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General Studies Series

PLANNING AND PROGRAMMING THE INTRODUCTION OF CAD/CAM SYSTEMS

A REFERENCE GUIDE FOR DEVELOPING COUNTRIES

Prepared by

Industrial Planning Branch
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Preface

At the recommendation of the ninth session of the Economic and Social Commission for Asia and the Pacific (ESCAP) Committee on Industry, Human Settlements and Technology held at Bangkok from 10 to 16 September 1985, the UNIDO Sectoral Studies Branch and the ESCAP/UNIDO Division of Industry, Human Settlements and Technology organized a technical working group on production and use of machine tools in the engineering industry of ESCAP developing countries (Industrial Development Fund Project No. UC/RAS/86/020). The technical working group, which met at Singapore from 17 to 21 November 1986, and was hosted by TECHNONET ASIA, was a direct follow-up of the UNIDO/ESCAP project entitled "Review and appraisal of industrial progress at the regional level".

The participants in the technical working group formulated concrete conclusions and recommendations at regional and national levels which are included in the final report of the meeting issued by the Sectoral Studies Branch as Sectoral Working Paper Series No. 55 (UNIDO/PPD.17). Specific joint work with UNIDO was also suggested, *inter alia*, the organization of a workshop on CAD/CAM systems for Asian developing countries dealing in particular with information, training, personnel, hardware and software. To follow up this recommendation, UNIDO jointly with ESCAP and TECHNONET ASIA, organized a Workshop on CAD/CAM Systems for Small- and Medium-Scale Engineering Industries in selected ESCAP Developing Countries (Industrial Development Fund Project No. XP/RAS/88/005) at Singapore from 9 to 20 May 1988.

The reference guide here presented must, therefore, be seen as a direct follow-up of UNIDO studies and projects already undertaken, especially the technical working group on machine tools and the workshop. This reference guide will be used as study and referral materials on CAD/CAM systems for the small- and medium-scale engineering industries.

This reference guide was prepared by the UNIDO Industrial Planning Branch in collaboration with TECHNONET ASIA, Singapore, as consultant to UNIDO. Sections 12 to 15 were prepared by Professor A. Nee, Director of the CAD-CAM-CAE Centre, National University of Singapore, also as consultant to UNIDO.

Tables and graphics without indication of the source are the responsibility of the consultants.

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References to dollars ($) are to United States dollars, unless otherwise stated.

The following abbreviations are used in this publication:

AI	Artificial intelligence
BR	Boundary representation
CAD	Computer-aided design
CAE	Computed-aided engineering
CAM	Computer-aided manufacture
CMM	Co-ordinate measuring machine
CAPP	Computer-aided process planning
CECIMO	European Committee for Co-operation of the Machine Tool Industry
CIM	Computer-integrated manufacturing
CMPP	Computer-managed process planning system
CNC	Computer numerical control
CPU	Central processing unit
CRT	Cathode ray tube
CSG	Constructive solid geometry
DNC	Direct numerical control
DXF	Data interchange format
EXAPT	Extended-automatically-programmed tool (programming language for NC machines)
IGES	International Graphics Exchange Standard
LAN	Local area network
NC	Numerical control
NIC	Newly industrializing country
OSI	Open systems interconnection
PC	Personal computer
PRIDE	Pinch roll interactive design expert/environment
QA	Quality assurance

1. A NEW APPROACH FOR THE INDUSTRY OF DEVELOPING COUNTRIES

The decade of the 1980s has presented a considerable challenge to the industry of developing countries especially in the form of increased competition at home and abroad, inflation, soaring cost of labour, and increased material and plant machinery cost. Many enterprises in the newly industrializing countries (NICs)* have met these challenges by employing computer-aided technologies which resulted in increased productivity. In the industrialized countries, application of computer systems in the engineering industries is widespread both for design and manufacture of components.

With the advent of the new technology associated with CAD/CAM, the performance of the small and medium engineering industries in many developing countries (especially NICs) has been remarkably enhanced since the early 1980s. In developing countries, small- and medium-scale enterprises have become aware of their technological deficiencies in turning out competitive products with respect to product design, cost and delivery dates.

The traditional advantage of cheaper labour in developing countries has greatly lost its significance in face of the greater flexibility of modern production systems using computer-aided facilities.** This new technology directly contributes to significant cost reduction and faster production in all types of engineering industries. Small- and medium-scale enterprises in developing countries now are realizing the necessity of upgrading their production techniques by employing better production methods. This will require the blending of new technologies with the existing set-up in order to improve efficiency and reduce production cost. Thus, entrepreneurs will have to face the question of what new approaches the engineering industries should adopt?

The rapid development in micro-electronics and informatics has had spectacular effects on the growth of capital goods industries in developed countries. Unfortunately, the benefits are not much visible in developing countries as the diffusion of new technology utilization has not effectively reached the prospective users. Appropriate application of these new technologies at the enterprise level could perhaps help developing countries in producing high-value-added capital goods at the small and medium industries level in the engineering sector.

The use of numerical control and computer numerical control production machines in the engineering industries sector could enhance the competitiveness of capital goods industries of developing countries. The utilization of micro-electronics-based (computerized) machineries will assist in reducing the present wide technological gap that exists between developed and developing countries and thus accelerate the industrial development pace of the latter. It is undeniable fact that the future prosperity of developing countries will largely depend on how much of the new technologies are using, not necessarily on making them.

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* The term "NICs" is used extensively to describe developing economies, be they countries, provinces or areas, where there has been particularly rapid industrial growth. It does not imply any political division within the ranks of developing countries and is not officially endorsed by UNIDO.

** See "Capital goods industry in developing countries: a second world-wide study", Sectoral Studies Series No. 15, vol. I (UNIDO/IS.530); and the final report of the UNIDO/ESCAP Technical Working Group on Production and Use of Machine Tools in the Engineering Industry of ESCAP Developing Countries, Singapore, 17-21 November 1986, Sectoral Working Paper Series No.55 (PPD.17).

Apart from the basic requirements for operating an efficient engineering industry through a proper man-machine-materials balance, the application of computer-aided facilities in the design and manufacturing line can also tremendously boost the production capability. Although this would require a sizeable initial investment, it would be offset within a relatively short time as compared with investment in traditional production hardware.

The terms CAD/CAM are applied in three different but interrelated contexts.*

(a) Computer-aided design (CAD)

A CAD system is a system which incorporates one or more computers for carrying out some of the calculations and actions involved in the design process (European Committee for Co-operation of the Machine Tools Industries (CECIMO) working party on standardization).

(b) Computer-aided manufacturing (CAM)

A CAM system is a system which incorporates one or more computers for carrying out some of the tasks involved in the organization, scheduling and control of the operations involved in the manufacture of the product. Where machining is involved, a CAM system will usually involve computer-numerical-control (CNC) machine tools and means for producing part programmes for them and it may also involve a central computer for scheduling, planning and control of the operation of the system. It may involve a direct numerical control (DNC) system using either the central computer or a separate computer control of stores, orders etc. (CECIMO working party on standardization).

(c) CAD/CAM system

A CAD/CAM system is a system in which computers are used to carry out some of the tasks involved in designing and manufacturing a product. In particular, computers are often used to produce part programmes for the CNC machines in the system directly from the design data (CECIMO working party on standardization).

CAD/CAM systems have a large potential to be diffused quite rapidly in developing countries thanks to the very recent and very substantial decrease in cost related to the emergence of personal computer-based CAD/CAM systems. Developing countries may be able to use CAD/CAM for leap-frogging in the field of design since the CAD CAM software embodies accumulated design and drafting experience. Such experience is currently a scarce resource in most developing countries, which is indicated by their heavy reliance on foreign technical licences.

The value and benefits of CAD/CAM are now well recognized by the metalworking and engineering industries, which achieve productivity improvements of more than 3:1 with faster and better-quality designs and more accurate drawings. The question for developing countries is which system is most suitable for them and how they can get the most out of it.

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* See, Recent Trends in Flexible Manufacturing (United Nations publication, Sales No. E.85.II.E.85), p.18. A glossary of CAD-CAM Terms is attached in the annex to this study.

2. INTRODUCTION TO CAD/CAM

2.1 What is CAD/CAM?

CAD/CAM is an acronym for "computer-aided design/computer-aided manufacturing". The term CAD/CAM refers to the integration of computers into the manufacturing processes to improve productivity. Business computers crunch numbers and data, CAD/CAM systems store, retrieve, manipulate and display graphical information.

Traditionally, a design is created by rubbing graphite on paper and refined by the use of an eraser. In a CAD/CAM system, an engineer interacts with the system to develop product design in detail, monitoring the work constantly on a television-like graphics display. By issuing commands to the system, and responding to system prompts, the engineer creates the design - manipulating, modifying, refining - all without ever having to draw a line on paper or recreate an existing design element. Once satisfied with the design, the engineer can command the system to make a "hard copy", or generate a computer tape to guide CNC machine tools in manufacturing and testing the part. Figure 2.1 shows the broad categories of CAD/CAM activity which can be applied for the manufacturing industries.

2.2 Early developments

CAD/CAM began with the development of interactive graphics in the early 1960s. One of the earliest developments in interactive graphics was the Sketchpad Project at the Massachusetts Institute of Technology. Data was entered via a hand-held light pen, and as the computer sensed the position of the light-pen on a cathode-ray-tube (CRT) display scope, the coordinate data were stored in its memory. By specifying points on the scope and executing simple computer commands, the user could quickly generate straight lines, circles, arcs and other geometries. With this technique, the user could easily produce an entire diagram on the display screen. And the data base of coordinates stored in the computer could subsequently be used to manipulate the display image, produce hard-copy drawings, or be entered as an input to some form of geometric analysis. A feature that made interactive graphics so appealing was that the communication with the computer was carried on in real time. Feedback from the computer was almost instantaneous, permitting the interaction to take place almost in a conversational mode.

Several interactive graphics systems were developed in the 1960s. Their use, however, was restricted mostly to very large companies that developed their own in-house systems using expensive mainframe computers. By the early 1970s, interactive graphics could be performed on less-expensive minicomputers. Initially, these interactive graphics systems performed little more than simple automated drafting. But as computer hardware became more powerful and software was refined, the capabilities of graphics systems expanded dramatically. These systems now permit the user to perform a much wider range of geometric manipulations and sophisticated analysis.

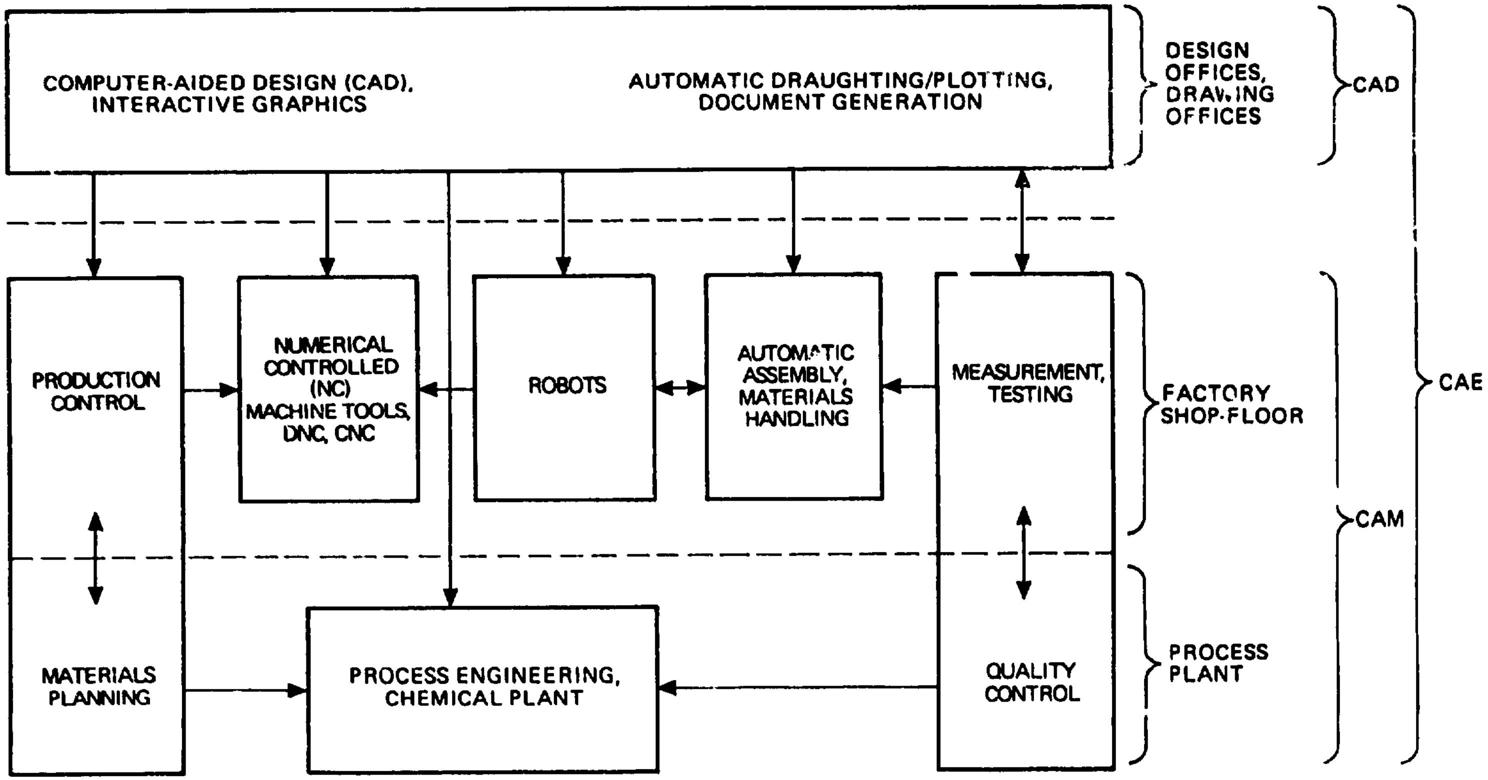


Figure 2.1 Broad categories of CAD/CAM activities

2.3 Recent state of the art

For the more sophisticated drafting packages, a user can temporarily "erase" portions of a complex model from the screen to see the area under construction more clearly, then the deleted area can be recalled later to complete the model. Likewise, portions of the model may be enlarged to view and add minute details accurately. And the model may be moved and rotated on the screen for the user to view at any angle. When the design is complete, the system may automatically add dimensions and labels. After the part geometry is defined with a complete model, the user can have the computer calculate properties such as weight, volume, surface area, moment of inertia or centre of gravity. A finite element package may be used to determine the stress, deflections, and other structural characteristics. After the analysis, the display screen may show colour-coded stress plots, the deflected shape of a part subjected to a given load, or even an animated mode shape showing how the structure might vibrate and deform during operation.

As a result, with a CAD/CAM system, designers can view complex forms from various angles at the push of a button instead of having to construct costly, time-consuming physical models and mock-ups. Changes can be made quickly and inexpensively at the keyboard or data tablet without requiring alteration of drawing or physical models. In addition, computer displays can produce realistic simulations of product operations before any hardware is produced.

After the design is completed, the resulting geometric data stored in computer memory may be used to produce numerical control instructions for making the part on automated machine tools. Formerly, the preparation of numerical control instructions was performed manually by experienced programmers. The program was then tested on the machine and refined several times before the part was machined properly. Many of these tedious and costly operations are now reduced with CAD/CAM systems. Numerical control instructions can now be produced automatically for a range of part types, and tool paths simulated on the display screen to verify and refine the programme more quickly.

2.4 Benefits

The most obvious benefit of CAD/CAM is increased engineering productivity. This is probably the single consideration that influences most potential users to invest the high capital outlay for implementing a CAD/CAM system. Initially, productivity may decline somewhat due to learning and familiarization with the system. The overall productivity increase during the first year of operation is typically 2 to 1. Succeeding years may show further productivity increases as high as 20 to 1 depending on the application. A 3 to 1 or 4 to 1 increase is a common norm for most well-established CAD/CAM systems. In a typical mechanical design application, a 2 to 1 productivity increase is usually sufficient to justify the installation of a CAD/CAM system. Three check-lists presented in figures 2.2, 2.3 and 2.4 show the major CAD/CAM benefits, management control benefits and intangible benefits which can be derived from the system's application.

Another benefit of CAD/CAM is the increased analytical capability placed at the fingertips of a user. This allows rigorous product analysis that would otherwise be quite impossible to perform manually. Reduced product and development cost is a direct result of increased engineering productivity. In many applications, computer simulation of an entire mechanical system or

Figure 2.2 Checklist of major CAD/CAM benefits

ITEM	DESCRIPTION
IMPROVED PRODUCTIVITY	CAD/CAM systems have been responsible for dramatic productivity increases in many professional engineering activities. The most important of these are: -Drafting -Documentation -Design -Estimating -Order entry -Manufacturing
BETTER MANAGEMENT CONTROL	CAD/CAM systems have contributed to closer and better informed management and control of: -Engineering data -Engineering data distribution -Projects -Production scheduling -Estimating -Order entry
INTANGIBLE BENEFITS	Many important benefits of CAD/CAM are difficult or impossible to quantify, nevertheless, they contribute in a very real way to the success of the technology. The most prominent of these benefits are: -Standardization of graphics -Standardization of methods -Good-quality draftsmanship -Reduced vulnerability to error -Faster response -Professional development -Good staff morale

Source: Computervision-EDB Training Unit

Figure 2.3 Checklist of CAD/CAM management control benefits

FUNCTION	MANAGEMENT AND CONTROL BENEFITS
ENGINEERING DATA MANAGEMENT	CAD/CAM system data is organized into libraries of associated files. Some have significant capabilities for organizing the information they hold for easy retrieval. These capabilities, together with access control facilities such as passwords and group identifiers, force a measure of management control over engineering data that is otherwise overlooked.
ENGINEERING DATA DISTRIBUTION	When CAD/CAM systems have telecommunication capabilities they provide a valuable means of distributing up-to-the-minute engineering information. In this way, remote manufacturing plants always have instant access to the most recently released documentation.
PROJECT MANAGEMENT	Project control charts and critical path diagrams stored in a CAD/CAM system can easily be revised daily to give management an up-to-date tool for decision making. In addition, CAD systems can capture other information (such as design time or drafting time) that is useful for controlling the project.
SCHEDULING	Flexible scheduling of machine tools to achieve their greatest possible utilization is an important function of manufacturing management. By interfacing the manufacturing data base available from a CAD/CAM system with order entry and shop schedule data, management can react properly and readjust manufacturing schedules when machine tools fail, orders are cancelled, or material is unavailable.
ESTIMATING	When used as an estimating tool, CAD/CAM systems can ensure that all material costs and labour charges are captured and that uniform estimating procedures are followed. In addition, there is much greater control over the engineering data and cost information in use by all estimators at a given time.
ORDER ENTRY	The value of computer-based order entry systems is well known. Integrating CAD/CAM with order entry can provide greater scheduling flexibility especially where drawings or manufacturing control tapes must be linked to each order.

Source: Computervision-EDB Training Unit

Figure 2.4 Checklist of intangible CAD/CAM benefits

ITEM	BENEFIT
STANDARDIZATION OF GRAPHICS	Human communication is an important aspect of the workings of an engineering team and standard graphics reduces the time and effort required for recording and exchanging ideas in clear unambiguous terms. CAD/CAM systems enforce standards in a pleasent and positive way by making it easier to comply than to use special symbols or parts.
STANDARDIZATION OF METHODS	By storing pre-programmed producers for common design and drafting tasks, CAD/CAM systems reduce the tendency of some engineers to reinvent the wheel and waste their creative energies. In addition, standard methods help others to understand what was done when designs are reviewed.
QUALITY	A CAD/CAM system can help mediocre and novice draftsmen produce superior-quality drawings. Accuracy and penmanship is independent of operator skill, and legibility problems are completely eliminated.
ERROR CONTROL	CAD/CAM systems have design rule checking software for many applications, and this has proven to be extremely effective for spotting errors. Also, because CAD/CAM takes the drudgery out of design and drafting, the engineer is free to concentrate his efforts on his work.
FASTER RESPONSE	Quite apart from productivity issues, it is possible to produce results faster using CAD/CAM than by manual methods, even when unlimited manpower is available. This increases the number of engineering options in situations where time is a critical factor.
PROFESSIONAL DEVELOPMENT	Knowing how to use a computer is an increasingly important skill for professional engineers. Exposure to CAD/CAM systems builds knowledge and confidence in this area and provides a strong motivation (for engineers) to learn and use the general computational capabilities of CAD/CAM systems.
STAFF MORALE	CAD/CAM lets engineers feel more productive as they concentrate on the creative aspects of their work. This gives them a greater sense of accomplishment than is possible when struggling with masses of repetive detail. A desire to work with state-of-the-technology tools is also a factor that should not be overlooked.

Source: Computervision-EDB Training Unit

product is possible. In this way, functional characteristics such as vibration, noise, stress distribution, etc, can be analyzed with the system instead of having to build costly prototypes.

Perhaps the greatest and the most subtle benefit of using CAD/CAM is enhanced creativity of the user. It is a direct result of a compatibility between the human mind and interactive graphics. This is attributed to the ability of the brain to grasp graphical data quickly - a picture is worth a thousand words.

3. SYSTEM HARDWARE

This section looks at a hypothetical CAD/CAM system and examines the various peripherals available. The facility includes the work station (with CRT display, function and alphanumeric keyboard, digitizer and other operator input devices), the plotter (pen, electrostatic storage, computer output to microfilm (COM) and others) and software (high-level, application and others). A CAD/CAM system makes use of the computer's ability to store large amounts of information and process it quickly and accurately. Data are stored in disk drives and magnetic tape units. A magnetic tape allows the transfer of software or designs, drawings and manufacturing information from the disk to a magnetic tape and back onto the disk when needed. The operator enters design or manufacturing information into the system by means of an electronic pen, graphics tablet and a keyboard which is used to communicate with the computer. The designs, messages and other information from the computer appears on a graphics display screen. The operator's dialogue with the computer is both conversational and visual.

3.1 Host computer system

Large-scale mainframes from CDC, Prime, DEC, IBM, UNIVAC etc. are often used as host computers in computer graphics environments. A powerful host computer can often support many CAD/CAM work stations and at the same time other non-graphic work. A host computer would not ordinarily be connected to the CAD/CAM facility through a high-speed direct connection, and very often it can be remote from the CAD/CAM facility. A typical set-up is the IBM CADAM system.

3.2 Stand-alone system

A typical stand-alone CAD/CAM system is often referred to as a "turnkey" system. Some systems use minicomputers as the central processing units. Depending on the configuration and power of the minicomputer, 2 to 8 work stations can be supported. Typical commercial vendors in this category are Computervision, Calma, Applicon, McAuto, Autotrol, Intergraph and Gerber. Some systems are truly stand-alone in the sense that each work station is self-contained in terms of central processing unit (CPU), storage device and input device. Typical commercial vendors are Hewlett Packard, Silicon Graphics, SUN and Apollo.

3.3 Graphic terminals

The interactive graphics terminal is the window through which the operator views graphics data stored and manipulated in the computer. Most interactive graphics terminals display multiple views of a design - typically front, top, and side orthographic views, in combination with a three-dimensional isometric view. These views generally are displayed simultaneously on a split screen. Any design changes made on one view usually are added to the others automatically.

Some terminals are referred to as "intelligent" terminals as they have built-in software that removes some of the data-handling burden from the CPU to which they are connected. Ordinary terminals are, on the other hand, referred to as "dumb" terminals. Some terminals use a dual-screen arrangement (such as Intergraph), one screen being used for viewing graphics display and another for prompting instructions. Although this arrangement provides greater area for the graphics manoeuvring, one of the objections is too much head turning in watching both screens at the same time.

No matter what type of terminal configuration is used in CAD/CAM systems, all screens are CRTs that produce pictures in much the same way as a home television. The functional elements of a CRT are contained in a glass enclosure resembling a television picture tube. A heated cathode in the CRT emits electrons that are accelerated and focused into a fine beam. This beam is deflected onto a phosphor-coated screen that glows, producing a visible trace where the beam strikes it. These high-speed traces are scanned many times a second to form the images seen by the user. There are three basic types of screens in CAD/CAM, each using a different approach for deflecting the beam and rewriting the image. These are refresh, raster and storage display.

(a) Raster screens (or raster-scan)

This is the familiar type used in home television sets. It is also known as digital television or scan graphics. The electron beam is moved continuously in a fixed pattern, very rapidly in the X axis (producing a single horizontal line in approximately 67 microseconds) and much slower in the Y axis (scanning the entire screen vertically at about 16 milliseconds). At the end of a vertical scan, the beam resumes its horizontal scanning. The raster displays create an image with a matrix of tiny dots called pixels. The electron beam scans the entire screen from top to bottom, illuminating each pixel in an on-off pattern stored in a computer memory.

Advantages. Since the display is rewritten constantly, images may be animated and manipulated on the screen in real time. As the raster scan rate is fixed, the images do not flicker. In addition, raster displays are bright and may display colour. This feature is very useful in creating stress plots, mode shapes and other images where particular details must be enhanced or differentiated.

Disadvantages. The major disadvantage includes the comparatively poor resolution of the image (particularly in low-resolution systems) as compared to the crisper images available with both refresh and storage tube systems. Vertical and horizontal lines are acceptable, but sloping lines are made up of a series of "jaggies". This effect may not be objectionable in many data presentation and picture-possessing applications, but might be unacceptable for very high-quality engineering drawing requirements.

(b) Refresh screen (vector-refresh, stroke-writing, random scan)

A refresh screen uses the beam to directly trace out the lines of the image, painting and repainting each line from end-point to end-point. Refresh systems normally operate at such a rate that the image appears to be steady to the eye. (Note: The eye remembers a picture for about 70 milliseconds. However, if the image is not presented at about 2.5 times that rate, the eye perceives the image as flickering).

Advantages. Since the picture is constantly being "refreshed", the image on the screen can be animated. This is an advantage in applications such as kinematics or modal analysis that often require display motion. In addition, the display can be modified rotated or translated on the screen without the system having to redraw the picture as with storage screens. In addition, the images are bright, crisp and clear, making the terminal quite suitable for complex engineering applications. Images of varying shades of gray and multicolour images can also be displayed.

Disadvantages. One of the major limitations of a refresh terminal is that complex images with many line segments may appear to flicker. Typically the flicker-free limit is about 2,000 characters per frame or 2,000 inches of line per frame. This is a result of the relatively long time required for the system to retrace all the lines. Another disadvantage is the large amount of random access memory required to store an image while it is being displayed. The refresh screens are also more expensive than the other display systems.

(c) Storage screens

Storage tube CAD/CAM terminals became commercially available in 1969 when Tektronix introduced its direct-view storage tube. The most commonly used storage tube terminals do not include any display picture memory since that function is served by the tube's ability to store a picture continuously on the display. This feature reduces overall CAD/CAM system cost because memory costs are cut. The storage tube does not continuously retrace the image lines. Rather, a flood gun constantly bombards the entire screen with electrons that by themselves have energy just below the threshold to illuminate the phosphor. When struck by the high-energy writing beam, the screen changes potential in the vicinity of impact, allowing the flood-gun electrons to illuminate the phosphor along the track indefinitely.

Advantages. Excellent resolution and can display extremely complex images with relatively little computer memory and processing. The screen is also flicker-free and a low-cost hard-copy accessory is available.

Disadvantages. Relatively low brightness and contrast, and this requires ambient lighting to be dimmed to allow a clear display. The lack of multicolour capability or shades of gray prevents colour display and graphics. In addition, storage tube characteristics prevent the use of a light pen. Another major disadvantage is that no selective erasing is possible. Once an image is displayed and stored, it must be completely erased and repainted on the screen from scratch to change any part of it. In a complex graphical display, repainting the entire image to change a small detail can be time-consuming.

3.4 Operator input devices

A variety of devices allows a CAD/CAM operator to communicate with the computer without having to learn programming. These devices allow him to pick a function from a menu, to enter text and numerical data into the system, to modify the picture shown on the screen and finally to construct the desired picture.

(a) Keyboard

Several kinds of keyboards are used with CAD/CAM terminals. The conventional typewriter-like alphanumeric keyboard allows the operator to enter commands, symbols and text and to request information.

The keyboard is often used to enter precise, non-graphical data such as dimensions or measurements into a programme, so that the display will accurately present all important data relating to a current design. These keyboards may also include special graphhics-oriented buttons - for example, to move a cursor up or down, left or right, or to transmit memory file content back to the host computer. In many systems, the CAD/CAM terminal also is equipped with a separate box containing programme-controlled push-buttons (such as zoom, rotate etc.). Typical set-ups of this type can be found in Computervision and IBM CAD/CAM systems.

(b) Data tablet, electronic/light pen and menu

Data tablet. A data tablet is a drawing tablet on which a drawing is made using an electronic pen. In one form, the data tablet is an electronic unit which consists of a rectangular grid of 1,024 x 1,024 lines. Generators within the tablet pulse the lines, producing discrete signals in response to a pencil-like stylus moved by the operator. The location of the stylus relative to the tablet is determined by decoding the stylus signal. This decoded information is used like the output of the trackball. A line or spot corresponding to the stylus position is made to appear on the screen. Most data tablets allow some separation between the stylus and the tablet surface, i.e. the stylus need not be in contact with the tablet surface. Therefore, a sheet overlay containing programme menus can be placed on top of the data tablet. An operator can choose a particular command by placing the stylus over the overlay menu. The coordinates of the data tablet are picked up by the stylus and sent to the computer where a particular command will be issued.

Electronic/light pen. An electronic/light pen has become almost synonymous with interactive CAD/CAM systems, although the term "light pen" is more of a misnomer. The light pen does not write with light, but rather detects changing light as it appears on the screen. The pen may use a photodiode or a phototransistor as the light-sensitive element. It may also use a fibre-optics bundle to pipe the light to a higher-sensitivity, faster-response photomultiplier.

On refresh and raster screens, the events which appear on the screen occur in time sequence even though to the eye they appear to be occurring simultaneously. A light pen detects light at a discrete time and generates a computer interrupt at that time. Additional software and processing is required to determine what to do about the interrupt. Since the interrupt is a time-dependent function, normal light pen operations are not possible with a storage tube because the time reference is lost.

A light pen can be used either for pointing (selecting) or drawing. It can be used to point to information already on the screen, to designate a location on the screen where information is to appear, or to enter information directly. Before the light pen can be used to create graphics, a tracking symbol (a crosshair) must appear on the screen. For example, to draw a line, a tracking symbol (cursor) must first be generated, usually by software. With software, the tracking symbol is made to follow the pen as it moves across the screen. The operator, by activating the appropriate function keys, can designate what action the system is to take as a result of light pen motion, either to draw a series of dots along the light pen path, or to connect the starting-point with the present pen position.

Menu. A menu is a device used to enter commands into the system quickly. It has squares or pads marked on an electronically sensitive surface (usually found on the graphics tablet). Each square can be defined to perform a command or series of commands when activated with the electronic/light pen.

(c) Cursor controls

These devices let the operator simultaneously develop changing X and Y signals to direct a cursor (tracking symbol) on the screen. The operator indicates a particular point by activating a button or other control when the cursor appears at that location on the screen.

Thumb wheels/keys - The simplest way to generate cursor movement is by separating X and Y cursor-control keys or knobs.

Track ball - This device mechanically couples a control element to both the X and Y generators, so that a single operator motion can drive both transducers simultaneously.

Joystick - Similar to the track ball except that it provides a small, bat-like handle that the operator moves.

Mouse - Similar to the track ball except that the ball is placed below. A number of buttons are available for selecting the various commands.

(d) Voice data entry

One of the most recent innovations in function menu selection is voice data entry. In this method, the operator enters menu commands verbally by speaking into a microphone. These systems have the capacity to store almost 100 menu items (called a vocabulary) created by a user. The user "teaches" the system to recognize the vocabulary by entering the menu function into the microphone several times. Because of differences in voice inflection, accent, and enunciation, each operator must individually train the system.

Voice data entry is a very efficient method of selecting menu items, since it frees the operator's hands to manipulate other devices and permits him to concentrate more attentively on the display screen.

3.5 Output devices

In a CAD/CAM system, plotters and displays complement each other. A display is capable of rapidly presenting a relatively low-accuracy picture so that the user can react to it, perhaps making changes interactively in a real-time mode. A plotter, on the other hand, can generally make large, highly accurate drawings but more slowly. Typically, displays are used to make the initial decisions, and plotters to make the record copies.

The accuracy of a hard-copy plot can be considerably higher than the apparent accuracy and quality of the image on the display. Generally, a CAD/CAM system contains a picture description which may define points by 16 bits (rather than 10 bits as in most CRTs). The CRT image may deteriorate visually after digital to analog conversion through the display generator, but the picture description display file retains its high accuracy. Therefore, when that display file is used to drive higher-accuracy plotters, plotted data can be reproduced to an accuracy consistent with the digital definitions.

(a) Pen plotter

Typical CAD/CAM systems use an electromechanical pen plotter to plot data and make engineering drawings. The earliest and perhaps most widely used is the drum plotter. Plot paper is wrapped around the drum and the drum rotated by a digital stepping motor. The rotation provides one deflection axis while the pen, mounted on a gantry across the drum, provides the other deflection axis. Drum plotter offers relatively high speed, and the plots can be of unlimited length. Early drum plotters were excellent for plotting data, but because of the relatively poor off-axis line quality, were not adequate for most engineering drawing applications. Flatbed plotters have better accuracy and are more suitable for the most exacting engineering requirements, including the making of templates and PC artwork for semiconductor chips. Typical repeatabilities are of the order of 25 microns (0.001 inch).

(b) Electrostatic plotters

While it takes seconds or less to display an image on the CRT, the time required to plot that same drawing on a precision plotter may take tens of minutes. In an effort to reduce plotting time at the expense of some drawing quality, electrostatic plotters were introduced.

Essentially, these plotters consist of a combination of wire nibs spaced from 100 to 200 per inch. As in the drum plotter, the paper's motion provides one axis of deflection. Instead ofa pen moving along the other axis, however, the information is progressively scanned across the nibs, and those nibs needed to place a dot on the paper are activated. Unless the electrostatic plotter data is in a raster format, some form of software or hardware scan conversion is required between the digital picture file and the plotter. In addition, an electrostatic plotter can have an unlimited length paper and it is much faster than an electromechanical plotter (typically 100:1). An electrostatic plotter can also be used at a high-speed to produce quick preliminary drawings. After the design is completed and refined, the pen plotter is used to produce accurate, high-quality documentation.

(c) Digitizer plotter

Since the pen of flatbed plotters is under computer control, some kind of pick-up is needed to indicate to the system the location of the pen. It is feasible, then, to provide an additional operator control so that the pen can be positioned by the operator. When the pen is thus positioned, the digital coordinates of its position can be entered into the system.

(d) Computer-output-to-microfilm (COM) units

Drawing storage is a continual problem for large engineering facilities. Such companies may have 100,000 drawings or more that need to be stored and retrieved. One solution is the use of microfilm, using computer-output-to microfilm (COM) units now available.

4. CAD/CAM JUSTIFICATION

The introduction of CAD/CAM into a company very often entails reorganization of its structure and may initially involve huge capital outlays not only for the system hardware and software but also for staff additions, special training etc. This section looks into some of the direct and indirect monetary savings or cost benefits, while indirect benefits could mean improved product quality, enhanced product safety and a number of other implicit and intangible benefits. Figure 4.1 describes the major areas where CAD/CAM improves productivity.

(a) Improved product quality

The quality of a product is very often judged by its performance or function, its reliability, maintainability and safety. With powerful CAD/CAM packages, a problem can often be analyzed more thoroughly and accurately. Any possible fault or potential dangers can be identified at a much earlier stage. For example, the vibration, deflection and motion of a structure under stress can be simulated with a CAD/CAM system. Individual modes can be created and weaknesses identified. Previously, this could not have been possible as a large number of prototypes has to be made, which is both time-consuming and expensive. McDermott, a leading offshore engineering company, simulates the launching of a large offshore platform on a CAD/CAM system before the actual installation as any mistake at the site will cost millions of dollars as well as numerous human lives. Figure 4.2 shows how a typical mould design can be made by CAD/CAM in stages, from the design stage to the finished product.

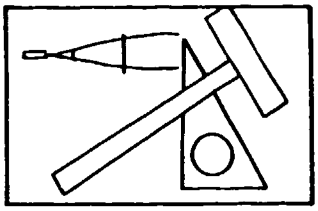
(b) Shorter project span times

Today, project lead time can have considerable impact on a product's competitiveness and marketability. Current CAD/CAM techniques can have a significant impact on reducing project span time. Reduced project span time can mean considerable monetary savings in a number of ways, such as lower interest payments on borrowed funds for a project, more efficient use of personnel through better scheduling, reduction of unnecessary data and lower computer run costs. Shorter span time for a project may very well be the basis for winning a contract which, in turn, could represent millions of dollars of business. Figure 4.3 gives a typical estimate of the time savings in mechanical design through the use of a graphics system.

In test or research and development environments, CAD/CAM systems permit tuning of trial parameters in real time. Input trials of parameters at a graphic console can be processed in seconds and the output viewed on the display. The quick assessment potential for each set of parameters and the immediate visualization of the effects of changes would eliminate tedious manual data reduction, permit completion time on calibration of from one day to several months, eliminate many superfluous computer runs and lessen the need for much expensive test data. Figure 4.4 describes a typical comparison of time for design work on a structural part with and without CAD application.

