutting tools. Work holding devices are used to locate and hold the workpiece to generate features. In order to ensure the dimensional accuracy, tolerance and surface finish on the feature, inspection equipments are required. Part features play a vital role in the selection of machine tools, fixture and inspection equipment.

Now sixth step which has to be performed is the determination of machining condition and manufacturing time. The controllable variables of machine condition are cutting speed (υ), feed (f) and depth of cut (d).

Minimum cost per piece, maximum production rate and manufacture lead time are same for the model to be optimized for high production and less cost.

APPROACHES TO PROCESS PLANNING

There are basically two approaches to process planning which are as follows :

(i) Manual experience-based process planning, and

(ii) Computer-aided process planning method.

Manual Experience-based Process Planning

The steps mentioned in the previous section are essentially same for manual process planning. Following difficulties are associated with manual experienced based process planning method :

- It is time consuming and over a period of time, plan developed are not consistent.
- Feasibility of process planning is dependent on many upstream factors (design and availability of machine tools). Downstream manufacturing activities such as scheduling and machine tool allocation are also influenced by such process plan.

Therefore, in order to generate a proper process plan, the process planner must have sufficient knowledge and experience. Hence, it is very difficult to develop the skill of the successful process planner and also a time consuming issue.

Computer-Aided Process Planning

Computer-aided process planning (CAPP) helps determine the processing steps required to make a part after CAP has been used to define what is to be made. CAPP programs develop a process plan or route sheet by following either a variant or a generative approach. The variant approach uses a file of standard process plans to retrieve the best plan in the file after reviewing the design. The plan can then be revised manually if it is not totally appropriate. The generative approach to CAPP starts with the product design specifications and can generate a detailed process plan complete with machine settings. CAPP systems use design algorithms, a file of machine characteristics, and decision logic to build the plans. Expert systems are based on decision rules and have been used in some generative CAPP systems.

CAPP has recently emerged as the most critical link to integrated CAD/CAM system into inter-organizational flow. Main focus is to optimize the system performance in a global context. The essentiality of computer can easily be understood by taking an example, e.g. if we change the design, we must be able to fall back on a module of CAPP to generate cost estimates for these design changes. Similarly for the case of the breakdown of machines on shop floor. In this case, alternative process plan must be in hand so that the most economical solution for the situation can be adopted. Figure 9.2 is one such representation, where setting of multitude of interaction among various functions of an organization and dynamic changes that takes place in these sub functional areas have been shown. Hence, the use of computer in process planning is essential.

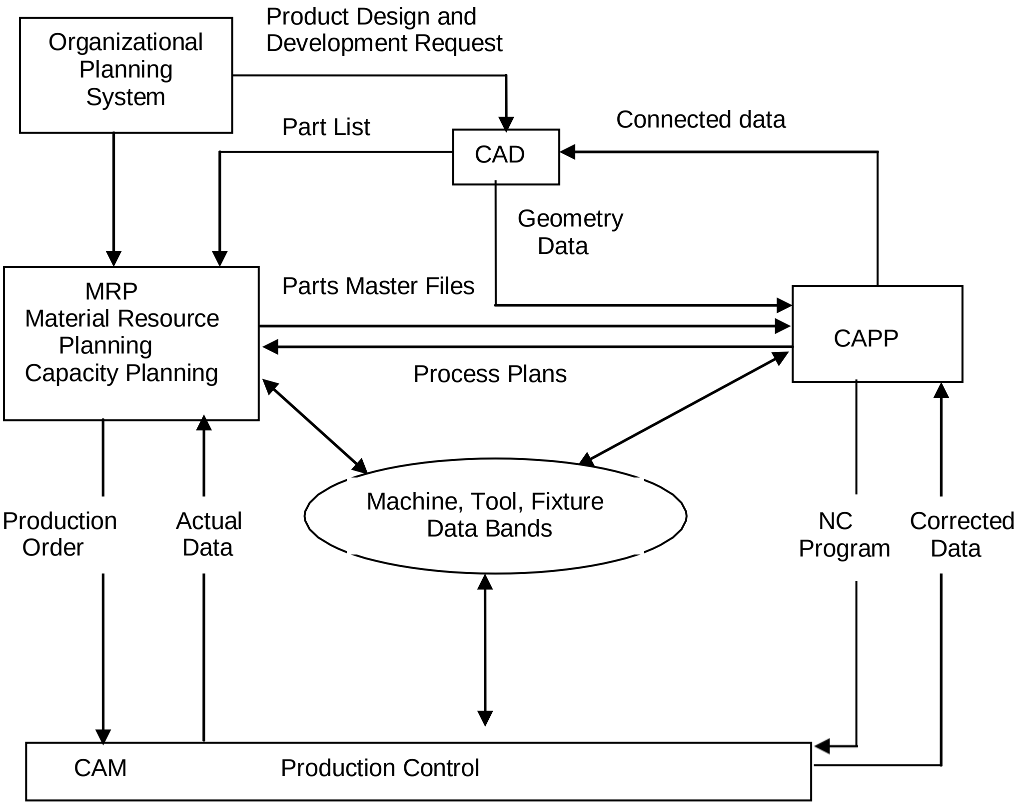


Figure 9.2 : Framework for Computer Aided Process Planning

CAPP is the application of computer to assist the human process planer in the process planning function. In its lowest form it will reduce the time and effort required to prepare process plans and provide more consistent process plan. In its most advanced state, it will provide the automated interface between CAD and CAM and in the process achieve the complete integration with in CAD/CAM.

1. Advantages Over Manual Experience-based Process Planning

The uses of computers in process plan have following advantages over manual experience-based process planning :

(i) It can systematically produce accurate and consistent process plans.

(ii) It leads to the reduction of cost and lead times of process plan.

(iii) Skill requirement of process planer are reduced to develop feasible process plan.

(iv) Interfacing of software for cost, manufacturing lead time estimation, and work standards can easily be done.

(v) Leads to the increased productivity of process planar.

With the emergence of CIM as predominate thrust area in discrete part industries process planning has received significant attention, because it is the link between CAD and CAM. Hence, computer aided process planning (CAPP) has become a necessary and vital objective of CIM system.

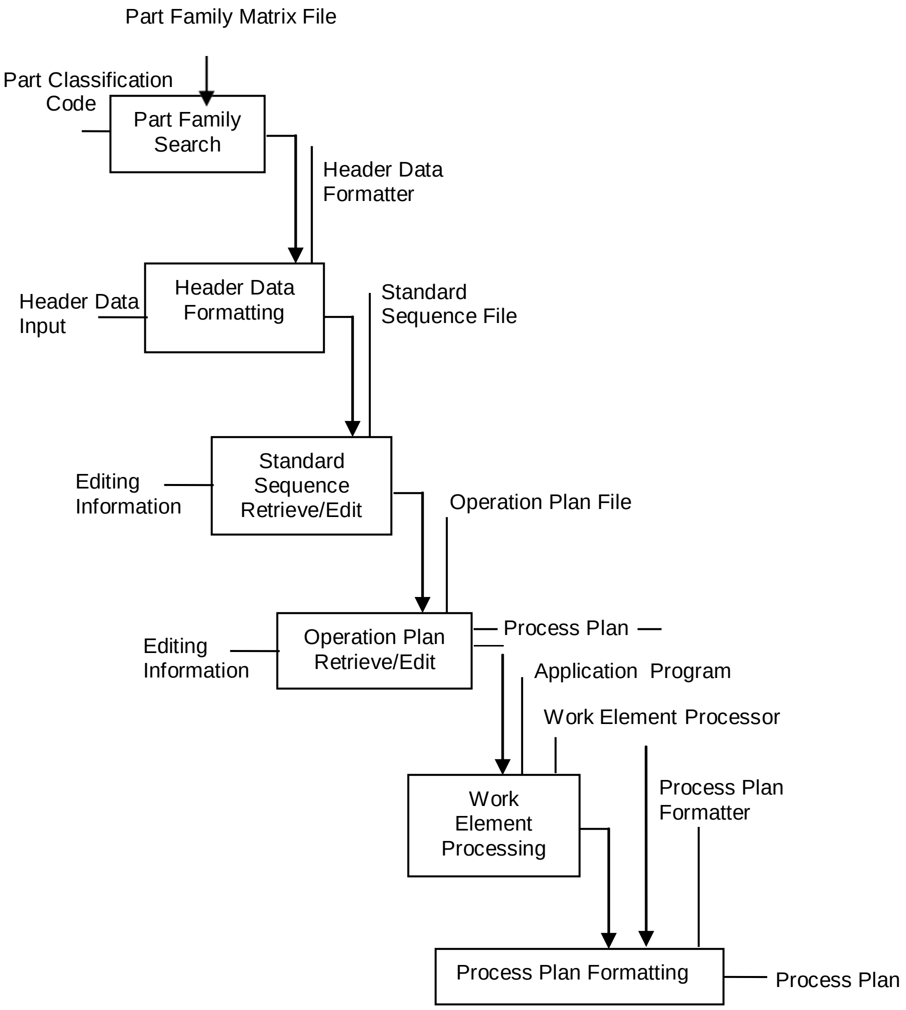


Figure 9.3 : Flow Diagram of the CAPP Process Planning System

2. Steps Involved in CAPP

Now-a-days, rapid progress is being made in the automation of actual production process and also the product design element. However, the interface between design and production presents the greatest difficulty in accomplishing integration. CAPP has the potential to achieve this integration. In general, a complete CAPP system has following steps :

(i) Design input

(ii) Material selection

(iii) Process selection

(iv) Process sequencing

(v) Machine and tool selection

(vi) Intermediate surface determination

(vii) Fixture selection

(viii) Machining parameter selection

(ix) Cost/time estimation

(x) Plan preparation

(xi) Mc tape image generation.

APPROACHES TO COMPUTER-AIDED PROCESS PLANNING

In recent days, several computer-aided process planning systems are available for use for a variety of manufacturing operation.

These systems can broadly be clarified into two categories :

(i) Variant computer aided process planning method.

(ii) Generative computer aided process planning method.

The details of these are explained in next subsections.

Variant Process Planning, Advantages and Disadvantages

Variant process planning approach is sometimes referred as a data retrieval method. In this approach, process plan for a new part is generated by recalling, identifying and retrieving an existing plan for a similar part and making necessary modifications for new part. As name suggests a set of standard plans is established and maintained for each part family in a preparatory stage. Such parts are called master part. The similarity in design attributes and manufacturing methods are exploited for the purpose of formation of part families. Using coding and classification schemes of group technology (GT), a number of methods such as coefficient based algorithm and mathematical programming models have been developed for part family formation and plan retrieval. After identifying a new part with a family, the task of developing process plan is simple. It involves retrieving and modifying the process plan of master part of the family.

The general steps for data retrieval modification are as follows :

3. Establishing the Coding Scheme

A variant system usually begins with building a classification and coding scheme. Because, classification and coding provide a relatively easy way to identify similarity among existing and new parts. Today, several classification and coding systems are commercially available. In some extreme cases, a new coding scheme may be developed. If variant CAPP is preferred than it is useful for a company to look into several commercially available coding and classification systems (e.g. DCLASS, JD-CAPP etc.). Now, it is compared with companies before developing their own coding and classification system. Because using an existing system can save tremendous development time and manpower.

(i) Form the Part Families by Grouping Parts

The whole idea of GT lies into group numerous parts into a manageable number of part families. One of the key issues in forming part families is that all parts in the same family should have common and easily identifiable machined features. As a standard process plan are attached with each part family, thereby reducing the total number of standard process plans.

(ii) Develop Standard Process Plans

After formation of part families, standard process plan is developed for each part families based on common part features. The standard plan should be as simple as possible but detailed enough to distinguish it from other.

(iii) Retrieve and Modify the Standard Plans for New Parts

Step1 to step 3 are often referred as preparatory work. Each time when a new part enters the systems, it is designed and coded based on its feature, using the coding and classification scheme, and than assigned to a part family. The part should be similar to its fellow parts in the same family. Also, family’s standard plan should represent the basic set of processes that the part has to go through. In order to generate detailed process routes and operation sheets to this part, the standard plan is retrieved from the data base and modified. Modification is done by human process planar. After this stage parts are ready for release to the shop.

The success of aforementioned process planning system is dependent on selection of coding scheme, the standard process plan and the modification process, because the system is generally application oriented. It may be possible that one coding scheme is preferable for one company and same is not for other company.

Due to use and advancement of computers, the information management capability of variant process planning is much superior. Otherwise it is quite similar to manual experience-based planning.

4. Advantages and Disadvantages of Variant CAPP

Following advantages are associated with variant process planning approach:

(i) Processing and evaluation of complicated activities and managerial issues are done in an efficient manner. Hence lead to the reduction of time and labour requirement.

(ii) Structuring manufacturing knowledge of the process plans to company's needs through standardized procedures.

(iii) Reduced development and hardware cost and shorter development time. This is an essential issue for small and medium scale companies, where product variety is not so high and process planner are interested in establishing their own process planning research activities.

5. Disadvantages of Variant Process Planning Approach

Following disadvantages are associated with variant process planning approach

(i) It is difficult to maintain consistency during editing.

(ii) Proper accommodation of various combinations of attributes such as material, geometry, size, precision, quality, alternate processing sequence and machine loading among many other factors are difficult.

(iii) The quality of the final process plan largely depends on the knowledge and experience of process planner. The dependency on process planner is one of the major shortcomings of variant process planning.

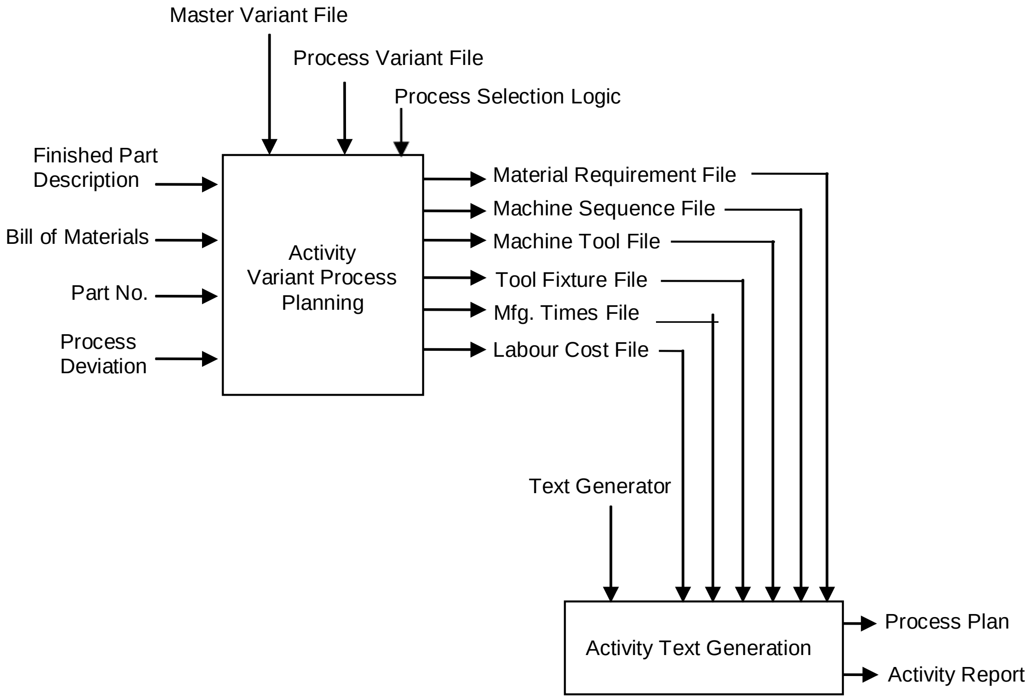


Figure 9.4 : Framework of Variant Process Planning Activity

Some of the most widely used process planning method developed by various company are mentioned as follows :

(i) Mc Donnell-Douglas automation company under the direction and sponsorship of Computer Aided Manufacturing International (CAM-I) developed a system where CAPP can be used to generate process plan for rotational, prismatic and sheet metal part.

(ii) Organization for Industrial Research (OIR) and General Electric Company have developed and another process plan named as MIPLAN. It accommodates both rotational and prismatic part, and is based on MICLASS coding.

Generative Process Planning, Advantages and Disadvantages

In generative process planning, process plans are generated by means of decision logic, formulas, technology algorithms, and geometry based data to perform uniquely processing decisions. Main aim is to convert a part form raw material to finished state. Hence, generative process plan may be defined as a system that synthesizes process information in order to create a process plan for a new component automatically.

Generative process plan mainly consists of two major components :

(i) Geometry based coding scheme.

(ii) Proportional knowledge in the form of decision logic and data.

6. Geometry-based Coding Scheme

All the geometric features for all process such as related surfaces, feature dimension, locations, on the features are defined by geometry based coding scheme. The level of detail is much greater in generative system than a variant system.

For example, various details such as rough and finished state of the part are provided to transform into desired state.

7. Proportional Knowledge in the Form of Decision Logic and Data

Process knowledge in the form of decision logic and data are used for matching of part geometry requirement with the manufacturing capabilities. All the methods mentioned above is performed automatically.

Operation instruction sets are automatically generated to help the operators to run the machines in case of manual operation. NC codes are automatically generated, when numerically controlled machines are used.

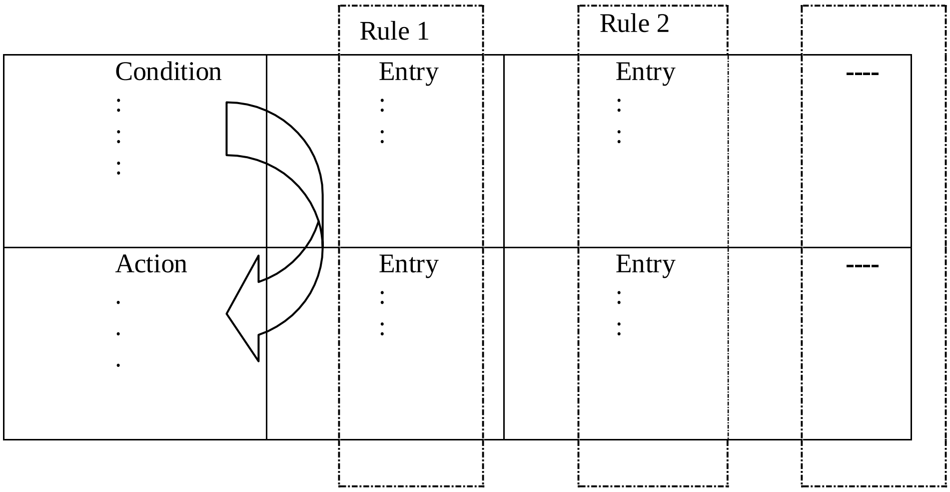


Figure 9.5 : Framework of a Decision Table

Manufacturing knowledge plays a vital role in process planning. The process of acquisition and documentation of manufacturing knowledge is a recurring dynamic phenomenon. In addition, there are various sources of manufacturing knowledge such experience of manufacturing personnel, handbooks, supplier of machine tools, tools, jigs and fixtures materials, inspection equipment and customers etc. Hence, in order to understand manufacturing information, ensuring its clarity and providing a framework for future modification, it is not only necessary but also inevitable to develop a good knowledge structure from wide spectrum of knowledge. Flowchart, decision trees, decision tables, algorithms, concepts of unit machined surfaces, pattern recognition techniques, and artificial intelligent based tools are used to serve the purpose. A brief discussion on decision table is given below.

The basic elements of decision tables are condition, action and rules. They are represented in the form of allocation matrix. Figure 9.4 is one such representation where condition states the goal that we want to achieve and action states the operation that we have to perform. On the basis of experience the expert rules are formed by entry values to establish the relationship between condition and action.

Table 9.1 is one such representation where entry are of Boolean-types (true, false, don’t care). Similarly, in Table 9.2, continuous value type entries are shown.

8. Table 9.1 : Boolean Value-Type Entries

Length of bar ≥ 8 in.	T*	F	
Diameter of bar ≤ 1 in.			
Diameter of bar ≥ 1 in.	T		T
-	-	-	-
Extra Support	T		

* T : *True;* F : *False;* blank : *don’t care.*

9. Table 9.2 : Continuous Value-type Entries

Length of bar (in)		≤ 4	≥ 4	≤ 16	≥ 16
Diameter of bar (in.)	≤ 0.2	> 0.2	1>diameter>0.2	≥ 1	
Extra support	T		T		T

* T : *true*; blank : *do not care*

The decision making process works as follow.

For a particular set of condition entries, look for its corresponding rule from that rule determine the action.

10. Advantages of Generative Process Plan

Generative process plans have a number of advantages. Among the major ones are the following :

(i) They rely less on group technology code numbers since the process, usually uses decision tree to categorize parts into families.

(ii) Maintenance and updating of stored process plans are largely unnecessary. Since, any plan may be quickly regenerated by processing through the tree.

Indeed, many argue that with generable systems, process p lans should not be stored since if the process is changed, and out-of-dated process plan might find its way back into the system.

(iii) The process logic rules however must be maintained up to dated and ready for use. This provides the process planner with an assurance that the processes generated will reflect state-of-the-art technology.

Description of various generative and variant and generative CAPP systems is mentioned Table 9.3.

11. Table 9.3 : Some of the Variant and Generative CAPP Systems

CAPP System	Part Shapes	Process Planning Approaches	Characteristics and Commercial Situation	Programming Languages Used	Developers
CMPP	Rotational	Generative	Uses English like language(COPPL)	FORTRAN 77	UTRC (USA)
GENPLAN	All	Variant and Generative	Interfaced with CAD\CAM		Lockheed-Georgia(USA)
GT-CAPP	All	Generative	Part family code used		Rockwell Inc (USA)
KAPPS	Rotational and Prismatic	Generative	Part family numbers used	LISP	Kobe Univ. (JAPAN)
MIPLAN	Rotational and Prismatic	Variant	Expert system based on MICLASS		OIR and GE Co.(USA)
RTCAPP	Prismatic	Generative	Generic shell		USC (USA)
TURBO-CAPP	Rotational	Generative	Knowledge based interfaced with CAD	PROLOG	Penn. State Univ (USA)
XPLAN	All	Generative	Expert system based on DCLASS	FORTRAN 77	Tech. Univ. of DK (Denmark)
XPLAN-R	Rotational	Generative	Expert system based on DCLASS	FORTRAN 77	Tech. Univ. of DK (Denmark)
XPLANE	Rotational	Generative	Knowledge based	FORTRAN	Twente Univ. Tech. (Netherland)
XPS-1	All	Variant and Generative	COPPL used	FORTRAN	UTRC and CAM-I (USA)

(***Source* :** Alting and Jhang (1989))

Knowledge-based Process Planning

The main forces behind to apply knowledge-based (KB) techniques for CAPP is the requirement of large amount of human expertise in CAPP. Based on the previous discussion, one realizes that a productive CAPP system must contain tremendous amount of knowledge – facts about the machine and shop environment as well as rules about sequencing machining operations must be included. A traditional CAPP program cannot learn new knowledge without a programmer explicitly rewriting it. The rigidity of traditional methodology endangers the implementation of CAPP systems. A KB system stores knowledge in a special manner so that it is possible to add, delete and modify facts and rules in the knowledge base without rewriting the program, i.e. it learns new things according to embedded learning procedures.

A complete set of manufacturing knowledge is not equipped by any existing knowledge-based process planning system. Most of these systems focus on a small portion of the issues in the domain of automated process planning using an expert systems approach. Some of them are :

12. EXCAP Family of Process Planning Systems

EXCAP, EXpert Computer-Aided Process Planning, developed by Davies and

Darbyshire, is a knowledge-based system for rotational part process planning.

EXCAP-A and EXCAP-Y are previous generations of the current member of the EXCAP family of process planning systems.

13. GARI

GARI is the first AI-based CAPP program to appear in the literature. It is implemented in MACLISP and operates on CII-Honeywell Bull HB-68 computer under the MULTICS operating system. GARI utilizes production rules in its knowledge representation and generates a process plan from a model of the part. It emphasizes the “conflict resolution”. The knowledge is rather subjective and specialized. As a result, in the planning process, “compromises are often necessary.”

14. TOM : Technostructure of Manufacturing

TOM is another production rule-based CAPP system written in PASCAL and runs on VAX computer. TOM was designed to accept input in two ways: (1) directly entering part desecration by the user, and (2) translating design data from COMPAC CAD system. TOM can deal with “holes” exclusively.

15. SIPP : Semi-Intelligent Process Planner

SIPP is an AI-based CAPP system for the creation of metal parts using chip metal removal operations. It is written in PROLOG and utilizes “frames” as its knowledge representation scheme instead of using production rules. Frames are used to represent two types of knowledge: (1) information about the characteristics of various kinds of machinable surfaces, and (2) the capabilities of various machining processes.

16. SIPS

SIPS, another AI-based CAPP system which selects machining operations for the creation of metal parts, is a successor to SIPP. It is written in LISP and is currently being integrated into the AMRF (Automated Manufacturing Research Facility) project, where it is used to select machining operations on a feature by feature basis.

Like SIPP, SIPS also employs branch and bound search strategy for the least-cost-first solution in its inference engine. The basic difference between SIPP and SIPS is that SIPS used a new knowledge representation technique, called hierarchical knowledge clustering, instead of “flat” frames to represent problem-solving knowledge.

17. TOLTEC

TOLTEC is a system equipped with some learning capability. It takes input as feature-based part description interactively. The features are represented in a frame structure. It generates output in a form of operations and their sequence.

18. Turbo-CAPP

Turbo-CAPP is a knowledge-based CAPP system written in PROLOG and capable of :

- extracting and interpreting surface features from a 2&1/2-D CAD data base.
- performing intelligent reason for process planning.
- learning new process and machining capabilities.
- generating alternative process plans (based on the current status of the knowledge base).
- creating generic NC part programs for automated.