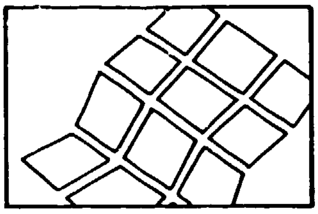
Figure 4.1 Where does CAD/CAM improve productivity?

Where Does CAD/CAM Improve Productivity?



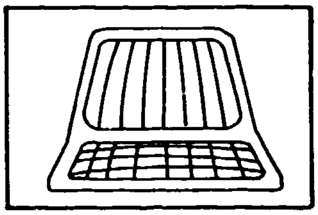
Drafting

Drawings with recurring features or drawings that are frequently updated are much more efficiently drafted and maintained with a CAD system.



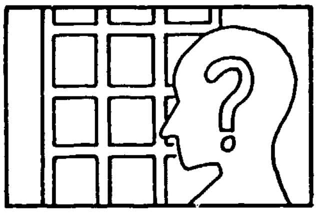
Documentation

Bills of material and technical illustrations are very quickly produced if they can be derived from data already stored in a CAD system.



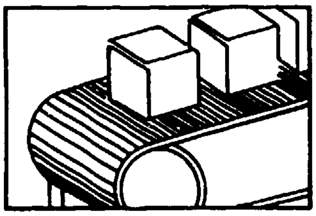
Design

Calculations of area, volume, weight, deformation, thermal flux, and so on are best performed by a computer. CAD systems can either perform these calculations themselves or prepare input for larger general-purpose computers from graphical data already stored in the CAD system. Also, design tasks that involve fitting together or housing a number of parts are very efficiently done with some CAD systems.



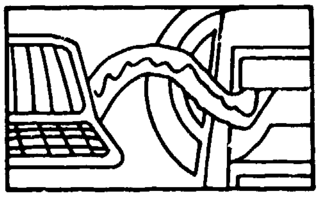
Estimating

The ability of some CAD systems to associate, store, and recall graphical and text data has been put to good use by engineering estimators. Experience has shown that this approach is more productive than manual methods and captures more cost information.



Order Entry

Some manufacturers have found that a lot of time can be saved by integrating order entry with their CAD system. Major savings can occur in this area when an order must be tied to specific engineering drawings.

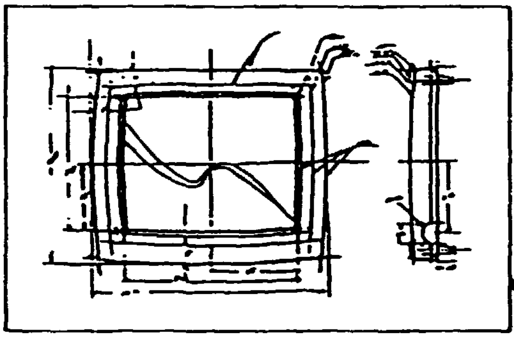


Manufacturing

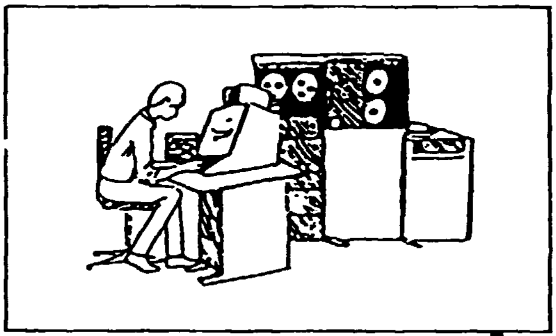
Many CAD/CAM systems include software for producing NC tapes and other items used for planning the manufacturing process from information entered and stored in the system during the design phase. This greatly reduces the effort necessary to get a part into production.

Source: Daratech Associates, Cambridge, Massachusetts

Figure 4.2 Anatomy of product design, mould design and manufacturing via CAD/CAM

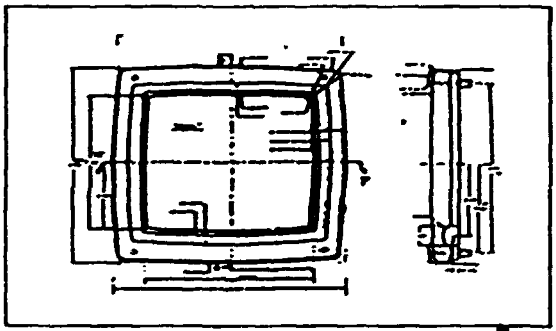


1. PRELIMINARY PRODUCT DESIGN

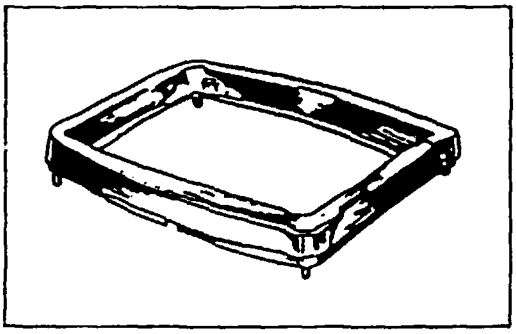


2. GRAPHIC INPUT

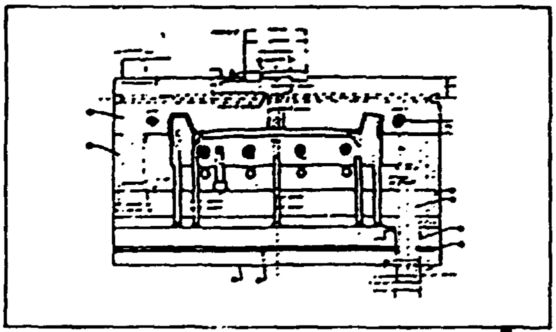
This seven-part illustration follows a typical sequence from preliminary product design to finished product utilizing CAD/CAM. The preliminary design (1) is entered into a graphics terminal (2) where it is refined, detailed and dimensioned, resulting in the final product design (3). Next the mould is designed using standard components in the computer program. Then cavity and core are located in the mould (4) and machining operations simulated on the video terminal screen. At this point a 3-D model of the product (5) may be drawn on the screen and rotated, enlarged, sectioned, etc. as required. Next CNC machining of the mould (6) is performed, controlled by a computer-generated tape. Finally, the mould will be used to produce the finished part (7).



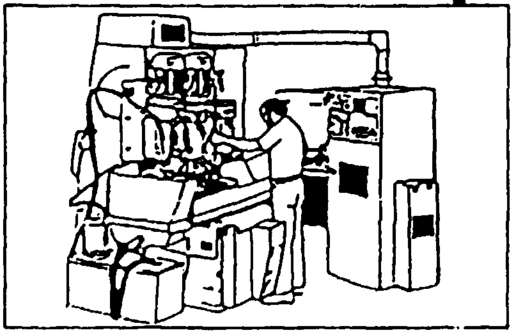
3. FINAL PRODUCT DESIGN



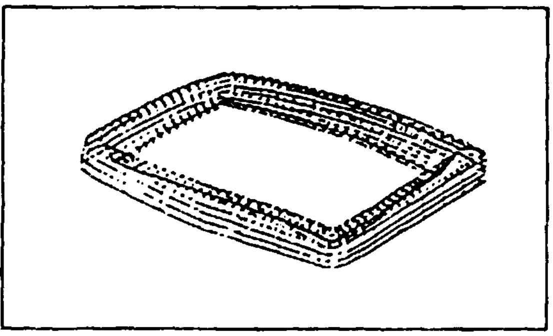
7. FINISHED PRODUCTS



4. MOULD DESIGN



6 CNC MACHINING



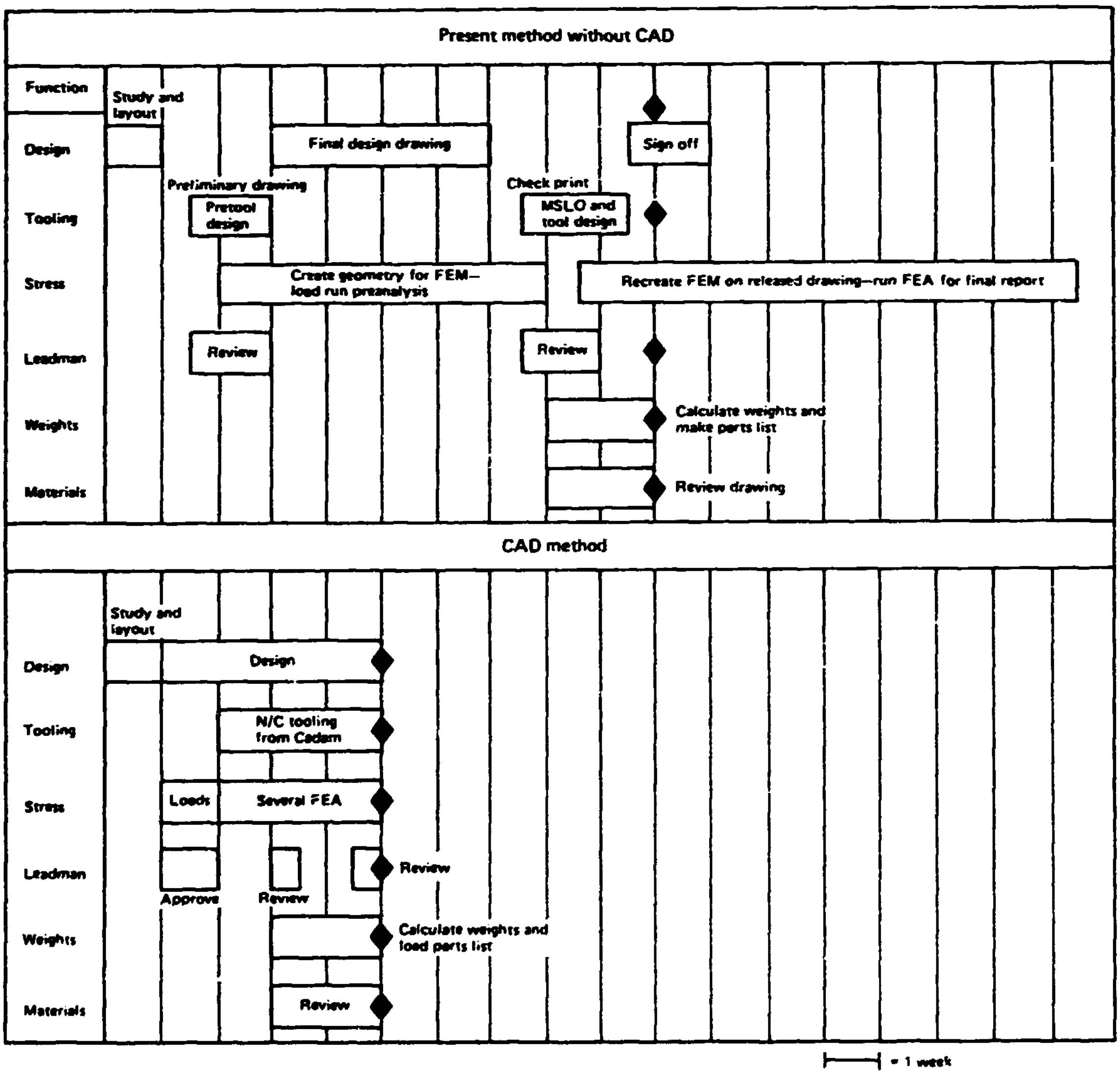
5. MODELLING OF DESIGN
ON GRAPHICS TERMINAL SCREEN

Source: D.M.E. News, January-February 1982

Figure 4.3 Estimates of time savings in mechanical design by use of a graphics system

	KEY AREAS	HOURS REQUIRED		PERCENTAGE SAVINGS
		CONVENTIONAL MEANS	WITH GRAPHICS	
INPUT DEFINITION (10 HOURS)	. Sketches	2	1.5	25
	. Description	1	1	0
	. Specification and parameter constraint	3	2	33
	. Verbal communication	1	1	0
	. Photographs and slides	0.5	0.5	0
	. Existing similar parts	1.5	1	33
	. Other means	1	1	0
	SUBTOTAL	10	8	20
CONCEPTUAL DESIGN (40 HOURS)	. Sketching constraints	2	1	50
	. Drawing an initial concept	16	12.5	22
	. Evaluate the concept	2	2	0
	. Study alternatives	14	7.5	46
	. Analyze and select the best concept	2	1.5	25
	. Refer to standard catalog	2	0.5	75
	. Miscellaneous	2	2	
	SUBTOTAL	40	27	33
ASSEMBLY LAYOUT (50 HOURS)	. Study the concept	2.5	1.5	40
	. Sizing drawings and views	1	0.5	50
	. Draw constraints	2.5	2.5	0
	. Refer to standard parts catalog	5	3.5	30
	. Study functional requirements	2.5	1.5	40
	. Select and specify standard parts	2.5	1.5	40
	. Hardline the design	19	13	32
	. Generate auxiliary views sections	15	9	40
	SUBTOTAL	50	33	34
	TOTAL (OVERALL DESIGN ACTIVITIES)	100	68	32

Figure 4.4 Comparison of time for design of a structural part with and without CAD/CAM



(c) Reduced labour hours

A significant amount of paperwork can be reduced through the use of a CAD/CAM system. In a manufacturing environment, documents such as routing sheets, tool lists, bills-of-material lists, machine loading capacity charts, production scheduling etc. can now all be handled by a system. Tedious calculations on areas, volumes, moments of inertia, mass centre etc, can be achieved in seconds without having to spend hours of labour. Reduced labour hours would mean a shorter project time as described previously. The productivity is increased and more contracts can be signed without additional manpower.

(d) Power of a CAD/CAM system

It may be an overstatement to say that many problems can be solved only through CAD/CAM technology. However, the statement is essentially true and CAD/CAM readily lends itself to improved techniques. For example, in applications involving the layout of piping, ducting and wirings, it was previously almost impossible to check for all possible interferences. This is generally the case since objects which are three-dimensional in nature cannot be studied efficiently from conventional two-dimensional drawings. There is no easy way to visualize clearances and interferences in a two-dimensional mode. Present day two- and three-dimensional systems provide the needed flexibility of analysis and presentation.

In numerical control (NC) machining, a cutter path can be simulated to check for interferences, and optimized cutting parameters such as feed speed can be generated automatically.

One of the important features of CAD/CAM is geometric modelling, the representation of part size and shape in computer memory. The modelling technique is extremely useful as many design and manufacturing functions use it as a starting-point.

The most powerful method for analyzing a structure on a computer is reckoned to be the finite element technique. This method determines characteristics such as deflections and stresses in a structure otherwise too complex for rigorous mathematical treatment. A CAD/CAM system is virtually indispensible for such applications, and with the graphics post-processing power, the data generated can be converted into visual form for quick interpretation.

(e) Reduced data handling and better management information

Interfacing of various programmes on a CAD/CAM system greatly reduces the repeated manual handling of both input and output data. Centralized control of planning data further reduces the dependency on the planner's skills in a manufacturing environment. It is now possible to capture "years of experience" on a computer memory.

(f) Enhanced users' knowledge

Users of CAD/CAM systems not only perform their jobs more efficiently but they also derive greater job knowledge in the process. This extended purview, in turn, has many benefits to the user. Improved knowledge and awareness of applications and of the interaction of applications offers some hope for coming to grips with the expanding technical complexity of the modern world.

The freedom of the human mind to concentrate on the more essential parameters of a project, made possible by CAD/CAM, offers a major potential for increased productivity and better solutions to complex problems. This value is, however, too abstract and difficult to quantify.

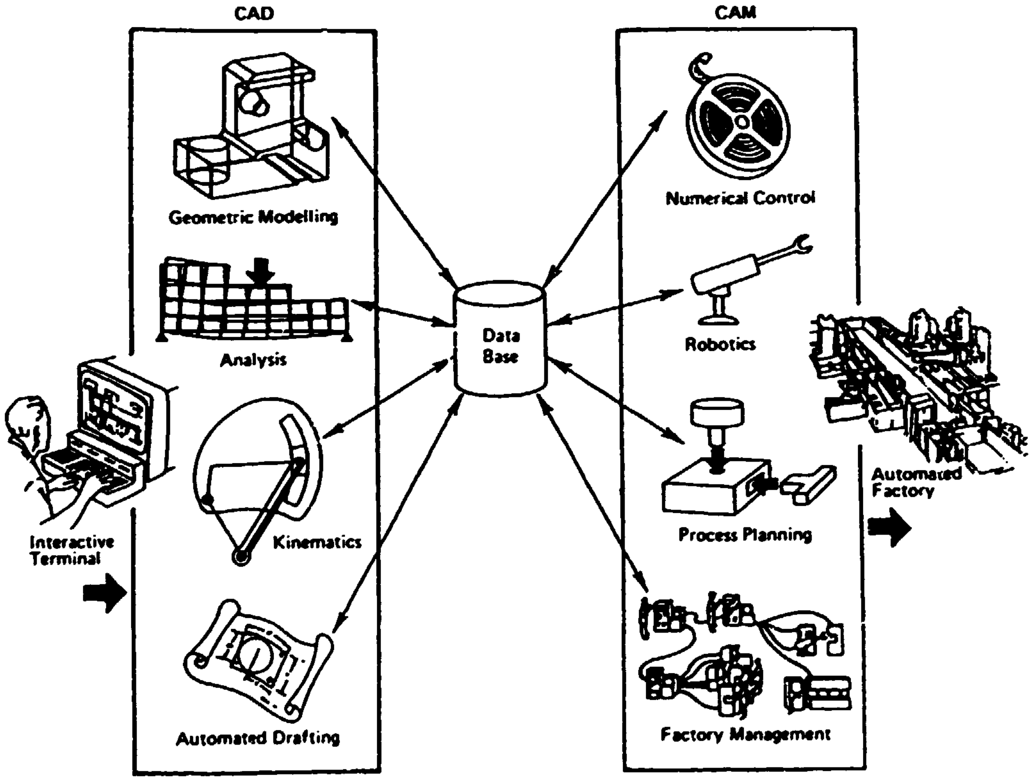
(g) Cost-effectiveness

Direct cost-effectiveness may be easier to qualify in terms of dollars and cents. If a case can be made clearly that a CAD/CAM system produces cost reduction, then all the other areas mentioned earlier are like frostings on the cake. Cost reduction in this sense is the most conservative approach, but it is certainly a benefit that the non-technical management and financial people can readily understand. For a more conservative organization, it may be justifiable enough for a CAD/CAM acquisition.

5. FUNCTIONS OF CAD/CAM

CAD/CAM technology is advancing so rapidly that it may not be familiar to many people - even to someone directly involved with its development. Some regard CAD only as automated drafting and CAM as merely NC tape preparation. Others include all engineering tasks performed with a computer as CAD/CAM. Actually, CAD/CAM is comprised of distinct functional areas. Experts group CAD functions in four major categories: geometric modelling, engineering analysis, kinematics and automated drafting. And present activity in CAM technology centres around four main areas: numerical control, process planning, robotics and factory management. The different categories of CAD/CAM functions are depicted in figure 5.1.

Figure 5.1 Different categories of CAD/CAM functions



5.1 CAD functions

(a) Geometric modelling

A designer constructs a geometric model on a CAD/CAM terminal to describe the shape of a structure to the computer. The computer then converts this pictorial representation into a mathematical model which it stores in a data base for later use. The model may be recalled and refined by the user at any point in the design process. And it may be used as an input for virtually all other CAD/CAM functions.

Since a number of functions depend on the model, geometric modelling is often considered to be one of the most important features of CAD/CAM. For example, the geometric model may be used to create a finite element model for stress analysis. It may serve as an input for computer-assisted drafting to produce engineering drawings. Or it can be used as a basis for producing NC tapes for fabricating a part.

Most earlier modelling was performed with wire frames that represent the part shape with interconnected line segments. Depending on the capabilities of the system, the model may be two-dimensional, two and a half-dimensional, or a full three-dimensional model. However, three-dimensional wire frames often do not adequately represent the solid nature of an object and sometimes require further definition by the user, such as automatic hidden-line removal. An advanced geometric modelling technique that overcomes this problem is three-dimensional solid modelling.

In the most common form of three-dimensional solid modelling, models are constructed with building blocks of elementary solid shapes called primitives. Typical commercial packages are: SYNTHAVISION developed by Mathematical Applications Group Inc., PATRAN-G by PDA Engineering, MEDUSA on Prime, Geomod by SDRC, ME30 by Hewlett Packard, EMS by Intergraph etc. There are well over 30 such commercially available programmes. Other experimental solid modelling programmes have been developed around the world, mostly in universities. However, these generally are not as refined and lack the extensive software support of the commercially available programmes.

Because the geometric model ultimately is used as a basis for machining a part, geometric modelling and, in particular, surface modelling is tied closely to NC technology.

(b) Engineering analysis

The most powerful method of analyzing a structure on a computer is probably the finite element method. With this technique, a structure is represented by a network of simple elements that the computer uses to determine stresses, deflection and other structural characteristics.

In an integrated system, a user can call up the geometric model of the part and create a finite element model quickly and easily using automatic node and element generation routines. Once a part is modelled, the user specifies loads and other parameters. The model can then be analyzed with commercial packages such as NASTRAN, STRUDL, ANSYS, ABAQUS, ADINA etc.

One of the most recent developments in CAD/CAM analysis concerns the combination of analytical and experimental data to create a total system model. By this method, rigid parts are analyzed using the finite element technique. Characteristics of elastic components such as shock absorbers and isolation mounts are determined by testing. The data is combined to create a system model, which is then exercised to predict structural behaviour during operation. For example, input data for an automotive analysis may simulate wheel unbalance, braking, turning or tyre impact with a curb or manhole. The computer predicts the response of the overall vehicle to these conditions. The method is useful in improving the structural integrity of a range of vehicles such as trucks, buses and tractors. It is also useful for other machines such as machine tools and home appliances.

(c) Kinematics

The equations associated with complex mechanisms such as four-bar linkages are extremely difficult to set up and solve. As a result, designers traditionally used pin-and-cardboard models or cumbersome graphical methods to develop practical mechanisms.

CAD/CAM kinematic programmes can plot or animate the motion of linkages and complex mechanisms. Calculating the displacement, velocity and acceleration at any desired points becomes a relatively simple matter. At present, there are numerous kinematic packages but only a few are refined sufficiently to be commercially practical. Examples are ADAMS and DRAM from the University of Michigan, IMP from the University of Wisconsin, KINSYN from George Washington University and LINCAGES from the University of Minnesota. The ADAMS, DRAM and IMP programmes require a user to enter problem-oriented language statements as inputs. The computer then produces link positions, forces, velocities, accelerations and other output data. KINSYN and LINCAGES develop mechanism designs based on required motion paths. LINCAGES requires a user to enter path data on a keyboard, whereas KINSYN utilizes more interactive graphics. A user specifies motion requirements on an electronic tablet with a stylus. The computer immediately displays a linkage configuration capable of providing that motion path on the terminal screen.

(d) Drafting

Computer-assisted drafting features automatically produced detailed text and engineering drawings on command from the geometric model data base or from inputs entered by a user at the graphics terminal.

Most of the systems have automatic scaling and dimensioning features. Changes made to one view are automatically added to other multiple views. Function menus, in addition, permit a user to specify points, locate lines, enter text, and produce cross-hatching at any position as desired. Two-dimensional and three-dimensional schematic layouts can be performed easily as symbols can be stored and recalled.

These automatic features coupled with the high speed of computer-driven plotters enable users to produce new drawings five times faster than with manual drafting methods. And design changes can be made up to 25 times faster with CAD/CAM. It has been envisaged that by the year 2000, 50 per cent of the drawing-boards will have been replaced by drafting systems.

5.2 CAM functions

The various functions integrated in a CAM system are illustrated in figure 5.2. The following sections describe the individual functions undertaken in a CAM system:

(a) Numerical control

One of the most well developed areas of CAD/CAM technology is in numerical control. This is the technique of controlling a machine tool with pre-recorded, coded information to make a part. Automatically programmed tools (APT) is the original and most universally accepted language. Recently, many other types of APT-like languages have been developed. NC instructions are generally stored on punched paper tapes or magnetic tapes for controlling a machine tool. Recent systems use CNC, a set-up in which a machine is handwired to a minicomputer where NC instructions are stored. The most sophisticated systems use a direct numerical control scheme in which several minicomputers are linked to a central mainframe.

Traditionally, experienced programmers write NC instructions directly from engineering drawings. Then the programme is tested on a machine tool and refined a number of times to remove any errors. These time-consuming iterations can significantly increase the cost of machining a part. Now creation and verification of NC instructions can be made much easier. For example, less machine tool time is spent verifying the cutting paths by checking the tooling programme with computer simulation. In addition, the computer itself can now generate NC instructions directly from the geometric data base, although these capabilities are generally restricted to flat or turned parts.

(b) Process planning

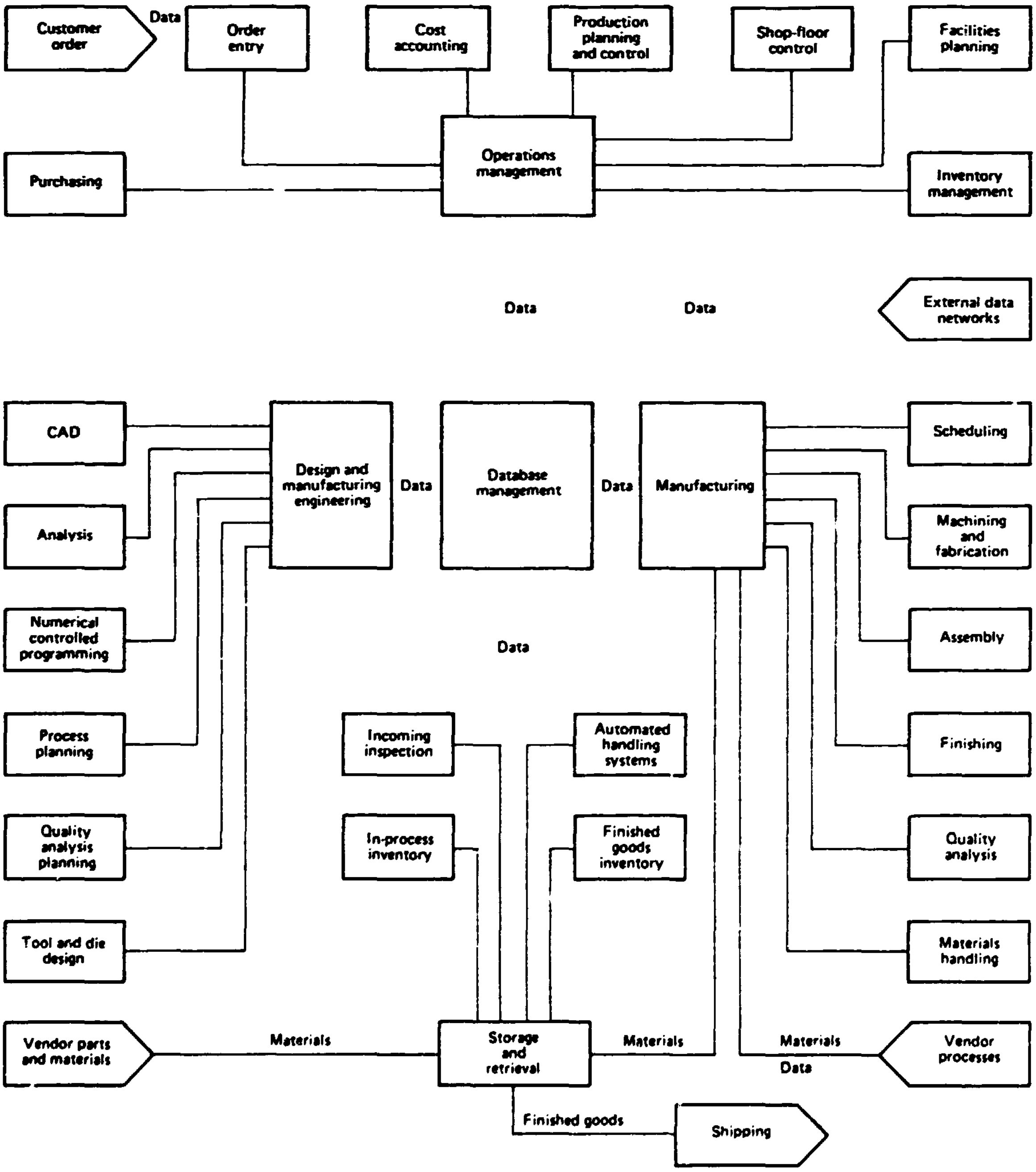
Process planning is a much broader function that considers the detailed sequence of production steps required to fabricate an assembly from start to finish. Essentially, the process plan describes workpiece status at each work station along the line. As such, process planning has been a part of manufacturing for some time. But only recently has the computer been used in this activity.

One important aspect of process planning systems is group technology. This concept organizes similar parts into families to allow fabrication steps to be standardized. Computer-aided process planning is often considered as the integrator between CAD and CAM, and it is estimated that over 50 systems have been developed world-wide.

(c) Robotics

Robots are automated manipulator arms that perform a variety of material handling tasks in a CAD/CAM system. Robots may select and position tools and workpieces for NC machines, or they may carry equipment or parts between various locations on the shop floor. They may also use their grippers to grasp and operate drills, welding torches and other tools.

Figure 5.2 Computer-aided manufacturing



Most robots at present are programmed in a so-called teach mode. In this approach, a user physically leads the robot through the individual steps of an operation. This type of manual teach-programming is time-consuming and error-prone. Also, programme changes usually require the entire sequence of steps to be repeated. At present, advanced programming languages with which robot instructions may be issued through a computer are being developed. One of them is the IBM AUTOPASS, which attempts to eliminate the need for issuing detailed instructions to the robot. The programme automatically determines the grip points and motion paths from the geometric data base.

Some languages are intended to operate with artificial sensory input that enables the robot to act more independently. For example, the Standford Research Institute Robot Programming Language (RPL) includes capabilities for interpreting video signals, enabling the robot visually to identify parts. Draper Industrial Assembly Language (DIAL) developed at Charles Stark Draper Laboratory uses electronic force-feedback to simulate human sense of touch in assembling components.

Present plans for future CAD/CAM development have co-ordinated teams of robots and NC machine tools divided into group-technology work cells. A robot can usually service two or more NC machines, performing much the same as a human technician.

(d) Factory management

Factory Management ties together the other CAM areas to coordinate operations of the entire manufacturing facility. Factory management systems rely heavily on group technology, with individual manufacturing cells fabricating families of similar parts. Computers perform various management tasks such as inventory control and scheduling in material requirements planning systems.

Predictions are that individual manufacturing cells ultimately will be linked together and controlled by a unified computer system, paving the way for overall factory automation. Production technology forecasts by some experts indicate that factories totally automated by computers will be a reality before the end of this century.

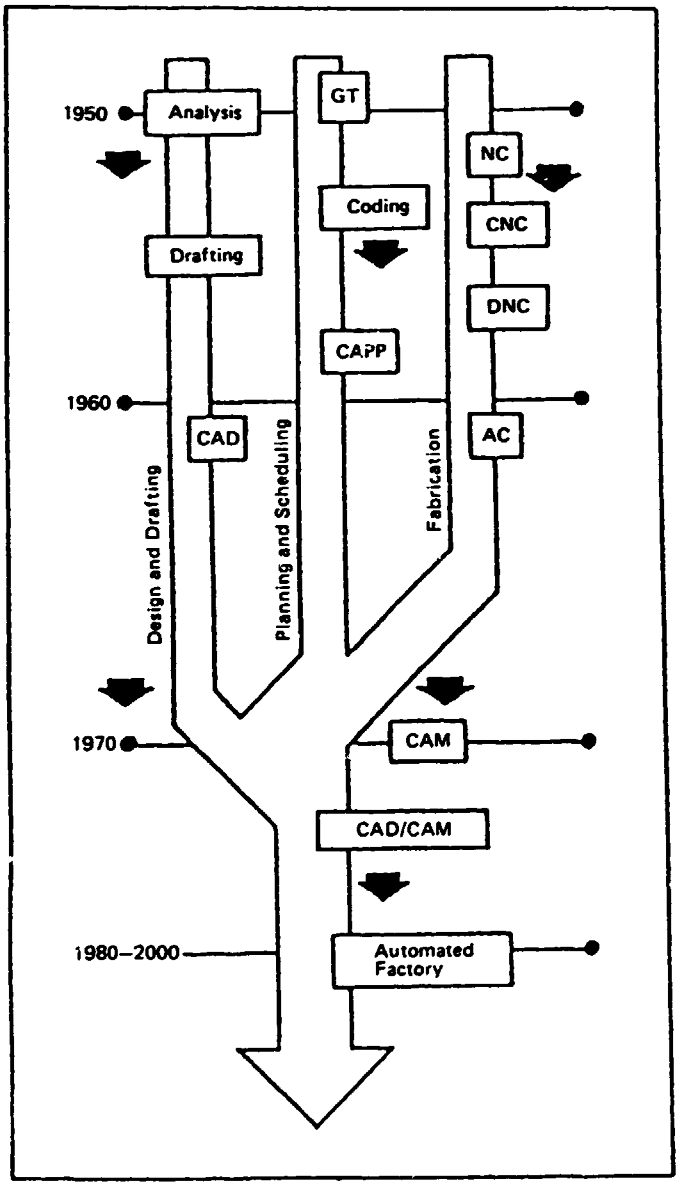
The various stages in the development of the different elements leading to an automated factory is depicted in figure 5.3 and figure 5.4.

5.3 Example of CAD/CAM applications in metalworking industries

The metalworking processes had been associated with mankind since the iron age, when human beings first discovered that metal can be shaped in both cold and hot states with applied force and pressure. The fact that shaped metal can further be used as tools to shape other metal soon lead to a host of discoveries and inventions that accelerated the progress of science and technology.

With the advent of computer and CAD/CAM technology, metalworking processes have changed quite drastically from that of traditional design, prototyping and final product to that of computer-aided design, simulation and manufacturing. This paper examines a few major metalworking processes and reports some of the computer aids which are available at present.

Figure 5.3 Evolving technologies of CAD/CAM



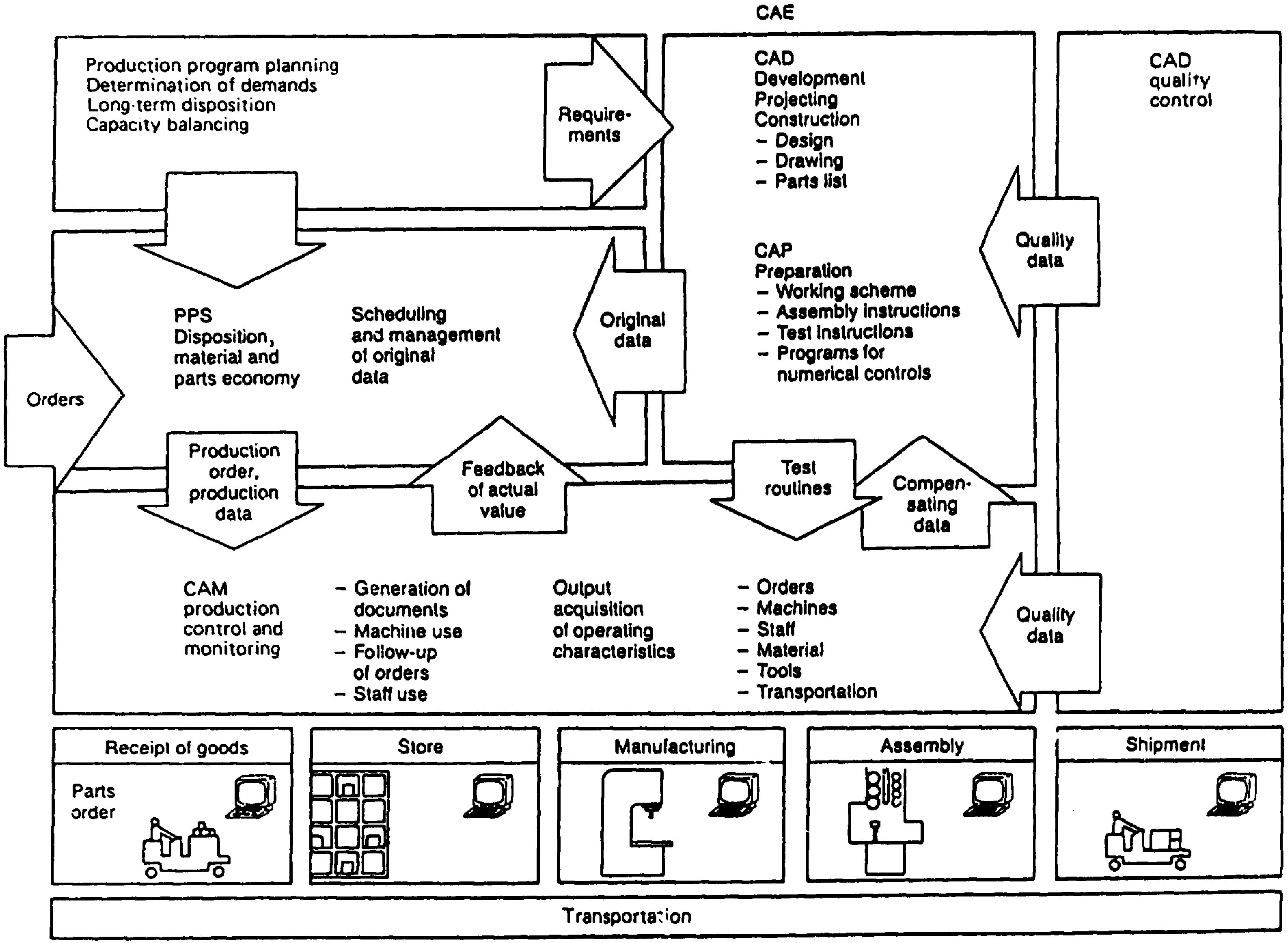


Figure 5.4 Main functions of computer-integrated manufacturing

5.3.1 Metal-forming processes

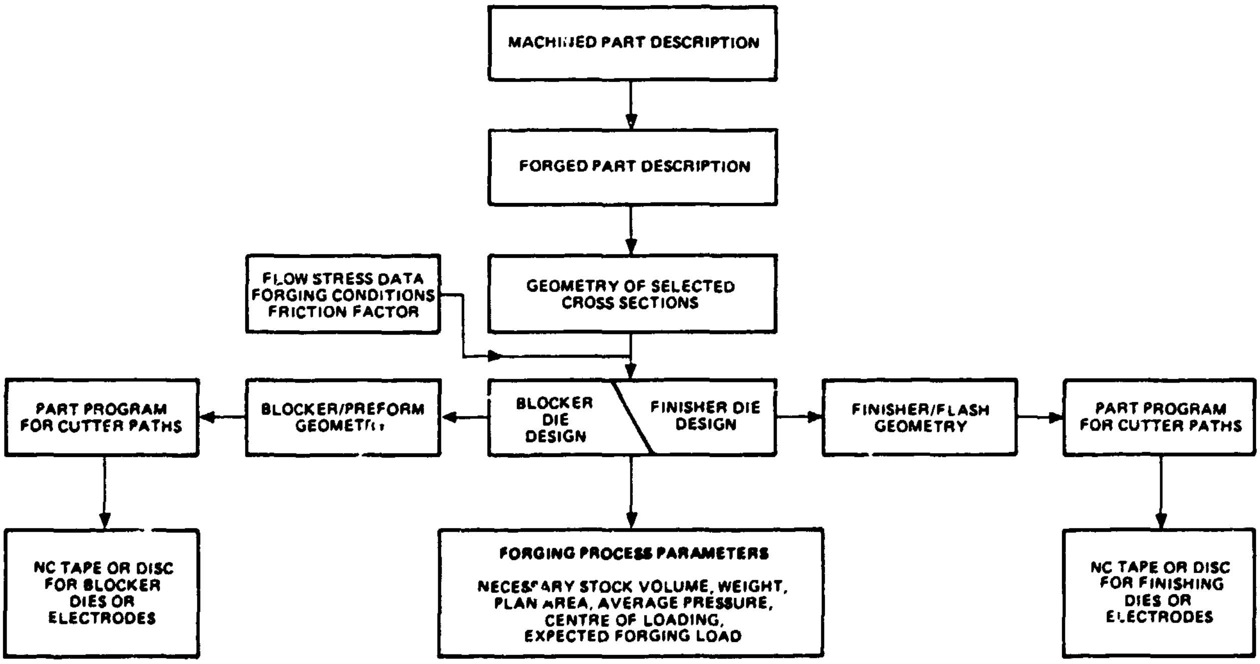
The major metal-forming processes can be classified into forging, extrusion and rolling. A brief description of the computer aids associated is given in the following sections.