Turbo-CAPP is designed to handle strictly symmetric rotational parts. It employs a backward chining inference mechanism for plan generation. In the process of creating process plan and NC codes, the system must acquire knowledge from the user from time to time.

19. XPS-2 Family of CAPP Systems

CAM-I started the first structured development of process planning systems. It then embarked on a form-feature based, generative planning project, XPS and accomplished with the completion of XPS-2 in 1987. The form feature used to implement XPS-2 were taken from a "feature taxonomy" developed by CAM-I.

20. Other Knowledge-Based CAPP Systems

Rather than aforementioned Knowledge-Based CAPP System some other KB process planning systems are in existence :

(i) CMPP (Austin, 1996) is a planning system for planning cylindrical parts (also for some non-cylindrical features). It performs dimension, tolerance, and stock removal analysis based on a sophisticated algorithm with the objective of optimizing tolerance capabilities of shop equipment.

(ii) Hi-MAPP developed by Brenfi and Khoshnevis.

(iii) Wolfe and Kung in 1984 developed a CAPP system, which reads part geometry from a PADL model and generates process plans automatically.

Variant or Generative, Which to Use?

What CAPP approach (Variant or Generative) is better? This question has been constantly asked but, there is no definite answer to it.

Generally speaking, a variant system is better for manufacturing setting where similar parts are manufactured repetitively. Because parts are similar, Group Technology can easily be implemented and shows quick and significant return on investment (ROI). Because similar parts are produced repetitively, process plan can be retrieved, slightly modified and used, without going through too much trouble. On the other hand, generative process planning is better suited for a manufacturing environment in which part does not exhibit too much similarity and new part are introduced on a regular basis. In this case, benefits cannot be gained from Group Technology due to dissimilarity of parts. Because, new parts are regularly introduced, historical data does not have too much value to the process planner. However, aforementioned approach is a rough guideline for selecting the appropriate CAPP approach.

3. SAQ 1

(a) What is process planning?

(b) What are the various steps in developing a process plan?

(c) Why the need for CAPP arises?

(d) What are different approaches to CAPP? Describe briefly.

(e) Briefly describe the "Knowledge based Process Planning".

(f) Write short notes on following :

  (i) Manual experience based process plan.

  (ii) Computer Aided Process Plan.

FEATURE RECOGNITION IN CAPP

As we have seen that CAPP system usually serve as link in integrating the CAD and CAM. However, it is only the partial link due to lack of part feature information provided by existing CAD/ Drafting system. Part feature information is an essential data for CAPP. In other words, it is a tedious job for CAPP to understand the three dimensional geometry of the designed part from CAD system in terms of their engineering meaning related to assembly and manufacturing. Generally, all CAPP planning method and systems suffered from such type of problem and is referred as feature recognition in CAPP.

Hence, objective of feature recognition is to bridge the gap between the database and automated process planning systems by automatically distinguishing the feature of a part from the geometry and topological data stored in the CAD system. The essence of feature recognition can easily be understood by taking an example as shown in Figure 9.6. This figure is defined by a constructive solid geometry tree that represents a block primitive and a cylinder primitive combined by the Boolean operator "-". Shape and dimension can easily be identified by these schemes but, some higher level information is not provided by this scheme such as, whether the hole is blind hole or through hole. Such types of information are called as feature. Hence, features play a vital role in CAPP. In order to identify features and to solve CAD / CAPP interface problem, feature recognition is one of the most efficient technique.

Feature recognition transforms a general CAD model into an application specific feature model. In general, a generic part feature recognition system must be able to resolve following issues.

(i) Extract design information of a part.

(ii) Identify all surfaces of part.

(iii) Recognize reasons about\and\or interpret these surfaces in terms of Part features.

Once the features are classified, the automated planning system could develop the required process plan to make the part and hence, eliminate the need for a human to translate the CAD data into something that process planning system can understand.

Here, it is pertinent to mention that feature recognition is not only applicable to CAPP system but it can also be applied to various other engineering applications that require information about feature of parts classification and automated coding in GT.

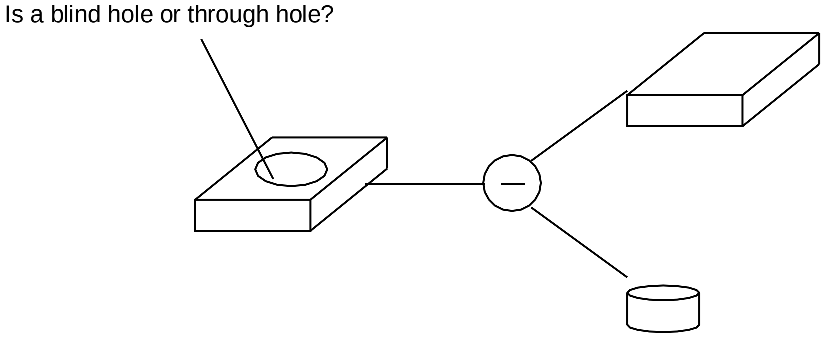


Figure 9.6 : Advance Level Information

Approaches to Part Feature Recognition

The most robust description of any part is provided through solid modelling. Therefore, these appear to be a logical starting point for developing a feature recognition system. Henderson and Anderson developed a system called **FEATURES** to perform automatic feature recognition using data from solid modelling system. A FEATURE simulates the human interpretation of part features. The system consists of a feature recognizer, extractor, and organizer. For objects containing swept features, this system performs well. This approach is encouraging because, conceptually, it can be applied for more complex parts. The FEATURES system uses the boundary representation (BREP) of a part, which denotes the faces, edges and vertices (FEV). Thus, features such as holes must be derived from more primitive data.

1. Table 9.4 : A Brief Review and Recent Trends in Feature Recognition Research

Author	Part Feature-recognition System	Recognizable Features
CAM-1	From feature taxonomy	--
Choi	CAD/CAM-compatible, toll-oriented process planning system.	Holes, Slots, Pockets
Henderson and Anderson	Extraction of feature information from 3-D CAD data.	Holes, Slots, Pockets
Jalubowski	Syntactic characterization of machine part shapes.	Rotational part family
Kakazu and Okino	Pattern-recognition approaches to GT code generation.	Rotational GT code
Kakino et.al.	A method of parts description for computer-aided production planning.	Grooves, steps, flanges
Kung	Feature-recognition and expert process planning system	Holes, Slots, Pockets
Kyprianou	Shape features in geometric modelling	Rotational part family
Lee	Integration of solid modelling and data base management for CAD/CAM	--
Liu	Generative process planning using syntactic pattern recognition.	--
Srinrasan, Liu and Fu	Extraction on manufacturing details from geometric models	Rotational part family
Woo	Computer-aided recognition of volumetric designs	--

Representing FEV contained in a BREP graph. As a result a hole may be present as a collection of faces that must be recognized from the part data.

A number of approaches to part feature recognition for rotational as well as prismatic parts have been developed. These different approaches are enlisted as follows :

(i) Syntactic Pattern Recognition

(ii) State Transition Diagram and Automata

(iii) Geometry Decomposition Approach

(iv) Expert System Rule Logic

(v) CSG (Set Theoretic) Approach

(vi) Graph Based Approaches

The syntactic pattern recognition and/or expert logic approach are mainly applied for feature extraction of rotational part feature recognition. The complexity increases in case for prismatic parts due to lack of rotational property. In this case, the difficulty of both representation of a generic object and recognition of its feature increases extensively. A brief review and recent trends in feature recognition research has been enumerated in Table 9.4.

In next subsection, we have discussed the graph based approach to feature recognition.

Attributed Adjacency Graph Based Approach for Feature Recognition

Following three steps are involved in Graph based feature recognition

(i) Generating graph based representation of the object to be recognized.

(ii) Defining part features.

(iii) Matching part features in the graph representation.

2. Generating Graph Based Representation of the Object to be Recognized

During first step graphs are used for representation of the object. This step is necessary because data extracted from the data base are usually in the form of boundary representation (BREP) and can not be used for feature recognition. Information regarding the type of face adjacency and relationship between the sets of faces should be expressed explicitly to recognize a feature. Here, attribute adjacency graph (AAG) has been used to demonstrate the recognition process.

Attributed Adjacency Graph

An AAG can be defined as a graph $G = (N, A, T)$, where N is the set of nodes, A is the set of arcs, T is the set of attributes to arcs in A such that :

- For every face f in F, there exists a unique node n in N.
- For every edge e in E, there exists a unique arc a in A, connecting nodes n_i and n_j, corresponding to face f_i and face f_j, which share the common edge e.
- "t" is an attribute assigned to every arc a in A, where :

  $t = 0$ if the faces sharing the edge form a concave angle (or " inside" edge)

  $t = 1$ if the faces haring the edge form a convex angle (or "outside" edge).

The AAG is represented in the form of matrix as follows :

$$\begin{array}{cc} & \begin{array}{ccccc} F_1 & F_2 & \cdots & \cdots & F_n \end{array} \\ \begin{array}{c} F_1 \\ F_2 \\ : \\ : \\ F_n \end{array} & \left(\begin{array}{ccccc} E_{1,1} & E_{1,2} & E_{1,3} & \cdots & E_{1,n} \\ : & : & : & : & : \\ : & : & : & : & : \\ : & : & : & : & : \\ E_{n,1} & E_{n,2} & \cdots & \cdots & E_{n,n} \end{array}\right) \end{array}$$

where

$$E_{ij} = \begin{cases} 0 & \text{if } F_i \text{ forms a concave angle with } F_j \\ 1 & \text{if } F_i \text{ forms a convex angle with } F_j \\ \phi & \text{if } F_i \text{ is not adjacent to } F_j \end{cases}$$

Hence it can easily be understood from above observation that AAG defines the shape of a part uniquely up to its topology, if and only if the faces are cut orthogonally.

3. Definition of Part Feature

First we have to define what actually feature is? In general any shape can be feature if their manufacturing meanings are defined. There are mainly six features which are commonly used in manufacturing. These are step, slot, three side pocket, four side pocket, pocket (or blind hole) and through hole. Figures 9.7(a-f)

F_1 is adjacent to F_2 and F_4

represent some of the features and their surfaces are labeled.

Four-side Pocket

F_1 is adjacent to F_2 and F_4

F_3 is adjacent to F_2 and F_4

F_2 is adjacent to F_1, F_3, and F_4

F_4 is adjacent to F_1, F_3 and F_2

F_1 forms concave (90°) angles with F_2 and F_4

F_2 forms concave (90°) angles with F_3, F_1 and F_4

F_3 forms concave (90°) angles with F_2 and F_4

F_4 forms concave (90°) angles with F_1, F_2 and F_3

Blind Hole (Pocket)

F_1 is adjacent to F_2, F_4 and F_5

F_2 is adjacent to F_1, F_3 and F_5

F_3 is adjacent to F_2, F_4, and F_5

F_4 is adjacent to F_1, F_3, and F_5

F_5 is adjacent to all other surfaces of the pocket

F_1 forms concave (90°) angles with F_2, F_4 and F_5

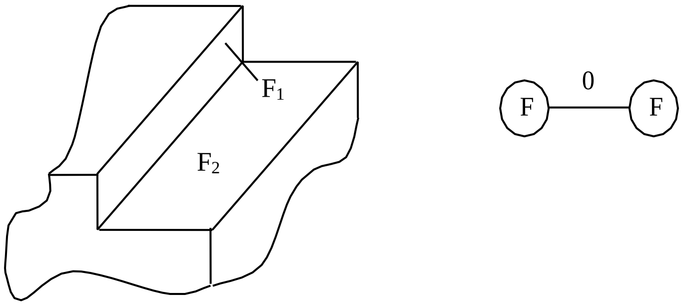
F_2 forms concave (90°) angles with F_3, F_1 and F_5

F_3 forms concave (90°) angles with F_2 and F_4 and F_5

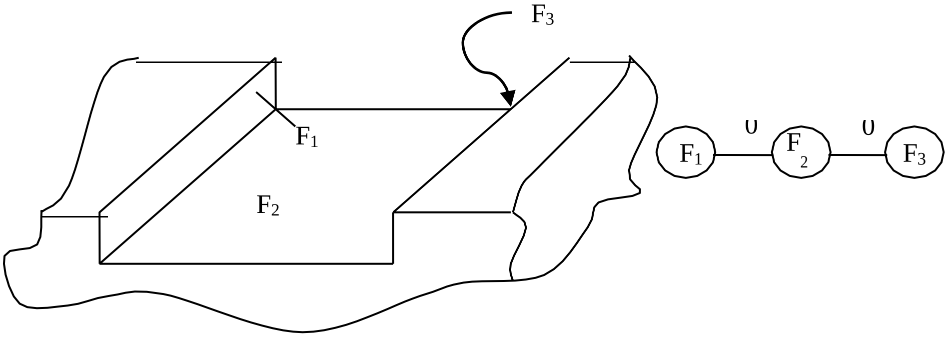
F_4 forms concave (90°) angles F_3, F_1 and F_5

F_5 forms concave angle (90°) with all other surfaces of the pocket

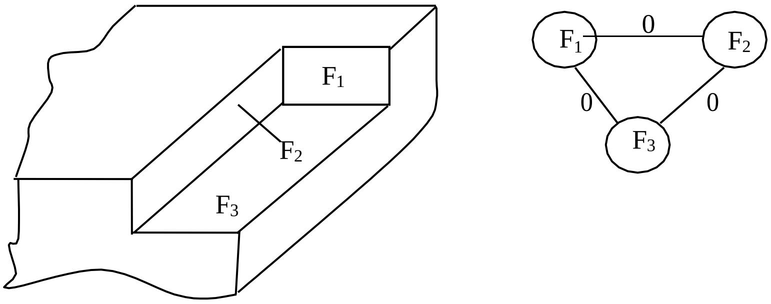
(a)



(b)



(c)



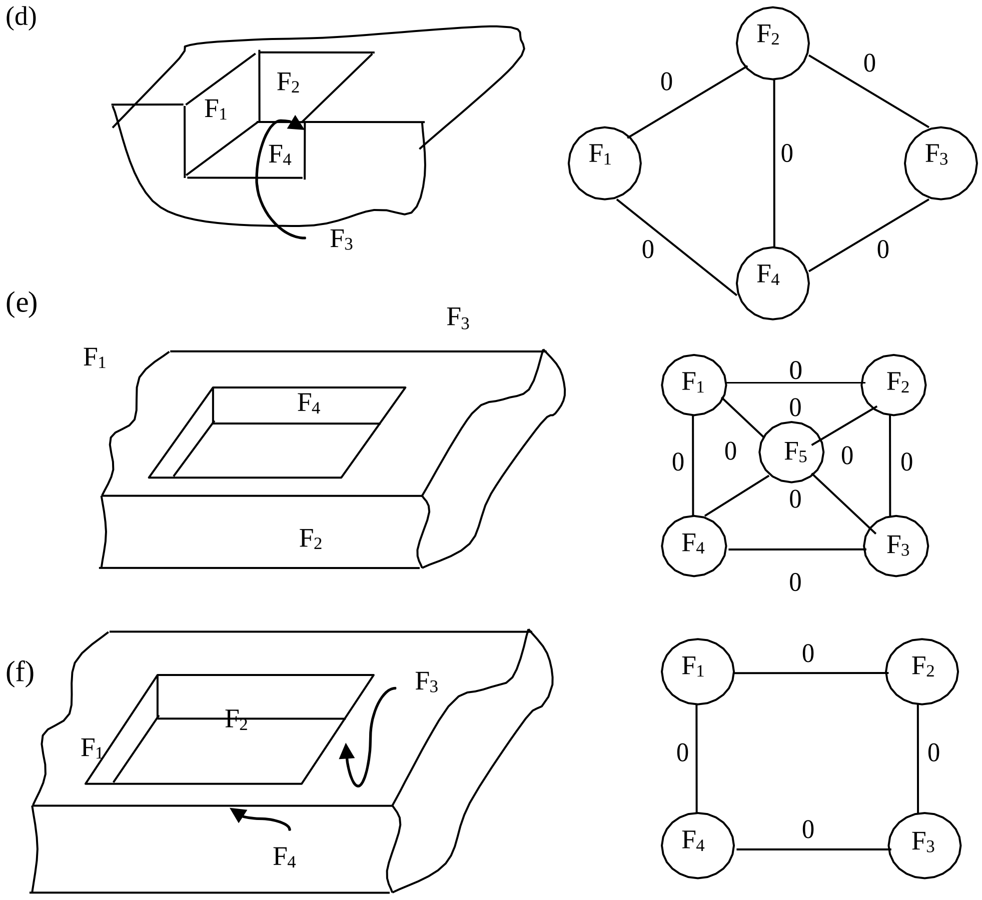


Figure 9.7(a-f) : Various Features

4. Matching the Features

After execution of step 1 and 2, the main task is to recognize AAG subgraph instead of recognizing machining features in parts. Because, complete AAG graph represents the part and subgraphs represent the features. It is computationally complex task to identify subgraphs in a graph. Although, there is no general way or algorithm to solve the problem.

Joshi and Chang, 1988 used an algorithm to identify the components of the graph that could form a feature. The algorithm is based on the following observations :

A face that is adjacent to all its neighbouring faces with a convex angle 270^o does not form part of a feature. This observation is used as a basis for separating the original graph into subgraphs that could corresponds to features. The separation is done by deleting some nodes of the graph. The delete node rule follow *IF THEN* rule and given as follows. For all nodes :

> *If* (all incident arcs of a node have attribute “1”)
>
> *Then* (delete this node (and all the incident arcs at the node) from AAG)

Delete node rule actually delete rows and column that represent the nodes in the matrix. Now feature recognition rule are applied to identify that whether or not a sub-graph represent a feature. On the basis of feature definition some rules are written. In order to identify features some rules are given as follows :

For a Given AAG

> *It is* a four side feature if
>
> > (The AAG subgraph has four nodes) *and* (The number of arcs with attribute “0” is the number of nodes plus one).
>
> *It is* a pocket feature *if*
>
> > (The AAG subgraphs have five nodes) *and* (The number of arcs with attribute”0” is the number of attributes plus three).

In some of the cases, delete node rule fails. This is due to the intersection of features. Delete node rule cannot separate complete AAG graph into subgraphs, particularly for the case when features intersects. Hence, only for those cases when features are disjoint, delete node rule can be applied.

Following procedures are used to separate the subgraphs for intersecting features.

- Delete all 1 arcs
- Form the subgraphs that may or may not represent the features.
- If not all the subgraphs, represent features, restore the one arc deleted within the subgraph.

The main task of this procedure is to separate the graphs into subgraphs. If the procedure is successful, it greatly reduces the computational effort otherwise graph remains unchanged.

An Illustrative Example

An example is taken from Li (1992), which is illustrated as follows

5. Example 9.1

It is easy for human to recognize that the part shown in Figure 5.14(a) has a slot and a pocket feature. In this example, however, we simulate the computer to apply the feature recognition algorithm discussed earlier. We, therefore, want to solve the following problem :

(i) Develop the AAG of the object, (ii) Give the matrix representation of the AAG, and (iii) Recognize the features in this object.

6. Solution

(i) First, we have to label each surface of the part. Given that the part is labeled as shown in Figure 9.8(a), we develop the AAG as shown in Figure 9.8(b) from the definition of AAG. By the definition of AAG we mean that each surface of this part is represented by a node and each edge by an arc with attribute 1 or 0.

(ii) For propose of inputting the AAG graph into the computer, we have to convert the graph to matrix form. The matrix representation of AAG is given as follows.

F_1 F_1 F_2 F_3 F_4 F_5 F_6 F_7 F_8 F_9 F_{10} F_{11} F_{12} F_{13} F_{14} F_{15}
F_2 **2.** **9 0 9** . . . F 0 0 1 9
F_3 . 9 0 1 4 9 0 1 9
F_4 . . 9 0 0 1 9
F_5 . . . F 9 9 1 9
F_6 . . . 1 5 . 9 9 9
F_7 . . . . . 9 1
F_8 9
F_9 . . . .
F_{10} . . . .
F_{11} . . . .
s y m m e t r
F_{12} . . . .
F_{13} . . . .
. . . .
. . .

```
9 9 9 9 9      9 9 9 ┐
9 9 9 9 9      9 9 9 |
9 9 9 9 9      9 9   |        9 |
9 9 9 9 9      9 9   |        9 |
9 9 9 9 9      9 9 9 |
9 9 9 9 9      1 1 1 |
1 9 9 9 9      9 1 1 |
9 1 9 9 9      9 1   |        1 |
. 9 1 9 9      9 1   |        1 |
. . 9 1 9      9 1 1 |
y . . 9 0      9 1 1 |
. . . . 9      0 1 1 |
. . . . .      9 1   |        1 |
. . . . .      . 9   |        9 |
. . . . .      . . 9|┘
```

(iii) Apply the delete node rule of the algorithm; that is delete the nodes connected with all “1” attributer arcs. Also delete these “1” arcs. Doing this on the adjacent matrix, we remove the rows and columns without 0 elements. For example, row 15 and column 15 represent this type of arc and can be deleted. After all such arcs are deleted, the present matrix will result into two unrelated sub-matrices. Each sub-matrix represents a sub-graph. We find that “0” in column 12, which is $F_{12.}$ We find that two disjoint subgraphs are generated (from Figure 9.8(d)). Figure 9.8(c) gives the same structure as the one shown in Figure 9.8(b), which corresponds to the slot feature. Thus the first feature that is recognized is the slot feature. In the computer this matching is achieved by applying the identifying rules. That is, if AAG subgroup has three nodes and the number of arcs with attribute “0” is 2, and then it is a slot. Also, because Figure 9.8(d) has the same structure as the one shown is Figure 9.7(e), it is a pocket. As there are no more features to be recognized. We conclude that there are two features in this part, a slot and a pocket.

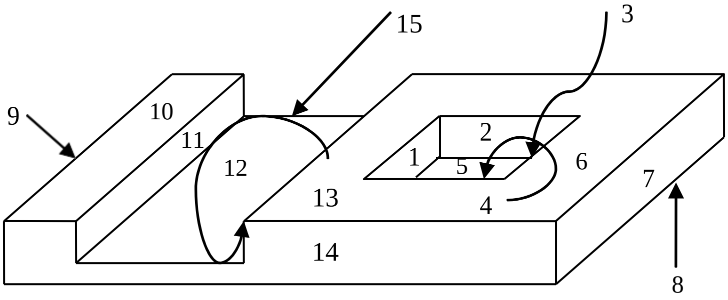


Figure 9.8(a)

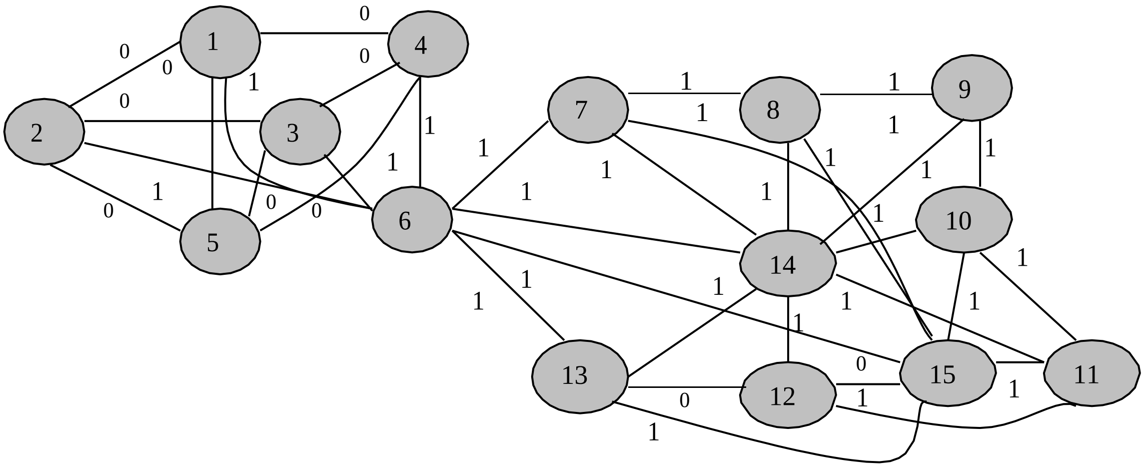
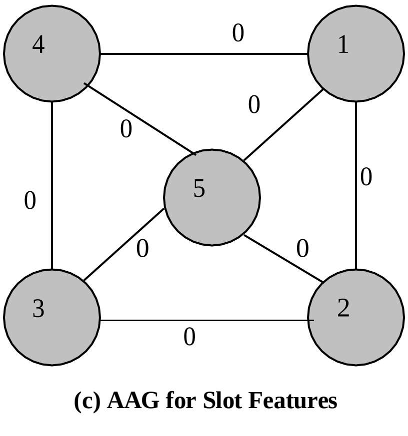


Figure 9.8(b) : AAG for the Example Part



(c) AAG for Slot Features

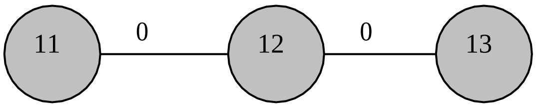


Figure (d) : AAG for Pocket Feature

RECENT TRENDS IN CAPP

In the global competitive market, various areas such as design process planning, manufacturing and inspection plays a vital role in reducing cost and lead time. In the various areas, different kind of interference mechanism has been developed. A lot of difficulty arises while integrating the goal in CIM environment. For example, all functional areas have its own standalone relational database and associated database management system. One of the main difficulties posed in CIM environment is the incompatibility of software and hardware incompatibility. Hence, it is not only desirable but also inevitable to develop a single database technology to address these problems. The major challenges of and research areas are to make CAPP system affordable to the medium and small scale manufacturing industries. Hence recent trends in CAPP systems include :

- Automated translation of the design dimensions.
- Tolerances into manufacturing dimensions.
- Tolerances considering process capabilities.
- Dimensional chains.
- And to make CAPP system affordable for small and medium scale manufacturing industries.