(a) Forging

Forging is the process of physically deforming metals to specified shapes using compressive force exerted by a hammer, a press or an upsetting machine. The process of forging is considered to be the oldest of all metalworking processes. Significant changes in forging techniques have taken place in the last two decades.

A brief outline of an integrated CAD/CAM approach to hot forging is shown in figure 5.5. The most critical information necessary for forging die design is the geometry of the forging to be produced. The forging geometry is obtained from the machined part drawing by modifying this part geometry to facilitate forging. This activity can be performed readily with a CAD/CAM system with software for geometry handling, drafting, dimensioning and NC machining. Using well-proven analyses based on the slab method or FEM techniques, forging load and stresses can be obtained and flash dimensions selected for each section.

Figure 5.5 Outline of an integrated CAD/CAM approach for hot forging



At present, there are a number of overseas institutions specialized in CAD/CAM of forging dies such as the Battelle Laboratories at Columbus, Ohio, and the Swedish Institute of Production Engineering Research.

(b) Extrusion

The extrusion process, like forging, is another complex metalworking process which can be handled effectively with computer aids.

The CAD approach consists of material modelling, i.e. the development of rigid-plastic and rigid-viscoplastic FEM models, the development of a generic flow rule and constitutive-behaviour model for partially and fully dense materials and the techniques for the design and manufacture of streamlined dies.

Figure 5.6 depicts the simulation of material flow through a streamlined die using CAD techniques. Figure 5.7 shows the shape of an EDM electrode which can be used to make the extrusion die. Few commercial packages are available, and work in this area is mainly done in the research institutes such as the Air Force Wright Aeronautical Laboratories and the Battelle Laboratories.

Figure 5.6 Simulation of material flow through a streamlined die, 1100 aluminium at 20° C, die length = 3 inches

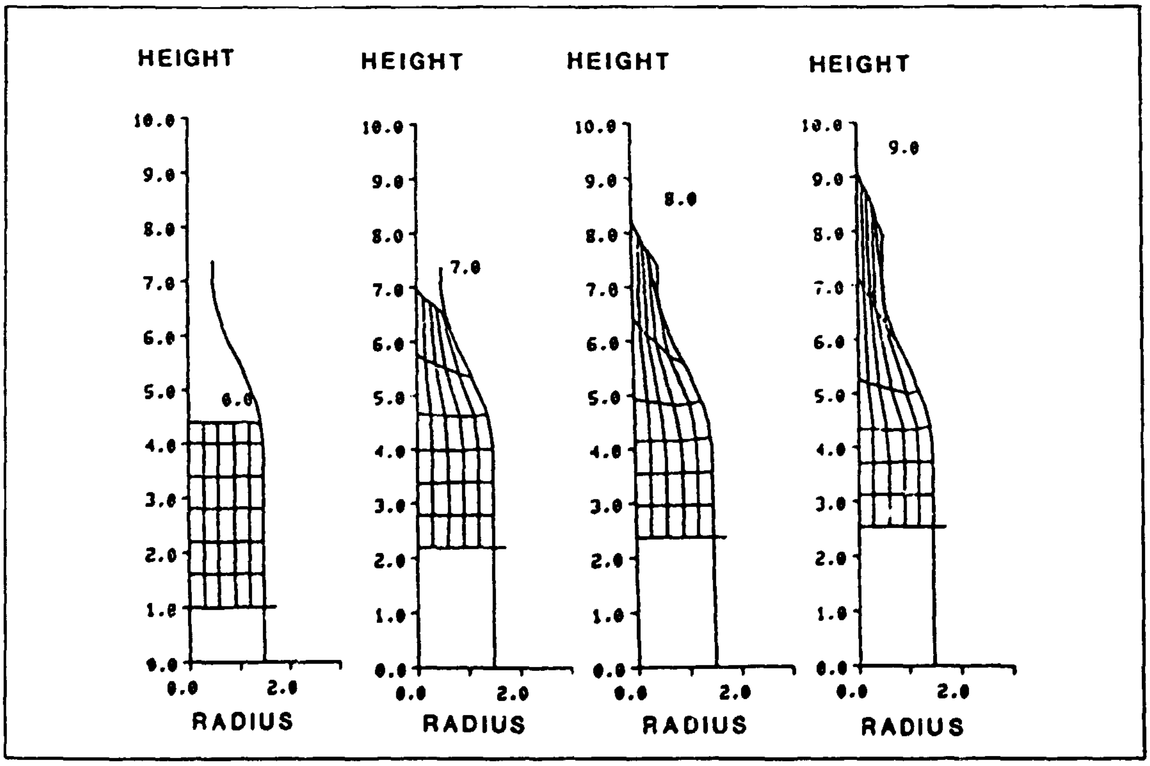
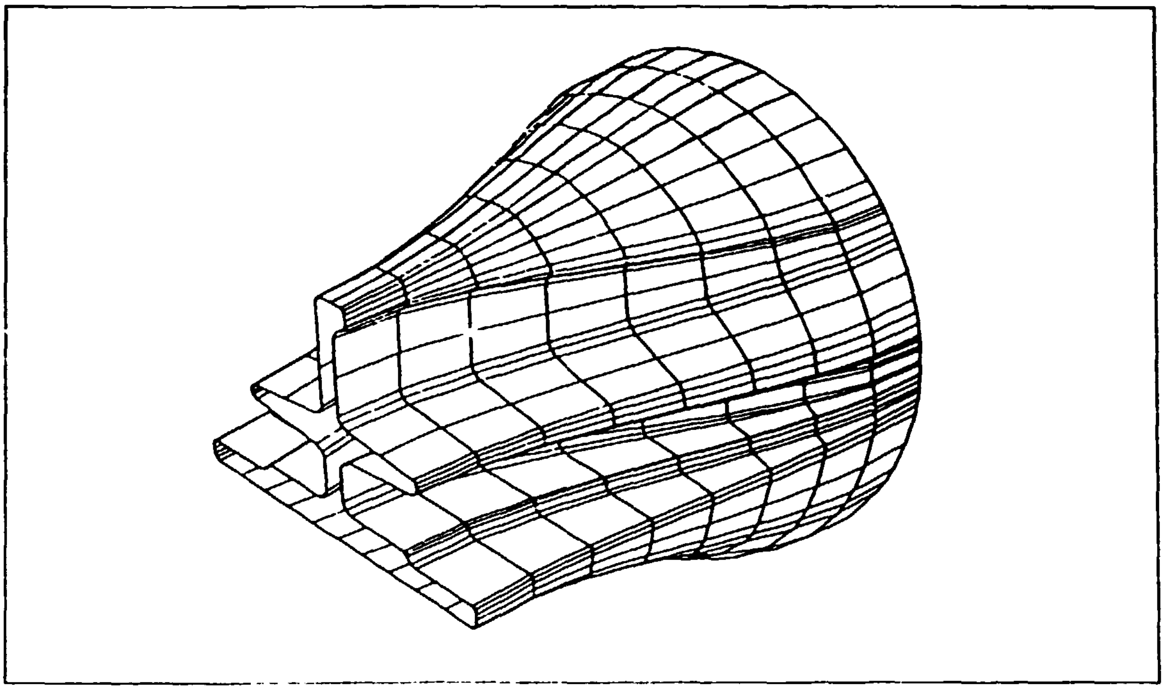


Figure 5.7 A perspective projection of an EDM electrode for streamlined extrusion die sinking



(c) Rolling

The rolling of complex shapes has been regarded as an economic process for obtaining not only structural shapes but also precision profiles for high technology applications, such as turbine blades and vanes. Rolling tools, particularly for complex shapes, are traditionally designed through experience and trial-and-error methods. The main problem encountered in rolling is the determination of lateral spread in the roll gap which could be solved using lateral spread formulae, plasticity theory and experimental results.

The approach to roll pass design is therefore based on the determination of the different steps required to reach a final shape from a relatively simple preform (round, square or plate). Computer programmes are used to determine and optimize the roll pass schedule. The final result is a complete technical drawing of a set of rolls and data generated can be used for the direct NC production of the rolls.

5.3.2 Sheet metal work

(a) Blank development

A number of commercial packages are available for determining the blank size of folded sheet metal. These packages are capable of unfolding a formed sheet metal to flat patterns, and automatically consider adjustment of bend allowances, modification of corner details of box-shaped products to match tooling requirements and verification of the adjusted pattern by checking dimensions and relationship of parts of the folded product. Examples are the Medusa Sheet Metal System from Computervision and the Intergraph Sheet Metal Development System.

(b) Nesting

Nesting has important applications not only in sheet metal work but also in garment, woodworking and leather industries where irregular patterns need to be cut from the raw sheets. The main objective of any nesting programme is to achieve an optimal layout so that material saving can be obtained. Programmes may also consider constraints peculiar to the special type of operation involved and they usually provide NC output to drive cutters and other devices. Several commercial systems are available, but the layout is mostly interactive rather than automatic. Commercial packages are the Autotrol Nesting System, Autonest from Autokon Manufacturing Modules designed for the flame-cutting operation in the shipbuilding industry, and a number of packages such as the AM-5 System developed by Gerber for the garment industry.

(c) Progressive die design

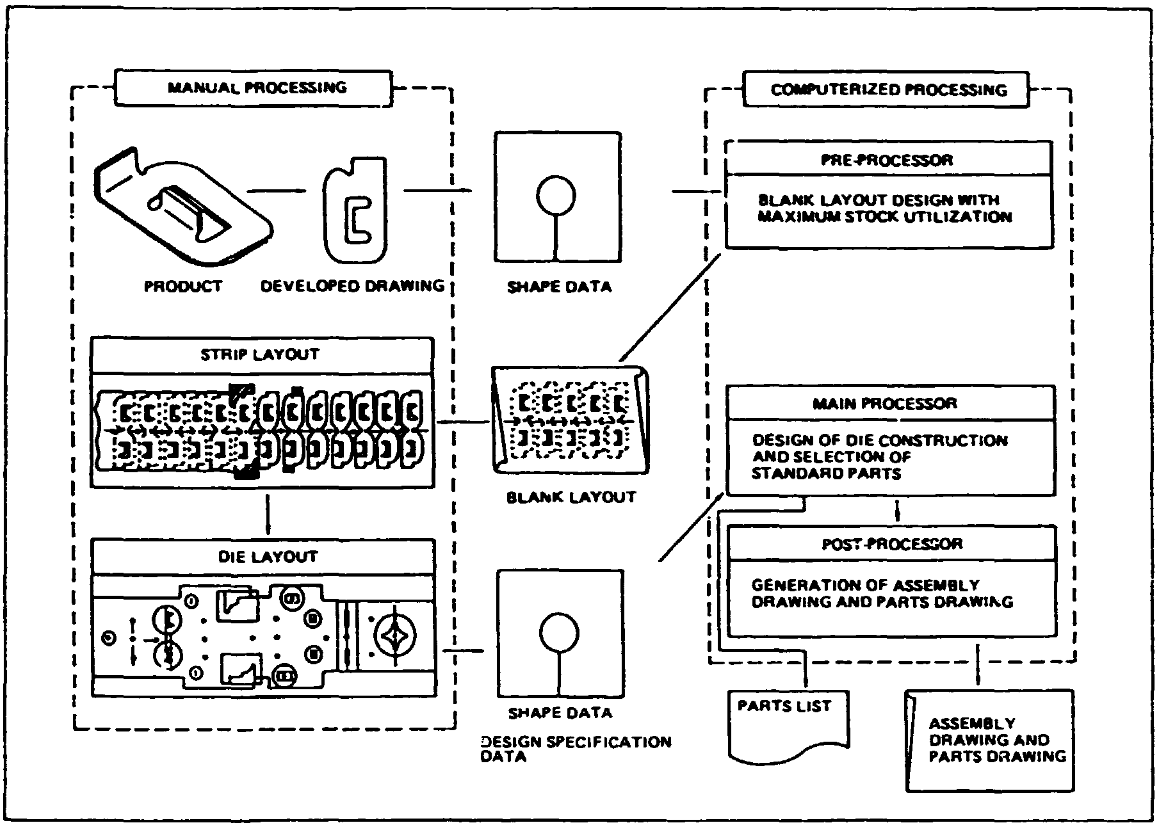
Die design is an area that has traditionally been associated with highly skilled craftsmanship. As fewer craftsmen are being trained nowadays and as dies are becoming more complex and highly-graded, there is a strong need for computerization in this field. Most of the progressive die design programmes have been started at the universities and research institutes. Fanuc and Computer Engineering Inc. have produced good commercial progressive die design systems with outputs linked to NC machine tools.

In almost all the systems, the following stages are considered:

(a) Product geometry input;
(b) Definition of pilot holes as the reference of the feed amount of material;
(c) Yield calculation;
(d) Blank layout and stage determination;
(e) Stacked drawing, skeleton drawing and strip layout drawing checks after determining punch geometries and layout;
(f) Designation of various holes such as mounting bolt holes, lifter pin holes, dowel pin holes etc. and determination of the plate conception of each die plate;
(g) Generation of NC machining data.

Figure 5.8 shows a typical conceptual approach for a progressive die CAD system.

Figure 5.8 A typical conceptual approach for CAD system of progressive die



(d) Nibbling

Nibbling is a method of cutting large blanks of small batches from raw sheets. The blank is produced by the progressive nibbling of standard-shape punches around its periphery. One of the major commercial vendors is Amada, which produces the complete nibbling machine together with the programme. A number of other NC machining packages also contain NC nibbling as one of the standard features. An NC nibbling programme usually carries out the following operations:

(a) Works out the number of punches and shapes required;
(b) Works out the number of strikes and time needed;
(c) Matches profile with specific finish;
(d) Works out the correct indexing sequence.

(e) Machining

Numerous commercial packages on small and large systems are available. Some of the programmes available on personal computers are becoming more powerful and versatile. Examples are Pathtrace, ANICAM, Personal Machinist and the NC Programmer from Autodesk.

Typical capabilities include:

(a) Geometry creation and definition;
(b) Tool library;
(c) Numerically coded control;
(d) Dynamic tool display;
(e) On-screen CL file;
(f) Color-coded feed rates;
(g) Options for turning, milling, wire-EDM and nibbling;
(h) DNC option.

(f) Process planning

The capabilities of most of the process planning systems include variant as well as generative techniques covering some of the following areas:

(a) Machining of rotational parts;
(b) Machining of prismatic parts;
(c) Sheet metal fabrication;
(d) Assembly operations;
(e) Welding operations.

Commercial systems such as LOCAM from Logan Assoc are available on personal computers. Computer-aided process planning (CAPP) has received much attention as it is often considered as a missing link between CAD and CAM. By bridging the CAD-CAM gap through the development of CAPP, it makes a big step forward towards computer-integrated manufacturing (CIM).

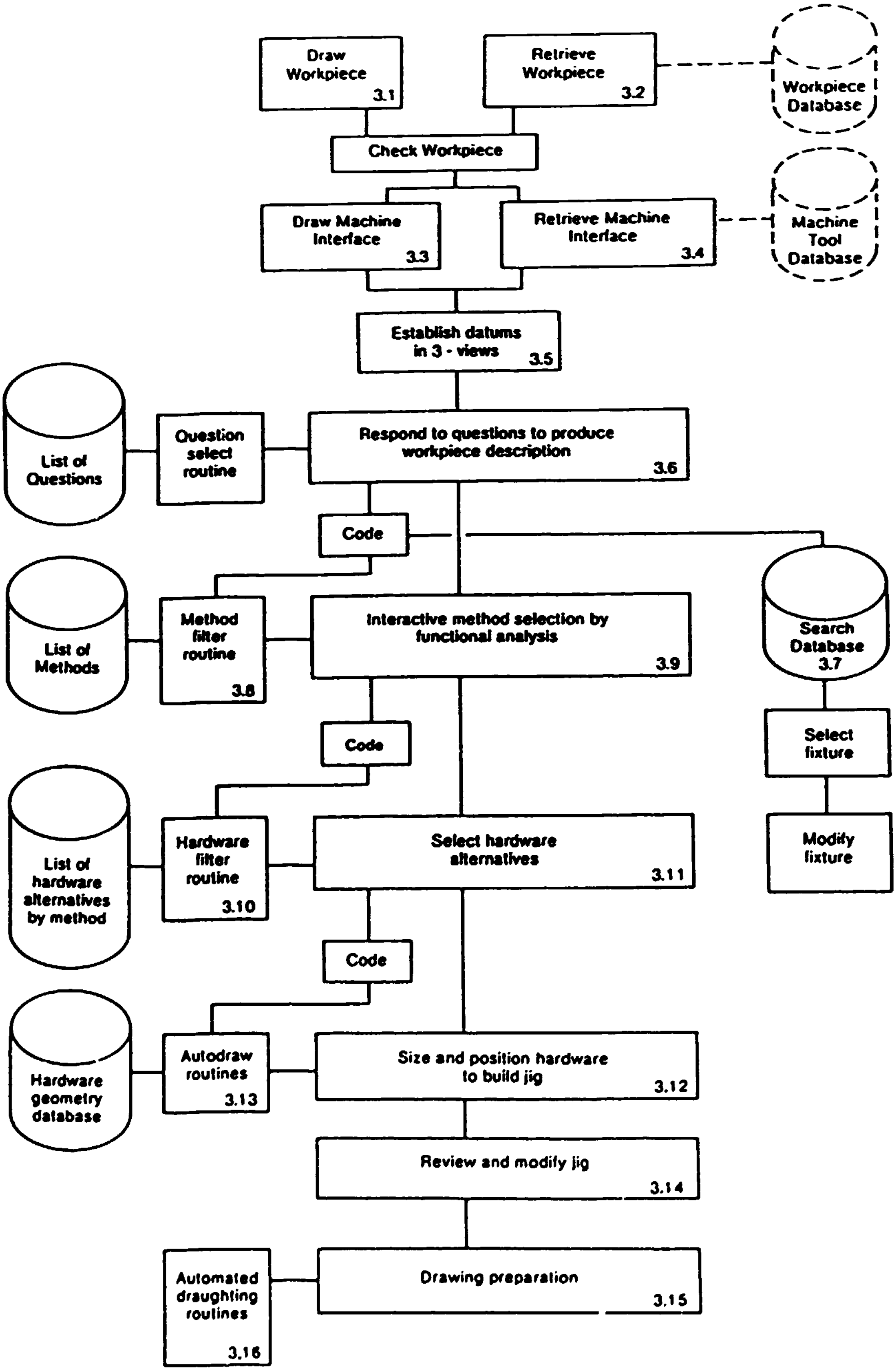
(g) Fixture design

Computer-aided fixture design is of relatively recent origin as it is an area where few algorithms exist and it is largely based on the experience, intuition and knowledge of the individuals. The typical approach used follows that of expert system development where a knowledge base is used to contain facts and rules of fixture design and an inference engine to decide which rule to apply. The following important functions and elements need to be considered:

(a) Workpiece location and tolerance relations;
(b) Workpiece clamping and securing devices;
(c) Workpiece support;
(d) Cutter guidance;
(e) Loading and use of use;
(f) Fixture body.

A typical block diagram depicting the CAD/CAM design procedure of fixtures is shown in figure 5.9.

Figure 5.9 A block diagram representation of the CAD/CAM design procedure of figures



6. CAD/CAM SYSTEM EVALUATION AND SELECTION

6.1 Introduction

It is quite difficult to select all the competing hardware and software alternatives available in CAD/CAM systems. Assuming that the decision has been made to purchase a system, the first step is to develop the selection criteria. These criteria should be developed by an in-house committee for CAD/CAM evaluation. The committee will follow the selection procedure from beginning to the final decision.

Based on the criteria set, short-listed vendors will be called up for initial meetings. An initial list can usually be trimmed down to three or four potential vendors following initial discussions and visits for demonstrations. These vendors should then be subject to a more intensive selection procedure. This will have a number of objectives including, firstly, to test the systems and ensure that they do meet the specified requirements, and, secondly, to compare them to enable a final selection to be made.

Buying a CAD/CAM system will require studies of many important issues such as its features, performance, the type and quality availability and delivery of services. Buying a turnkey CAD/CAM system involves many intangibles in addition to the CAD/CAM hardware and software. At the initial stages, every step of assistance from the suppliers will contribute to the success of the system operation. Under a turnkey system, the vendor will deliver the product and install, check and provide it in a form ready for use.

The vendors and suppliers would not only be responsible for the training of operators, designers and management staff, they would also offer or provide services for preventive and remedial maintenance. The cost involvement and payback should be viewed in consideration of the total package. Buyers can also expect the vendors' full commitment to the functioning of the system. Only by considering all these factors can an effective comparison be reached.

It would not be right to buy a system by looking at its physical features and prices only. The practical business issues are to be considered in respect of its effective application and adaptation into the organization. The credibility of the vendors is also to be examined with respect to their integrity, business philosophy, financial resources, systems design capability, knowledge of the buyer's applications and needs and their service records.

The vendor's business strategy will be to establish a continued credible business relationship with the customers. The vendors should not only be bound by the contractual obligations, but they should also extend their extra-contractual, moral commitments to the buyers. The buyers should make all necessary attempts to verify the financial standing of the vendor from all possible sources so that any financial inadequacy does not impede the system acquisition process.

While contacting a vendor to inquire about CAD/CAM systems, a user should provide detailed information on the application areas so that the vendor can recommend the appropriate type of system and its management considerations. The buyer should look into the vendor's offer of a system with respect to its full features, suitable application, high-performance ability and the support the vendor would be able to provide after the sale.

The services needed by a particular user may vary from one to another according to the employees' experience level with the CAD/CAM system. First time users will require elaborate training programmes for the operators and management staff. Experienced users will require the assistance of the suppliers in the integration of the new system with existing operations.

6.2 CAD/CAM application areas

CAD/CAM systems can be used to improve the efficiency in many areas of a company's operations. When a company is contemplating of the use of CAD/CAM, all departments that may ultimately use the system should be identified so that their particular requirements can be included in the specification, although circumstances and detailed requirements may possibly change during the course of evaluation. Although a company may not initially install a system having all of the facilities identified in this way, it should ensure that it can be expanded to meet the company's ultimate requirements.

Some of the CAD/CAM application areas are discussed in section four. A brief summary of the areas are as follows:

Design:	Mechanical draughting
	Schematic drawing
	Design analysis
	Finite element analysis
	Coding and classification
	Parts listing
Manufacture:	NC programming
	Jig and fixture design
	Sheet metal development
	Nesting
	Factory layout
	Process planning
	Robot programming
Other areas:	Technical publications
	Tendering and estimating

6.3 Evaluating the system hardware and software

Evaluating a CAD/CAM system's hardware and software is no easy task. Conceptually, the process consists of first establishing what will be required of the system, then evaluating the system's functional capabilities, operational characteristics and performance in the light of these requirements.

The number of competing CAD/CAM systems has grown dramatically in recent years. Most manufacturers have adapted their basic products to exploit more than one market, and it is now commonplace to see substantially the same hardware being offered (with a different software superstructure) as a mapping system, a printed circuit board system, an integrated circuit system, an architectural design system, or a mechanical design, draughting and manufacturing system.

The key to a successful evaluation programme is a comprehensive requirements analysis. A CAD/CAM system tends to be good in some areas and not so good in others; thus, a meaningful evaluation can be made only if all the requirements against which each system is to be judged are clearly defined and well understood. During the course of the requirements analysis, each system requirement should be examined and weighed according to its relative importance. What will emerge will be a list of needs, ordered by priority, that can later be used as a basic set of evaluation criteria against which the features and characteristics of competing systems can be measured.

Since a thorough evaluation can be very time-consuming, the requirements analysis should first be used to review superficially the competing systems and to narrow the list to two or three, which can then be evaluated in detail.

Broadly speaking, there are three characteristics of the integrated hardware and software for the buyer to consider, namely, utility, performance, and potential. Utility is what the system can do, and the relative difficulty of making the system do it - in other words, the system's functional capability, ease of operation, and the ease of learning to operate the system. Performance is the system's efficiency and capacity for useful work, that is, efficiency of on-line storage utilization, data communication capacity, reliability and maintenance performance, throughput, and response time. Finally, potential has to do with the system's ability to fulfill future needs - for example, the potential for expanding the system's utility and throughput with additional storage, applications and work stations, and the potential for integrating it with other data-processing systems.

The major CAD/CAM system characteristics (hardware and software) together with some suggestions on how to evaluate them are described below.

(a) Functional capability

The applications that a system can handle and the way in which a system performs them are all part of its functional capability. This includes such things as its capabilities for geometric construction, draughting, modelling, properties calculation, data base management and report generation.

To evaluate a system's functional capability, start by studying the vendor's specifications. Discuss the needs with the vendor and ask for written clarifications whenever necessary. Visit similar systems to see if the capabilities needed are being realized in practice. Some typical examples of what is wanted should be demonstrated by the vendor to confirm that they can be done by the system.

(b) Ease of operation

The system operation should be easy for the operators and users. It is an important consideration because, in the long run, it affects the performance of the system. What makes this characteristic so difficult to measure objectively is that its negative results affect the operator by quickly tiring him out or making it difficult for him to run the system. The vendor is not a good source of information here because, naturally, he will feel his system is superior in this regard. Current users will be more objective, but they may have learned to live with the inconveniences and may not be aware of them any longer. Probably the best way to evaluate this characteristic is to seek the opinion of people who have had experience with all the systems being evaluated, or a series of representative tasks can be devised to demonstrate the human effort involved in carrying them out.

(c) Ease of learning to operate the system

The ability quickly to learn to operate a system is important where there will probably be many casual operators. However, it must be kept in mind that what is good for the casual operator is not necessarily good for full-time operators, who generally prefer power and speed over simplicity and help from the system. Again, this is a subjective characteristic, but the experiences of other users can be very helpful. Having each vendor demonstrate a few representative functions will also help evaluate the difficulty of learning to operate a particular system.

(d) Performance characteristics

Throughput and response time is really a measure of the rate at which the system does its work. It is a measure of the quantity of function executions that the system can peform per unit time. While most systems can easily handle the throughput load generated by a single work station as the number of active work stations increases, the peak throughput capacity can quickly be reached. When operating close to peak throughput, the readiness of a system to accept further work diminishes and its response to operator requests for action slows down. This reduction in response time is the system's way of metering its work flow to match its throughput and prevent overloads. The slowed response drastically reduces the productivity of the operators. Thus, the system's throughput is an especially important factor in multi-station, host-centred systems because of its bearing on average work station productivity. Even where a system is work-station-based, a low throughput capacity can slow work station response time down considerably and cause operator productivity to fall. In some systems, partial response to operator action is made even at peak throughput capacity. These requests are queued, then executed when the required capacity becomes available. This smooths some peaks in throughput demand, but it is not effective for all functions or in situations where a high rate of work station requests are maintained for any length of time. Thus, the required throughput capacity is set by what is deemed an acceptable work station response time. Work-station response time should be evaluated in terms of its effects on operators' productivity.

(e) On-line storage utilization

Graphics systems store graphics and other data on-line for fast reference and for use as a basis for constructing new data. Systems are rated in terms of their storage capacity but this rating does not take into account the efficiency with which this storage is utilized. For example, one megabyte of on-line storage will typically hold one-dimensional drawings. However, if storage is more efficiently utilized or if the data structures used are more efficient, one megabyte may be able to store five- or even six-dimensional drawings. This gives a storage-efficient system a significant price and performance advantage.

The best way to evaluate storage utilization is with an actual benchmark test. To do this, first create a representative set of model, drawing, text and programme files on the system being tested. The amount of each type of data should be in the ratio expected under typical operational conditions. Next, using different file names, it can be examined how many files fit into on-line storage. The results will show which system is most efficient.

(f) Data communication capacity

If the system requirements call for one or more communication links, the throughput penalty imposed by these links should be evaluated. The important thing to determine is the communication load's influence on the ability of the system to maintain its normal work-load. All throughput and response time tests should be run with transmitting and receiving data at their full rated capacity and also with the links turned off. This will establish the magnitude of the performance degradation that can be expected. While all systems display some degradation, those equipped with more sophisticated communications interfaces (and software) usually perform better.

(g) Reliability and maintenance performance

Reliability and maintenance performance can have a significant bearing on a system's long term productivity. Vendors usually build many features into their systems that are designed to increase reliability and reduce repair time. These features include such things as built-in diagnostics, parity checks, flip-out equipment racks, forced air cooling and reliable trouble-free software. However, these features themselves do not speak for the actual reliability performance of the system.

(h) Potential

Expansion potential. The potential of the system to accommodate growth in all areas is another important characteristic to evaluate. While evaluating, first review the vendor's currently available stock of application software and determine if any of it is appropriate for future applications. Review software available through users in the same way. Finally, evaluate the vendors' statement about future development in line with their record of new releases of software and capacity of the software development team to deliver it on the planned date. Evaluating the potential for expanding a system's throughput is more difficult. First, review the limit of the capacity to expand main memory, cache memory and on-line storage.

Potential for integration with other systems. Networking of a CAD/CAM system into a network of other CAD/CAM or general-purpose data processing computers has been shown to improve productivity and make it possible to integrate design, analysis and manufacturing in a synergetic way.

For easy access and evaluation, the relevant check-list should be considered. The criteria and considerations that should be used for each company are different and as such, the general check-list should be adapted to the specific needs of a particular company.

6.4 Evaluating vendor services

The services that can be expected by the users from a vendor are described below. From these services, each user can perhaps form ideas on the quality of services the vendors are offering especially in the selected areas.

(a) Staff training

These include operator and management training courses as well as management seminars on important issues. To evaluate these, buyers should examine the range of services offered, available facilities, materials, and equipment used. Courses should have a formal syllabus. Materials should include reference and tutorial texts with plenty of illustrated examples and exercises. Laboratories should have up-to-date equipment, and there should be enough of it so that no more than two or three students have to share a terminal. The instructors should be teaching professionals, knowledgeable in management and with experience in the customer's industry. The series of courses should then be studied, starting from basic courses intended for the beginner, up to courses for professionals with intermediate and expert skills.

(b) Applications assistance

These services consist of on-call assistance with everyday problems as well as on-site help with major problems or transitions to CAD/CAM. Examine the experiences of the staff. How long have they been with the vendor? How much and what kind of experience do they have with the vendor's CAD/CAM system? How much experience do they have in the buyer's industry? Can you trust them with your proprietary information? How easy will it be to get on-site help at your geographic location?

(c) Management assistance

These services consist of installation planning, transition planning, facilities management planning, operations audits, productivity audits etc. How well qualified are they to provide these services? Have they had any success in the buyer's type of industry? Do they understand the buyer's actual needs?

(d) Hardware maintenance

Hardware maintenance is provided either on a contract basis or as an on-call service. Maintenance contracts are basically agreements to provide sufficient parts and labour to keep a specific system operational over the life of the contract - usually one or two years. On-call service is typically an agreement to provide remedial services at the prevailing rates for parts and labour. To obtain the most from a system, the system down time must be reduced to an absolute minimum.

(e) Software maintenance

A large software system, such as that contained in a CAD/CAM system, may not be perfect and bugs may occasionally cause the system to malfunction in unpredictable ways. These malfunctions can range from "system crashes" in which the entire system will halt and have to be restarted, to situations where certain system commands will not execute the functions. Some of these malfunctions may not harmfully alter other parts of the software or the stored data. Sometimes, irretrievably large amounts of data and programmes may be lost.

Most vendors have an ongoing software development programme whose objectives are to enhance the functional capability of the software and fix as many of the known bugs as can be found. Typically, a new release of software is made several times a year and distributed to the users. These updates are compatible, functionally enhanced, and more reliable versions of the previous software.

To evaluate software maintenance, study the following: How often are new releases made? What are the vendor's policies with respect to compatibility of new releases? Must a new release be implemented to obtain further support? How difficult (and how disruptive) is it to implement a new software release?

How are bug reports handled? Will individual bug fixes be made available, or will it be necessary to wait for a new release? How long is it before a fix for a reported bug finds its way into a release? What are the vendor's obligations with respect to correcting reported bugs? What are the vendor's obligations with respect to the consequences of catastrophic damage to the data base by a software bug or a bad correction?

6.5 Step-by-step approach for CAD/CAM evaluation and selection

Development of the selection criteria involves determining the precise needs of the user company for a CAD/CAM system. However, this should not be done exclusively on basis of current functions within the company. The management should consider future needs as well as current needs. The use of a CAD/CAM system will present opportunities and new challenges in the user company, and these opportunities should be carefully analyzed.

It is important that the top technical management group conduct discussions with experts in the national specialized institutions, if any, and with the vendors, and that it visits several installations with configurations similar to the system under consideration. During the visits, the opinions and experiences of the personnel who manage and operate the system should be noted. In addition to the visits to user companies, a trip to the corporate headquarters of each vendor should be arranged. This will provide information regarding the plans and philosophies of the various CAD/CAM companies.

From all of these various sources, it should be possible to develop a comprehensive list of applicable criteria for the prospective user company. A representative check-list of considerations and criteria for selecting a CAD/CAM system is presented in figure 6.1. The criteria and considerations that should be used for each company are different, and any general check-list should be adapted to the specific needs of a particular company. The check-list should be useful to a prospective user company in developing its own criteria for evaluating alternative CAD/CAM systems.

Some of the more difficult issues to deal with in evaluating a CAD/CAM system should be noted. First, how will the user company evaluate the case or complexity of interfacing with the current information systems that are concerned with product data or product logistics data? These data include purchasing, material requirement planning, vendor tracking, quality, and scrap-and-rework accounting systems. Secondly, how will the user company accommodate system growth to encompass more users, more work stations, networking, new products, and new production technologies, without abandoning the short-term need to achieve early benefits? These issues are different for each business, and no general approach will be applicable. A prospective user company must incorporate these kinds of questions as subjective factors in their decision process.

For evaluation, the user company should enlist three or four most attractive vendors and their respective systems. The vendors should have systems with sufficient technical emphasis compatible with the user company business.