1.SAQ 2

(a) What do you mean by Feature Recognition?

(b) What are different steps of Graph based approach?

(c) Mathematically define AAG.

(d) Discuss about future trends in CAPP.

(e) What are the achievements of CIM?

SUMMARY

In the early 1970s, the function of process planning received very little attention. Today, manufacturing environment has become more complex and competition has become more intense. Hence, process planning has been accepted as critical to the success of many companies. Process planning bridges the gap between design and manufacturing. In addition, it has been acknowledged to be the link between CAD and CAM. As a result process planning is recognized as a vital element in CIM environment.

This unit dealt with process planning where more focus was concentrated on CAPP. It begins with the introduction of process planning and its various components. We discussed and illustrated with examples the element of process planning, such as analysis of part requirement; selection of the raw workpiece; determining manufacturing operation and their sequences; selection of machine tools; selection of tools, jigs or fixtures and inspection equipment; and determining machining condition and manufacturing times (setup time, processing time and lead time). After that Computer Aided Process Planning is discussed by explaining the reason why Computer Aided Process Planning has recently received much attention both in industry and academia. It follows by an overview of basic approaches for building Computer Aided Process Planning system : variant and generative. It then discusses the basic component required in a variant or generative system. A few existing knowledge based Computer Aided Process Planning systems are reviewed. After that, principles of making decisions for using either variant or generative approaches are discussed. Feature recognition in Computer Aided Process Planning has been discussed with a brief review of part feature recognition approaches. In this unit, we limit our exposition to the graph based approach to feature recognition. And finally focuses are made on recent trends in Computer Aided Process Planning.

KEY WORDS

Process Planning	:	Process planning is a production organization activity that transforms a product design into a set of instruction (Machine tool setup etc.) to manufacture market part or produced economically and competitively.
Computer-Aided Process Planning	:	Computer aided process planning has recently emerged as the most critical link to integrate CAD/CAM system into inter-organizational flow.
Variant Process Planning	:	In this approach, process plan for a new part is generated by recalling, identifying and retrieving an existing plan for a similar part and making necessary modifications for new part.
Generative Process Planning	:	In Generative Process Planning, process plans are generated by means of decision logic, formulas, technology algorithms, and geometry based data to perform uniquely processing decisions.
Feature Recognition	:	Objective of feature recognition is to bridge the gap between the database and automated process planning systems by automatically distinguishing the feature of a part from the geometry and topological data stored in the CAD system.

ANSWERS TO SAQS

Refer the relevant text in this unit for Answer to SAQs.

3. Introduction to FMS

Intense competition in the global market for mechanical parts manufactured on machine tools and other metal working equipment has compelled manufacturers to reduce delivery times and quote competitive prices even for relatively small orders. In many situations, manufacturers have to deliver customized products to the consumers. The batch size is ever-decreasing, and the need to meet specific customer needs calls for considerable flexibility in the working of the manufacturing system. In this situation, the requirements that a modern manufacturing facility has to meet can be detailed as follows:

- High productivity for all batch sizes, large or small
- Shorter throughput times

- Lower storage costs
- Reduced labour if not altogether avoiding labour
- Reduced handling
- Flexible production system to incorporate product changes at short notice to meet customer’s specific requirements
- Sensing and taking care of such eventualities like tool breakage.

Conventional high volume production facilities such as automatic equipment and transfer lines do not fulfill these requirements. This provided sufficient reason for manufacturing engineers to turn attention to alternative approaches to manufacturing.

Flexible manufacturing cells and flexible manufacturing systems have been evolved to meet the requirements listed above.

The functions of many manufacturing equipment have already been automated through the use of CNC and PLC. The next stage is to automate the wider manufacturing environment comprising the following activities:

- Management of resources
- Storage, preparation and transport of raw workpieces and finished components
- Acquisition, processing and evaluation of production data
- Inspection of workpieces and continuously monitoring the performance of production equipment
- Testing of products

- Developing software to control all the above operations.

In such a process of integrated automation it is necessary to combine a number of machines, both mechanically and in terms of data processing into a closely linked manufacturing unit. In this way, highly automated manufacturing units (cells) are created which are capable of handling a number of different workpieces without interruptions due to operations like setting up workpieces, tool change, inspection etc. Monitoring and process correction facilities through appropriate sensors are also part of the system so that operator intervention is kept to a bare minimum. Manufacturing cells normally contain 1 to 4 production machines. In addition to various “service machines” such as measuring machines and washing machines) and transport systems like automated guided vehicles, rail guided vehicles and conveyors for the workpieces and for the tools. The cell computer simultaneously controls the manufacturing operations within the manufacturing cell.

Subsystems of FMS

There are three major subsystems in FMS:

(i) Computer-controlled manufacturing equipment (e.g. numerically controlled machine tools, robots, gantry loaders, palletizing systems, washing stations, tool pre-setters, in- process inspection systems etc.)

(ii) Automated materials storage, retrieval, transport and transfer system

(iii) Manufacturing control system (including both machine tool, tool and logistics control) Some FMS’s have additional subsystems. For example, in a machining application there may also be systems for presetting tools, storing and retrieving tools, disposing of chips and cutting fluids, washing and inspection workpieces. These subsystems must be linked together to achieve integrated manufacturing operation.

Scope of FMS

Although this was initially developed for machining applications, the concept of FMS has subsequently been used in a variety of other manufacturing applications, such as:

- Assembly of equipments
- Semiconductor component manufacturing

- Plastic injection moulding
- Sheet metal fabrication
- Welding
- Textile machinery manufacture

Such systems have proved to be practical and economical for applications with the following characteristics:

- Families of parts with similar geometric features that require similar types of equipment and processes
- A moderate number of tools and process steps
- Low to medium quantities of parts
- Moderate precision requirements

FMS Compared to other types of Manufacturing Approaches

One-off and low volumes of production are normally carried out by conventional general purpose machine tools. When the number of parts in a production run is more it is called batch production. A batch production shop is best suited for small quantities of many different types of parts. The very nature of production makes the operation of a job shop less efficient than an automated production line.

Since the job shop must be provided the greatest degree of flexibility, most of its operations are manual. They are normally equipped with general purpose CNC machine tools. Hard automation with dedicated equipment is best suited for the production of very large quantities of identical parts. Production of automobile components in a transfer line falls under this category. A large portion of the manufacturing industry involves the intermediate level of batch operations that lend themselves to the FMS approach. In this case volume is less but varieties are more.

FMS thus basically attempts to efficiently automate batch manufacturing operations. They are an alternative that fits in between the manual job shop and hard automation. FMS is best suited for applications that involve an intermediate level of flexibility and low or medium quantities. Fig. 28 shows the different types of production systems and it can be seen from the figure that FMS fits into the intermediate range of production.

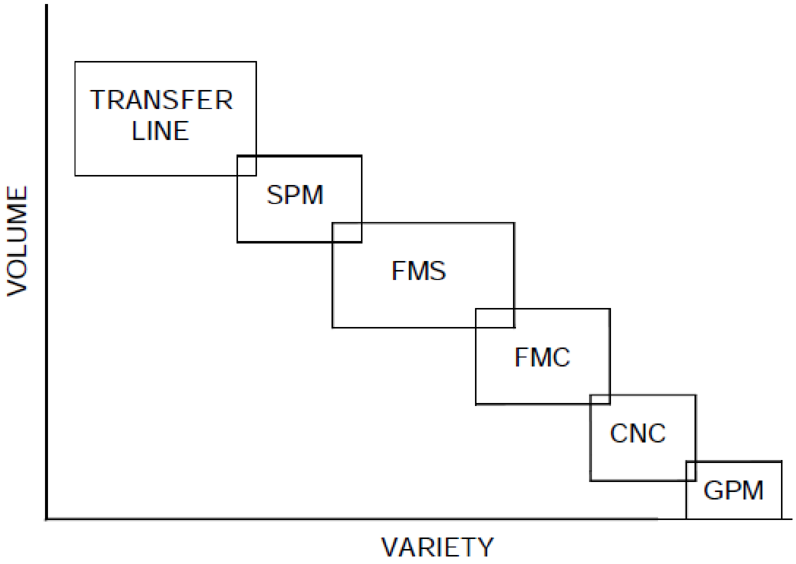


Fig. 28 Types of Production Systems

General purpose machines can accommodate a large variety of parts. They are manually operated and therefore production volumes are low. CNC machines can accommodate variety but the production volume is less as the machines are not optimized for the highest productivity for a specified type of job. It can be seen that FMC and FMS satisfy both variety and volume equally well. If we take special purpose machines, variety is much restricted. Transfer lines are dedicated usually to manufacture a component and hence can be said to have the minimum variety.

Types of FMS

FMS has been classified in several ways. Some of these classifications are still valid but the discussion in this book is restricted to three basic types:

Flexible Manufacturing Cells (FMC)

The simplest, hence most flexible type of FMS is a flexible manufacturing cell. It consists of one or more CNC machine tools, general purpose or of special design interfaced with automated material handling and tool changers. FMC's are capable of automatically machining a wide range of different workpieces. They are usually employed in one off and small batch production as independent machining centres, but are frequently the starting point for FMS.

A turning centre fitted with a gantry loading and unloading system and pallets for storing work pieces and finished parts is a typical flexible turning cell. If the turning centre is incorporated with either in-process or post process metrology equipment like Renishaw probes or inductive measuring equipment for automatic offset correction, the productivity of the system improves and wastage due to rejection is reduced. Automatic tool changers, tool magazines, block tooling, automatic tool offset measurement, and automatic chuck change and chuck jaw change etc. help to make the cell to be more productive.

One or two horizontal machining centres with modular fixturing, multiple pallets, advanced tool management system, automatic tool changer, automatic head changer or automatic magazine changer, robots or other material handling systems to facilitate access of the jobs to the machine also constitute a flexible machining cell.

An FMC can also comprise a turning centre, machining centre and pick and place robots or other materials handling systems. Fig. 29 shows the block diagram of a flexible manufacturing cell. This consists of a CNC lathe, a machining centre, a small automatic storage and retrieval system, two robots for loading and unloading the machines and a small rail guided vehicle to carry the component from one machine tool to another. The system is controlled by a PLC and a couple of personal computer.

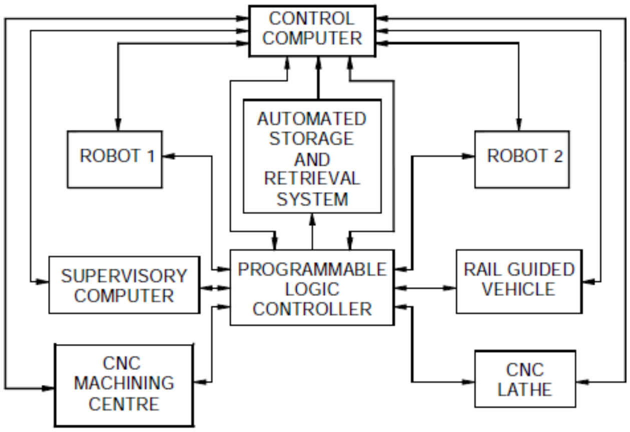


Fig. 29 Flexible Manufacturing Cell

Flexible Turning Cells

One of the most important advantages of CNC machines is their flexibility. The flexibility in this particular context means that these work centres enable the production of components in short batches. The production can be planned to meet immediate requirements because the change over time is short. In order to enable the production set up to change over from one component to another component in the shortest possible time, several technological features have to be added to the turning machines. This section describes some of these important features.

There are several ways to cut down idle time and component change over time and improve the productivity and flexibility of CNC turning centres. Flexible turning cells generally employ turning centres instead of CNC lathes. The availability of C-axis and the live tools in the turret enable the process designer to complete not only turning but also operations like milling, off-centre drilling, tapping, and helical groove cutting etc in one set up. This means that all operations required to completely machine a component can be carried out in one set up itself.

The relatively high cost of CNC machines means that the machine hour rate is several times that of conventional machines. This necessitates not only increasing the utilization by cutting down idle time but also working on all the three shifts of the day as well as during holidays. This calls for a high degree of automation. By using automatic part changer, automatic tool changer and adopting process automation through sensing and feedback devices like tool breakage sensors, automatic tool length offset compensation, in-process or post-process gauging and program correction, automatic chuck changing and chuck jaw changing, it will be possible to achieve fully automatic unmanned machining.

Flexible Transfer Lines (FTL)

Flexible transfer lines are intended for high volume production. A part in a high volume production may have to undergo large number of operations. Each operation is assigned to and performed on only one machine. This results in a fixed route for each part through the system. The material handling system is usually a pallet or carousel or conveyor. In addition to general purpose machines, it can consist of SPM’s, robots and some dedicated equipment. Scheduling to balance the machine loads is easier. Unlike conventional transfer lines, a number of different workpieces can be manufactured on the FTL. The resetting procedure is largely automatic.

Flexible Machining Systems

Flexible Machining Systems consists of several flexible automated machine tools of the universal or special type which are flexibly interlinked by an automatic workpiece flow system so that different workpieces can be machined with the same machine configuration. The characteristic feature is the external interlinkage of the machines, unrestricted by cycle time considerations. Different machining times at the individual stations are compensated for by central or decentralized workpiece buffer stores. Flexibility is applied to machines because of CNC control and flow of products from one machine to another which is possible through flexible transport system. Flexibility is characterized by the system's ability to adapt to changes in the volumes in the product mix and of the machining processes and sequences. This means that a FMS will be able to respond quickly to changing market and customer demands.

Benefits of FMS

FMS's are designed to provide a number of advantages over alternative approaches (Fig. 30). These are listed below:

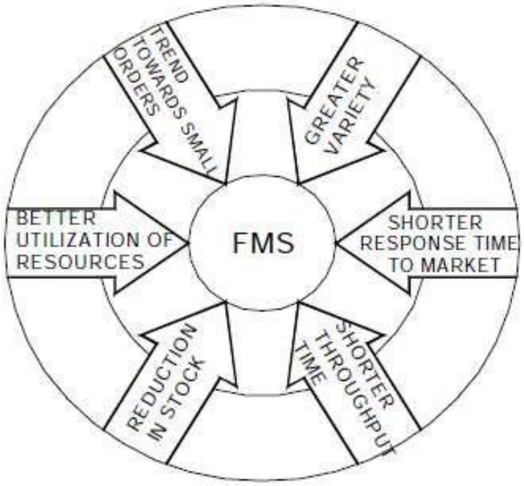


Fig. 30 Benefits of FMS

Reduced cycle times

- Lower work-in-process (WIP) inventory
- Low direct labour costs
- Ability to change over to different parts quickly
- Improved quality of product (due to consistency)
- Higher utilization of equipment and resources (Utilization better than standalone CNC machines)
- Quicker response to market changes
- Reduced space requirements
- Ability to optimize loading and throughput of machines
- Expandability for additional processes or added capacity
- Reduced number of tools and machines required
- Motivation for designers to add variations and features to meet customer requirements.
- Compatible with CIM

Some of these advantages can lead to significant cost savings. Direct labour can be eliminated almost entirely. Cycle time and WIP can be reduced to a fraction of what is normally experienced in a manual operation. An FMS is designed to have the production machines working most of the time rather than standing idle.

This can be explained with the help of Fig. 31. On any manually controlled work centre, the total time available for production per year is 8760 hours. Out of which the company loses 14.3 % of the time on account of Sunday being a weekly holiday. Paid holidays result in production loss of roughly 1.5%. An employee may also be eligible for paid leave (casual leave, earned leave etc.) and this may reduce the available working hours by 8%. The efficiency of production in the third shift is usually less and the production loss due to it is about 14% (assuming only 50% of the normal efficiency in the third shift). In India, a major cause for loss of production is employee absenteeism due to medical or other reasons. A factory employee is eligible to avail unto 90 days leave a year, enjoying the benefits from Employee's State Insurance. The average absenteeism in many industries varies. If we assume that the loss of production due to absenteeism is approximately 7%, the net available production time is only 55%. Assuming an efficiency of production of 80%, the work centre time utilized comes down to 44%.

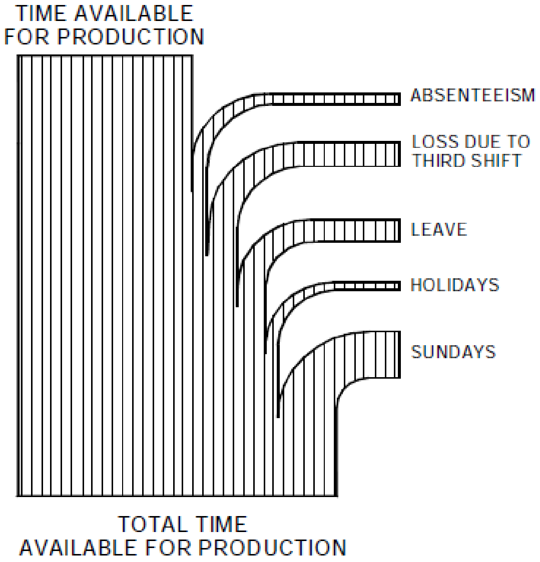


Fig. 31 Loss of Production Time

In the case of conventional manually operated metal cutting machines, the actual time utilized for removal of material is about 30-35% of the working time. The rest of the time is spent on non-productive operations like setting up of work and tools, inspection or procuring tools etc.

In the case of efficient operation of CNC machines this percentage increased to 80 to 85%. In FMS, one can achieve as high as 90-95% efficiency. Another important feature of FMS is that an FMS can produce parts even if the employee is absent or even if it is a holiday. The significance of FMS must be apparent from this fact. An automated material handling system and a computer-based production scheduling system are needed to keep the machines fed with parts. FMS uses computer automation techniques to lower the overall cost of production operations.

Major Elements of FMS

Each of the major subsystems in an FMS performs a number of functions and is dependent on the others to make the entire system work. The functions will vary, depending upon the type of equipment and manufacturing operations involved.

Production Equipment

The production equipment used in FMS depends upon the product manufactured.

(i) FMS for sheet metal work: The work centres used in sheet metal FMS include turret punch presses, laser machining centres, press brakes, guillotines etc. A typical FMC consists of sheet stacking system, sheet unloading device, sorting conveyor, turret punch press, right angle shear, loading device and automatic storage.

(ii) FMS for machining: This type of FMS typically has a number of machining centres and/or turning centres to provide general purpose machining capabilities. Machining centers offer the greatest flexibility, since they can perform many different machining operations. (e.g. milling, drilling, and boring). This is made possible by a toolchanging system that is either built into or supports the machining centre. A part can therefore undergo multiple machining processes at a single workstation. Special purpose machines may also be included in the FMS to perform operations which are unique or require more efficiency (e.g. turning, grinding). Washing machines and inspection machines also form the equipment of FMS. The family of parts which the FMS is designed to produce will determine the capabilities required from the machine tools (e.g. accuracy, size, power etc).

Support Systems

Automated machine tools typically require several systems to support their operation. The tools required to perform the multiple processes of a machining centre or a turning centre may be stored in magazines at each machine or in central tool storage. Local magazines provide fast access as well as backup capability but in a large FMS a central tool facility may be more efficient. Centralization not only permits the total number of tools to be minimized; it also provides the opportunity to perform additional functions automatically, such as:

(i) Measurement of tool wear
(ii) Tool pre-setting
(iii) Tool regrinding, repair and maintenance
(iv) Replacement of broken or worn tools

Many automated machine tools have built-in systems to monitor tool wear and detect tool breakage. They may use probes or non-contact techniques such as acoustic emission for this purpose. When a tool needs replacement, the machine can signal the tool room for the delivery of a replacement. This may be performed by an AGV or gantry set up or RGV. Elaborate tool management support is an integral part of FMS software. With this software, operating personnel can have effective centralized control of a large tool inventory. Automated machining operations also need to have the chips cleaned off the workstation and the workpiece. This may be performed by robots or special washing stations. Cleaning may involve turning the workpiece over, vacuuming and washing.

Materials Handling System

- A FMS typically needs several materials handling systems to service the machines.
- A transport system to move workpieces into and out of the FMS (e.g. overhead conveyors, gantry systems, AGV’s, RGV’s)
- A buffer storage system for queues of workpieces at the machines (e.g., pallets)
- A transfer system to load and unload the machines (e.g. robots, transfer fixtures)

For these systems to work effectively, they must be synchronized with the machine operations. The location and movement of workpieces must be tracked automatically. This is done by using sensors on the materials handling system and workstations.

They may be either contact devices (e.g. switches) or non-contact devices (e.g. optical, tags or proximity devices).

Automatic Guided Vehicles (AGV)

AGV is one of the widely used types of material handling device in an FMS. These are battery-powered vehicles that can move and transfer materials by following prescribed paths around the shop floor. They are neither physically tied to the production line nor driven by an operator like forklift. Such vehicles have on-board controllers that can be programmed for complicated and varying routes as well as load and unload operations. The computer for the materials handling system or the central computer provides overall control functions, such as dispatching, routing and traffic control and collision avoidance. AGV's usually complementing an automated production line consisting of conveyor or transfer systems by providing the flexibility of complex and programmable movement around the manufacturing shop.

Advantages of using AGV systems in FMS

(i) Flexibility: The route of the AGV's can be easily altered, expanded and modified, simply by changing the guide path of the vehicles. This is more cost effective than modifying fixed conveyor lines or rail guided vehicles. It provides direct access materials handling system for loading and unloading FMS cells and accessing the automated storage and retrieval system.

(ii) Real time monitoring and control: Because of computer control, AGV's can be monitored in real time. If the FMS control system decides to change the schedule, the vehicles can be re-routed and urgent requests can be served. AGV's are usually controlled through wires implanted on the factory floor. The control is effected using a variable frequency approach. Radio control, an alternative to in-floor mounted communication lines, permits two way communications between the on-board computer and a remote computer, independent of where the vehicle is i.e. whether it is in the parking place or whether it is in motion. To issue a command to a vehicle, the central computer sends a bit stream via its transmitter using frequency shift keying methods to address a specific vehicle. The signal transmitted from the base station is, therefore, read by the appropriate vehicle only. The vehicle is also capable of sending signals back to the remote controller, to report the status of the vehicle, vehicle malfunction, battery status, and so on.

(iii) Safety: AGV's can travel at a slow speed but typically operate in the range 10 to 70 m/min. They have on-board microprocessor control to communicate with local zone controllers which direct the traffic and prevent collisions between vehicles as well as the vehicle and other objects. A bumper is attached to some designs of AGV's to prevent collision. AGV's may also incorporate warning lights, fire safety interlocks and controls for safety in shops. During design, the use of simulation can help detect whether there are enough vehicles to perform the necessary load, unload and transportation tasks and thus optimize the utilization of the AGV system. Because these vehicles have to work in a tandem with highly organized FMS cells as well as with automated warehouses under computer control, their level of performance will affect the entire efficiency of the FMS.

Automated Storage and Retrieval Systems

A key part of any materials handling system is storage. Major advances have been made in recent years to automate the storage and retrieval of product and materials by employing sophisticated materials handling machines, high-density storage techniques and computer control. Such systems come in a variety of forms and sizes depending on the materials handling and storage job that has to be done. They often take the form of automated warehouses which use automatic storage and retrieval systems, conveyors and computers to control the materials handling machines and to track and control the inventory. The characteristics of such warehouses include:

(i) High density storage (in some cases, large, high-rise rack structures)

(ii) Automated handling systems (such as elevators, storage and retrieval carousels and conveyors).

(iii) Materials tracking systems (using optical or magnetic sensors)

In such a storage system, the computer can keep track of a large number of different parts, products and materials and can assign bin locations to optimize the use of storage space. When such a system is tied into the production control system, parts and materials can be replenished as they are consumed on the factory floor, keeping the work in process (WIP) to a minimum.

Categories of AS/RS

The automatic storage and retrieval system can be classified into several types. Some of them are:

- Unit load AS/RS
- Mini load AS/RS
- Man-on-board AS/RS

- Automated item retrieval system
- Deep lane AS/RS

Basic Components of AS/RS

An AS/RS normally consists of:

- Storage structure
- Storage and retrieval machine
- Storage modules
- Pick-up and deposit stations

Special Features of AS/RS

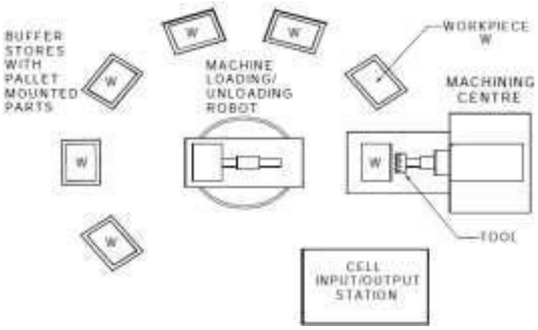
Some of the special features of AS/RS are:

- Aisle transfer cars
- Full/empty bin detectors
- Sizing stations
- Load identification stations

Buffer Storing of Parts

In an FMS, parts move from one work cell to another where the various processing tasks are performed. Because of the almost random production facilities of FMS, the destination cell might not always ready to accept the incoming part and the part has to wait in a buffer store. These and other bottlenecks in the materials handling problems can be successfully detected by simulation. Buffer stores for parts will always be desirable. Figure 19.8 shows a typical FMC cell layout where buffer stores are used as an integral part of the cell as well as the overall materials handling system.