The benefit-cost ratio represents an attempt to deal with the selection process in an orderly quantitative manner. It is not an objective measure because its components are determined by the collective judgments of the

Figure 6.1 Checklist of considerations and criteria for selecting a CAD/CAM system

A. General considerations

1. Cost

- Hardware
  - CPU
  - Added Stations
  - Peripherals
- Software
  - Turnkey basic package
  - Added specialty packages
- Hardware maintenance
- Software maintenance
- Specials
- Spares
- Documentation
- Training
- Transportation
- Facilities
- Supplies
- Field support
- Support personnel

2. Service

- Contract
- Parts location
- Turnaround
- Warrantee and discontinuance clause
- Software bug service
- Software service

3. Quality

- User group existence
  - and support
  - Corporate quality
  - Responsiveness
  - Financial stability
  - Number of installations
  - Growth
- Reliability
- Simultaneous operation
- Crash recovery
- Power loss recovery
- Environmental sensitivity
- Human factors considerations
  - Hardware
  - Software
  - Response time
- Output device speed
- Interfaces
  - Communication
  - Plotters
- Product documentation
- Training

4. Delivery and logistics support

- Staging/in-plant benchmark
- Packing
- Installation aid
- Pre-delivery inspection
- Installation guide
- Receipt acceptance
- Supplies
- Revisions
- Billing
- Proprietary agreement
- On-site debugging

5. System management

- High-speed peripherals
- User diagnostics
- File management software
- Expense reports and logging

6. Programming

- High-level vendor language
- Standard language
- Assembly language
- Source availability
- Clear documentation
- User protection
- Diagnostic aids
- Data base access
- Clear interfaces

7. Miscellaneous

- Compability with existing equipment
- Graphic terminal control
  - Operator input methods
  - Prompting
- Plotting control

B. Application

1. Electrical design applications

- Logic diagrams
- Circuit diagrams
- Schematics
- Electrical wiring
  - Cables
  - Harnesses
  - From/To lists
- Integrated circuits
- Printed circuit boards
- Hybrid circuits
- Rules checking
- Bill of materials

Figure 6.1 Checklist of considerations and criteria for selecting a CAD/CAM system (cont'd)

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2. Electrical interfaces
    - Circuit analysis
    - Logic and timing
    - Field analysis
    - Router
    - Test vector generator
3. Electrical numerical control packages
    - Drill
    - Board router
    - Autoplacement/Insertion
    - Cable weaving
    - Wire wrap
4. Documentation
    - Handbooks
    - Perspective
    - Organization charts
    - Flow diagrams
    - PERT charts and scheduling
5. Interface
    - Photoplotter
    - Line plotters/scribe
    - Point plotters

C. Applications-Mechanical

1. Mechanical design
    - Logic diagrams
    - Process diagrams
    - Schematics
    - Architectural drawing
        - Plant layout
        - Structural steel design
        - Piping
        - From/To lists
        - Mapping
    - Sheet metal design
    - Two-dimensional mechanical design and drafting
        - Point functions
        - Line functions
        - Arc functions
        - Conic functions
        - Dimensioning
        - Line type
        - Text, arrows
        - Witness line suppression
        - Character height
        - Flage note
    - Three-dimensional mechanical design and drafting
        - Wire-frame or solid modeling
        - Hidden line removal capabilities
        - Surfaces and planes
        - Curves and curved sections
    - Tool design
    - Jig and fixture design
    - Nameplates
    - Dimensionless drawings
2. Mechanical interfaces
    - Stress analysis
    - Finite element modeling (FEM)
    - Modal analysis
    - Flow analysis
    - Mechanism analysts
    - Mass properties determination
    - Geometric properties
    - Spline analysis
3. Manufacturing planning packages
    - Computer-aided process planning capabilities
    - Metal forming NC programming
    - Nesting of sheet metal parts for efficient cutting
    - Machining NC programming
    - Automatic NC functions
    - Other NC functions
    - NC default values
    - NC interfaces

individual who evaluates the CAD/CAM systems. Despite this unavoidable imperfection, the ratio offers the virtue of being an organized, systematic and quantitive procedure for dealing with the selection problem.

The CAD/CAM benefit-cost ratio is determined by a step-by-step analysis method. The list of criterion and considerations will be used as a starting point. For a particular company, this list may vary depending on the company's specific needs. For example, a company which manufactures mechanical components will want to emphasize mechanical applications and minimize the importance of electrical applications in their list of CAD/CAM criterion. For each of the three major headings in the list, a weight is assigned that reflects the importance of that general factor to the user company. For example, the weights might be assigned as follows:

A.	General considerations	50
B.	Applications - electrical	15
C.	Applications - mechanical	35
		100%

Within each of the above categories, a total of 1,000 possible points are allocated among the various criterion within the category. For example, under "General considerations", the point allocation might be as follows:

(1)	Cost	200
(2)	Service	150
(3)	Quality	250
(4)	Delivery and logistics support	100
(5)	System management	50
(6)	Programming	150
(7)	Miscellaneous considerations	100
	Total possible points	1,000

Then, within each of these headings, points would be assigned to the various subdivisions in a similar manner. The process of allocating points to the various criterion is based on the judgment of the user company as to the relative importance of each particular criterion.

After this allocation process is completed, the rating of the candidates will be made for each individual criterion. Out of the possible number of points for a given criterion, each candidate's strength will be assessed on the basis of its merits in that category.

Upon completion of the scoring procedure, the scores for each candidate are summed within each of the three major headings. The sums are then multiplied by their weighing factors for that heading and added together to get the final total score for each candidate. For example, the scores for a hypothetical vendor A might be as shown in the following table.

CAD/CAM system evaluation by vendor A

Criteria	Score		Weight (percentage)	Weighted Score
(1) General considerations	650	by	50	325
(2) Applications - electrical	600	by	15	90
(3) Applications - mechanical	800	by	35	280
Total CAD/CAM system score				695

Each of the three or four candidates would have a total score which is considered to reflect the relative value of the system.

So far, the price of the system has not been taken into account. This is accomplished by calculating the benefit-cost ratio. The ratio is determined by dividing the total CAD/CAM system score by the associated price of that system. It is most convenient to express the price to the nearest $1,000 and to truncate the three trailing zeros. To illustrate, suppose that there are three candidates with scores and prices as shown in the table below.

Comparison of benefit-cost ratio of CAD/CAM systems of three vendors

Item	A	B	C
(1) Total system score	695	737	495
(2) Price of the system	$142,000	$156,000	$112,000
(3) Truncated price	142	156	112
(4) Benefit-cost ratio (1/3)	6.79	4.72	4.41

In this analysis, candidate A has the most favourable benefit-cost ratio. Although candidate B has a total system score which is greater, its higher cost leads to a lower relative value of benefit-cost ratio which is being used here as the final decision criterion.

After selecting the system with the highest ratio, the next step in the evaluation procedure is to invite the vendor to run a benchmark to analyze the performance of its system. Through this benchmark, a group of specific problems representative of user company applications will be tested. The problems in the benchmark should include an appropriate mix of design and manufacturing problems. The problems selected should represent the intended applications of the CAD/CAM system by the user company. The total number of problems in the benchmark depends on their complexity, with perhaps three or four problems being typical. The design problems should require the CAD/CAM system to accomplish the necessary engineering analysis and to prepare the appropriate design documentation (engineering drawings, bills of material etc.). The manufacturing problems should also force the system to accomplish the desired analysis or planning function and to produce the required documentation in hard-copy or soft-copy form (e.g, NC punched tape or programme stored in computer memory).

The purpose of the benchmark is to validate the vendor's claims for his system. The reason for benchmarking only the system with the highest benefit-cost ratio is that this procedure is usually very costly for both vendor and prospective user. In addition, lengthy delays can result from trying to evaluate more than one benchmark. The vendor should know that if he has been requested to do a benchmark, he is very close to a purchase order. If the benchmark is successful (as it should be), the system is selected. If not, the second-best system, in terms of benefit-cost ratio, is requested.

Another approach for an evaluation and selection exercise is also suggested by the CAD/CAM experts. Depending on the user company's need, each major criterion will be weighted according to its relative importance. A typical situation will be illustrated for CAD/CAM systems evaluation for a tool and die making company. The following subheadings cover some of the major issues that could be considered carefully when evaluating a CAD/CAM system:

Hardware - 25%

(a) CPU power
  - Number of MIPs, raw crunching power of CPU

(b) Number of work stations supportable
  - Usually applies to host or semi-host systems where a number of work stations are attached to a minicomputer or mainframe computer. This is directly related to the CPU power and usually varies from 4 to 20.

(c) Work-station features
  - Screen size and resolution
  - Dual or single screen
  - Ergonomics

(d) Dedicated processor
  - Mathematics co-processor
  - Graphics processor
  - Hard-wired dedicated processors

(e) Upgradability and expandability
  - The capability of the system to be upgraded in terms of memory size, storage capacity, number of I/O ports etc.

(f) Compatibility with other computers
  - Whether the computer architecture is open or closed
  - Whether industrial standards are followed

(g) Normal use of CPU power apart from CAD/CAM applications
  - There are times when the computer may be needed to do other things apart from CAD/CAM. Is this capability available?

(h) Networking
  - Networking with other computer systems through local area network (LAN) to share peripherals, to exchange data etc.

Software - 40%

(a) How well does it meet the company's requirements?
  - Usually one of the most important critera.
  - Also depends on whether the company is sure of what it wants.

(b) User-friendliness
  - Can the software package be learned easily?

(c) Command flexibility
  - Can users create their own commands?

(d) Are software packages fully integrated?
  - How is the data base of one software linked to another?
  - Do all the packages share the same data base?
  - Typical application will be linked from geometric modelling to NC and finite element analysis.

(e) Availability of third party and public domain software is usually available, can the software be supported on the system?

(f) Customization
  - No software package can meet the exact requirement of individual companies, can software be fully customized?

Support Service - 20%

(a) Training/training programmes
  - Period of training
  - Number of places provided
  - Training content
  - Tailored training available?
  - Trainer's qualification

(b) Application support
  - Provide solution to special problems
  - Work jointly with client in solution of problems

(c) Maintenance support: software and hardware
  - Maintenance schedule
  - Bug fixing
  - Number of maintenance engineers
  - Location of nearest office

Vendor's reputation - 15%

(a) Organization stability/future directions
  - Ability to withstand shake-outs
  - Financial strength
  - Technical competence
  - Future expansion programmes

(b) Proven installations (local and global)
  - Number of installations
  - User satisfaction
  - User group activities

(c) Local agent representation
  - Mainly sales representatives; are they technically competent?
  - Strength and reputation of local agent

Other considerations

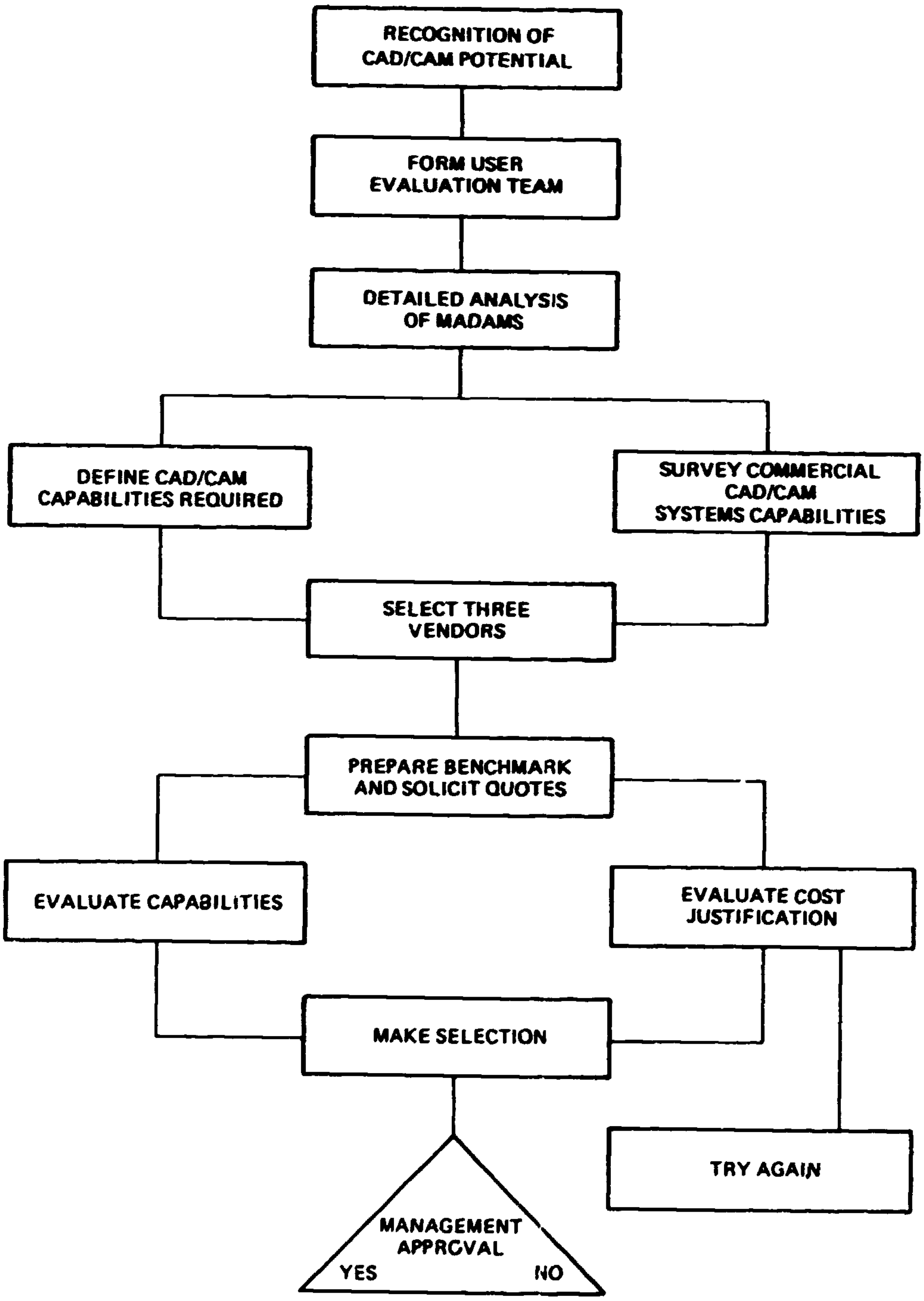
(a) Cost - including training, maintenance
(b) Delivery time-frame
(c) Warranty period provided

Each major consideration can be measured by putting points according to its weight. Relative positions can be assessed by putting all points in a matrix shown in figure 6.2. Schematic diagrams (figures 6.3 and 6.4) describe various stages involved in the CAD/CAM evaluation, selection and acquisition processes.

Figure 6.2 CAD/CAM system evaluation matrix

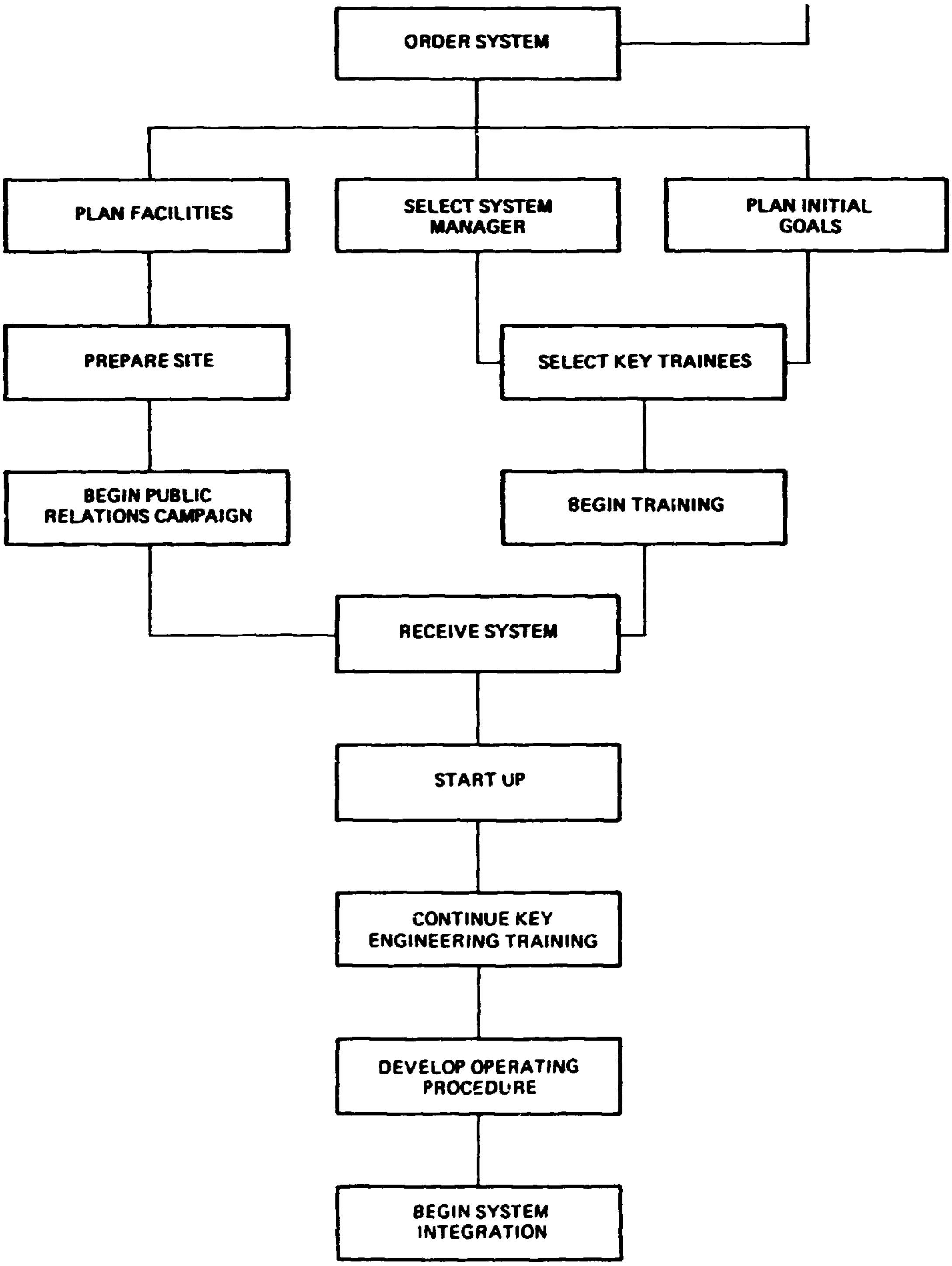
Supplier Specification	Vendor 1	Vendor 2	Vendor 3
1. <u>Hardware</u> Brand and model RAM Performance CRT display Hard disk Floppy disk Tape drive Tablet Network Warranty			
Price			
2. <u>Software</u> Host operating system Application software CAD CAM FEM Postprocessor Solid modeller Plastic analysis Mouldbase Surface shading Plotter driver Warranty			
Price			
3. <u>Annual maintenance</u> Hardware Software			
Total/year			
4. <u>Training</u> Hardware Fee Duration Software Fee Duration			

Figure 6.3 Phase I



Source: Computervision-EDB Training Unit

Figure 6.4 Phase II



Source Computervision-EDB Training Unit

7. COST INVESTMENT ANALYSIS OF SYSTEM INSTALLATION

The decision to buy a CAD/CAM system for the economic benefit of the organization will require many careful considerations and analysis. The difficult issues the management encounters in arriving at a decision whether or not to buy the system involve the correct forecasting of their ability to integrate the system within the organization, its possible impact and the external conditions influencing the business trends. The management would accept all opportunities emanating from the system's utilization up to a point where incremental benefits equal the incremental costs. Nevertheless, the decision will also be influenced by national and international economic trends and growth prospects. The proposal for CAD/CAM investment will be viewed with other current and future investment opportunities and commitment. So, the management must be convinced that CAD/CAM will have higher potentials in terms of investment on return. A thorough study of the problems and alternatives will reveal to the management the tangible and intangible benefits that will accrue from the investment. The analysis of the economic value of a CAD/CAM investment can be carried out in three ways:

(a) Analysis of the engineering activity to be carried out;
(b) Analysis of the benefits of the CAD/CAM system; and
(c) Financial analysis of the investment.

The engineering activity analysis will entail a comprehensive listing of activities and quantify CAD/CAM needs for those engineering activities. After that, year by year forecasting will be made on how the system helps in upgrading productivity resulting from the application of the system. While analyzing this, the functional capabilities of the system should essentially match the specific engineering activities such as design, analysis, drawing or programming. The net analysis results should be compared with traditional methods for the necessary comparison.

The financial analysis to calculate the actual economic gain should include calculation of: net investment; operating cash flow; economic life; and timing of investment and cash flow.

Investment analysis will include the consideration of effective life span of the system operation to achieve its planned objectives. For depreciation calculations, a CAD/CAM system is generally classified as three-year property if utilized in research and experimentation, and for other uses it can be considered as five-year property, although these considerations will largely depend on the situation in the individual country.

Prices from different vendors are more or less similar for turnkey CAD/CAM systems of comparable features and capabilities. The market prices are quite competitive and this prevents significant variations in system pricing. The price range of a personal-computer-based CAD/CAM system at current market prices is as follows:

	Price range (dollars)
(1) Hardware cost	
- Two personal computers AT, EGA, hard disk, mouse	10,000-15,000
- Plotter	6,000-10,000
- Digitizer	1,000- 2,000
- Tape back up	1,000- 2,000
(2) Software	
- CAD package	3,000- 4,000
- CAM package	12,000-16,000
- Finite element analysis	4,000- 5,000
- Data banks	5,000- 6,000

A typical work-station-based CAD/CAM system would vary depending on the components used to comprise the system. Consider a minimum and a maximum three-dimensional mechanical design system. A typical system set up with indicative prices would include the following:

	Price range (dollars)
Work-station (4 units)	60,000-90,000
Plotter	20,000-50,000
Application software	
- CAD package (3 licenses)	70,000-90,000
- CAM package (1 license)	40,000-50,000

A larger, more powerful system with four work stations might include the following:

	Price range (dollars)
CPU, storage, and console	90,000
Plotter	50,000
Design work stations	90,000
Applications software	50,000
	280,000

It should be noted that price bargaining between vendor and potential customer often revolves around the software.

The prices indicated above are approximate and were applicable at the time of this writing (June-July 1988). They are subject to change due to currency fluctuation, impact of new technologies, economies of scale in future manufacturing and other factors. For example, a drastic reduction in the price of hardware items can be expected if the future follows the trends of the past.

Since the early 1980s, a few suppliers started marketing CAD and CAD/CAM systems based on microprocessors and personal computers (PCs). The advantages of these systems for the small and medium size factory is that they can be customized to individual requirements and are user-friendly.

The earlier microprocessor-based system involved mostly CAD and CAD/CAM systems based on work stations networked with multiple coprocessors and large memories. IBM PC AT has been successfully run by a United-States-based company (Autodesk Inc) with its CAD and draughting software since 1982. At that time, most user companies were only operating CAD/CAM for two-dimensional detail draughting which was within a microprocessor capacity. Pathrace and Hurco, two United-Kingdom-based companies marketed a microcomputer-based dedicated CAD/CAM system machining process. Microcomputer-based CAM packages cover 2 1/2- and three-dimensional horizontal and vertical milling, 2- and 4-axis with C-axis turning, punching, nibbling and wire EDM (2- and 4-axis) and oxyfuel gas cutting. Operating features include automatically calculated feed speeds and depth of cut with the aid of user-definable menus and interactive cutter-path graphical simulation.

8. INSTALLATION OF THE CAD/CAM SYSTEM

8.1 The system environment

A controlled and monitored environment for the CAD/CAM system is necessary to ensure accurate and reliable operation of the system. CAD/CAM systems typically comprise three major modules, each requiring a different environment affected by the following factors: temperature range; humidity range; and temperature and humidity changes.

The first major module is the computer. The temperature and humidity are critical and should be controlled and monitored continuously. This area should also be a limited-personnel-access area to prevent rapid environment changes caused either by large groups of people or by exposure of the room to outside-controlled temperatures and humidity through doorways. Temperature should be kept in a constant range from 16°C to 22°C. Rapid variations in temperature, even within the range, must be avoided to prevent physical changes and stress to components, and expansion and contraction of recording media. Even though CAD/CAM computer systems are relatively small, they still require effective temperature and humidity control.

The second category of major system modules includes those components that are accuracy-dependent, such as photoplotters, drum plotters and digitizers. Photoplotters, especially when used for integrated-circuit and printed-circuit-board art work generation, require stringent temperature and humidity controls to prevent changes in film size and emulsion characteristics. Accuracy of large digitizers is affected by temperature and humidity because of the expansion and contraction qualities of the surface and the grid matrices used for digitizable points.

The last major module is the interactive work station, which consists of electronic components and a viewing device. Large temperature variations should be avoided. Since the operator is going to spend most of his time here, his comfort must be assured. A suitable office environment ranges from 20° to 22°C with from 40 to 60 per cent relative humidity.

In all the above major CAD/CAM modules, the main consideration is temperature variation. On any CAD/CAM equipment, the variation should not exceed 5°C per hour.

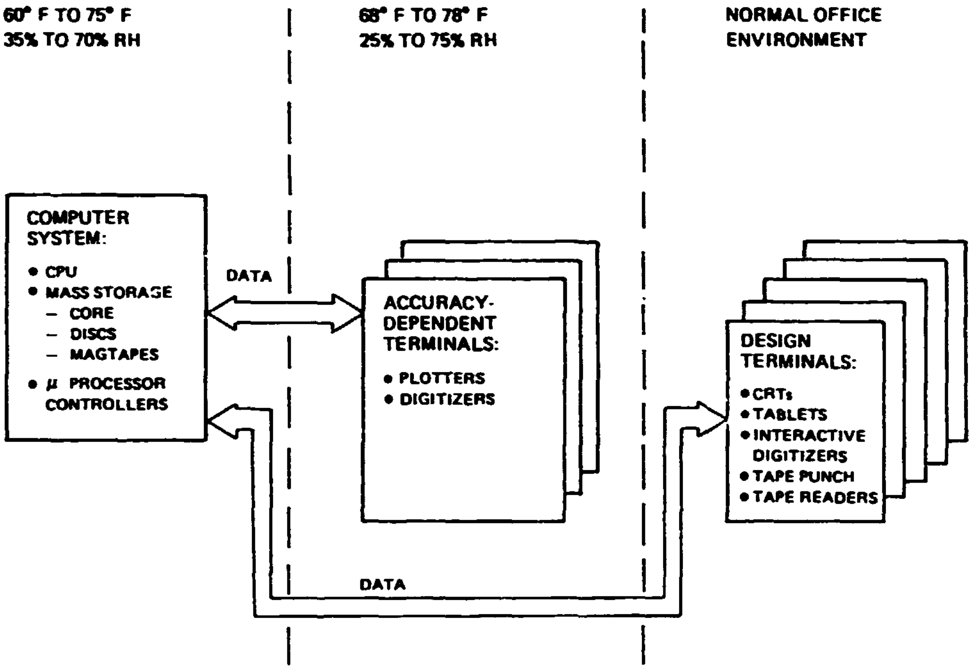
The recommended temperature and humidity range for each module is depicted in figure 8.1.

A good way to calculate the required amount of cooling for the modules in a given area is to use the following formula:

Sum of the watts of all modules x 3.4 = British thermal units/hour.

This is a gross formula which provides safety margins that include people lights and average gradient due to change in area environment.

Figure 8.1 Temperature/humidity



Source: CAD/CAM Handbook (Computervision Corporation)

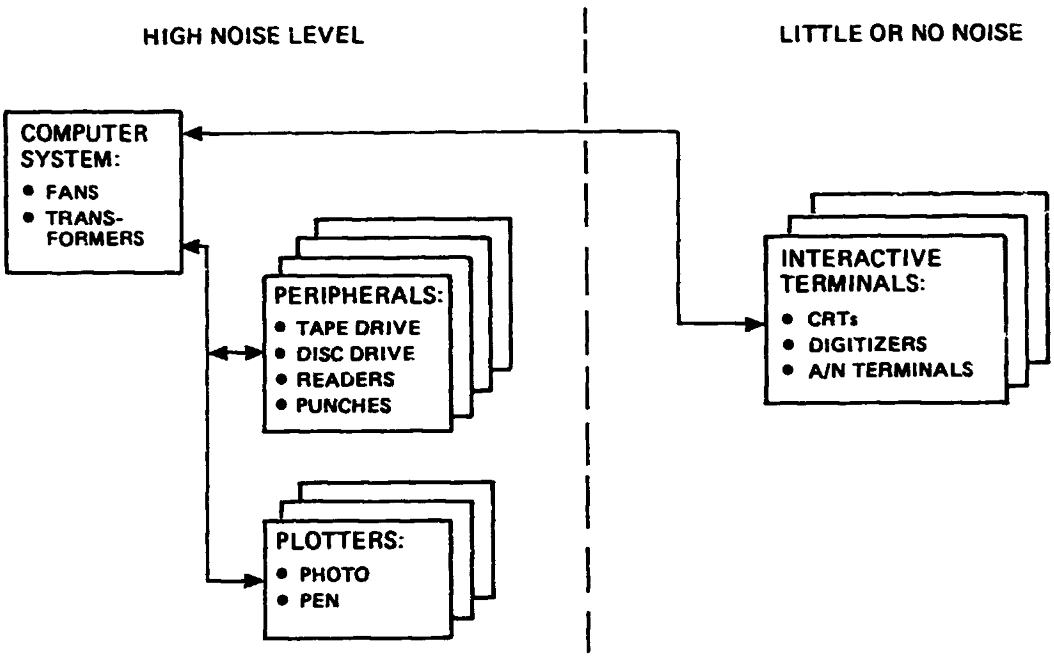
Air purity is another consideration in the CAD/CAM system environment. A good rule of thumb is that airborne particles in the form of dust or grease should not exceed that of a normal office environment. Paper dust is especially harmful. Therefore, any paper tape punches in the system should be located away from mechanical devices such as disk drives, magnetic tape drives and plotters.

The recommended environment conditions are summarized as follows:

(1) Air-conditioning temperature: 20°C with 5 per cent variation
(2) Relative humidity: 50 per cent with 5 per cent variation
(3) Air purity
  (a) Computer/disk: free of cigarette smoke and excessive dust
  (b) Terminals: comparable to normal office environment

Noise may also affect productivity. Excessive noise is distracting. The system is best fragmented into two major modules, as depicted in figure 8.2.

Figure 8.2 Noise level



Source: CV CAD/CAM Handbook

8.2 The system layout

The first major consideration is the location of the CAD/CAM system. Whether the system is centralized or the work stations are scattered in remote locations, they should be readily accessible to all users with a minimum of time and travel.

Most companies centralize their systems. The main advantages are as follows:

(a) Ease of maintenance;
(b) Better control over usage;
(c) Limited duplication of effort;
(d) Standardized rules and regulations on projects and data base management;
(e) Single budget and cost control;
(f) Reduced installation costs;
(g) Less operating personnel;
(h) More communication between operators;
(i) Faster and more effective formal training; and
(j) Better control over integration of multiple applications.

Before the actual placement of the CAD/CAM modules, the general physical attributes of the room must be discussed in terms of windows, lighting, storage and electrical requirements.

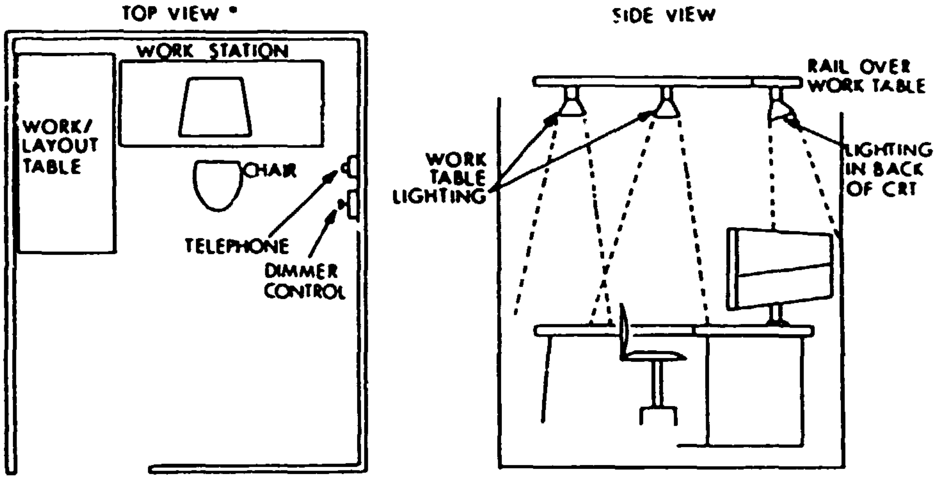
There are three criteria to consider in locating windows:

(a) Outside light;
(b) Work station environment; and
(c) Computer room environment.

Ideally, no outside light should be allowed into the work station area or the computer room area. It is distracting to the operators; it may cause reflections, either directly or indirectly, onto the screens; and above all, it could cause the temperature of the units and general environment to increase sufficiently to cause system damage.

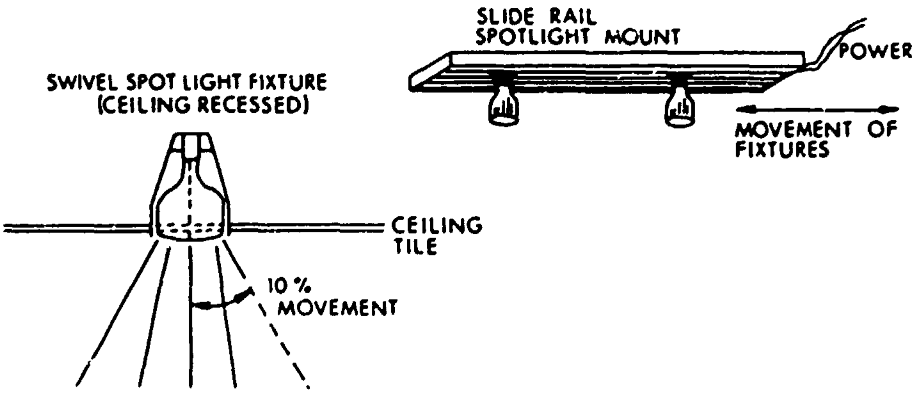
Room lighting in the work station area is critical. Storage tubes are inherently dimmer than raster scan tubes, so that sunlight shining on the tube face will tend to eliminate the image. In addition, the image of the operator may be reflected on the screen. Overhead lighting can cause glare. It is, therefore, important to illuminate the work station area in subdued light by using light intensity control. Recommended layout of lighting and controls for a work station is shown in figure 8.3.

Figure 8.3 Layout of lighting and controls



Of special importance is lighting placement. The work-table area must be well-lit with lights placed from the ceiling with off-centre movement of 10 degrees (figure 8.4).

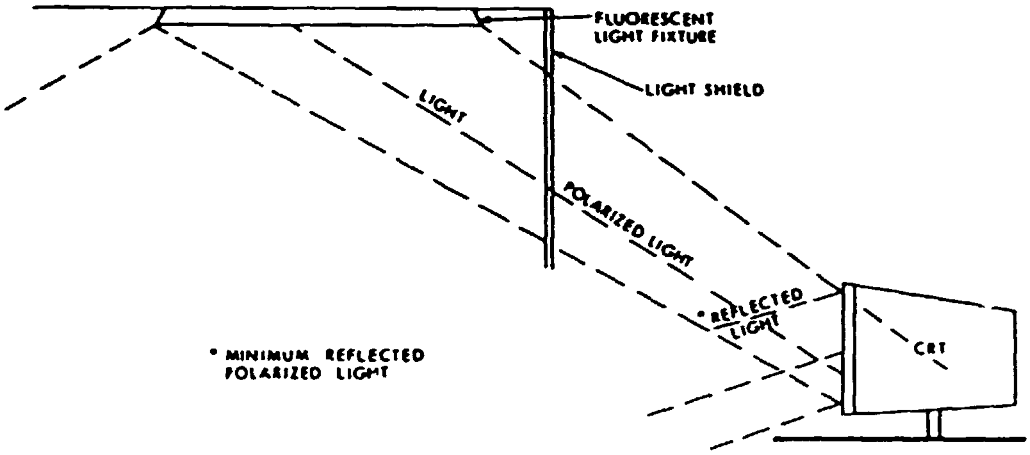
Figure 8.4 Lighting placement



The light should be directed at the back portion of the work station, preventing any direct light from reflecting on the CRT screen. Some general rules to be considered are summarized as follows:

(a) Work stations should be indirectly lighted;
(b) Work-tables should be directly lighted;
(c) Ceiling lights should not be directly reflected on the CRT screen;
(d) Fluorescent ceiling lights should be shielded with light-polarizing plastic (figure 8.5);
(e) Dimmer controls should be handy to operators.

Figure 8.5 Placement of fluorescent ceiling lights



8.3 System power requirement

Reliable system operation requires stable, noise-free power. Because of the various characteristics and power criteria of the system modules, power requirements are generally classified into three groups.

Class I: Voltage- and noise-sensitive modules

The computer system and plotters must provide sustained, error-free operation over long periods of time. Therefore, these modules require voltage regulation and noise suppression for optimum reliability. A class I power module provides both voltage regulation and noise suppression in a single package.

Class II: Noise-sensitive modules

Mass storage devices require noise protection and isolation, but not a high degree of regulation, to achieve optimum reliability. This stems from their intrinsic insensitivity to voltage variations due to the inertia of the spinning platters. Also, mass storage devices require extremely high starting currents which would make an adequately regulated source very costly. For noise suppression and line isolation, a commerically available class-II power transformer is recommended.