Fig. 32 Typical FMC Layout



In the case of turning centres, the machining time may be of the order of a few minutes. A gantry robot is used for loading and unloading the component. It is better to present the raw workpieces in a pallet to the gantry. Finished workpieces can be deposited in another pallet. The empty raw material pallet and the filled finished part pallet will be transported by the AGV. Buffer store is also recommended for sheet metal items. Machining centres with multiple pallets (2, 4, 8 or more) incorporate adequate buffer capacity to last several hours.

Chip Removal and Washing Stations

Workpiece cleaning is important, especially before the part goes to the inspection station or assembly station, because un-removed swarf can cause problems during the inspection cycles or assembly. The swarf removal is done at the washing station of the FMS. The pallet with fixture part is loaded on to the washing station, where it is located as if it was a table of any other machining station. It is tilted, by a hydraulic mechanism, while being rinsed under high pressure coolant or pressurized air supply. Then, while reverting to its load/unload position, the pallet is blown clean with compressed air. Once the part is clean, it can be taken away by a robot or AGV together with its pallet.

2. *Computer Control System*

The computer control system of an FMS integrates several sub-systems including: CNC systems
Support system controllers Materials
handling system controller Monitoring and
sensing devices Data communication
system
Data collection system
Programmable logic controllers
Supervisory computer
This control system must also integrate other computer systems if existing in the factory. The FMS
system must also communicate with the following systems:

- The CAD/CAM system which generates the CNC programs for the machine tools

- The shop floor control systems which schedules loading and routing of the work
- The management information system (MIS) system which provides management with reports on the performance of the system

The various controllers and computers can be arranged in the form of a LAN for this purpose. The type of the supervisory computer depends upon the size of FMS. A powerful server will be adequate as a control computer.

Optimization of FMS

An FMS requires considerable investment. Thorough planning and analysis should precede the purchase of a FMS as the FMS should be designed to provide efficient operation. Following are some approaches which should be considered in order to optimize the overall efficiency and effectiveness of FMS:

i. Minimizing the process cycle time: The process must be designed to minimize machining and handling.

ii. Maximizing the utilization of each machine: This can be done by balancing the work load in the system and real time scheduling.

iii. Use of automated storage systems to keep work ready for machines to process:

The raw work parts must be replenished as and when needed to avoid starving the work centres.

iv. Provision of adequate sensors for the detection of errors or problems: This includes the detection of the presence and absence of parts, jamming, tool wear, machine failures, and so on. This can be done with the use of vision systems, limit switches, proximity switches etc. In some cases special sensors like tool monitoring systems are used.

v. Backup capabilities: Redundancy is important in ensuring trouble-free operation of the FMS. The system should be able to run even when failures occur (e.g., use spare tools, provision to isolate defective machines, supply of alternative materials and transport paths, additional machine capacity).

vi. Incorporation of in-process or post-process measurement and inspection techniques: These assure product quality and reduce scrap and rework.

vii. Use of identification marking techniques: Bar codes and RFID tags are now popular for identifying products as well as components. This permits automatic tracking of workpieces and tools.

A great deal of effort is required to implement FMS. They are complex systems that require careful planning and thorough design. Some of the major tasks in selecting a FMS are:

- Selecting a family of parts that is both similar in design as well as in application. Group technology concepts can be used for this purpose.
- Specifications of the capabilities and performance requirements of the subsystem and total system.
- Bench marking the performance of the alternative proposals.
- Economic justification of the system.
- Determining the size of the system.
- System simulation for optimization.
- Selection of the equipment for the FMS.
- Design of the control systems.
- Selection and training of the personnel to run the system.

Operational Elements of a typical Flexible Manufacturing Cell

Figure 33 shows a flexible manufacturing cell. The various functional elements of the FMC are discussed below:

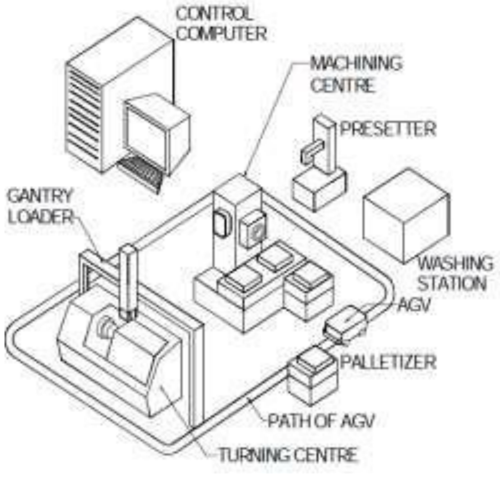


Fig. 33 Flexible Manufacturing Cell

The FMC Software

The software system for the flexible manufacturing cell is designed on the basis of the functions the FMC expected to perform. The basic system offers standard interfaces to various software functions. It also handles communication between the individual software modules and between the software modules and any peripherals (printers, other computers).

The CNC controls associated with the cell are accessed via appropriate programs. The basic system also supports or performs the following functions:

- System generation and parameterization
- System initialization
- Collection and display of error messages
- Log functions

Types of Data Associated with the Flexible Manufacturing Cell

A typical FMC system handles four different types of data: Master data, control data, status data and general management data. These data are generated from CAD, CAP and CAM functions (Fig. 34).

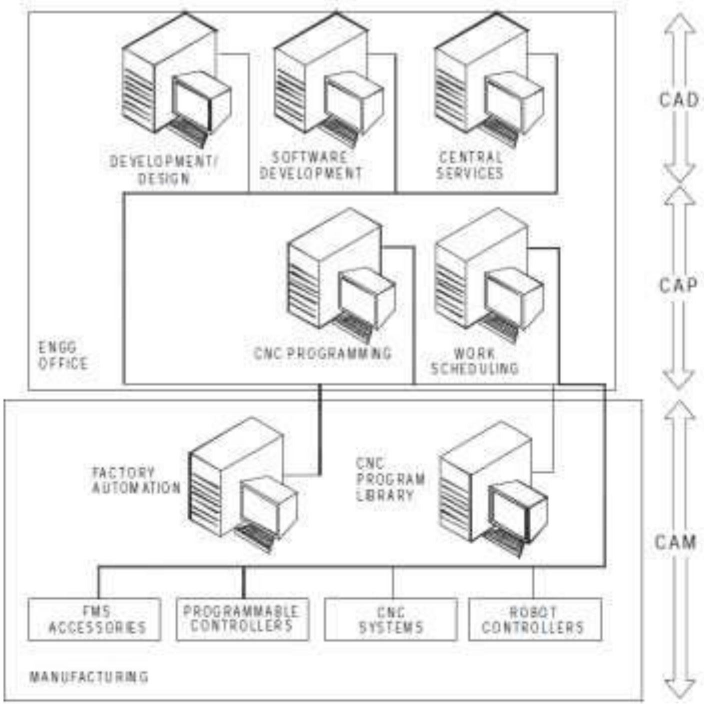


Fig. 34 Generation of FMS data

UNIT V
COMPUTER AIDED PLANNING AND CONTROL AND COMPUTER MONITORING

Material requirement planning is not only a technique for planning "material" requirements. It is also a logic that relates all the activities in a company to customer demands. People can manage all the resources in a company by using MRP logic together with data processing in other areas. This entire system is called a Manufacturing Resources Planning System, or MRP II. With the introduction of technological enhancements such as open systems platforms and client/server architecture, MRP II systems are now evolving into Enterprise Resource Planning Systems (ERP). An ERP system plans not only the allocation of manufacturing resources but also other resources, and has applications in service as well as manufacturing industries. In this book, we concentrate our discussion on manufacturing.

3. Nature of Demands

All systems are implemented to satisfy customers' demand. There are different sources of demand for a product and its component items. Some item requirements are determined by the needs of other items while others are specified by customers. The former requirements also come from customers, but indirectly. Item requirements can be classified as dependent and independent demands.

- *Independent demand*

  Demand for an item that is unrelated to the demand for other items. Demand for finished goods, parts required for destructive testing, and service part requirements are examples of independent demand.

- *Dependent demand*

Demand that is directly related to or derived from the bill of material structure for other items or end products. Such demands are calculated and need not be forecasted.

A given inventory item may have both dependent and independent demand at any given time. For example, a part may simultaneously be used as a component of an assembly and also sold as a service part. Production to meet dependent demand should be scheduled so as to explicitly recognize its linkage to production intended to meet independent demand.

4. MRP Input Data

MRP is to translate the requirement of end products stated in MPS into the requirement of components and materials. MPS is the most direct input to MRP. Other input data include inventory status, bill of material (BOM), fundamental data in item master file, and shop calendar.

- *MPS*

  MPS is the schedule for end items. It states the quantity and timing of production of specific end items. Master production scheduling is a procedure to determine the production schedules and the available-to-promise (ATP) of the end products. Based on MPS, MRP calculates the replenishment plans from the items in the level below the end products down to the raw materials

- *BOM*

  BOM describes the structure of the products. It states, from level to level, the components needed to make the parent items. By using BOM, the requirements of end products are expanded to include the requirements of the components, and hence the requirements of all the lower level materials.

- *Inventory Status*

  In expanding the lower level requirements, what we obtain are gross requirements. Gross requirement is not the real requirement. Net requirement is calculated by subtracting the inventory from the gross requirement. Since MRP is time-phased, both on-hand and on-order inventories are considered. On-hand inventory is the present inventory; on-order inventory is the future inventory, and has to be represented by both quantity and receiving date.

- *Fundamental data in item master file*

  The attributes of all items including raw materials, works-in-process, semi-finished goods, or finished goods, are expressed in the item master file. Part number, lead-time, safety stock, lot-sizing rule, low level code, etc. are required by the MRP processor. Low level code is used to determine the sequence of MRP calculation. Safety stock and lot-sizing rule are used to decide the quantity of the material replenishments. Lead-time is used to decide the time to replenish the required materials.

- *Shop Calendar*

  MRP systems are time-phased. Time bucket is an interval used to break time into discrete chunks. The length of a time bucket is defined according to the characteristics of a business. Commonly used time bucket includes week and day, i.e., numbered-week calendar (00-99) and numbered-day calendar (M-day calendar, 000-999). Planning horizon is the amount of time the master schedule and MRP extend into the future. The planning horizon should cover at least the cumulative lead-time to produce a product.

5. Integrity of MRP Input Data

Data integrity means completeness, timeliness and accuracy. Input data should be provided by related people or machine in time and accurately. If required data is not entered into the system properly, MRP will produce nothing but garbage. MRP is supposed to provide users with credible data but errors destroy the credibility and turn the MRP into a More Ridiculous Plan.

Discipline, attitude and training are the keys to data integrity. Education of employees is the most important factor. Information or data processing auditing must occur regularly to keep the data valid. Management must accept the responsibility for the training, discipline and motivation of everyone who handles data. All the employees handling data must assume responsibility for quality of data handled.

The objective of data integrity is to find and eliminate the causes of errors. Companies using MRP/ERP systems should incorporate auditing, self-checking and self-correcting features into the systems.

Automatic data integrity checks of input data include existence test (e.g. part number, transaction code), reasonableness test (e.g. abnormal quantity or unit-of-measure), diagnostic test (e.g. prior transactions required), internal detection (e.g. negative inventory balances), and purging residences of undetected errors (e.g. closing out old shop or purchase orders)

6. MRP Procedure

MPS procedure consolidates the independent demands of forecasts and customer orders to determine the requirements of the end products in each time bucket in the planning horizon. After netting the on-hand and on-order inventory, and offsetting the lead-time, the production schedule of the end products, MPS, is determined. In MPS procedure, the available-to-promise (ATP) is also determined. MPS is then fed into the MRP procedure to determine the requirements of the lower level components and raw materials.

The gross requirements of components are determined by calculating the planned order releases (POR) of the parents via single level BOM explosion. The net requirements are calculated by subtracting the on-hand inventory and scheduled receipts (on-order) in each time bucket. After the consideration of lot-size, the net requirements are transformed into the planned order receipts. Planned order receipts appear in every period. Lead-time offsetting shifts the planned order receipts backward and derives the POR which are the MRP result of current item. The MRP procedure continues to explode the POR to obtain the gross requirements of its components. The MRP repeat the procedure until the POR of all the items are determined. The flow chart of the MRP procedure is described in Figure 3.

The net requirement in a period is determined in MRP procedure by the following formula, Net

requirement = Gross requirement – Available inventory

The available inventory for the first period is

Available inventory = On hand inventory + Scheduled receipts of the first period
– Allocations – Backorders – Safety stock.

And, for the other periods

Available inventory = Projected available balance at the end of last period

+ Scheduled receipts of the current period

If the calculated net requirement is positive, then it is the net requirement of that item in that period. In this case, the projected on-hand balance at the end of that period is less than the safety stock, and the projected available balance is the projected on-hand balance plus the planned order receipt in that period. If the calculated net requirement is negative, then it is the projected available balance at the end of that period.