Class I and II modules must meet the following criteria:

(a) The power source must not be shared with large motors or other equipment that may produce voltage dips, surges, transients or spikes;

(b) The average voltage must remain within a 5 per cent tolerance;

(c) They must be free from voltage impulses. A line monitor placed on the source should not record an impulse of 1.5 x nominal voltage during normal operating hours;

(d) When the power source does not satisfy the regulations and noise requirements, or where brown-outs are anticipated, the power will need special conditioning. Power modules or line filters will provide the voltage stabilization and isolation required.

Class III: Normal electrical modules

This category is included to distinguish the interactive terminals clearly from the rest of the system.

8.4 System component arrangements

CAD/CAM system components and their arrangements are dependent on many variables which include centralized versus remote location; size of system versus floor space allocation; present versus future system usage; and any modifications and variations thereof.

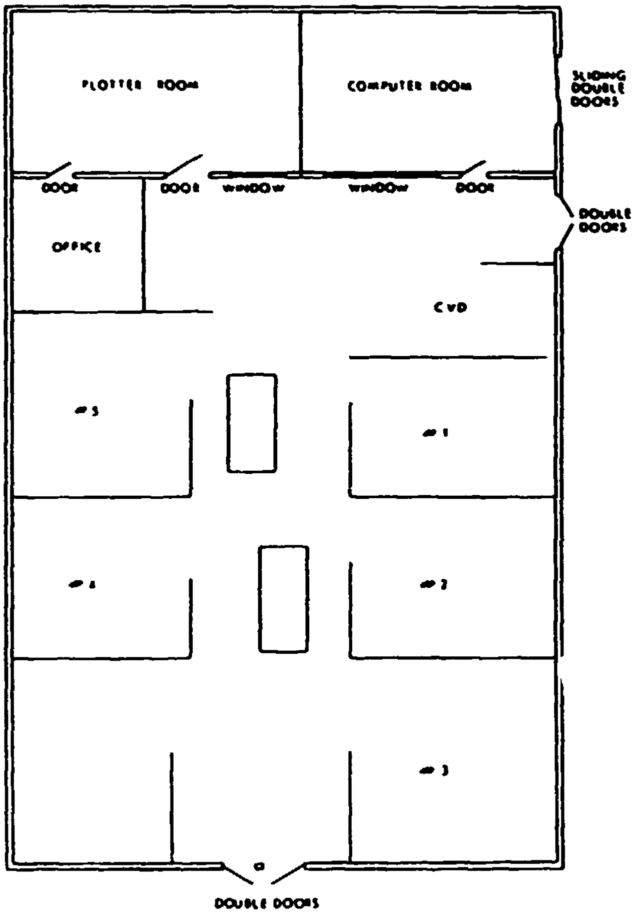
Initially, it is most feasible to cluster the work stations. This enhances operator learning and promotes discussion - thus learning. Assuming that the CAD/CAM system is initially centralized, optimal room layout elements are as follows (figure 8.6):

(1) Outside wall - from floor to ceiling
(2) Inside walls (work station cubicles) - 1.2 m x 1.6 m
(3) Work station cubicles floor area - 3 m x 3 m
(4) Work station floor - tiled
(5) Computer room floor - (a) tiled, (b) raised (optional)
(6) Lighting for computer room - standard ceiling fixture
(7) Lighting for work station - standard ceiling plus variable position and intensity control
(8) Windows - thermopane or heavy plate glass
(9) Personnel access - standard door
(10) Equipment access - double doors

Other elements in the layout include: telephone location; cleaning facilities; storage space; and physical and visual access to plotters and the computer room.

Lastly, the final layout should be approved by both the user and the system vendor.

Figure 8.6 Room layout



8.5 Planning the installation

A detailed schedule should be drawn up in the planning stage, and major highlights or milestones should be outlined chronologically and methodically. This can be accomplished by using a site preparation and facilities milestone schedule showing all the necessary operations in the order in which they will occur. The following is a summary of the key highlights for the milestone chart:

(a) Space and power requirements are finalized;
(b) Requirements of the proposed site are surveyed and finalized;
(c) The facilities are constructed;
(d) The completed facilities are inspected and accepted;
(e) The system is delivered;
(f) The system is unpacked and inventoried;
(g) The system is installed;
(h) Acceptance tests on the system are performed;
(i) Training and production commence.

There are generally three major phases given in terms of months prior to delivery and including the following steps:

Phase I (4-6 months before delivery)

(a) Select system site;
(b) Propose site layout;
(c) Determine power requirements;
(d) Define and locate physical constraints for structural components (beam, pillars etc);
(e) Prepare facilities drawings;
(f) Request and award construction bids;
(g) Start facilities construction.

Phase II (2-4 months before delivery)

(a) All major construction started or in progress. Installation of ceilings, walls, doors, windows and floor;
(b) All electrical systems rough-wired;
(c) Air-conditioning installed;
(d) All furniture, telephones, drapes and lighting fixtures ordered.

Phase III (Final month before delivery).

(a) Construction completed on all facilities;
(b) Power devices installed and checked out;
(c) Air-conditioning tested and initially balanced.

Although it is usually difficult to plan, the optimum situation is to have the system delivered on the very same day the facilities are ready. Proper planning and management of the plan will have definite effects on one-time installation costs.

9. MANAGEMENT APPROACH FOR IMPLEMENTATION OF A CAD/CAM SYSTEM

It is quite appropriate at the outset for the prospective user company to question whether it needs a CAD/CAM system. The question should be answered by analyzing current and projected work-loads in the company. The analysis might be based on the following general approach:

(a) Determine the size of the work-load in the various applicable functions of the company (design, manufacturing planning etc.);

(b) Estimate the amount of the work-load that is applicable to a CAD/CAM system;

(c) Identify priorities among the different areas;

(d) Use the prioritized list of work load areas established to develop the features of an appropriate CAD/CAM system for the company.

This general approach may lead to the conclusion that a CAD/CAM system is not appropriate for the company. Either the work load applicable to the CAD/CAM system is not sufficient to warrant the expense of the system, or the list of features includes a significant number of items which are not available on existing CAD/CAM systems. In the second case, the company may be faced with circumstances under which it would want to develop its own CAD/CAM capability or to extend the capability of an existing computer system.

Assuming that the company's conclusion is that a CAD/CAM system is needed, the following general procedure and guidelines are appropriate for implementing the system.

The management should decide how to feed in the CAD/CAM system in the existing organization. The departments, typically engineering, draughting, manufacturing and quality control, should extend their support in implementing procedural changes needed by CAD/CAM managers. This makes the management job extremely delicate, and high-level understanding would be needed to deal with the situation. Figure 9.1 depicts the typical CAD/CAM transition planning model.

Figure 9.1 CAD/CAM transition planning model

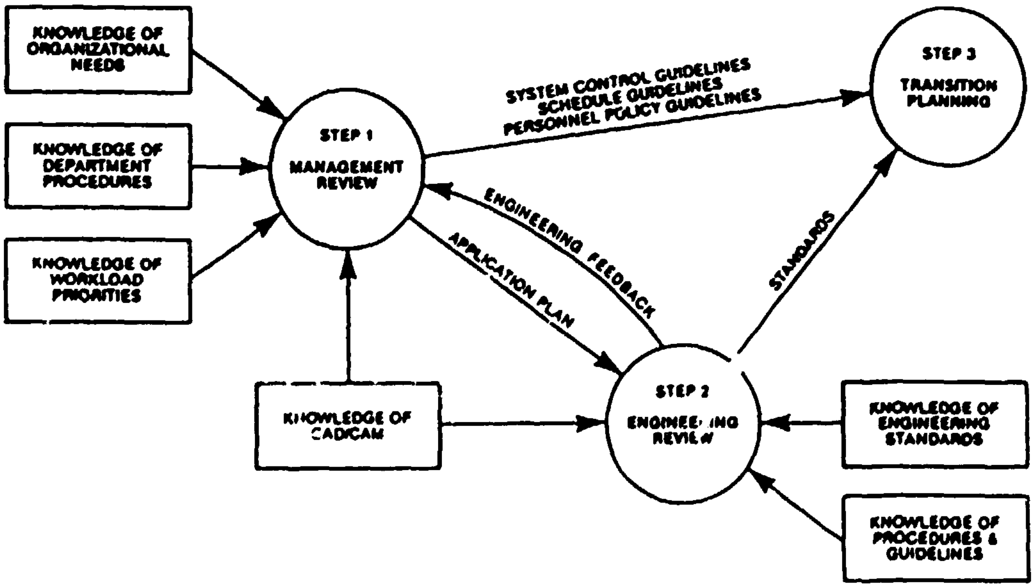
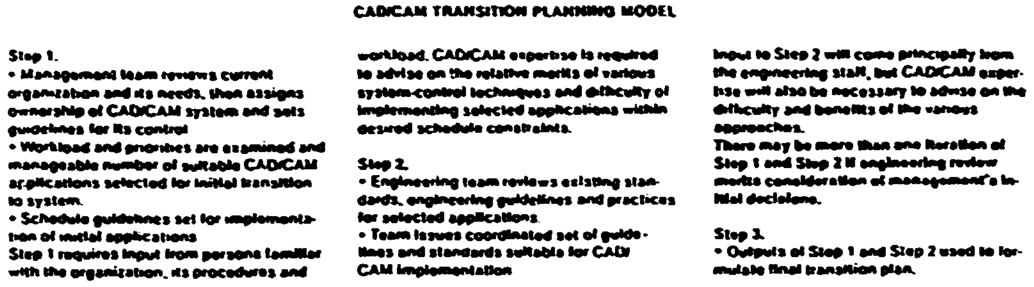


Figure 9.1 CAD/CAM transition planning model (cont'd)



CAD/CAM TRANSITION PLANNING MODEL

Step 1.

- Management team reviews current organization and its needs, then assigns ownership of CAD/CAM system and sets guidelines for its control
- Workload and priorities are examined and manageable number of suitable CAD/CAM applications selected for initial transition to system.
- Schedule guidelines set for implementation of initial applications

Step 1 requires input from persons familiar with the organization, its procedures and workload. CAD/CAM expertise is required to advise on the relative merits of various system-control techniques and difficulty of implementing selected applications within desired schedule constraints.

Step 2.

- Engineering team reviews existing standards, engineering guidelines and practices for selected applications.
- Team issues coordinated set of guidelines and standards suitable for CAD/CAM implementation

Input to Step 2 will come principally from the engineering staff, but CAD/CAM expertise will also be necessary to advise on the difficulty and benefits of the various approaches.

There may be more than one iteration of Step 1 and Step 2 if engineering review merits consideration of management's initial decisions.

Step 3.

- Outputs of Step 1 and Step 2 used to formulate final transition plan.

A number of major steps that the management should address are indicated below.

(1) Defining the role of CAD/CAM within the organization

The decision to set up a new department will depend on the existing organization and long-range objectives. However, staff attitudes, growth plans, and management control philosophy will also play a part in the course of action decided upon.

(2) Defining the system's objectives

Limit the type and amount of work that will initially be done on the system. Both applications and projects should be restricted to a manageable number. It is important quickly to establish the credibility of the system in terms of its usefulness and payback potential. Limit doing more than can be managed. Once the first applications are running, new ones will be easier to implement.

(3) Staffing and training

In general, existing staff should be trained. CAD/CAM is a tool with which productivity improvement is effected, and it is designed to be used by draughtsmen, engineers, and technicians - not computer operators. Expert operators can help speed up training and serve as peer models for existing staff. The best criteria in selecting staff for training are their engineering skills and their enthusiasm for CAD/CAM. As CAD/CAM is utilized, there will be a great demand for experienced people. There should be a plan to keep people on board. Finally, co-ordinate training classes according to the timetable for installation and acceptance so that freshly trained personnel will not become stale by the time the system is available for use.

(4) Programming

Understand how much programming will have to be done initially, and try to keep it to a minimum. Programming requires technical expertise and knowledgeable management supervision that will be acquired later. Set up controls over programming and function menu design - they become standards for symbols and procedures and should be well considered and documented. Controls will also save much duplication of effort.

(5) Payback accounting

Plan how you will demonstrate that the system was a justifiable investment. Plan a reporting system that will show not only the system's performance in terms of its initial justification but how it performs in other areas as well. Turn-around time, quality of work, cost per unit of design, cost per square foot of drawing, and cost per NC part programme are all items that should be tracked both before and after installation.

(6) Acceptance test planning

Some vendors have standard acceptance tests. Others negotiate an acceptance procedure with the buyer before purchasing. Be sure you understand the significance of each item in the acceptance test, and make sure that both the spirit and significance of the test are complied with.

(7) Operations planning

In addition to higher-level issues, it is important to establish a plan for the day-to-day operation of the system. The objective of such a plan is to protect the integrity of the system and the information in it, and, at the same time, to set the framework for an efficient, smooth-running operation.

(8) Access control

Since the operation involves complex systems with solid modelling and advanced capabilities, casual operators will not utilize the system efficiently. Identify the departments and individuals that will have access privileges and allocate specific resources to each (work station time, on-line storage space, plotter time). Nominate key operators for systems management work, and assign passwords and account numbers to all authorized users.

(9) Control time

It may be necessary to schedule work station access at formal weekly meetings according to the priority of the various projects in progress. Remember that the system is not always available and that people frequently underestimate the time they need. A good scheduling scheme will make provision for people who missed their scheduled terminal sessions because the system was down, and for people who find they need extra time.

(10) Control data

Protect data from accidental erasure by scheduling on-line storage back-up. Protect data from being lost by organizing a tape library and a physical storage system. Protect data from theft with password control, tape reel control and communications-line access security. Protect data from casualty losses such as fire, smoke and water damage and demagnetization.

(11) Maintenance control

Maintain log system performance including monthly totals of down time and cause of failure. Log software problems and their resolutions. Notify the vendor and track resolution. Track preventive maintenance. Review maintenance of the system with the vendor on a regular basis. The vendor should keep a close watch on system performance.

(12) Forward plan

Look at new applications for your system. Explore how it may be even more productive if integrated with other related systems. Regularly reassess the system and the available technology to see how it might be improved, but be prepared to wait a long time for custom software from the vendor.

10. IMPACT OF CAD/CAM APPLICATION ON THE ORGANIZATION

The use of computer systems in the engineering industry is widespread for both design and components manufacturing. A powerful stimulus has been created in the engineering industries by radically improving their productivity through the application of new information technology. Managers in developing countries have started thinking whether they should introduce CAD/CAM in their production set-up to cope with the competition. The foremost consideration they are to make is whether the CAD/CAM application will bring out spectacular achievements and better-quality work for the enterprises. The positive impact of the application of CAD/CAM on the enterprises is reflected in figure 10.1.

When the individual companies evaluate the benefits of CAD/CAM systems, the standard criteria include increased speed and accuracy of design, links between the product design process and its manufacture and the management planning information which comes from a computerized data base. Generally speaking, for the small and medium-size enterprises, the purchase of a system is not simply a move to increase productivity or expand the market share, it is a step necessary for survival in the market with high-value-added products.

After acquisition of the system, it is critical to see the transition from the previous situation to a CAD/CAM manufacturing environment. It is advisable to take appropriate measures for proper adoption of the system otherwise it will be difficult to rectify later on. There have been many reports of failures due to lack of adequate planning and management attention. Figure 10.2 shows how the specialists can help in the smooth implementation of CAD/CAM in a new environment. The CAD/CAM system affects the technology and human aspects of the organization, so that any mistakes will lead to the ultimate rejection of the system. CAD/CAM system analysis will explore three conditions which require the use of a CAD/CAM system. They all result from market factors and design applications, certainly not from the size of the company. They are:

(a) The increasing complexity of products;
(b) The requirement to bring products to the market quickly; and
(c) The need to increase productivity in order to increase profit.

The two functions, CAD and CAM, tend to blend into a single, multifaceted operation. The three conditions can be met by well-known CAD/CAM capabilities - speed, accuracy, ability to calculate and compare complicated relationships, integrated design and manufacturing processes, and the provision of usable and accessible information for management planning. For companies with small margins and the resultant inability to absorb losses or endure long periods of product development, CAD/CAM capabilities are essential.

It is advisable that the management should be well prepared to accept the CAD/CAM system with the support of the managerial staff. To cope with the situation, it has been observed that management tends to hire CAD/CAM specialists to advise them on how to smooth the transition. Still, many companies undertake the change-over operation successfully without the help of specialists. To understand how this can happen, it is necessary carefully to examine the activities that take place before, during and after the transition to CAD/CAM and the contribution they can make. Before installation of the system, it is necessary to establish necessary guidelines strictly to be followed by in-house trained staff. This planning involves actions like how the system will be controlled, who will have access, schedules for work station use, training of the staff, and the task for which the system will be utilized.

Figure 10.1 Positive impact of CAD/CAM application

ITEM	DESCRIPTION
IMPROVED PRODUCTIVITY	CAD/CAM systems have been responsible for dramatic productivity increases in many professional engineering activities. The most important of these are: -Drafting -Documentation -Design -Estimating -Order entry -Manufacturing
BETTER MANAGEMENT CONTROL	CAD/CAM systems have contributed to closer and better informed management and control of: -Engineering data -Engineering data distribution -Projects -Production scheduling -Estimating -Order entry
INTANGIBLE BENEFITS	Many important benefits of CAD/CAM are difficult or impossible to quantify, nevertheless, they contribute in a very real way to the success of the technology. The most prominent of these benefits are: -Standardization of graphics -Standardization of methods -Good-quality draftsmanship -Reduced vulnerability to error -Faster response -Professional development -Good staff morale

Figure 10.2 How specialists can help smooth the transition to CAD/CAM

SPECIALISTS	INSTALLATION PLANNING	SYSTEM START-UP	ADVANCED OPERATIONS
CAD/CAM, CAE MANAGEMENT SPECIALIST	Help with: Planning strategy Identification of critical issues Knowledge of CAD/CAM, CAE capabilities and performance Personnel selection	Help with: Test and acceptance Personnel performance audit	Help with: Integration strategy Networking strategy Applications inventory Future planning
EXPERIENCED CAD/CAM, CAE OPERATORS		Help with: Test and acceptance Training Peer role model Recognition of system malfunction Function menu implementation	Help with: Applications programming
CAD/CAM, CAE SOFTWARE INTERNALS PROGRAMMERS			Help with: System modification System enhancement System bug fixes

Source: Daratech Associates, Cambridge, Massachusetts.

The management purchases a CAD/CAM system to increase the productivity of an engineering or draughting department with the expectation of higher productivity. The managers involved in the management of the CAD/CAM system want to show their credibility, in other words, to establish the system's credibility and overcome the expensive image of CAD/CAM. After installation of the system, a considerable portion of the system's time will be consumed by the training and familiarization exercise for the operators. However, within a few weeks of time spent effectively, most of the work station time will be devoted to productive work. The trained operators, in turn, can train fellow operators. In many cases, the hired specialists may find difficulty in understanding the specific engineering tasks and company documentation standards. As such, they should become completely familiarized with these aspects before being assigned for any task. Engineering firms experience that it is easy to train the existing engineering staff on the system rather than hiring new staff. Once the system has been put to successful operation for a while, there is often need for developing some special capabilities or functions not available in the standard system. Often, this programming is required to implement specific development programmes of the enterprise. Sometimes, developing such skills at the small enterprise level is unrealistic. It requires a programming background and through knowledge of the complex software to meet the situation. Sometimes, it is advisable to seek assistance from experienced vendors or software specialists.

To ensure the effective operation of the CAD/CAM system, three types of specialists should be developed within the enterprise:

(a) Work-station operators with or without teaching skills;

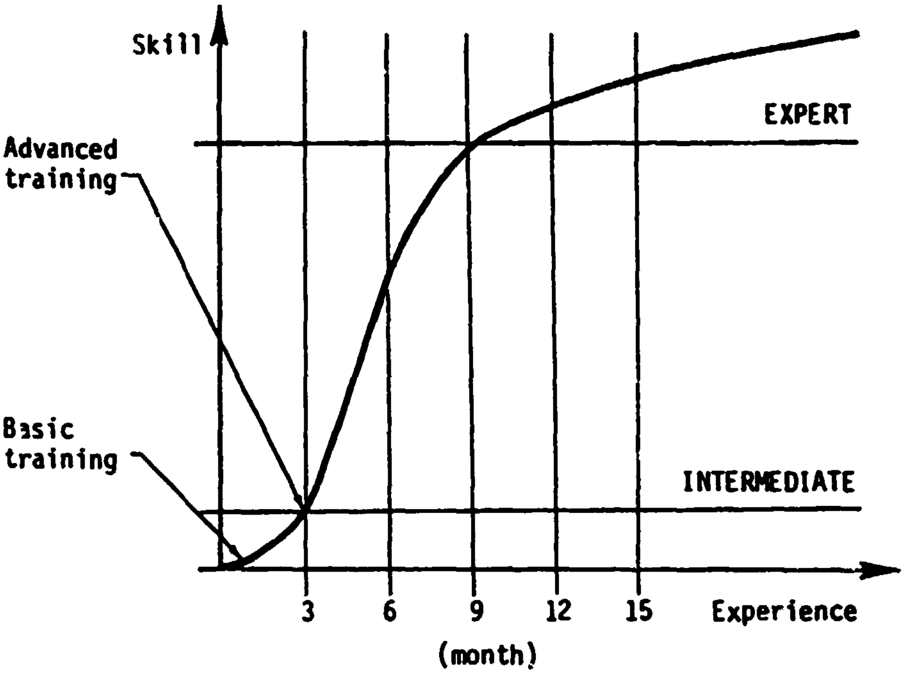
(b) Personnel possessing knowledge of the system's internal functioning and able to make modifications of software;

(c) Management staff with planning capability and the know-how to run the system most effectively and to select the proper course of action.

The managers usually receive the vendors' assistance in training the staff. They expect the staff to learn about the system and acquire the necessary skills to put the system into operation. They also expect an appreciation of CAD/CAM potential to develop and to demonstrate its benefits to the staff in order to stimulate their readiness in accepting the changes in work style and organization. The vendors often try to influence the staff psychologically to enhance their interest in starting up the system. The engineering staff and draughters look forward to CAD/CAM training since it brings a new challenge to their assignments. They are fascinated by the computer graphics and by learning new skills on computer technology. They are also excited by the possibility that drudgery will go out of their work.

Generally, the experience is that a majority of the staff can be trained to handle the systems within a time span of six months. The staff range includes engineers, draughters, tracers, artists, technicians and secretaries involved in the department. The graph in figure 10.3 shows that reasonably qualified persons can attain expertise after their involvement with the system for about nine months.

Figure 10.3 Typical CAD/CAM operator's learning curve



Source: Daratech Associates, Cambridge, Massachusetts.

The training programmes offered by the turnkey operators vary widely in both quality and quantity. Some offer courses at the buyers' premises and use newly purchased equipment while others conduct the programme regularly in standard courses on their own premises in well-equipped classrooms and laboratories. The courses should be conducted by full-time professional instructors. The class size is usually limited to 10 or less and the laboratories should have facilities for two or three students to share one terminal. Off-site training is sometimes preferable because the participants are not distracted, which can possibly happen at the user's plant. The programmes include classroom as well as hands-on practice in the laboratories, which are usually aided by audio-visual material and tutorial notes. The timing of the training can be important for the organization. It is advisable to schedule training before the system is installed. The training courses are generally conducted for different target groups such as for managers, programmers and operators. Courses targetted for operators generally take one to two weeks. Similarly, for the programmers, it takes one to two weeks. Management courses are conducted to meet individual needs but are usually offered prior to installation. Some sample courses are outlined below.

(a) Basic operator's course

An entry-level course designed to teach basic skills, such as turning the system on and off, operating the work station components, controlling the command structure, graphics creation and editing commands, use of on-line storage, use of magnetic tape and diskettes, elementary dimensioning, text insertion and function menu design.

(b) Advanced operator's course

An operator's course designed to teach operators with about three months' experience advanced commands and techniques, such as the use of data structures, data extraction for bill-of-material and other reports, generating NC manufacturing tapes, three-dimensional operations, solid modelling, parts properties extraction and creating models for finite element analysis.

(c) Applications programming course

A programmer's or advanced operator's course designed to teach how to design, code, debug, and install special-purpose programmes in a graphics design language, including language structure, statement format, vocabulary, operating system interface, entering, editing, compiling, installing, executing and debugging a programme and saving a programme on disk or tape.

(d) Management course

A manager's course designed to teach the elements that go into pre-installation planning and system management, for example work station layout, lighting, access scheduling, data management, security, personnel selection and training, hiring, wage scales, labour-management relations, career paths in CAD/CAM and establishing a high-productivity environment.

11. SOLID MODELLING AND CAD/CAM APPLICATIONS PROGRAMMES

11.1 Introduction

Geometry is central to the design and production of mechanical and other discrete objects. Craftsmen formerly carried geometry in their heads or relied on physical models. Drawings were adopted as the primary medium of geometric specification with the rise of mass manufacturing and job specialization as they are effective means for communicating geometry between humans.

The advent of computer technology led to a wave of "computerization" of draughting in the 1970s. Computer-aided draughting is now a household word. An ordinary draughting system, however, cannot automatically calculate the mass properties of defined objects, or produce perspective views with "hidden lines" automatically suppressed. Current systems are limited primarily by deficiencies in their internal representations. This is leading to a new generation of different and powerful systems - the so-called solid modelling systems.

The term solid modelling encompasses an emerging body of theory, techniques and systems focused on "informationally complete" representation of solids. Solid modelling has created a new dimension in CAD/CAM. While wire-frame and surface models define a part's edges or sections of its surface, a solid model completely defines its enclosure. A solid model ensures a physically realizable shape and may be unambiguously interpreted by CAD/CAM applications programmes.

11.2 A review of wire-frame and surface models

(a) Two-dimensional wire-frame model

The two-dimensional wire-frame model is similar to an undimensioned, unannotated drawing. The coordinates and entities can be interactively measured from a two-dimensional wire-frame model with excellent precision. A two-dimensional wire-frame model uses draughting primitives such as points, lines, circular arcs, ellipses and splines. Multiple views are constructed, and draughting techniques may be used to show parts of the wire-frame in different views. The two-dimensional wire-frame model has many of the same important limitations as a drawing, in particular the following:

(a) It is often ambiguous. Human interpretation is needed to construct a part from the model and the value of what is constructed is dependent on the interpretation of the person building the part, as well as other design information;

(b) It is difficult to read and analyze. Spatial relationships between parts in a complex assembly are hard to visualize. Auxiliary views and sections are often needed to clarify a drawing;

(c) It is likely to contain error. Because of ambiguity and interpretation problems, a two-dimensional wire-frame model cannot be easily checked by a human for errors and inconsistencies. For a computer programme, such checking is even more difficult, thus it is likely that many errors will go undetected.

(b) Three-dimensional wire-frame model

A three-dimensional wire-frame model uses three-dimensional extension of two-dimensional wire-frame primitives; three-dimensional points (x, y, z), straight lines between points, circular arcs and ellipses on a plane and spline curves fitted to a series of points. Three-dimensional wire-frame models are much easier to read and visualize than are two-dimensional wire-frame models.

Although they greatly extend the usefulness of CAD/CAM systems for mechanical design, three-dimensional wire-frame models are not sufficient for the following reasons:

(a) The faces spanning the wire-frames are not defined by the model, they are inferred. On a single wire-frame, enclosing faces can often be defined in different ways, causing ambiguity. This ambiguity is probably not a serious limitation for a human interpreter, but it makes automatic, consistent interpretation by a computer programme very difficult and subject to error;

(b) Curved surfaces are not fully represented. The type and position of a curved face must be inferred from its edges. It is difficult to discern where the surface of an object changes from pointing towards the viewer to away from the viewer, since this is associated with specific views and is not properly part of three-dimensional models;

(c) A designer builds a face by specifying its edges. Constructions or calculations are required to determine the edges where two faces intersect. With this approach, the user must define a part in terms that the model understands (that is coordinate geometry) rather than in terms that the user understands (that is, dimensions and features).

(c) Three-dimensional surface models

Three-dimensional surface models typically define bounded sections of continuous surfaces. Each bounded section represents a face on a part or a patch which is part of a larger face. The face or surface patch is bounded by three-dimensional lines and curves (three-dimensional wire-frame entities). The surfaces may be simple surfaces such as planes, cylinders and spheres. They may also be more complex representations of ruled surfaces, extrusions and rotations of spline curves, and sculptured surfaces.

Three-dimensional surface models are important in CAD/CAM for representing many shapes which cannot be adequately modelled with wire-frames. These shapes include surfaces of turbine blades, automobile bodies etc.

Surface models alone are not suitable as a general means of representing mechanical parts. One of the basic problems is that a surface model does not effectively handle irregular regions of a surface.

(d) Hybrid wire-frame - surface model

Many CAD/CAM systems have included three-dimensional wire-frame modelling combined with representations of faces which are on "regular" surfaces. The addition of these faces overcomes one of the limitations of the three-dimensional wire-frame model: the model can be unambiguous and complete, but is still not guaranteed to be so. Therefore, the hybrid approach has many of the same limitations of the three-dimensional wire-frame: it neither assures completeness nor does it prevent errors.

11.3 Solid model

A solid modelling system is an interactive computer graphics system for designing complete three-dimensional shapes of mechanical parts and assemblies. Features of a solid model include the following:

(a) It is a computer representation of a fully-enclosed three-dimensional shape;

(b) It is complete and unambiguous. Because it is complete, it is a single representation useful for all CAD/CAM tasks. Because it is unambiguous, it is suitable for the automation of many (if not all) CAD/CAM tasks;

(c) It assures that only physically realizable parts are modelled. A solid model cannot have a face missing, a dangling edge or an edge going inside the part;

(d) It provides a means of high-level, global shape definition. This can be done with Boolean operators, which combine two shapes to form a new shape. For example, two parts may be added (union) to form a model that has the features of both, or one part may be subtracted (difference) from another to make a hole or a depression of its shape.

11.4 Applications

The following summarizes some of the engineering tasks which can be performed with the solid model:

Engineering tasks	Specific mechanical applications
Design and layout	Assembly layout New part design Selection of standard parts Positioning in assemblies Tolerance specification Interface and clearance specifications
Analysis and testing	Interference checking Fit analysis Weight and balance of assemblies Part properties (volume and section) Structural analysis (section loading discrete elements, finite element analysis) Articulation of mechanisms Kinetics Tolerance accumulation Test data collection and analysis
Documentation	Drawing generation Technical illustrations Sales illustrations Bill-of-materials listings

Manufacturing engineering	Process planning Pictorial illustrations NC programme generation NC programme verification Inspection programmes and instructions Robot programming and verification Factory layout
Engineering tasks	Specific mechanical applications
Management	Review and release Engineering changes Project control and monitoring Selection of standard parts and assemblies Design standards

11.5 Creating solid models

A large variety of different ways to create and modify solid models are provided in commercial packages. The following three basic sets of modelling tools are used.

(a) Tools for initial shape creation. These tools create objects which are refined, combined and modified in subsequent modelling;

(b) High-level shape operators, which modify the overall shape of an object in single operations;

(c) Low-level shape operators, which modify detailed features of a shape.

(a) Initial shape creation

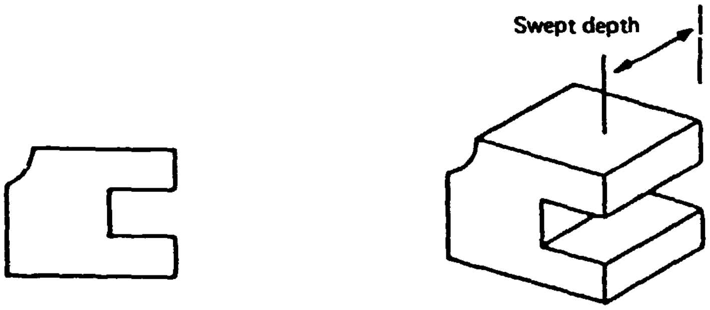
The typical modelling strategy to create a detailed and complex design model is to create a basic shape and then modify it by using both low-level and high-level operators to add and combine it with other shapes.

Four methods of initial shape creation are available, namely individual face construction, sweeping, lofting and generation of primitive objects.

Individual face construction. This involves the construction of a solid model shape by adding or modifying individual faces. Its advantage is that it is closely related to the three-dimensional wire-frame and surface modelling methods used in CAD/CAM systems.

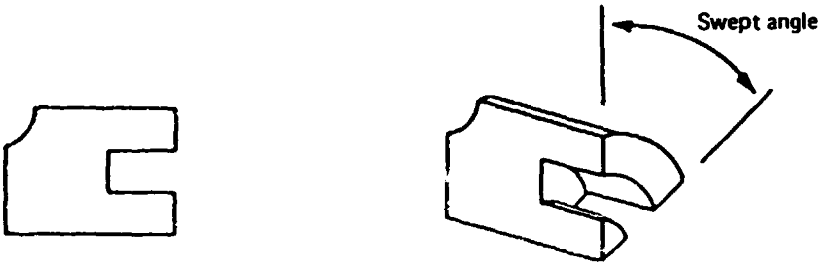
Sweeping. Sweeping transforms a two-dimensional shape into a prismatic or axisymmetric shape (figure 11.1). It requires the definition of a two-dimensional section and a curve, or an axis, for the projection of a section. The limitation of sweeping is that it is not sufficient for all objects or for the addition of further detail to the objects that result from it. Sweeping is, therefore, a valuable tool for solid modelling, but other tools are needed in conjunction with it.

Figure 11.1 Sweeping



A. Extrusion 2D shape

Extruded – Solid shape



B. Turning 2D shape

Lofting. Lofting consists of a series of two-dimensional section curves which are defined and positioned in the perpendicular dimension to create a sculptured surface. The lofted surface either passes exactly through all the points of the sections, or it is smoothed and approximates the sections. Either method may be needed in particular applications.

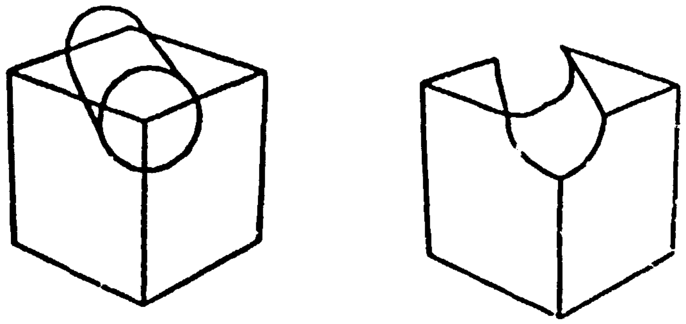
Generation of primitive objects. Primitives are "instant" or pre-programmed objects that can be called up on command. Primitives are characteristically simple parametric objects that are easily dimensionable, that is, their dimensions can be readily changed. They include block, cylinder, tube, cone, sphere, wedge and torus.

(b) High-level shape operators

High-level shape operators modify an object (or multiple objects) in a systematic way from a single operator command. They include Boolean and unary operators.

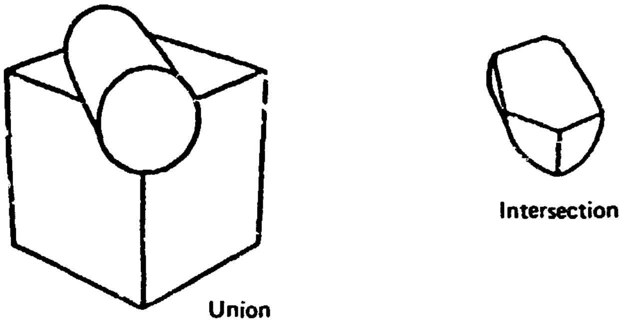
Boolean operators. Boolean operators combine the models of two objects and create a new model for the resultant object. They provide a powerful method of creating complex solid models. The basic operators are union, difference and intersection (figure 11.2). Interactively, Boolean operations make an effective method of creating and modifying complex solid models.

Figure 11.2 Boolean operators



Block and cylinder

Difference



Intersection

Union

Unary operators. Unary operators, which modify a single object, are as necessary as Boolean operators. Unary operators include transformation, copy, scale, mirror and distortion.

The Boolean and unary sequence for building an object model is shown in the following figure 11.3.

(c) Low-level shape operators

A feature is a physical part of an object, for example, a specific edge, a hole or a corner, which can be modified by low-level shape operators. Some of the low-level shape operators include filleting, chamfering, blending and tweaking. A tweaking operator can introduce a small draught angle to a face.

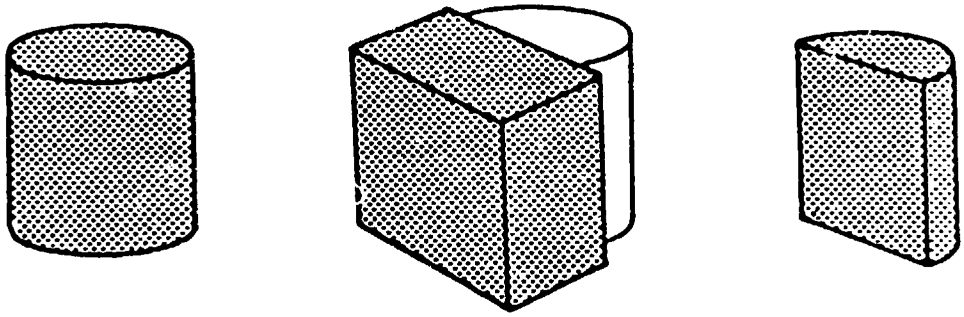
(d) Internal representation of a solid model

The three distinct methods of representing solid objects used in the present solid modelling systems are:

(a) Constructive solid geometry (CSG);
(b) Boundary representation (BR); and
(c) Spatial subdivision.

Constructive solid geometry (CSG). The CSG model is a recipe for the shape of the object, made with Boolean and other operations from primitive objects, or in some cases, from half-spaces, which are infinite spaces defined as one side of a plane, cylinder or other geometric surface. The CSG model can have a tree form or a list form. The tree consists of branches for each intermediate object leading up to the final part.

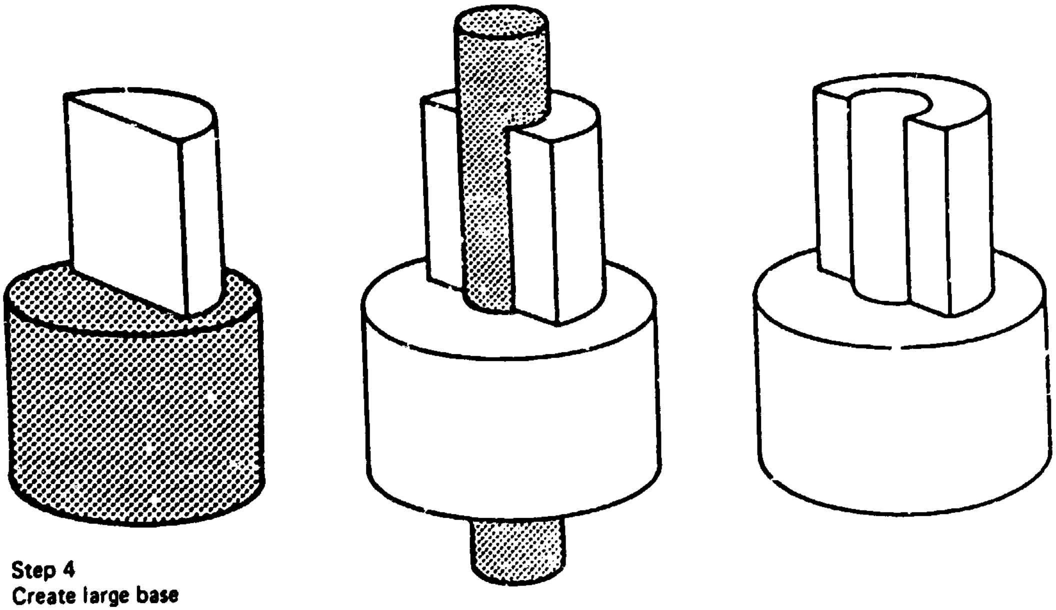
Figure 11.3 Boolean and unary sequence to build an object model



Step 1
Create small top
cylinder (primitive)

Step 2
Create block for
removal (primitive)

Step 3
Subtract block
from cylinder



Step 4
Create large base
cylinder (primitive)

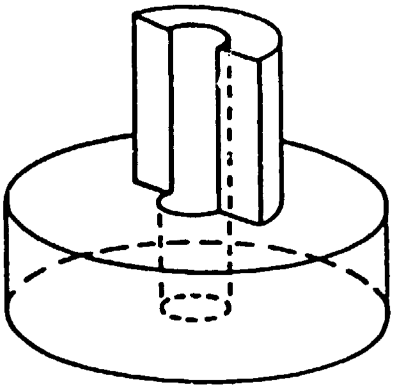
Step 5
Union: step 3 and
step 4 objects

Step 6
Create cylinder
for hole

Step 7
Subtract cylinder
for hole from
step 5 object

The CSG statement sequence to define the previous example part is shown in the following figure 11.4.

Figure 11.4 CSG statement sequence



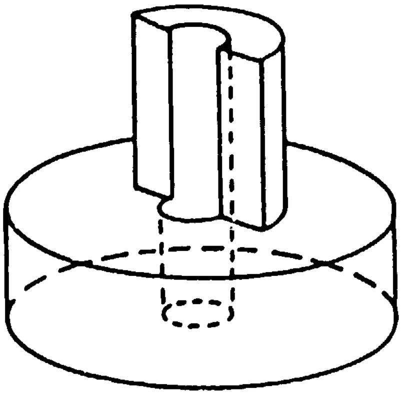
Model

1. CYL DIA = 2, LEN = 1, T = 0 (LGE BASE CYL)
2. CYL DIA = 1, LEN = 1, T = +1Z (SMALL UPPER CYL)
3. BLOCK LEN = 2, WID = 2, HT = 2, T = +1X, +1Z
   (Positioned to cover half of CYL2)
4. Difference 3 from 2
5. Union 4 and 1
6. CYL DIA = 0.5, LEN = 10, T = 0
7. Difference 6 from 5

The CSG sequence is also parametric, in that it can be evaluated for different values of primitive sizes and positions. The CSG model does not define a part in a way that can directly be used to create a projected image. A ray-casting evaluation procedure is used by some CSG modellers for image generation.

<u>Boundary representation (BR)</u>. This consists of a list of faces, edges and vertices on the final object and of the relations between these elements. The relations are typically pointers in the model, and are shown in the following figure 11.5 as arrows.

Figure 11.5 Boundary representation



Face list	Edge list	Vertex list
1. PLN (Bottom)	–	–
2. CYL (Large)	–	–
3. PLN (Mid) ◄	Circle Arc	–
4. PLN (Vertical)	–	► (0, 0.5, 1)
5. PLN (Vertical)	–	–
6. CYL (Small)	–	► (0, 0.5, 1)
7. PLAN (Top)	–	–
8. CYL (Hole) ◄	–	–

This method has certain advantages over the CSG model. To draw a wire-frame picture, the procedure involves reading each edge and adding it to a display list. This is a much faster way to generate a high-resolution image than evaluating a CSG model with a ray-casting procedure.

Spatial subdivision. Spatial subdivision divides object space into three-dimensional volume elements called "voxels". If this approach is used directly by subdividing object space into small elements, the amount of necessary storage quickly becomes unwieldy. A spatial subdivision system recognizes that the region of greatest interest in a model is at the surface; thus the system reduces the amount of storage used in the interior and exterior regions.

Comparison of internal representations. There has been much discussion among researchers and developers of solid modelling systems on the pros and cons of these three approaches. Some of the points made are summarized below:

(a) CSG models provide better capabilities for parametric modelling;

(b) CSG systems have a compact model and make efficient use of memory. However, when new models are made by copying and modifying old models, this advantage may disappear;

(c) BR models are faster and more efficient for many applications, including the interactive definition of new or modified solid models;

(d) Information associated with a face or an edge can be directly associated with a BR model. This is not so with a CSG model, since most bound faces are defined only when the model is evaluated.

12. GROUP TECHNOLOGY*

12.1 What is group technology

Group technology 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. 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 by arranging the production equipment into machine groups, or cells, to facilitate work flow. In product design, there are also advantages obtained by grouping parts into families. These advantages lie in the classification and coding of parts.

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 ususally closely correlated with the part's design attributes, this may not always be the case. Accordingly, classification and coding systems are often devised to allow for differences between a part's design and its manufacture. The reason for using a coding scheme is to facilitate retrieval for design and manufacturing purposes. In design, for example, a designer faced with the task of developing a new part can use the design-retrieval system to determine if a similar part is already in existence. A simple change in an existing part would be much less time-consuming than designing from scratch. In manufacturing, the coding scheme can be used in an automated process planning system.

Automated process planning is often referred to as computer-aided processing planning (CAPP) because the computer must be utilized. CAPP involves the automatic generation of a process plan (or route sheet) to manufacture the part. The process routing is developed by recognizing the specific attributes of the part in question and relating these attributes to the corresponding manufacturing operations. The use of an automated process planning system must be preceded by an appropriate parts classification and coding system.

Group technology, parts classification and coding and automated process planning are all interrelated. Group technology is the underlying manufacturing concept, but some form of parts classification and coding is almost a necessity in order to implement group technology and automated process planning.

12.2 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. Figure 12.1 shows 13 parts which may constitute a parts family in manufacturing, but their geometry characteristics do not permit them to be grouped as a design parts family.

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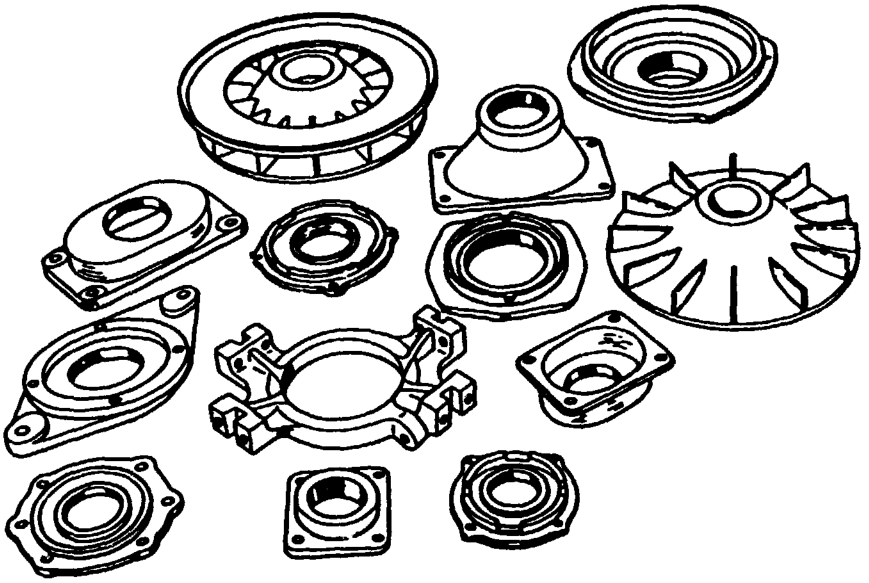
* This section was prepared by Professor A. Nee, Director of the CAD-CAM-CAE Centre, National University of Singapore.

Figure 12.1 Thirteen parts with similar manufacturing requirements but different design attributes



One of the big manufacturing advantages of grouping work-parts into families can be explained with reference to figures 12.2 and 12.3. Figure 12.2 shows a process-type layout for batch production in a machine shop.

Figure 12.2 Process-type layout

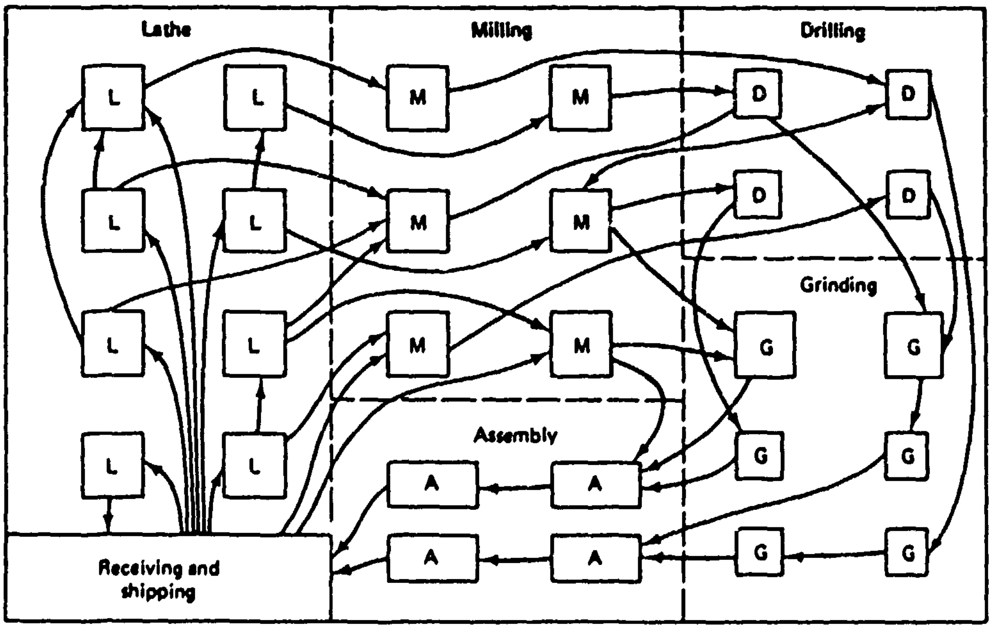
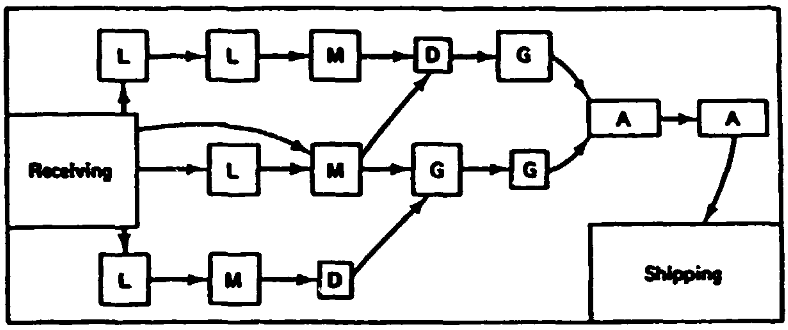


Figure 12.3 Group technology layout



The various machine tools are arranged by function. There is a lathe section, milling machine section, drill press section etc. 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 set-ups than necessary, long manufacturing lead times, and high cost. Figure 12.3 shows a production shop of 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 reduced workpiece handling, lower set-up times, less in-process inventory, and shorter lead times. Some of the manufacturing cells can be designed to form production flow lines, with conveyors used to transport work-parts between machines in the cell.

The greater 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:

(a) Visual inspection;
(b) Classification and coding by examination of design and
(c) Production data; and production flow analysis.

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.

The second method involves classifying the parts into families by examining the individual design and manufacturing attributes of each part. The classification results in a code number that uniquely identifies the part's attributes. This classification and coding may be carried out on the entire list of active parts of the firm, or some sort of sampling procedure may be used to establish the part families.

The third method, production flow analysis, makes use of the information contained on route sheets rather than part drawings. Work-parts with identical or similar routings are classified into part families.

12.3 Parts classification and coding

The most time-consuming and complicated of the three methods is parts classification and coding. Many systems have been developed throughout the world, but 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.

The major benefits of a well-designed classification and coding system for group technology have been summarized by I. Ham of the University of Pennsylvania as follows:

(a) It facilitates the formation of part families and machine cells;
(b) It permits quick retrieval of designs, drawings, and process plans;
(c) It reduces design duplication;
(d) It provides reliable workpiece statistics;
(e) It facilitates accurate estimation of machine tool requirements and logical machine loadings;
(f) It permits rationalization of tooling set-ups and reduces set-up time and production throughput time;
(g) It allows rationalization and improvement in tool design;
(h) It aids production planning and scheduling procedures;
(i) It improves cost estimation and facilitates cost accounting procedures;
(j) It provides for better machine tool utilization and better use of tools, fixtures and manpower;
(k) It facilitates NC part programming.

Although it would seem from the foregoing list that nearly all departments in a company can benefit from a good parts classification and coding system, the two main functional areas that use the system are design and manufacturing. As a result, parts classification systems fall into one of the following three categories:

(a) Systems based on part design attributes;
(b) Systems based on part manufacturing attributes;
(c) Systems based on both design and manufacturing attributes.

The types of design and manufacturing work-part attributes which are typically included in classification schemes are listed in table 12.4. It is clear that there is a certain amount of overlap between the design and manufacturing attributes of a part.

Figure 12.4 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
- Material type
- Part function
- Major dimensions
- Minor dimensions
- Tolerances
- Surface finish

Part manufacturing attributes

- Major process
- Minor operations
- Major dimension
- Length/diameter ratio
- Surface finish
- Machine tool
- Operation sequence
- Production time
- Batch size
- Annual production
- Fixtures needed
- Cutting tools

The parts coding scheme consists of a sequence of numerical digits devised to identify the part's design and manufacturing attributes. Coding schemes for parts classification can be of two basic structures:

(a) Hierarchical structure. In this code structure, the interpretation of each succeeding symbol depends on the value of the preceding symbols.

(b) Chain-type structure. In this type of code, the interpretation of each symbol in the sequence is fixed. It does not depend on the value of the preceding symbol.

Two classification systems will be discussed in the following subsections: the Opitz System and the MICLASS System. The Opitz Classification System was one of the earlier systems and is relatively simple to understand. The MICLASS System is more sophisticated but provides more features and options (such as a computer-automated process planning package).

(a) <u>The Opitz classification system</u>

This part classification and coding system was developed by H. Opitz of the University of Aachen, Federal Republic of Germany. It represents one of the pioneering efforts in the group technology area and is probably the best known of the classification and coding systems.

The Opitz coding system uses the following digit sequence:

12345 6789 ABCD

This system was designed specifically for machined components. The Opitz system is built in accordance with the decimal classification and the individual shape characteristics are arranged in the order of the machining operations. The first nine digits are intended to convey both design and manufacturing data. The general interpretation of the nine digits is indicated in figure 12.5. The first five digits, 12345, 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.

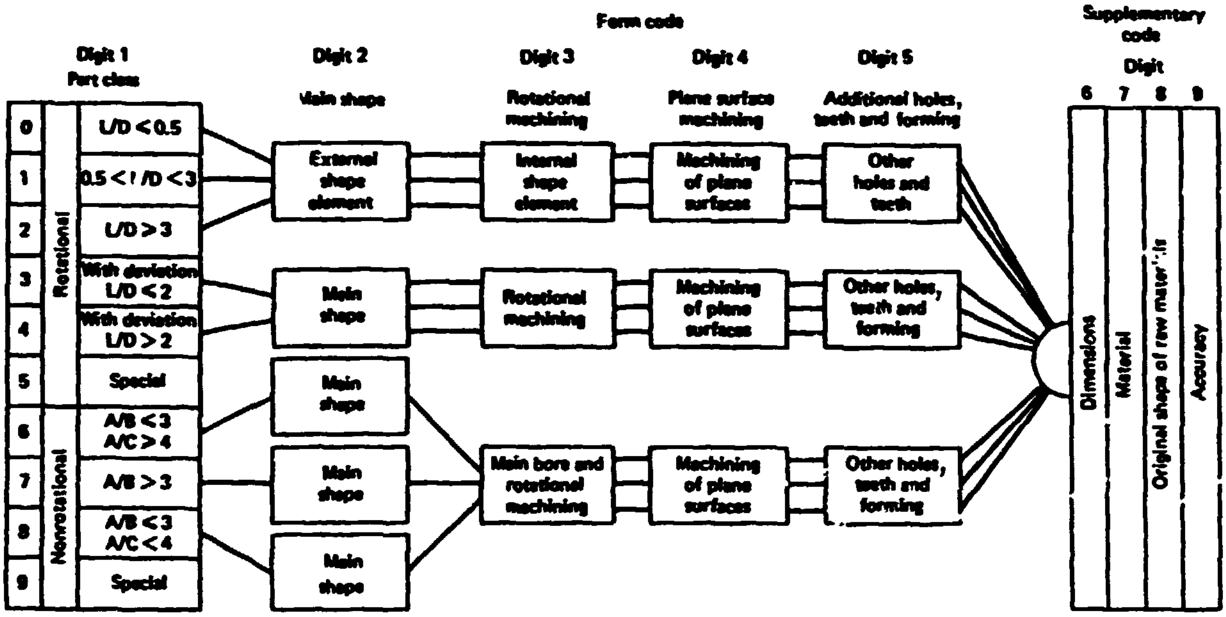


Figure 12.5 Basic structure of the Opitz system of parts classification and coding

The first digit defines the rough shape of the component and ensures a fundamental difference between rotational parts and non-rotational parts. In fact, digit numbers 0, 1 and 2 classify the rotational components into disc, short cylindrical and long cylindrical components respectively. Digit numbers 3 and 4 further classify the rotational products as having deviations from the truly rotational parts, that is, segments after rotational machining or hexagonal or cam-like components. The number 6, 7 and 8 denote the flat, long and cubic non-rotational components, while digit numbers 5 and 9 are reserved for special components peculiar to a particular industry or factory.

The second digit determines the external shape and the external shape elements. The third digit characterises the internal shape with its shape elements or the position of the principal bores. The fourth digit describes the machining of the flat surface. The fifth digit defines the subsidiary bores, the gear teeth and the form change work.

The digits are assigned from left to right, the part being classified in increasing detail with the higher value digits denoting that the part is more complex, that is, more difficult to produce. It has been pointed out that the sequence of code places is compatible with the sequence in which a part is designed and then produced. This facilitates the use of existing designs (or their slight modification) and ease of production planning.

A detailed breakdown of the form code is shown in figure 12.6.

Figure 12.6 Form code (digits 1 to 5) for rotational parts in the Opitz system, part classes 0, 1 and 2

	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<0·5		Smooth, no shape elements		No hole, no breakthrough	No surface machining		No auxiliary hole
1		0·5<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	No gear teeth	Axial, not on pitch circle diameter
2		L/D>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

(b) <u>The MICLASS system</u>

MICLASS stands for Metal Institute Classification System and was developed by TNO, the Netherlands Organization for Applied Scientific Research. The MICLASS system was developed to help automate and standardize a number of different design, manufacturing, and management functions, including:

(a) Standardization of engineering drawings;
(b) Retrieval of drawings according to classification number;
(c) Standardization of process routing;
(d) Automated process planning;
(e) Selection of parts for processing on particular groups of machine tools and
(f) Machine tool investment analysis.

The MICLASS classification number can range from 12 to 30 digits. The first 12 digits are a universal code that can be applied to any part. Up to 18 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 18 supplementary digits.

The work-part attributes coded in the first 12 digits of the MICLASS number are as follows:

1st digit	Main shape
2nd and 3rd digits	Shape element
4th digit	Position of shape elements
5th and 6 digits	Main dimensions
7th digit	Dimension ratio
8th digit	Auxiliary dimension
9th and 10th digits	Tolerance codes
11th and 12th digits	Material codes

One of the unique features of the MICLASS system is that parts can be coded using a computer interactively. To classify a given part design, the user responds to a series of questions asked by the computer. The number of questions depends on the complexity of the part. For a simple part, as few as seven questions are needed to classify the part. For an average part, the number of questions ranges between 10 and 20. On the basis of the responses to its questons, the computer assigns a code number to the part. An example of the application of the system is shown in figure 12.7 and the determination of the code number is shown in Figure 12.8.

12.4 Benefits of group technology

(a) Product design benefits

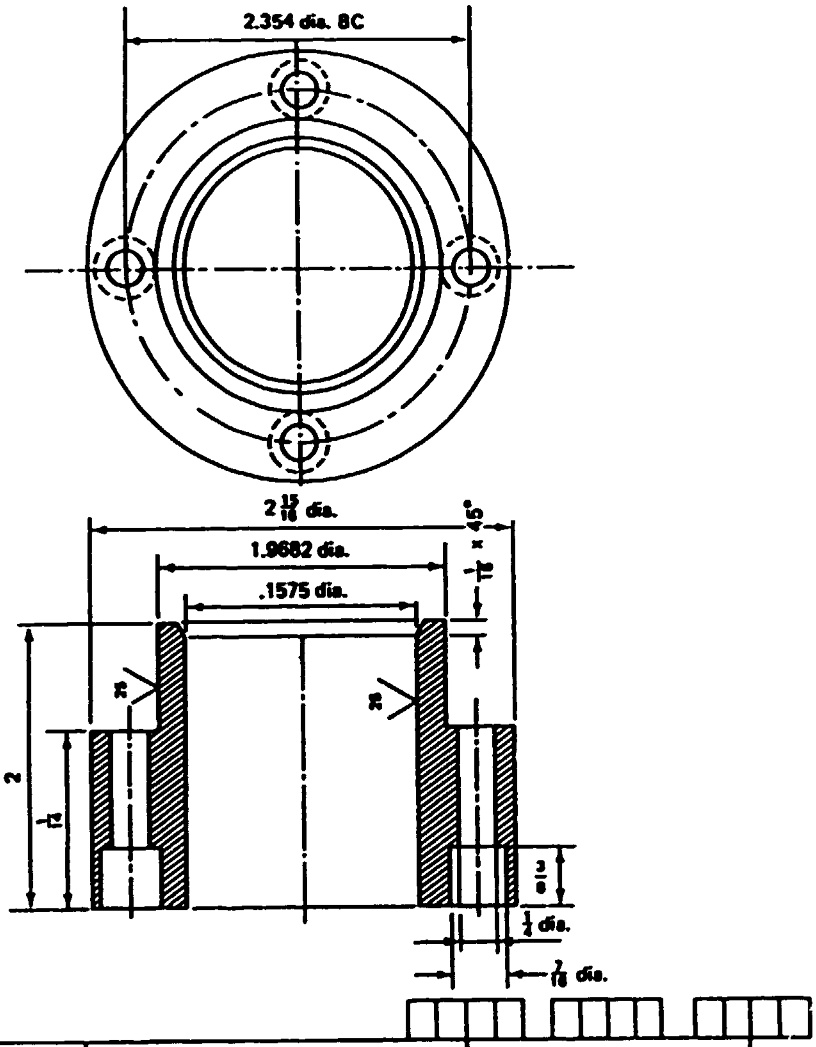
In the area of product design, the principal benefit derives from the use of a parts classification and coding system. When a new part design is required, the engineer or draughtsman can devote a few minutes to codify the required part. Then the existing part designs that match the code can be retrieved to see if one of them will serve the function desired. The few minutes spent searching the design file with the aid of the coding system may save several hours of the designer's time. If the exact part design cannot be found, perhaps a small alteration of the existing design will satisfy the function.

Another advantage of group technology is that it promotes design standardization. Design features such as inside corner radii, chamfers, and tolerances are more likely to be standardized with group technology.

(b) Tooling and set-ups

Group technology also tends to promote standardization of several areas of manufacturing. Two of these are tooling and set-ups. In tooling, an effort is made to design group jigs and fixtures that will accommodate every member of a parts family. Work holding devices are designed to use special adapters which convert the general fixture into one that can accept each part family member.

Figure 12.7 Workpart example



DRAWING	TOLERANCES	MATERIAL
TITLE		CC15
BUSHING	Fractional ± 1/64	
DRAWING NO:	Decimal ± 0.003	125 √ (25 √) ALL OVER EXCEPT AS NOTED
7		

Figure 12.8 Computerized MICLASS system determination of code for workpart of figure 12.7

```
  VERSION -A-

  3 MAIN DIMENSIONS (WHEN ROT. PART D.L AND 0)  2.9375 2 0
    DEVIATION OF ROTATIONAL FORM?   NO
    CONCENTRIC SPIRAL GROOVES?      NO

  TURNING ON OUTERCONTOUR (EXCEPT ENDFACES)?   YES
    SPECIAL GROOVES OR CONE(S) IN OUTERCONTOUR?  NO
    ALL MACH. DIAM. AND FACES VISIBLE FROM ONE END (EXC. ENDFACE + GROOVES)

  TYPING ERROR, ANSWER AGAIN?  YES

  INTERNAL TURNING?  YES
    INTERNAL SPECIAL GROOVES OR CONE(S)?   NO
    ALL INT. DIAM. + FACES VISIBLE FROM 1 END (EXC. GROOVES)?   YES

  ALL DIAM. + FACES (EXC. ENDFACE) VISIBLE FROM ONE SIDE?    YES

2 ECC. HOLING AND/OR FACING AND/OR SLOTTING?  YES
    IN INNERFORM AND/OR FACES (INC. ENDFACES)?  YES
    IN OUTERFORM?   NO

  ONLY KEYWAYING ETC.?  NO

  MACHINED ONLY ONE SENSE?   YES
    ONLY HOLES ON A BOLTCIRCLE AT LEAST 3 HOLES?   YES

  FORM-OR THREADING TOLERANCE?   NO

  DIAM. ROUGHNESS LESS THAN 33 RU (MICRO-INCHES)?   YES
    SMALLEST POSITIONING TOL. FIELD?.  .018
    SMALLEST LENGTH TOL. FIELD?   .0313

3 MATERIAL NAME?  CC15

  CLASS. NR. =  1271  3231  3144
  ******************************

  DRAWING NUMBER MAX 10 CHAR?   7
4
  NOMENCLATURE  MAX 15 CHAR?    BUSHING

  CONTINUE (1), STOP (2), SECOND PART AGAIN (3)?  2

  PROGRAM STOP AT 4690

  USED ________ UNITS
```

The machine tools in a group technology cell do not require drastic change-overs in set-up because of the similarity in the work-parts processed on them. Hence, set-up time is saved, and it becomes more feasible to try to process parts in such an order as to achieve a bare minimum of set-up change-overs.

(c) Materials handling

Another advantage in manufacturing is a reduction in the work-part move and waiting time. The group technology machine layouts lend themselves to the efficient flow of materials through the shop.

(d) Production and inventory control

Several benefits accrue to a company's production and inventory control function as a consequence of group technology. Production scheduling is simplified with group technology. In effect, grouping of machines into cells reduces the number of production centres that must be scheduled. Grouping of parts into families reduces the complexity and size of the parts scheduling problem. And for those work-parts that cannot be processed through any of the machine cells, more attention can be devoted to the control of these parts.

Because of reduced set-ups and more efficient materials handling within machine cells, manufacturing lead times and work in process are reduced. Estimates are that throughput time may be reduced by as much as 60 per cent and in-process inventory by 50 per cent.

(e) Process planning

Proper parts classification and coding can lead to an automated process planning system. Even without an automated process planning system, reduction in the time and cost of process planning can still be accomplished. This is done through standardization. New part designs are identified by their code as belonging to a certain parts family, for which the general process routing is already known.

(f) Employee satisfaction

The machine cell often allows parts to be processed from raw material to finished state by a small group of workers. The workers are able to visualize their contributions to the firm more clearly. This tends to cultivate an improved worker attitude and a higher level of job satisfaction.

Another employee-related benefit of group technology is that more attention tends to be given to product quality. Work-part quality is more easily traced to a particular machine cell in group technology. Consequently, workers are more responsible for the quality of work they accomplish. Traceability of part defects is sometimes very difficult in a conventional process-type layout, and quality control suffers as a result.

13. COMPUTER-AIDED PROCESS PLANNING*

13.1 Introduction

Manufacturing systems are constantly under great pressure to become more productive, flexible and reliable. Such systems must be able to cope with the consumer's variable requirements and be responsive to the rapidly changing technology. Factories are looking towards computer-integrated manufacturing systems where the entire manufacturing process from the product engineer's detailed drawings to the shop assembly and inspection can be placed under computer management and control.

In integrated manufacturing systems, computer control covers the following five main areas: management control; computer-aided design; automatic process planning; production scheduling control; and automatic manufacturing.

Traditionally, process planning has been regarded as a manual operation, usually carried out by qualified and experienced process planners or machinists. The creation of a good and optimum process plan is largely dependent on the individual skill of a planner and his aptitude for the planning task, his knowledge of manufacturing processes, equipment, materials and methods which are available in his production environment in particular. One of the problems often encountered with manual process planning is the difficulty in maintaining consistency of process plans created by different process planners, and to a certain extent, by the same individual. The reason for the inconsistency may be attributed to the complexity of process planning which requires the use of many disciplines including sequencing, machine selection, time-and-motion study, programming and material flow etc.

13.2 Definition and functions of process planning

Process planning can be defined as the process of determining the methods and the sequence of machining a workpiece to produce a finished part or component to design specifications.

Another definition is as follows: given the engineering design of an item which has to be manufactured, process planning is the act of generating an ordered sequence of the manufacturing operations necessary to produce that part within the available manufacturing facility.

Process planning, whether automatic or manual can be divided into a number of phases, in particular the following:

(a) Selection of processes and tools;
(b) Selection of machine tools;
(c) Sequencing the operations;
(d) Grouping of operations;
(e) Selection of workpiece holding devices and datum surfaces;
(f) Selection of inspection instruments;
(g) Determination of production tolerances;
(h) Determination of proper cutting conditions (depth of cut, feed, speed) to machine the workpiece to specified dimensions;
(i) Determination of cutting times and non-machining times for each operation, and eventually the corresponding costs;
(j) Editing of process sheets comprising all the previous information.

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* This section was prepared by Professor A. Nee, Director of the CAD-CAM-CAE Centre, National University of Singapore.

The flow chart of the successive phases of process planning is depicted in figure 13.1.

The final process plan is frequently called an operation sheet, route sheet or operation planning summary. The detailed plar usually contains the route, processes, process parameters and selection of machines and tools. The process plan provides the instructions for the production of the part. These instructions dictate the cost, quality, ad rate of production. A typical process plan is shown in figure 13.2.

13.3 Automated process planning

One of the earliest CAPP systems was developed under contract to Computer Aided Manufacturing International-Inc (CAM-I). CAM-I is a non-profit making organization, established in the United States in the early 1970s by a number of major United States manufacturing companies to provide leadership in the development of computer aids to manufacturing industry.

CAPP is based on the use of a classification and coding system to group parts into part families. The technique involved is group technology. Each part family has a common (or nearly common) process plan that is stored in the computer as a standard plan for the part family. Each standard plan is a sequential set of instructions that includes general processing requirements, jig and fixture data, machine data and detailed operating instructions. When a new component is planned, a process plan for a similar component is retrieved and subsequently modified by a process planner to satisfy special requirements. The typical organization of such a system is depicted in figure 13.3.

There are three modes of approach to the automation of process planning, namely the variant approach, the generative approach and a hybrid of the variant and generative approaches

The variant approach can be defined as the preparation of the process plan through the manipulation of a standard plan or of the plan of a similar part. Note that the CAPP system described earlier belongs to the variant approach.

The generative approach is the logical creation of a process plan from information available in a manufacturing data base with little or no intervention by a planner. Such a system must obviously be capable of applying a set of rules and a mass of data to the construction of a process plan in the same way as a human planner reasons when he constructs a plan.

The development of a generative process planning system requires the use of computer systems termed artificial intelligence, or more specifically, current research is based on a subset of artificial intelligence systems called expert knowledge systems or expert systems. Since the terms artificial intelligence and expert systems have been introduced, it is not inappropriate to briefly define the meaning of each.