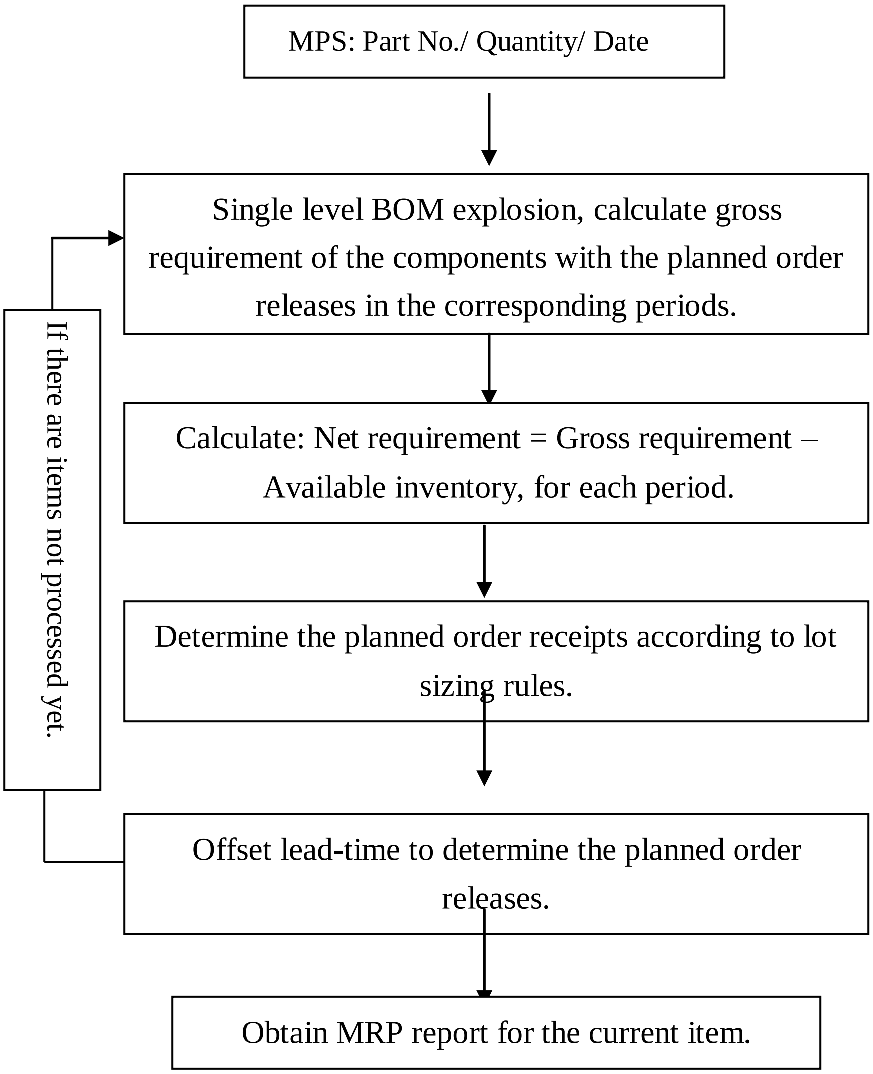


Figure 3: MRP Procedure

Let us examine a simple MRP case first.

7. *MRP Case 1: Sunglasses Sets*

Suppose a goggle sunglasses set is illustrated as in Figure 4.

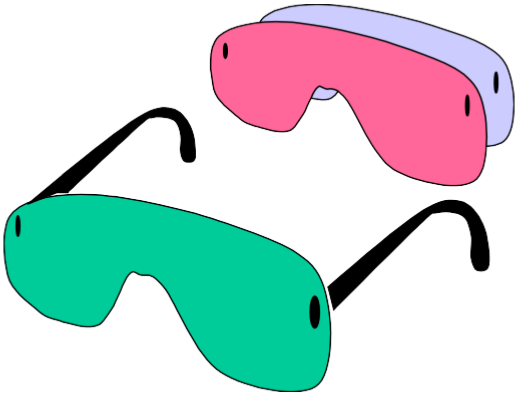


Figure 4: Sunglasses Set

In the end product, two temples are assembled to a single-piece lens to make a pair of sunglasses. Two spare lenses are sold along with the sunglasses. They are put in a plastic bag to form a sunglasses set. We ignore the plastic bag in the end product. The item master file is shown in Table 1.

Table 1: Item Master File of the Sunglasses Set

P_No	Name	LLC	LT	On-hand
A	Sunglasses set	0	1	5
B	sunglasses	1	1	40
C	lens	2	2	0
D	temple	2	3	50

In Figure 5, the quantities of the components required by per parent are expressed in the parentheses. For example, a sunglasses set is made of a pair of sunglasses and two lenses, and a pair of sunglasses is made of a lens and two temples. The data structure in a BOM file is shown in Table 2.

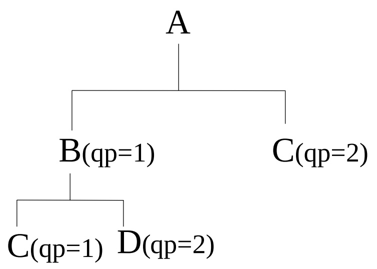


Figure 5: Product Structure for Sunglasses Set

Table 2: BOM File

Parent	Component	Qty-per
A	B	1
A	C	2
B	C	1
B	D	2

The requirements of the sunglasses set are shown in Table 3. The scheduled receipts for lenses and temples are shown in Table 4.

Table 3: Independent Demand for Sunglasses Sets

Period	1	2	3	4	5	6	7	8
A		40			50			50

Table 4: Schedule Receipts for Lenses and Temples

Period	1	2	3	4	5	6	7	8
C	100							
D		50						

The MPS/MRP procedure starts from the items with zero low level code, i.e., the end products. The calculations of MRP from the top level end product to the lowest level materials are shown in Table 5 to Table 8, and the summary of the MRP results is shown in Table 9.

Table 5: MPS Calculation for A

Period		1	2	3	4	5	6	7	8
GR			40			50			50
SR									
NR	5	-5	35			50			50
POR		35			50			50	

Table 6: MRP Calculation for B

Period		1	2	3	4	5	6	7	8
GR		35			50			50	
SR									
NR	40	-5	-5	45			50		50
POR				45			50		

Table 7: MRP Calculation for C

Period		1	2	3	4	5	6	7	8
GR		70		45	100		50	100	
SR		100							
NR	0	-30	-30	15	100		50	100	
POR		15	100		50	100			

Table 8: MRP Calculation for D

Period		1	2	3	4	5	6	7	8
GR				90			100		
SR			50						
NR	50	-50	-100	-10	-10	-10	90		
POR				90					

Table 9: Summarized MRP Report

P_No	source	1	2	3	4	5	6	7	8
A	make	35			50			50	
B	make			45			50		
C	purchase	15	100		50	100			
D	purchase			90					

8. MRP Case 2: International Airport Services

When an aircraft arrives at an international airport, a towing tractor marshals the aircraft to an indicated gate. Ramp services and cabin services are proceeded during the period when the aircraft stays. Ramp services include the toilet cleaning, gas refueling, etc. Cabin services include catering load, garbage dumping, etc. Figure 6 is a simplified aircraft services flow chart.

Since the times for the aircraft arrival and departure are scheduled, the marshaling services must be performed at predetermined times. The other services can be scheduled between the earliest start time (EST) and the latest start time (LST) as shown in Figure 7.

Figure 6: Simplified Aircraft Services

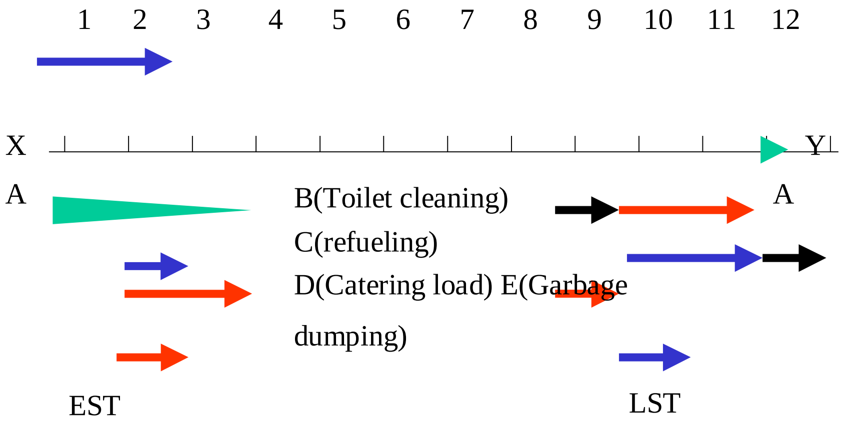


Figure 7: Scheduling of Airport Services

As item master files in the manufacturing, we now create a "service master file" shown in Table 10.

Table 10: Service Master File of Airport Services

Service Number	Service Name	Service Time	Phantom
X	Arrival	0	y
Y	Departure	0	y
A	Marshaling	1	n
B	Toilet cleaning	2	n
C	Refueling	1	n
D	Catering load	2	n
E	Garbage dumping	1	n

The structure of the services is shown in Figure 8. Since the service-time of a service means its duration, we have to count the loads of the resources in all time buckets from the start to the end of services. For example, the toilet cleaning service lasts two time units, its service-time is set as 2 in the service master file, and two records are defined in the "bill of service" file with offset-time (OT) 1 and 2. The quantity-per (QP) defined in bill of service file is the load of the service. The quantity-per of the toilet cleaning service is 2, which means two lavatory trucks are needed during the service. The offset-time and the quantity-per determine that two lavatory trucks are required during a period of two consecutive time buckets. Note that the service times in the service master file are used to create the offset-times in the BOM file, and the lead-times used by MRP are all zero.

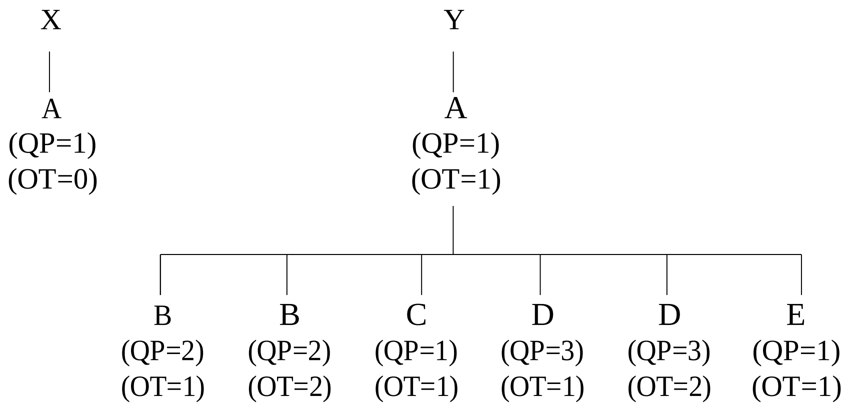


Figure 8: Service Structure for Airport Services

The data structure of the bill of service file is shown in Table 11.

Table 11: Bill of Service File

Parent	Component	Qty-per	Offset-time
X	A	1	0
Y	A	1	1
A	B	2	1
A	B	2	2
A	C	1	1
A	D	3	1
A	D	3	2
A	E	1	1

Suppose a certain aircraft is scheduled to arrive at time 1 and depart at time 12, the schedule is stated similar to MPS in the manufacturing cases, now we name it the master service schedule (MSS), as shown in Table 12.

Table 12: MSS for aircraft arrival and departure

Time	1	2	3	4	5	6	7	8	9	10	11	12
X	1											
Y												1

Services have neither inventories nor scheduled receipts as in the cases of manufacturing. Services must be provided at the moment when customers use it. In the MRP calculation procedure, gross requirements are the services that customers need. Since there is no on-hand or on-order inventory, the net requirement equals the gross requirement. Only two rows remain in the MRP reports. MRP is now renamed as “service requirement planning”, and the rows are named “required” and “scheduled”. The MRP procedure is described in Table 13.

In table 13, the scheduled service of A in time 1 required by X should not be exploded further. This can be done with a field of X-A record in the BOM file indicating no further explosion. The above example is for a single aircraft. The system will schedule all the flights in MSS, then use MRP procedure to calculate all the services required. The service requirements are scheduled by MRP at the latest start time. The system also calculates the EST schedule. Schedules are then adjusted manually or automatically between EST and LST to balance the load and capacity.

Table 13: Service Requirement Planning for Airport Services

P_No	time	1	2	3	4	5	6	7	8	9	10	11	12
X	Req	1											
	Schl	1											
Y	Req												1
	Schl												1
A	Req	1											1
	Schl	1										1	
B	Req											4	
	Schl									2	2		
C	Req											1	
	Schl										1		
D	Req											6	
	Schl									3	3		
E	Req											1	
	Schl										1		

This example explains how ERP is used in a service business. Time buckets are sliced as small as the minimal unit a service requires. All service times are multiple of the time bucket length. Lead-times are all set to 0 because the start time of the parent operation is exactly the end time of the child operation, or differs by 1, which can be controlled by offset-time. The service time determines how many time buckets are needed by an operation. An operation repeats, as a child item, the required time buckets times, say n, with offset-time from 1 to n in each BOM record. The service requirement planning uses the same functions of item master, BOM, MPS, and MRP in the ERP system. The idea can also be applied to manufacturing operations.