Figure 13.1 Flow diagram of process planning

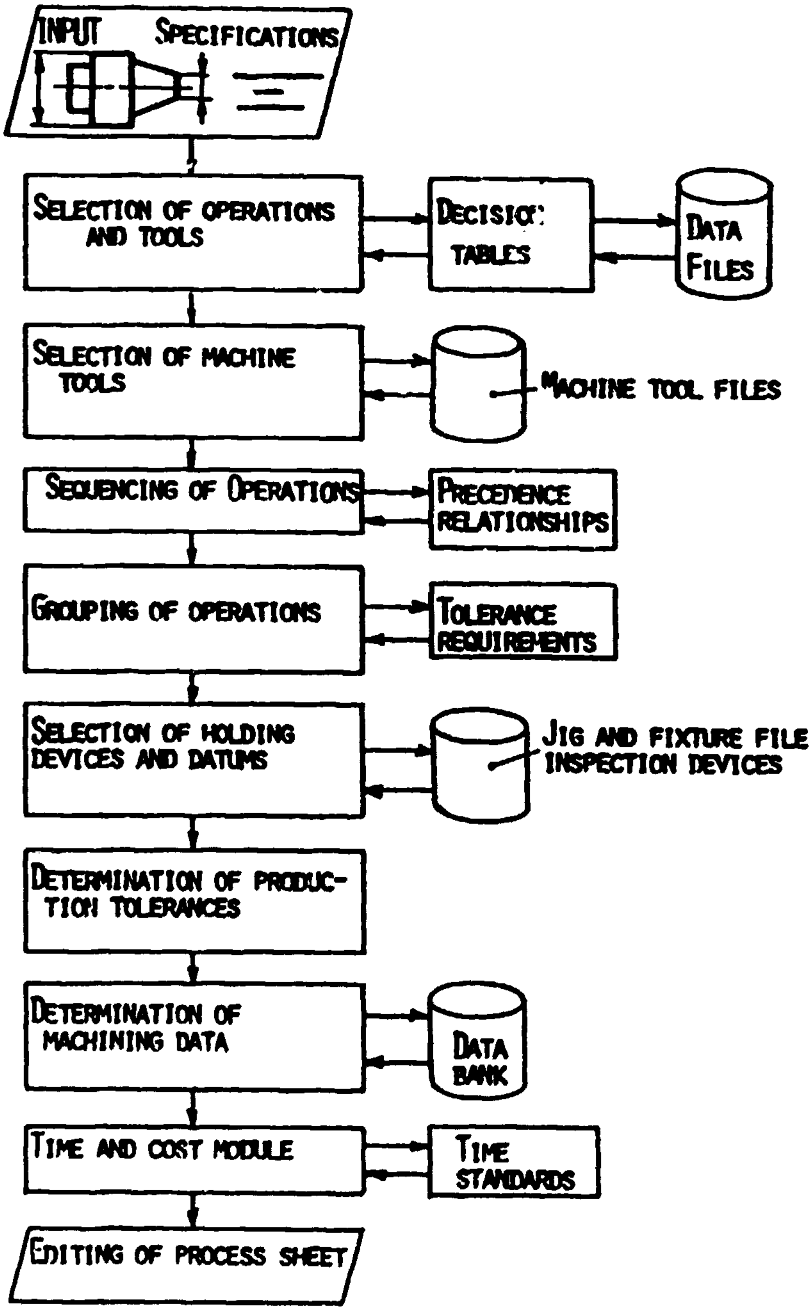
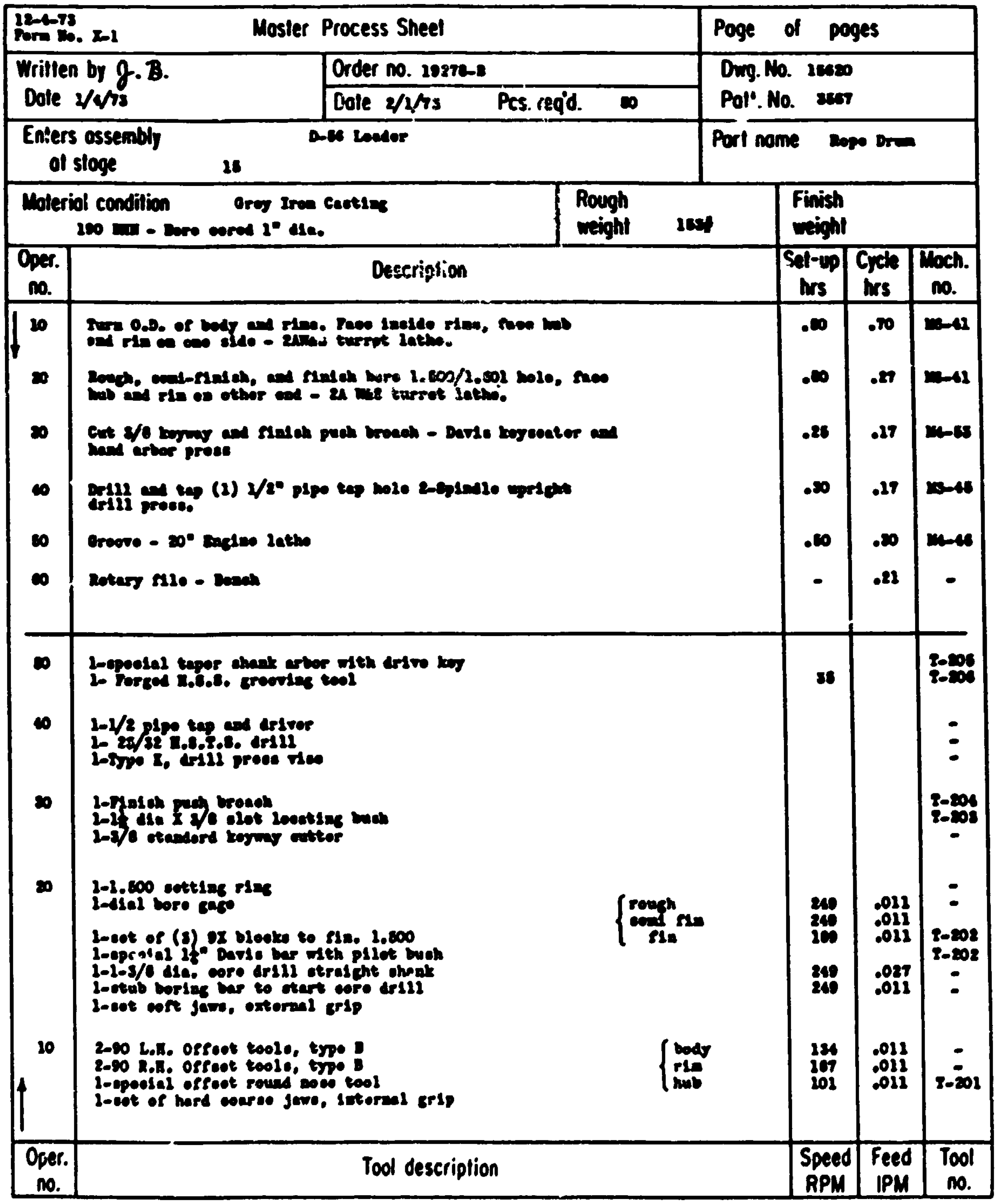


Figure 13.2 A typical process sheet for a small manufacturing organization

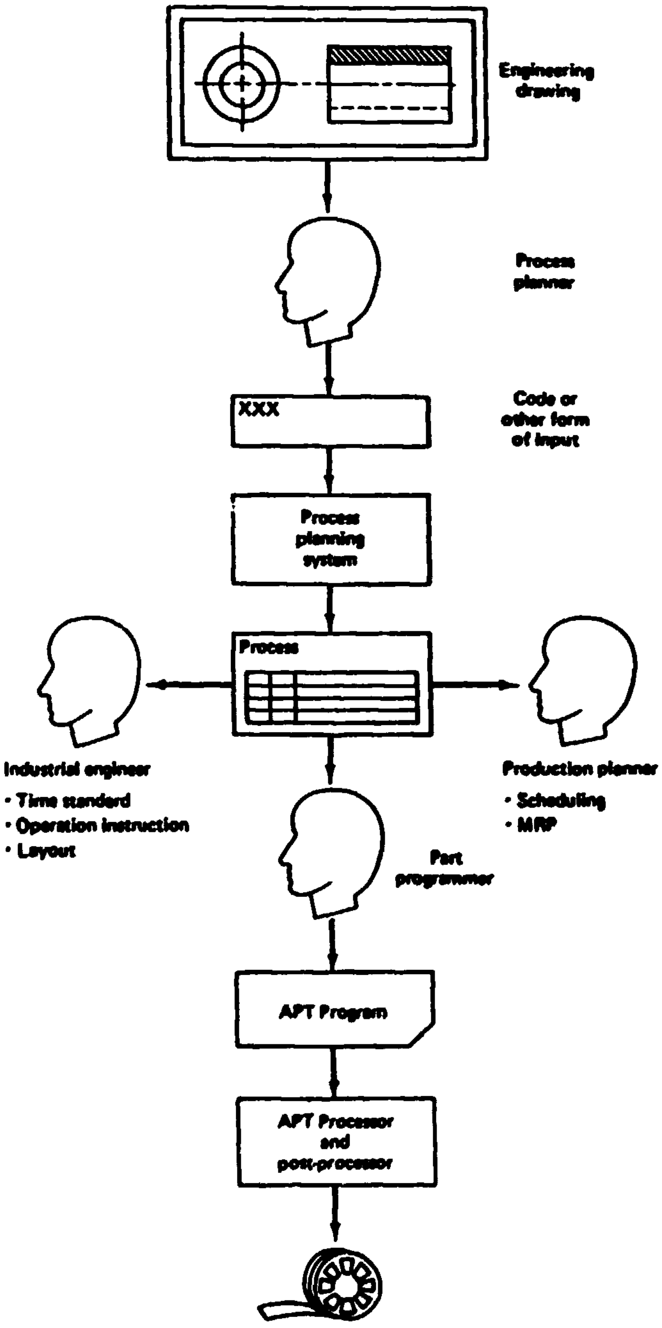


12-4-73 Form No. X-1	Master Process Sheet	Page of pages
Written by J. B. Date 1/4/73	Order no. 19278-B Date 2/1/73 Pcs. req'd. 50	Dwg. No. 15620 Pat'. No. 3567
Enters assembly D-56 Loader at stage 15		Part name Rope Drum
Material condition Grey Iron Casting 190 BHN - Bore cored 1" dia.	Rough weight 153#	Finish weight

Oper. no.	Description	Set-up hrs	Cycle hrs	Mach. no.
↓ 10	Turn O.D. of body and rims. Face inside rims, face hub and rim on one side - 2A W&S turret lathe.	.80	.70	M5-41
20	Rough, semi-finish, and finish bore 1.500/1.501 hole, face hub and rim on other end - 2A W&S turret lathe.	.80	.27	M5-41
30	Cut 3/8 keyway and finish push broach - Davis keyseater and hand arbor press	.25	.17	M4-53
40	Drill and tap (1) 1/2" pipe tap hole 2-Spindle upright drill press.	.30	.17	M3-45
50	Groove - 20" Engine lathe	.50	.30	M4-46
60	Rotary file - Bench	-	.21	-

50	1-special taper shank arbor with drive key				T-206
	1- Forged H.S.S. grooving tool		38		T-206
40	1-1/2 pipe tap and driver				-
	1- 23/32 H.S.T.S. drill				-
	1-Type K, drill press vise				-
30	1-Finish push broach				T-204
	1-1½ dia X 3/8 slot locating bush				T-203
	1-3/8 standard keyway cutter				-
20	1-1.500 setting ring				-
	1-dial bore gage	rough	240	.011	-
		semi fin	240	.011	
	1-set of (3) 9X blocks to fin. 1.500	fin	180	.011	T-202
	1-special 1½" Davis bar with pilot bush				T-202
	1-1-3/8 dia. core drill straight shank		240	.027	-
	1-stub boring bar to start core drill		240	.011	-
	1-set soft jaws, external grip				
10	2-90 L.H. Offset tools, type B	body	134	.011	-
	2-90 R.H. Offset tools, type B	rim	187	.011	-
↑	1-special offset round nose tool	hub	101	.011	T-201
	1-set of hard coarse jaws, internal grip				
Oper. no.	Tool description		Speed RPM	Feed IPM	Tool no.

Figure 13.3 Typical process planning system



Artificial intelligence has various definitions, but it can be described as being:

(a) A branch of computer science;
(b) A discipline, that is, it uses specialized tools and techniques;
(c) An approach to solving difficult problems usually thought of as requiring human intelligence to solve.

The problems to which artificial intelligence is being applied include:

(a) Natural language understanding;
(b) Robot vision;
(c) Data interpretation; and
(e) Decisions from incomplete data (for example certain forecasts)

Expert knowledge systems consist of a factual data base and a set of inferential or heuristic rules which use the factual data base to solve problems. The basic ingredients of an expert system are as follows:

(a) A problem statement with a goal;
(b) A knowledge base;
(c) A selector that identifies relevant knowledge;
(d) A strategy that determines which knowledge to apply in which order;
(e) An inference procedure that applies to the chosen knowledge;
(f) A working memory for storing parts of the solution as they develop;
(g) A friendly interface that helps the user.

13.4 Variant process planning

As mentioned previously, the variant process planning approach uses a data retrieval system to retrieve existing process plans. A variant process planning system uses the similarity among components to retrieve existing process plans. A process plan that can be used by a family of components is called a standard plan. A standard plan is stored permanently in the data base with a family number as its key. There is no limitation to the detail that a standard plan can contain. When a standard plan is retrieved, a certain degree of modification is usually necessary in order to use the plan on a new component.

In general, variant process planning systems have two operational stages: a preparatory stage and a production stage. During the preparatory stage, existing components are coded, classified and subsequently grouped into families. A family matrix is also constructed. The process begins by summarizing process plans already prepared for components in the family. Standard plans are then stored in a data base and indexed by family matrices (see figure 13.4). The preparatory stage is highly labour-intensive, with some reports indicating that it can take around 20 man-years to complete all the preparations.

The production stage occurs when the system is ready for planning new components. An incoming component is first coded according to a classification system. The code is then input to a part family search routine to find the family to which the component belongs. The family number is then used to retrieve a standard plan. The human planner may modify the standard plan to satisfy the component design. Figure 13.5 shows the flow of the production stage.

Figure 13.4 Preparatory stage

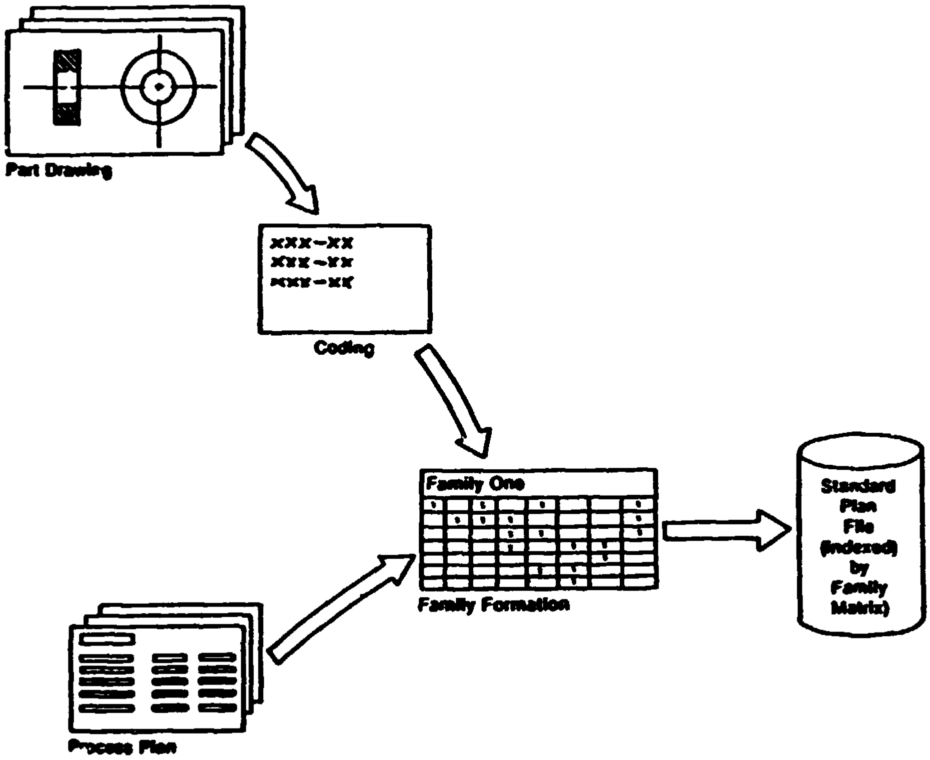
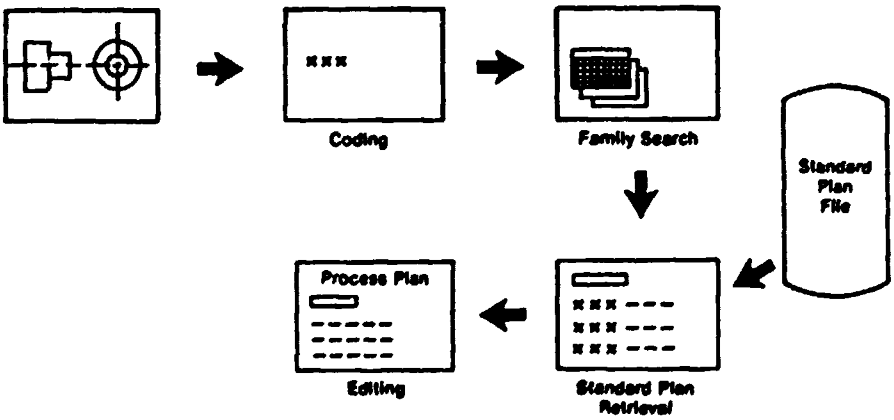


Figure 13.5 Production stage



13.5 Generative process planning

The generative approach to process planning utilizes an automatic computerized system consisting of decision logic, formulae, technology algorithms and geometry-based data to uniquely determine the many processing decisions for converting a part from a rough to a finished state. Unlike the variant approach, no standard manufacturing plans are pre-defined or stored. Instead, the computer automatically generates a unique operation sheet for a part every time the part is ordered and released for manufacturing.

A generative process planning system essentially consists of two major components. The first component is a geometry-based coding scheme for translating physical features and engineering drawing specifications into computer-interpretable data. The coding scheme defines all geometric features, feature sizes and locations and feature tolerances for all process related surfaces. The coding scheme not only describes the part in both the rough and finished state, but must be relatable to the processes in terms of capability to transform the part in each operation, the individual machines in each process group, the available tooling on each machine and the equipment for part positioning, clamping and driving. In efect, the coding scheme relates all the physical elements of the manufacturing process in a universally interpretable data language. The coding scheme for a generative system typically requires far greater detail than that required in the variant method.

The second component of a generative process planning system is the software, comprised of decision logic, formulae and technological algorithms, for comparing the part geometry requirements with manufacturing capabilities and availabilities. This involves determining the appropriate processing operations, selecting the machine for each operation, determining cut planning or other operational manufacturing details subject to available tooling and fixtures, and calculating the set-up and cycle times for each operation. The software can often consist of tens or hundreds of separate programmes linked together via a common geometry based coding scheme. An additional element of the software is a text file for printing the operation sheet and a procedure sheet for instructing the operator according to the methods selected by the computer. If the equipment is numerically controlled, then it is often economically feasible to have the computer generate the coded instructions necessary to control the tool paths and functions of the machine.

A number of sophisticated planning systems are currently being used in industry to plan turning operations on cylindrical parts. One of the more sophisticated generative systems is the Lockheed GENPLAN system. The most technologically advanced system in use today is probably the Computer Managed Process Planning (CMPP) system for cylindrical workpieces developed by United Technologies Corporation in conjunction with the United States Army Missile Command. CMPP automates the link between CAD and CAM by being able to accept geometric part data from a CAD system and perform planning functions to generate manufacturing process documentation, drawings or NC programming data. Many other systems have been developed by individual manufacturing companies, but, due to the proprietary nature of the work, many results have never been published or publicly disclosed.

The generative method of process planning, like the variant method, has many advantages in terms of automating the manual activities involved in creating manufacturing cost estimates, routings and instructions, thereby producing results which are more accurate, consistent and inexpensive. The generative approach has the added advantages that it is fully automatic and that an up-to-date operation sheet is generated each time a part is ordered. Thus, except for major revisions in decision logic due to new equipment or processing capabilities, the system does not require human intervention to construct, maintain, modify or create consistent process plans. However, designing and developing a generative process planning system is a formidable task. The project is complex, and represents a long-term investment of time, manpower and computer commitments. Furthermore, the development of a generative process planning system should be viewed in light of the future needs for integrated design and manfacturing functions. It is therefore important to have a clear understanding of the task involved.

13.6 Future of process planning

As a result of a study carried out in 1980, the United States Society of Manufacturing Engineers forecast the future of computer-aided process planning. The results indicated that, by 1990, 50 per cent of all process plans for parts and assemblies manufactured in the United States will be computer-generated. A number of factors strongly suggest that the need for automated process planning will continue to grow. High labour and capital equipment costs, decreasing availability of trained process planners and competition from higher productivity industries are some of the reasons. In addition, the availability and lower costs of computer hardware and more "transportable" software will greatly enhance the feasibility of automated process planning.

14. THE APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN MANUFACTURING*

14.1 Introduction

The term artifical intelligence (AI) was first used at the Massachusetts Institute of Technology in the late 1950s. The originator of the concept was involved with the development of the LISP-system that laid the foundation for this new research area. Hubert Spencer gave the term intelligence a biological interpretation, he considered it as inherited and innate. It is the way which the more intelligent type of animals adapts or adjusts its activities in the face of its complex and everchanging environmental circumstances.

The discipline of AI since its inception has been concerned with understanding how humans acquire, organize and use information. AI does not replace the brain with a computer. It means the design of machines so that they are able to adapt their activities to their environmental circumstances. It also means the use of the computer as a knowledge base in order to amplify human intellectual capacity to improve human ability and productivity.

From the point of view of the solution to the manufacturing productivity problem, AI techniques provide two major contributions. The first contribution comes from the insight and understanding which AI theories provide us as to how people do planning, resource allocation and general problem solving. By evaluating the AI results in these areas in the context of the manufacturing environment, we can develop a better understanding of the type and form of information which must be provided to improve the accuracy, timeliness and effectiveness of manufacturing planning and control activities.

The second contribution of AI research comes from the potential for direct application of the computer algorithm and information representation schemes to manufacturing problems. The applications fall into the following three major categories:

(a) Applications which attempt to duplicate natural human abilities (such as vision, language processing etc.);

(b) Applications which attempt to duplicate learned skills or expertise (expert systems, knowledge base etc.);

(c) Applications which improve the flexibility or effectiveness of traditional information management systems (Integrated Information Support Systems or IISS, Automated Manufacturing Research Facility or AMRF etc.).

Of the three major AI application classes outlined above, the expert system is the one which more discussion will be focused upon.

14.2 Expert systems/knowledge-based systems

(a) Manufacturing defined

Manufacturing has been defined by CIRP (1983) as "a series of interrelated activities and operations involving the design, materials selection, planning, manufacturing production, quality assurance, management and marketing of the products of the manufacturing industries". A manufacturing system is defined as "an organization in the manufacturing industry or the creation of manufacturing production. In the mechanical and electrical engineering industries, a manufacturing system, in general, has an

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* This section was prepared by Professor A. Nee, Director of the CAD-CAM-CAE Centre, National University of Singapore.

integrated group of function: viz. the sales, design, manufacturing production and shipping functions. A research function may provide a service to one or more of the other functions".

(b) What is an expert system?

An expert is a person who not only deals with situations definable by existing rules and data, but can use his knowledge to solve new situations. New situations are dealt with by reasoning using analogy, by using knowledge to create new rules and data, and by trying new rules and correcting them.

Three kinds of solutions can be defined for any specific problem:

(a) A solution which is arrived at by following a deterministic set of rules. Conventional computer programmes, written in declarative languages such as Fortran, Basic, Pascal or C, are of this kind.

(b) A solution arrived at by the use of a fixed set of rules and data, but by a control strategy which uses the rules differently, depending on the input data for the problem to be solved. Expert systems generally are of this kind. The set of rules and domain data is fixed, but their use is flexible.

(c) A solution arrived at by using not only a fixed set of rules, but also by automatically developing new rules during the computation process. This is more characteristic of the human mind and such programmes do not yet exist.

A programme known as an expert system uses a set of rules and data, and considers the whole as one logical system. Some peole, however, prefer to use the term "knowledge-based systems" rather than expert systems, but they are generally referring to the same thing. Knowledge-based systems, can be classified into two categories, namely, frame-based and rule-based. Frame-based reasoning relies on a hierachical representation of knowledge in the forms of "frames" which contain slots in which subconcepts or other frames can be integrated. Rule-based systems make use of the IF [antecedent], THEN [consequent] representation of knowledge. These IF-THEN, or production rules, as they are sometimes called, specify that if certain conditions exist, then a particular action should be taken. In both cases, the goal of the system designer is to build a system which has a certain degree of modularity so that an expert in the domain of application can add or modify the required knowledge to the system with minimum difficulty.

In running an expert system programme, a goal state is usually postulated, and the programme tries to prove the goal state. If a goal state cannot be proved by the rules and data in the programme, it cannot be solved. Hence, the program cannot deal with situations which are new, or a situation not solvable by the logical statements in the programme. Ideally we need a programme which can learn from the accumulated experience of working, and from interaction with the knowledgeable user. With existing techniques, the programme cannot create new rules as the predicate, or logical rule, is inserted by a programmer. We should desire that the rule itself be a structure which can automatically be given content. Such capability, however, does not yet exist.

As expert systems cannot deal with situations which are new, they are not really "experts" but "technical assistants". In the working situation where a high percentage of the problems to be solved are of a standard nature and where the reasoning processes built into the expert system can deal with them adequately in 80 per cent of the cases, the human expert will have his time free to deal with the remaining 20 per cent of the more intricate problems which really require an expert.

The primary benefits of expert systems can be stated as follows:

(a) Improving the capabilities of the experts themselves by freeing them from the more routine problems;
(b) Capturing the knowledge base of experts who are retiring;
(c) Acceleration of the transfer of critical knowledge;
(d) Capability of addressing problems which do not have a well-defined model or algorithmic solution.

14.3 Applications overview of expert systems in manufacturing

Several factors must be considered in the determination of whether a particular manufacturing problem area can be solved using the expert systems technique. These factors include problems characteristics, organizational goals, usage environment and development constraints.

There are approximately four broad categories of manufacturing problems which have been addressed by expert systems, namely:

(a) Design;
(b) Process planning;
(c) Scheduling; and
(d) Process control.

(a) Expert systems in the integration of design and manufacturing

Although there has been a great deal of interest in design for manufacturing problems, little work has been done from the standpoint of using rule-based techniques to address this problem. Most current applications of AI to design are focused on either creating the design itself, not necessarily with manufacturing requirements in mind, or on converting design data to information which can be used in process planning. One example of the former is PRIDE (pinch roll interactive design expert/environment). PRIDE is used to design paper-handling systems for copiers. It creates designs by representing kowledge of the design problem as a structured set of goals as well as design methods, generators and rules.

(b) Expert systems for process planning

Process planning is probably the most addressed area in manufcturing where expert and rule-based systems have been applied. GARI is an example of a process planning system developed at the University of Grenoble in France. It has a knowledge base of more than 50 rules and some 20 shape entities which can be handled by the system. Available machine tools are also described to GARI. The machine tool type, whether it is milling, drilling or grinding machine, will be defined with its important properties such as precision, dimension and distance between axes. On the basis of the number of rules, the GARI system can reason about how requirements of surface finish, angular tolerance for perpendicularity, countersink holes and their co-axiality etc. can be fulfilled when machining the part.

Another system called TOM was developed at Tokyo University and is used to deal with hole-machining operations. Other systems include EXCAP, for planning rotational operations, and AGFPO, for creating drawing process plans.

(c) Expert systems for manufacturing scheduling

Scheduling has not been given the attention that process planning has. This could probably be attributed to two reasons. First, there are more algorithms available for the scheduling task than for process planning. Secondly, the data manipulations required in scheduling are usually quantitative in nature, and most AI techniques deveoped to date have been concerned with symbolic manipulation. One of the systems is ISIS developed at Carnegie-Mellon in the United States. ISIS uses a type of search algorithm in order to schedule operations on machines. The search is guided by the application of a set of constraints which reflect, among other things, economic considerations, technological considerations, resource limitations and personnel requirements.

(d) Expert systems for process control

There have as yet been no successful applications of AI techniques to process control. The main reason could be the response time requirements of the controllers. The present run time of AI-based software is too long for effective control even at the lower level of the manufacturing process (for example, tool position control). Another factor inhibiting the use of these systems for lower-level process control is the need for precision in the control signal. It is not enough for a machine tool controller to direct an increase in cutting speed; the amount by which the speed is to be increased must be specified. Knowledge-based systems, by their qualitative nature, are inefficient in operations which require any degree of quantitative precision.

14.4 Future trends and limitations

At this point the bulk of research in applying AI techniques to manufacturing problems has been in the area of process planning. This has been primarily due to the lack of other automated methods for process planning as well as the symbolic nature of the reasoning involved. The integration of design and manufacturing has only gained attention in recent years and it will probably be some time before a well-defined body of knowledge is established which can serve as a base for AI software.

Expert and knowledge-based systems have certainly provided a technology base which will prove invaluable to future productivity improvements in manufacturing. Their usefulness is most apparent when a process plan or schedule has to be rapidly changed due to changing circumstances.

The present system, however, has several important limitations, as follows:

(a) Inability of the present system to recognize complex situations such as the lack of tools for unique problem-solving, the need for a self-enhancing knowledge base and the need for better means of communicating with the computer;

(b) An expert system dealing with a real problem has to deal with a considerable quantity of data and rules, which represents a significant problem;

(c) There is still a large gap between what AI offers and what manufacturing systems engineers require. AI tools developed in vacuo cannot be realistically tested before application to a particular problem and are, therefore, immature and unreliable;

(d) Current systems tend to deal with a small number of obvious cases and fail to work in more general cases;

(e) High cost of hardware and software, lack of qualified personnel and inadequate methods of acquiring and representing knowledge. The coupling of AI tools to industrial data bases and CAD is not yet achieved.

15. CAD/CAM ROBOTIC APPLICATIONS*

15.1 Introduction

The manufacturing aspects of CAD/CAM have traditionally been linked to NC machining, and some people even equate CAM to computer-aided machining instead of its usual definition. As the technology moved into the 1980s, the role of CAM in a CAD/CAM environment took on increased importance, especially considering its position as an integrator in helping industries to achieve the greater benefits of computer-integrated manufacturing (CIM).

The CIM concept encompasses a large number of computer-based automation applications. CIM can be thought of as a closed-loop feedback system whose prime inputs are proudct requirements and specifications, and whose prime outputs are finished products. CIM comprises software and hardware or product design for production planning and control and for production processes.

CAD/CAM is often regarded as an excellent CIM integrator for computer-based applications in manufacturing. The integration capability of CAD/CAM is derived from the very important use of the common engineering and manufacturing data base. This allows a product to begin its birth from engineering design of its geometry to form a product model which can be used for a variety of activities such as stress, vibration and temperature analysis to confirm the suitability of the geometry chosen. The same model can be used for the manufacturing activities including NC, manufcturing planning, tooling and fixturing, inspection and robotics. Each of these functions can access the product model and add its own results to the common data base.

15.2 The role of robots in a computer-integrated factory

A computer-integrated factory typically consists of modular subsystems, each controlled by computers which are interconnected to form a distributed computer system. These modular subsystems will have the following functions:

(a) Product design. This is performed interactively on CAD work stations. CAD software will enable section properties to be determined very quickly. The design is analysed by the various packages using techniques such as finite elements, animation etc.;

(b) Production planning. An optimized plan is worked out for the manufacturing process including the sequence of operation, machining parameters, tooling and fixturing requirements etc. Other aspects include scheduling and line-balancing, various conditions of purchased-part deliveries, available resources, product mix and priorities;

(c) Part fabrication. Part may be formed or machined by work stations, each controlled by a small computer that determines the loading sequence, machining or forming the part, and employ adaptive control incorporating diagnostic devices to detect tool wear and breakage;

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* This section was prepared by Professor A. Nee, Director of the CAD-CAM-CAE Centre, National University of Singapore.

(d) Material handling. This is done by different devices such as conveyor belts, automated guided vehicles, automatic warehouse, robots etc., throughout the plant;

(e) Assembly. Parts are assembled together to form subassemblies and final assemblies at computer-controlled work stations, each of which includes robots with or without sensors, parts orientation devices and other fixtures;

(f) Inspection. Parts are inspected by computer-controlled sensor systems during the manufacturing process or at the end of the process;

(g) Information and control. This includes: channelling of information via a distributed computer system that stores, processes, and interprets all the manufacturing data, including orders, inventories of materials, tools, parts and products; manufacturing planning and monitoring; plant maintenance; and other plant activities.

As can be seen from the above functions, robots play important roles in activities (c) to (f). Robots are indispensible in material handling, assembly and inspection processes.

Many of the computer-integrated factories consist of a number of integrated work-cells bearing different names such as flexible manufacturing cells, robot work-cells, robotic automated work-cells etc. The heart of such cells is the industrial robot. CAD/CAM robotic application is most efficient in the following activities: robot work-cell design; robot work-cell programming; and robot work-cell simulation.

A robot work-cell contains a number of items of equipment needed for robot applications. Typical equipment and facilities include machining centres, NC machines, conveyor systems and wash and inspection areas. The equipment in the work-cell must be arranged so that the robot work envelope includes all the required device areas. CAD/CAM is perfect for designing the equipment layout. Libraries of work-cell components can be stored on the CAD/CAM system and recalled when needed. A typical robot library contains a number of commercial robots along with their work envelopes.

CAD/CAM work-cell design results in many benefits. In particular, it:

(a) Reduces design time and costs;
(b) Allows more alternatives to be considered;
(c) Reduces lead time to design and lay out the cell; and
(d) Increases the quality of the designed components as well as the overall cell.

15.3 CAD/CAM robot programming and simulation packages

A number of CAD/CAM robot programming and simulation packages are available commercially. This section looks into the following packages:

(a) GRASP - BYG System Ltd., United Kingdom, runs on Prime, VAX and Apollo;
(b) Robographix - Computervision, available on the CADDS 4X Designer System;
(c) Robot Programming - Intergraph, runs on VAX;
(d) CATIA, runs on IBM;
(e) PLACE - McDonnell Douglas Automation Co., United States, runs on McAuto, VAX-based;
(f) Robocam - SILMA Inc, United States, runs on Apollo.

(a) Graphical Robot Applications Simulation Package (GRASP)

GRASP has the following features:

(a) Modelling. Grasp incorporates its own three-dimensional solid modeller. Objects are built up from a variety of basic primitive shapes such as cuboids, cylinders, polyprisms etc. The generalized kinematic robot modeller allows users to add their own robot models to the system. Pictures with the hidden lines removed can be produced;

(b) Robot control. Sophisticated robot control and programming facilities are provided which allow the creation, storage and replay of robot programmes. Robot control commands range from individual joint manipulation to powerful object level positioning of the tool centre point. Joint constraint violations are automatically reported and the path of the tool between programmed points can be defined;

(c) Programming. Robot programmes can be created which are independent of the positions of the robot and other objects in the workplace. Thus, different robots may be evaluated for a particular application and also objects may be repositioned in the workplace without the need to recreate or even edit the robot programme. This very powerful feature can save a lot of time in the workplace optimization process;

(d) GRASP incorporates an "event processor" which allows it to simulate the actions of objects and equipment other than robots and combine these actions with those of the robot. In addition, it allows flexible, time-based playback of robot programmes, merging of several programmes into a single one and estimation of cycle times;

(e) Off-line programming. GRASP can also be used to generate robot programmes off-line. All the data necessary for a robot programme would have been created within the system during the simulation. This can then be suitably post-processed for different robot controllers.

Figures 15.1 and 15.2 are generated using the GRASP package.

Figure 15.1 A typical robot assembly cell

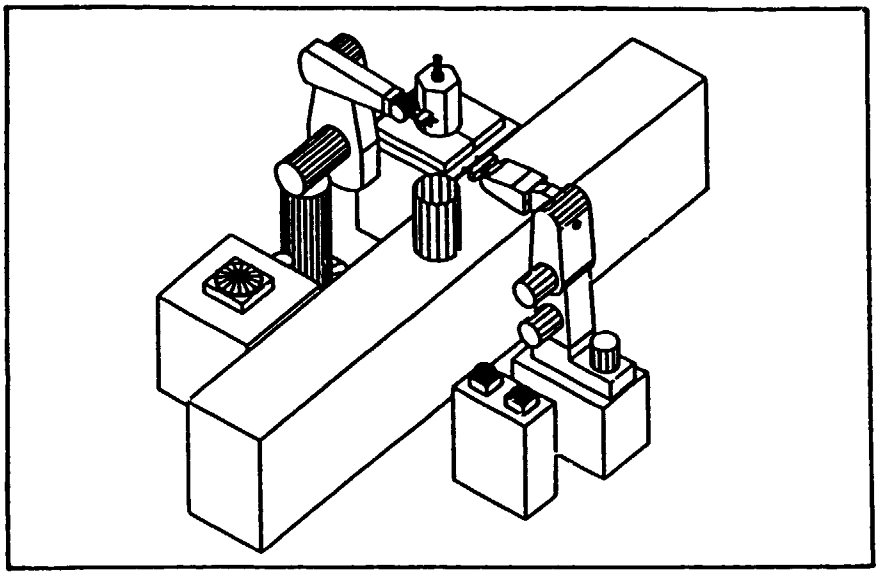
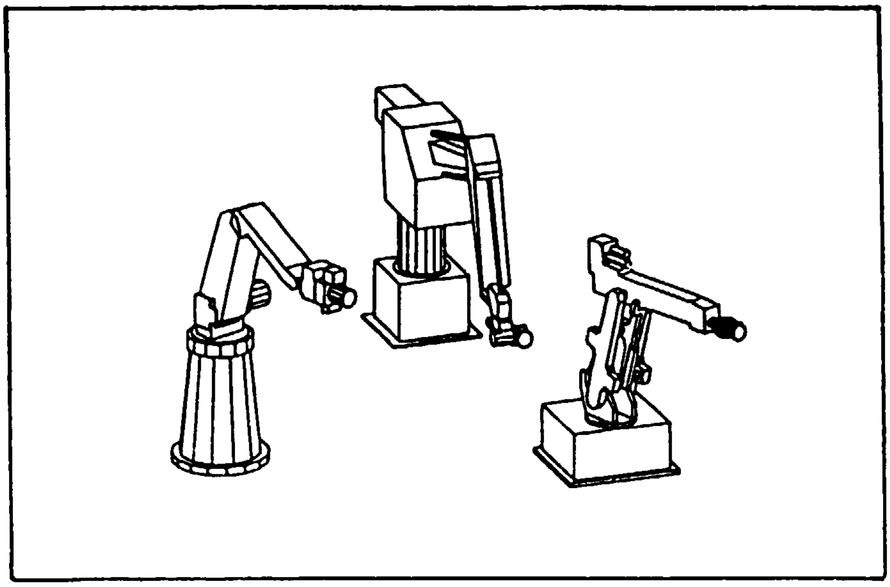


Figure 15.2 Robot models from the GRASP library



(b) Robographix

Robographix is Computervision's graphics off-line programming and simulation software. It consists of two parts: a robot path generator and robot description and language processor.

The robot path generator is the same for any robot. It generates the generic portion of the robot path. The robot description and language processor is specific for the target robot. It contains all the joint mathematics and the rules for transforming the robot path into the language or software input that the robot can understand. In this manner, it is analogous to an NC post-processor.

It has the following features:

(a) It provides interactive robot path generation using a menu of options;
(b) It provides up to six-axis control;
(c) It references libraries of robots contained in the system;
(d) It is able to enter any valid, non-motion robot command;
(e) It detects and inhibits joint limitations;
(f) Joint positions and link geometry can be statistically displayed;
(g) The full robot path can be dynamically simulated;
(h) Different robots can be tested on a single path;
(i) Point-to-point and continuous robot paths can be programmed;
(j) The robot path is processed to create the actual robot input.

(c) Robot programming

The robot programming package from Intergraph has the following features:

Operations planning and definition

(i) Robot definition. A three-dimensional graphics representation of the robot is created and stored for use during work cell composition and simulation. This graphics model is linked to its attribute data, such as make, model, power requirements, drive method and weight, as well as kinematic and axis specifications. Once completed, the robot library provides on-line access to robot geometry and attribute specifications for review or editing.

(ii) Controller definition. A separate controller library also contains geometric and parametric information and provides flexibility in configuring user-specified combinations of robots and controllers.

(iii) End effector definition. A third library contains graphics and attribute data for end effectors. Extensive graphics capabilities allow the user to design end effectors and special tooling requirements.

(iv) Work-cell component definition. A final library contains graphic and attribute data for the supporting equipment in the work-cell, including tables, transfer mechanisms, machine tools, power cables, safety devices etc. Attribute information attached to the graphics includes device classification and weight.

Work-cell composition

(i) Robot and component placement. Using graphics representations retrieved from the various libraries, the user lays out the work cell, positions the robot and supporting equipment for optimum work orientation and safety. A display of the robot's work envelope facilitates interference checking with other objects in the work cell.

(ii) Path generation. Within the work-cell, the user can describe the path used by the robot to perform a specific manufacturing operations. To generate a process path, robot reach limits and work points are defined and then ordered in a motion sequence. Robot reach limits can be verified through inverse kinematic analysis. The path also includes the motion type (point-to-point or continuous) and the motion speed (rate of axis travel).

Process simulation, editing and validation

(i) Animated simulation. The user can select animation display options which include stepping through the process frame by frame or automatic replay of the process. The animation sequence includes each element of the work cell: robot, controller, end effector and supporting equipment.

(ii) Linkage feedback. To further verify robot reach, the system calculates information on the joint angles of the robot and the proximity of the motion limit of the linkage. This allows the user to identify points in the process when a linkage approaches its angle limitation.

(iii) Programme sequence validation. During the animation sequence, the user can review graphically the ordering of work points in the process.

(iv) Cycle time estimation. Cycle time estimates assist the user in co-ordinating the timing of part movement through the work-cell and in adjusting robot movement to the human interface.

(v) Process review and edit. Process errors or weaknesses, detected during animated simulation, can be modified by editing specific parameters such as component positioning and logic.

Output

(i) Robot programme. The finished process - including ordered process logic, positional data, motion speed, motion type and supporting data - is output in a neutral file. This file can then be translated into an industry-standard robot language for use in a specific manufacturing facility. The neutral file can be processed with user-defined analysis routines such as special cycle time optimization etc.

(ii) Engineering plan drawings. The user can extract finished engineering production drawings for work-cell layout and installation as well as robot construction.

(d) CATIA

It provides facilities for a user interactively to create robots of choice, simulate the robot motions (and complex tasks to be executed by these robots), and aid in off-line programming of robots. These virtual robots, along with their associated facilities and coupled to standard CATIA functions, allow the design and evaluation of robot work-cells and workshops.

Through CATIA's solid geometry representation of objects, robot collisions can be checked. Visualization is aided through hidden line removal during simulation, colour shading, and the use of local work-station functions such as pan and zoom. Other features include:

(a) Ability to constrain the robot movement to follow a complex user-defined curve in space;
(b) Removal of the previous restriction as to the number of robot joints;
(c) True separation of the programming of tasks from the robot definition and from the objects in the robot environment.

(e) Place

McAuto developed PLACE (positioner layout and cell evaluation) as a simulation tool for designing and evaluating robotic cells. Three more modules were added: BUILD, a parameter-driven system that automatically creates the kinematic motion control equations for each robotic device; COMMAND, the module for creating the robot off-line programme; and ADJUST, a special set of procedures and software to do real-world cell calibration. The following features are highlighted:

(i) Cell design. PLACE has four key features for the users: computer simulation; user-controlled animation; dynamic three-dimensional picture control, and access to a library of robots. The user can do the following things:

- Position cell components dynamically;
- Define robotic arm motion;
- Check reach limits;
- Build motion sequences;
- Simulate object tracking and
- Analyse cycle times.

(ii) Graphic animation. A very useful feature during the layout phase is the interactive display of each of the robot joint positions. As the robot is moved towards its destination, the user gets immediate feedback if any of the joints reach a maximum allowable position. This information may require the robot or the other cell components to be repositioned to stay inside the robot reach envelope. Two columns of data are provided. One gives the current joint position; the second gives the maximum position of the joint in the current cycle. Once the basic positions of the cell components have been established, the designer can combine the individual motions into a sequence. The entire sequence can then be played to verify reach limits. In addition, since the speed of the robot and other moving objects in the cell can be controlled, cycle time anlaysis can be performed. A stop-watch function is provided to time partial or complete sequence motion.

(iii) Cell programming. COMMAND is used to replace the teach mode and make the programming of robots easier and more accurate. The procedures of COMMAND are described in the following section. First, process comands are written in the native language of the particular robot. Second, the PLACE motion sequences are called to execute at the user-specified location in the programme. Finally, the user programme is translated into a set of instructions compatible with the robot controller. Currently, translators for Cincinnati Milacron and Unimation (VAL) robots are available.

(iv) Cell calibration. ADJUST is used to feed positional data regarding the actual spatial arrangement of the robot on the factory floor back into the computer model. This data then automatically updates the PLACE model accordingly.

(v) Robot modelling. To accommodate the physically changing robots as well as to be able to add new robots quickly, BUILD is used to create geometry with the kinematics of the robot and automatically adds it to the robot library.

(f) ROBOCAM

The ROBOCAM package developed by SILMA, Inc, runs on the Apollo family of work stations. ROBOCAM offers both high-level language as well as using a mouse to intereact with a menu and a graphic display of the work-cell.

ROBOCAM also supports RISE, a high-level, arm-independent interactive language. This language is specifically designed for robot programming and supports many geometric shapes and operations. RISE is similar to PASCAL in syntax, however, it is an interpreted language leading to good interactivity. Since RISE is arm-independent, the same programme can be executed by different robots so that they may be compared in a particular application.

ROBOCAM has a small CAD subsystem which can be used to create and edit three-dimensional wire-frame models of work-cell components. Models can be saved in files and transferred between ROBOCAM and other CAD systems through an IGES interface.

(i) Co-ordinate specification. RISE supports several coordinate frames simultaneously, which can serve as the reference for specification of points. Each frame consists of a point in space and a three-space orientation of a coordinate system whose origin is at that point. Pre-defined standard frames exist at the manipulator base, the wrist and the tip of the end effector, in addition to an overall universe frame. Other frames can be defined in task-relevant locations as required. Each time a point is referred to relative to a frame, a choice can be made between Cartesian, cylindrical, or spherical coordinates. Also, the point may be specified in an absolute sense or relative to the previous point.

(ii) Accurate path simulation. ROBOCAM supports a family of path generation techniques and selects the one which matches that used by the robot manufacturer so that robot paths in simulation match the paths taken by the actual device. The user can specify the desired duration or speed for a tool motion. An error message is displayed if the motion would cause the robot to exceed the velocity or acceleration limits of any of its joints.

(iii) Multiple arms. Multiple robot manipulators working together in a single work-cell can be simulated, with a separate programme written for each of the robot controllers. These programmes interact with each other through signal-and-wait primitives. Other devices such as conveyors and automated guided vehicles can also be simulated, with the user specifying the way in which the various elements in the work-cell are connected. A general simulation capability then allows the entire system to be simulated. A central computer controlling multiple robots and other moving devices can also be programmed and simulated. ROBOCAM supports language translators for selected industrial robots. After a RISE programme has been debugged in simulation, the programme can then be translated into the native language of the target robot. This translation is performed via an intermediate language called ROODE which is unusually simple, but complex enough to support the features found in RISE. ROBOCAM drives the actual robot in either an on-line or off-line mode.

15.4 Summary of typical features of robot simulation packages

The following features are available on most of the packages described in the previous section:

(a) Solid or wire-frame modeller to represent robot and other elements in the robotic cell;
(b) Robot library which contains data such as power, joint, kinematic and axis specifications;
(c) Cell design - defines cell components and can position cell elements dynamically;
(d) Joint constraint and limitation detection;
(e) Animation or simulation of object tracking;
(f) Collision and interference checking;
(g) Path generation and cycle time analysis;
(h) Off-line programming - generates robot programme off-line. Data created within the system during simulation are used directly as input.

16. THE SIGNIFICANCE OF PERSONAL COMPUTERS IN CAD/CAM FOR SMALL-SCALE METALWORKING INDUSTRY*

The use of personal computer in CAD/CAM is based to some extent on the philosophy of decentralized control or distributed intelligence. The idea is to put computing power where it is most needed and best used. Computing need not be centralized to be efficient, in fact, many users have found the opposite is true. PCs, when located nearer to where the action is, can be better suited to aid decision-making, data analysis, or information manipulation than corporate mainframe or even mini computers. In software, as well as in hardware, PC proliferation has opened up intense competition which has led to an industrial software explosion.

16.1 The introduction of PC-based CAD

(a) Advantages

When downsized for use on a PC, CAD lacks the speed or the features (or both) of its larger-system counterpart. Pictures are drawn slowly, files accessed tediously, such features as animation and, often, three-dimension perspective are missing, and the links to CAM are done slowly. But bringing CAD to the PC has opened up new users and new applications. The expensive growth in PC CAD is a direct function of its affordability. For around $5,000 a user can install a limited function system - PC, plotter, and software - with performance equal to what would have cost tens of thousands dollars just recently. The cost breakthrough has opened up new users in such specific activities as small-shops manufacturing and education and training. There are thousands of manufacturing facilities that simply do not have the volume of business to keep a traditional CAD system fully loaded. With CAD packages suddenly costing about $5,000 proprietors of those shops often felt compelled to try out a package, if for no other reason than to automate drawings.

Another user base, corporate users of large-scale CAD installations, found that, at around $50 per console hour, it was too costly to use their more powerful computers to perform routine data entry or simple two-dimensional drawings. Shifting some of that burden to less expensive PCs simple became a way to use resources more effectively. Producers of traditional CAD systems responded by offering PC versions of their larger systems, ensuring a certain amount of procedure standardization. Colleges and technical schools were early users of PC CAD because of its affordability. Later, corporate users of large-scale CAD systems began to realize that, once a person learned to use the basic concepts of CAD (any CAD, mainframe or PC) he or she could swiftly change to another, perhaps more sophisticated system.

(b) Disadvantages

However, for all of its promise, PC-based CAD presents prospective users with some challenges. For instance, there is a question of support. With traditional CAD hardware/software installations costing perhaps a couple of hundred thousand of dollars, the supplier could be expected to send a service representative for days at a time to get the system up and running with

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* Extracted from a document of the Economic and Social Commission for Asia and the Pacific, presented under the same title at the UNIDO/ESCAP/TECHNONET - CAD/CAM Workshop, held at Singapore from 9 to 20 May 1988.

customer personnel. Vendors of PC CAD software, whose products retail for only a couple of thousand or even hundreds of dollars, are unable to offer field service and have had to resort to relying on computer-store salespersons, who are very often not in a position to render adequate assistance in the field of software.

Transportability of data is another major area of concern. The information developed on a PC must be fully interchangeable with a host mainframe CAD system or another computer that generates NC part programmes from the design. In the United States, in particular, virtually all the established PC CAD packages offer a translator routine that converts a design to conform to the IGES (initial graphic exchange standard) format, the one adopted by committees of CAD vendors and users. Arguing that any product of a committee is cumbersome, some PC CAD vendors promote the use of their own proprietary format as a more efficient way to store and transfer graphic data. AUTOCAD's data interchange format (DXF), a prime example, is fast on its way to becoming a de facto standard.

16.2 PC operating systems

Apple's main task opeating system, for instance, which is inherently graphics-oriented, was an early choice for CAD. The impressive installed base of the IBM PC and the expanded capabilities of the AT version enabled the PC-DOS operating system to catch up, to the point where, one expert estimates, there are approximately 100 different CAD packages that run on the IBM PC/AT.

The problem of operating system and supporting hardware is an important one because most PC-based CAD is limited in its functions. Take three-dimensional design, for example. Many software packages are really 2 1/2-dimensional, in that isometric views are constructed by an extrusion - a second copy is made of the design and then the two copies are connected with lines that give the impression of three dimensions. Lately, microchip manufacturers have found it practical to produce special graphics add-on boards that incorporate special chips which have made even personal computers perform like dedicated work stations.

16.3 Part programming

Saving part programming time is another positive feature of PCs. In some types of industrial activities, for example, in production of precision measuring instruments involving torque sensors, transducer etc., considerable pressure comes from customers for numerous modifications. Even though some companies producing the above-mentioned equipment have a large base of manually programmed parts at hand, some new programme must be developed each work week. Now a number of companies use the PCs to programme new parts and to modify existing ones. Many part geometries are common to a number of sensors. This variety results in engineering libraries covering the parts to be made for the sensors, which in turn represent a data base well-suited to CAD/CAM technology.

In this connection, a case of design modification for a biaxial load cell for the tyre industry (United States experience) could be of interest. It was designed on CADKEY software running on an IBM/PC, which generated an IGES file totally defining all geometry. The file was transferred by floppy disc to the programming department, where it was reached by XL/NC software from PMX Inc., running on another IBM PC. This eliminated part programming from a print, producing the programme for a biaxial load cell for the tyre industry at a time saving of 50 per cent. The lead cell reads rotating-type biaxial forces after the tyre comes from the mould, providing data that reflects imbalance, and permits the tyre to be balanced.

Expanding the CAM element of sophisticated CAD/CAM part-programming software still costs considerably more than $5,000, and CAD/CAM software capable of handling any geometry and all kinds of machining, punching, three-dimensioned work, and contour cutting is not so cheap, but exotic systems are still dropping in price. A complete system, with PC, operating-system, data interchange, and specific programmes for a dozen functions - including programming, accounting, estimating, part tracking, inventory control, and cost anlaysis - could cost $50,000.

Small-scale shop flexibility and needs may have been the impetus for such scattered software developments, but it is not just the small-scale shops that now elect PCs for programming work. One reason is the low cost an practical possibility of setting up a separate part-programming department within any large production facility, permitting the machine shops to handle their own work, operating outside the company wide system of budget, reports and memoranda.

Some experts think there will always be need for shop-floor programming, especially in small-scale shops, but they anticipate more direct communications between large companies and small-scale shops that will amount to networking to permit direct data transfer. Subcontracting, placing overload work with small-scale shops and similar situations have already made it practical for a number of customers in some developed countries to exchange data. A current visible trend is for machine shops in large companies to select a PC because the programming software is available and relatively easy to use and then to add CAD functions.

While exotic part-programming systems are being developed for supermini computers, almost all of the features are available in a PC system, with some penalty in computer speed. The whole concept of part-programming by computer is still evolving and growing. In spite of the advantages in software, however, it is still the processing engineer in the shop who makes the most critical difference in part production. Selecting machining sequences is a necessary function that can make a profit or not. Actual machine shop (punching shop, cutting shop) experience and knowledge are always required to permit a skilled programmer to plot metalworking operations in a practical order that will result in an efficiently produced part. PCs have become so powerful and useful that, with this kind of software, they can compete with little disadvantage (mainly speed) with much larger but older systems. In some cases, they are justifiably equipped with hard-disc storage capacity, which is necessary for a software application.

16.4 Quality assurance (QA)

Even with the spread of automation many quality assurance (QA) tasks still involve essentially auditing functions, instead of real-time control functions. So they can be performed on smaller PC systems operating as adjuncts to an overall computer-integrated manufacturing (CIM) network. Given appropriate communications capabilities, such systems can become a significant information element of the CIM network.

QA software products currently available for PCs are as follows: measuring and calibration routines; CMM programming control and data interpretation; inspection routines; QA mangement plans; QA cost analysis;

reliability studies; sampling plans; statistical analysis; statistical process control and supplier-quality analysis. Computers can help to overcome many common measuring errors stemming from a variety of sources and provide the accurate data-recording and data-processing capability essential for any successful QA programme. For example, computerized gauge calibration and inventorying systems help to keep track of the location, use and calibration status of individual gauges, thereby ensuring that properly calibrated gauges are available for the task at hand. In fact, such a history of each gauge in the tool-crib inventory is essential to developing and maintaining a satisfactory gauge-calibration programme. Many SPC programs signal the occurrence of inconsistent data and thereby point out possible damage to a gauge.

Computerized data acquisition also reduces the opportunity for operator error. Typically, the operator no longer needs to read or interpret gauges because the value is automatically translated into an appropriate correction signal. This eliminates errors due to poor eyesight, fatigue, number transposition, transcription errors and bad operator technique. The application of computers can deal well with the following basic demands of quality-information flow:

(a) The effectiveness of quality information depends on the promptness of the related inspection report;

(b) Time lags that discourage effective action must be eliminated;

(c) Trouble-spots must be quickly brought to the attention of those who can do something about it;

(d) Good reporting formats must be established to indicate responsibility for action type of action and follow-up with a measure of the effectiveness of the action.

In fact, QA is a data-processing activity. That is why computers and associated software are beginning to play such an increasingly active role in its pursuit. QA, in particular, involves gauges, instruments and measuring machines that must be applied properly and used accurately, but the data they gather is pointless unless it is converted into information that can be used to control the manufacturing process. At the simplest level PCs can be used to record measurements, compare them with stored reference values, and print out the calculated deviations in an appropriate reporting form. Even the simple spreadsheet programme, available from a local computer vendor, can be used for calculations and presentation, list the master value in one cell and assign a simple arithmetic subtraction of the master value cell from the recorded value to another cell. Add a few well-chosen labels and any simple low-cost PC with dot-matrix printer will generate the desired record from manually input data. With the proper interfaces a variety of electronic gauges can be plugged directly into a roving cart-mounting computer for automatic report generation at the shop-floor inspection site. The obvious advantages of such approaches are the elimination of clerical errors and the automatic generation of the kind of documentation so essential for the workshops. Operator negligence is also avoided.

Other PC programme applications that are particularly important in any overall QA programme include the following:

(a) Tracking field complaints to establish product-performance data and initiate appropriate design and manufacturing changes. Such field reporting can also be used to maintain traceability information in the event of design modifications or, if needed, product recall;

(b) Incoming material inspection reporting, including cost analysis and work-load tracking;

(c) Tracking and reporting reliability and maintenance ability data for key components or processes;

(d) Quality planning and instructions using process-planning and word-processing techniques;

(e) Fault analysis of machines and processes, including the application of expert systems for fault diagnosis.

By far the most significant QA application of PCs is in connection with statistical process control, which was originally developed in the United States and introduced into Japan after the Second World War.

Traditional inspection techniques catch defects only after they have occurred. No amount of post-process inspection alone can prevent the manufacture of scrap. Defect-free output requires that the manufacturing process be controlled and that is where statistical method plays a key role. The whole point of such statistical process control is to study specific on-going processes in a timely fashion to keep them under satisfactory control; in contrast, post-process inspection aims at catching defects that have already occurred. In other words, statistical methods are intended for defect prevention instead of defect detection.

The underlying principles of statistical process control are simple standards of quality which require: establishing the capacity of the process; monitoring the process to detect any significant changes that indicate the process is going out of control; and making the necessary corrections to keep the process in control. The principle tools of statistical process control are frequency distribution, a tally of a number of times a given quality characteristic occurs and control charts to provide a graphic means of establishing whether a process is still under control. Probably one of the biggest reasons that many of the techniques of statistical process control have been neglected in the past is that the collection, organization, analysis, presentation and interpretation of data in a timely fashion and under the environmental conditions of the shop-floor have not been easy. It is one thing to ask operators to inspect their own work; record-keeping an calculations are another matter.

Electronic gauges with computer-compatible outputs and related software virtually eliminate the need for record-keeping and manual calculations. Not only do these approaches offer the ability to gather and process data, but they all offer the opportunity to generate a variety of reports and graphic statistical tools.

Among the main statistical tools that can be implemented on PC software are the following:

(a) Frequency distribution. A tabulation or tally of the number of times a given quality characteristic occurs within the sample being checked as a picture of the quality of the sample, it may be used to show at a glance the average quality, the spread of quality and the comparison of the quality with specific requirements. Such programmes are used in the analysis of the quality of a given process or product;

(b) Control chart. A graphic method of evaluating whether a process is in a state of statistical control involves plotting values of sample measurements from the process output with respect to the time when the curve of the control chart approaches or exceeds the limits (based on the frequency distribution of the process); some change in the process may require investigation;

(c) Sample tables. This involves a specific set of procedures that usually comprise acceptance - sampling plans, in which sample sizes and acceptance criteria, or the amount of 100 per cent inspection and sampling, are related;

(d) Special methods. This includes the analysis of tolerances, correlation and variances. Such programmes are used to analyse the quality implications of engineering designs or process troubles.

16.5 System software and hardware

Problems of the application of CAD/CAM may be divided as follows:

(a) System problems, related to the need to connect a large number of devices from different manufacturers, each requiring appropriate interfaces to allow the correct behaviour of the whole system;

(b) Technological problems, related to the enormous amount of information to be treated with very fast data transfer within a network, with real-time access to storage devices and with on-line data processing.

System problems are basically related to methods permitting free data movement through interconnections. The International Organization for Standardization (ISO) has defined a model for distributed computer networks, which is called the open systems interconnection (OSI) model. The OSI model subdivides the total communication process into seven layers and allocates specific functions to each layer. The OSI standard also defines each of the interfaces between the layers.

As far as technological problems (related to all classes of computer) are concerned, they constitute an existing challenge for applied research which includes employment of fibre optic links in computer networks,optical techniques for mass storage etc.

The term software refers both to the instructions that direct the operation of computer equipment and the information content, or data, that computers manipulate. Software is classified as being of two general types: system software that is used to manage the components of a computer system, such as computer operating systems that control input and output operations; and applications software that is designed to apply computer power to the performance of some task or tasks, such as CAD of turbines and pumps.

System software controls the hardware, including peripheral equipment such as printers, keyboards, displays and memory storage devices, and schedules and regulates the execution of application software depending on how much processing time and memory capacity they require. A recent trend, encouraged by the spread of PCs and independent software vendors, has been toward the standardization of system software, so that a large number of application programmes can run on different types of computer.

A noteworthy aspect of software and hardware design efforts has been in the area of systems integration. A system integrator combines standard hardware components with custom software - or certain standard software packages modified appropriately to end users' requirements. These programmes serve as software connections between disparate kinds of hardware.

17. FUTURE OUTLOOK OF CAD/CAM

CAD/CAM is one of the most dynamic growth areas in the computer industry. It has registered an annual growth rate of over 30 percent in recent years and is forecasted to grow at 50 percent in the coming years.

Over the past decade, CAD/CAM has provided hope and excitement about the prospects for the manufacturing industries. CAD/CAM technology has responded to industry needs for sophisticated interactive graphics, computer-controlled machine tools, intelligent robots, improved inspection techniques, and a host of other innovations to do manufacturing better. It is contingent upon management to make the most of this new technology, so that its full promise can be realized in the future.

Future prospects for CAD/CAM are greatly enhanced by developments in communications, microprocessors and associated software. Improved communication techniques will result in greater exchange of information among people, machines and computers. One of the manifestations of better communication will be the systems that permit engineers and operating personnel to access powerful computing techniques from a terminal which can be far removed from a large computer. The terminal might be as small as a conventional pocket calculator but will have the capability to communicate with a large computer.

Another clear trend that will have an impact on CAD/CAM is the greater use of microcomputers and microprocessors to construct a new generation of machines (for example, machine tools, inspection devices, robots and computer terminals) with built-in intelligence. The motivation behind this is improved utilization of equipment. For example, in CAD, a greater amount of local intelligence built into the design work stations translates into a larger number of these terminals that can be shared by one minicomputer. The same result occurs in the case of plotters and other peripheral devices. If the plotter contains sufficient local intelligence, it is capable of drawing complicated shapes based on relatively simple concise instructions from the minicomputer. The trends in this direction indicate that, within a few years, all the intelligence and computer power now present in today's CAD/CAM systems will be available at every terminal in the system. The use of these intelligent terminals in distributed systems will constitute the new family of CAD/CAM systems. With the trend towards lower computational costs, future CAD systems based on local intelligence will be cost-competitive with current systems. At the same time, the capability of the CPU, enhanced by distributed processing, can be expected to increase considerably.

The use of localized intelligence through the use of microprocessor-based systems will also influence manufacturing. The use of intelligent robots, machine tools, and inspection devices, connected to a host computer, will provide an important boost to automation. It will provide greater flexibility in production systems to deal with a variety of different products. Manufacturing and inspection instructions which have been prepared automatically on the host computer can be downloaded to the appropriate machine on the shop floor for execution.

The cost of computer storage continues to drop and this will have implications in CAD/CAM. It will become feasible to store tens of thousands of drawings on-line instead of the limited number characteristic of present systems. At some point in the future, the computer itself may become the principal storage component in file systems rather than relying so heavily on secondary storage. Secondary storage will be utilized principally in a back-up fail-safe role.

Graphics display technology is improving and this will affect other areas of operation within a company in addition to CAD. The price and performance of raster systems will become more and more favourable. High performance (that is, high resolution and fast response) is costly in these systems currently, but it is expected that hardware costs will continue to decline in the future. With this performance, the raster-type CRT will be the dominant graphics display device during the present decade and perhaps beyond. Competing display technologies include flat panels based on plasma or liquid crystal displays. The advantages offered by flat panel displays over the CRT are as follows:

(a) Much less depth and volume;
(b) Greater ratio of viewing area to depth;
(c) Better linearity and accuracy;
(d) Lower voltage required to operate; and
(e) Potentially greater resolution and contrast.

Because of the great market potential in home television, research in flat-panel technology will probably yield commercial products which are eventually competitive with raster-type CRTs.

The use of colour and solid modelling in computer graphics will become significant in design and other applications (industrial art, movie making, technical and other publications). New plotters and hard-copy units with enhanced colour capabilities will emerge to support the growth in colour and solids.

Another future trend which involves the combination of data base management systems with CAD systems is very limited at the present time. Advances in storage technology will influence this trend.

Voice recognition and vision systems technology will be refined and improved over the next decade. Computer terminals will be equipped to recognize and accept speech input as a means of speeding the input process. Future speech input systems will be included in the CAD/CAM environment. Vision systems will be used increasingly in computer-aided inspection systems. Vision is also an important emerging technology in robotics. Many future intelligent robots will be furnished with vision capability to perform their various industrial tasks.

Accompanying the technological innovations and improvements described above, there must also be a change in the way business is done in the manufacturing industries. With new communication techniques, there will be oportunities to have computers from different companies place purchase orders and communicate engineering data and specifications. With improvements in computers there will be opportunities for non-technical persons to use them.

Among the many changes in the operations of a manufacturing firm which are forced by the introduction of CAD/CAM, there will be a gradual dissolution of the traditional separation between design and production. Indeed, at some time in the distant future, it may be possible to look back at the impact of CAD/CAM on industrial progress and conclude that it was the integration of the design and manufacturing functions that was the most significant achievement of this technology.

The continuous advancement of CAD/CAM technologies is pushing industries to lower manufacturing cost and to enhance productivity. Design and production take the major amount of time in the manufacturing process. CAD/CAM ability can be best utilized in engineering applications, especially in the metalworking and plastic industries. The technique of solid modelling enables the manufacturer to analyze a new product under development without building a prototype.

As the sophistication of CAD/CAM systems increase, the manufacturing industries are realizing the cost-saving advantages associated with computer-aided production system. These production facilities can thus be gradually tied together to form an integrated production system to determine planning, engineering and manufacturing functions.

In order to make enterprises totally responsive to market demand, CAD/CAM has pushed not only the enterprises in developed countries to catch up with the new technologies, but enterprises in the NICs are also actively considering the utilization of CAD/CAM capabilities.

As the cost of hardware and software has been coming down and interest in CAD/CAM systems has risen considerably, minicomputers-based software packages have made the system more financially feasible for small and medium-scale enterprises.

Annex

GLOSSARY OF CAD/CAM TERMS

A

ABSOLUTE ACCURACY - Accuracy as measured from a reference which must be specified.

ABSOLUTE DIMENSION - A dimension expressed with respect to the initial zero point of a coordinate axis.

ACCEPTANCE TEST - A series of tests which evaluate the performance and capabilities of both software and hardware.

ACCESS TIME - The time interval between the instant at which information is: (1) called for from storage and the instant at which delivery is completed, i.e., the read time; (2) ready for storage and the instant at which storage is completed, i.e., the write time.

ACCURACY - (1) Measurement of the difference between the actual position of the machine slide and the position demanded; (2) conformity of an indicated value to a true value, i.e., an actual or an accepted standard value. The accuracy of a control system is expressed as the deviation or difference between the ultimately controlled variable and its ideal value, usually in the steady state or at sample instants.

ACTIVE STORAGE - That part of the control logic which holds the information while it is being transformed into motion.

ALGORITHM - A rule or procedure for solving a mathematical problem that frequently involves repetition of an operation.

ALPHANUMERIC OR ALPHAMETRIC - A system in which the characters used are letters A to Z, and numerals 0 to 9.

ALPHANUMERIC DISPLAY - Equipment, such as a cathode ray tube, which is capable of displaying only letters, digits and special characters.

AMT - Advanced manufacturing technology.

ANALOG - The term applied to a system which utilizes electrical voltage magnitudes or ratios to represent physical axis positions.

ANALOG DATA - The information content of an analog signal as conveyed by the value of magnitude of some characteristics of the signal such as amplitude, phase or frequency of a voltage, the amplitude or duration of a pulse, the angular position of a shaft or the pressure of a fluid.

ANALOG-TO-DIGITAL (A/D) CONVERTER - A device that changes physical motion or electrical voltage into digital factors.

APT (Automatically programmed tools) - A universal computer-assisted programme system for multi-axis contouring programming. APT III provides for five axes of machine tool motion.

APPLICATION PROGRAMMES - Computer programmes designed and written to value a specific problem.

ASCII (also USASCII) (American Standard Code for Information Interchange) - A data transmission code which has been established as an American Standard by the American Standards Association. It is a code in which 7 bits are used to represent each character.

ASSEMBLER - Computer programme that converts user-written symbolic instructions into equivalent machine-executable instructions.

ASSEMBLY - The fitting together of a number of parts to create a complete unit.

ASSEMBLY DRAWING - The drawing of a number of parts which shows how they fit together to construct a complete unit.

ASYNCHRONOUS TRANSMISSION - The transmission of information in irregular sections, with the time interval of each transmission varying and each section being identified by a start and stop signal.

ASYNCHRONOUS - Without any regular time relationship.

ATTRIBUTE - A quality that is characteristic of a subject.

AUTOMATION - The technique of making a process or system automatic. Automatically controlled operation of an apparatus, process or system, especially by electronic devices. In present-day terminology, usually used in relation to a system whereby the electronic device controlling an apparatus or process is also interfaced to and communicates with a computer.

AUXILIARY FUNCTION - A function of a machine other than the control of the coordinates of a workpiece or cutter - usually on-off type operations.

AXIS - (1) A principal direction along which a movement of the tool or workpiece occurs; (2) one of the reference lines of a coordinate system.

B

BACKGROUND - In computing, the execution of low-priority work when higher-priority work is not using the computer.

BACKGROUND PROCESSING - The automatic execution of computer programmes in background.

BASIC - Beginner's All-Purpose Symbolic Instruction Code. An algebraic language used for problem-solving by engineers, scientists and others who may not be professional programmers.

BATCH - A number of items being dealt with as a group.

BATCH PROCESSING - A manufacturing operation in which a specified quantity of material is subject to a series of treatment steps. Also a mode of computer operations in which each programme is completed before the next is started.

BAUD - A unit of signalling speed equal to the number of discrete conditions or signal events per second; 1 bit per second in a train of binary signals, and 3 bits per second in an octal train of signals.

BEHIND THE TAPE READER (BTR) - A means of inputting data directly into a machine tool control unit from an external source connected behind the tape reader.

BENCHMARK - A standard example against which measurements may be made.

BINARY CODED DECIMAL (BCD) - A number code in which individual decimal digits are each represented by a group of binary digits; in the -8-4-2-1 BCD notation, each decimal digit is represented by a four-place binary number, weighted in sequence as 8,4,2 and 1.

BINARY DIGIT (BIT) - A character used to represent one of the two digits in the binary number system, and basic unit of information or data storage in a two-state device.

BILL OF MATERIALS (BOM) - A listing of all the parts that constitute an assembled product.

BLOCK - A set of words, characters, digits or other elements handled as a unit. On a punched tape, it consists of one or more characters or rows across the tape that collectively provide enough information for an operation. A "word" or group of words considered as a unit separated from other such units by an "end of block" character (EOB).

BOOLEAN ALGEBRA - A process of reasoning using a symbolic logic and dealing with propositions or on-off circuit elements. It employs systems such as "and", "or", "not", "except", "if" and "then" to permit mathematical calculation.

BOOTSTRAP - A short sequence of instructions, which when entered into the computer's programmable memory will operate a device to load the programmable memory with a larger, more sophisticated programme - usually a loader programme.

BSPLINE - A mathematical representation of a smooth curve.

BUFFER STORAGE - (1) A place for storing information in a control for anticipated transference to active storage. It enables a control system to act immediately on stored information without waiting for a tape reader; (2) a register used for intermediate storage of information in the transfer sequence between the computer's accumulators and peripheral devices.

BUG - An error or mistake.

BULK MEMORY - A memory device for storing large quantities of data, e.g. hard disk, floppy disk or magnetic tape.

BUS - A conductor used for transmitting signals or power between elements.

BYTE - A sequence of adjacent bits, usually less than a word, operated on as a unit.

C

CALIBRATION - Adjustment of a device, such that the output is within a specified tolerance for particular values of the input.

CAMBRIDGE RING - A type of network for linking computers together which has been perfected by Cambridge University.

CANCEL - A command which will discontinue any canned cycles or sequence commands.

CANNED CYCLE - A preset sequence of events initiated by a single NC command, e.g., G84 for NC tape cycle.

CANONICAL FORM - A standard numerical representation of data.

CAPM - Computer-assisted production management.

CAPP - Computer-assisted process planning.

CARTESIAN COORDINATES - Means whereby the position of a point can be defined with reference to a set of axes at right angles to each other.

CATHODE RAY TUBE (CRT) - A display device in which controlled electron beams are used to present alphanumeric or graphical data on a luminescent screen.

CENTRAL PROCESSING UNIT (CPU) - The portion of a computer system consisting of the arithmetic and control units and the working memory.

CHANNEL - A communication path.

CHARACTER - One of a set of symbols. The general term to include all symbols such as alphabetic letters, numerals, punctuation marks and mathematical operators. Also, the coded representation of such symbols.

CHIP - A single piece of silicon which has been cut from a slice by scribing and breaking. It can contain one or more circuits but is packaged as a unit.

CIM - Computer-integrated manufacture.

CLDATA - Cutter location data (see CLFILE).

CLFILE - Cutter location file (see CLDATA).

CLOSED LOOP - A signal path in which outputs are fed back for comparison with desired values to regulate system behaviour.

CNC (Computer (computerized) numerical control) - A numerical control system wherein a dedicated, stored programme computer is used to perform some or all of the basic numerical control functions.

COMMUNICATIONS LINK - The physical means of connecting one location with another for the purpose of transmitting and receiving information.

COMPATIBILITY - The interchangeability of items.

COMPILER - A programme which translates from high-level problem-oriented computer languages to machine-oriented instructions.

COMPONENT - One of the parts of which an entity is composed.

COMPUTER - A device capable of accepting information in the form of signals or symbols, performing prescribed operations on the information and providing results as outputs.

COMPUTER-AIDED ENGINEERING (CAE) - The use of computing facilities in the integration of all aspects of design and manufacture to create an integrated engineering facility.

COMPUTER-AIDED DESIGN (CAD) - A process which uses a computer in the creation or modification of a design.

COMPUTER-AIDED MANUFACTURE (CAM) - A process which uses a computer in the management, control or operation of a manufacturing facility.

COMPUTER-AIDED DESIGN/COMPUTER-AIDED MANUFACTURE (CAD/CAM) - The integration of computer aided design and manufacture.

COMPUTER OUTPUT ON MICROFILM - Direct output from a computer to microfilm.

COMPUTER PROGRAMME - A series of instructions or statements in a form acceptable to a computer and prepared in order to achieve a certain result.

CONSOLE - Part of a computer system used for communication between the operator and the computer.

CONFIGURATION - The manner in which items are arranged.

CONTINUOUS PATH OPERATION - An operation in which rate and direction of relative movement of machine members is under continuous numerical control. There is no pause for data reading.

CONTOURING - An operation in which simultaneous control of more than one axis is accomplished.

COORDINATE DIMENSIONING - A system of dimensioning based on a common starting-point.

CORE MEMORY - A high speed random access data storage device utilizing arrays of magnetic ferrite cores, usually employed as a working computer memory.

CROSSHAIRS - A horizontal line intersected by a vertical line to indicate a point on the display whose coordinates are desired.

CURSOR - Visual movable pointer used on a CRT by an operator to indicate where corrections or additions are to be made.

CUTTER PATH - The path described by the centre of a cutter.

CYCLE - (1) A sequence of operations that is repeated regularly; (2) the time it takes for one such sequence to occur.

CYCLE TIME - The period required for a complete action. In particular, the interval required for a read and a write operation in working memory, usually taken as a measure of computer speed.

D

DATA - Facts or information prepared for processing by, or issued by, a computer.

DATA BASE - Comprehensive files of information having a specific structure such that they are suitable for communication, interpretation and processing by both human and automatic means.

DEBUG - To detect, locate and remove mistakes from computer software or hardware.

DECODER - A circuit arrangement which receives and converts digital information from one form to another.

DEDICATED - Devoted to a particular function or purpose.

DIAGNOSTIC ROUTINE - A programme which locates malfunctions in hardware or software.

DIGITAL - Representation of data in discrete or numerical form.

DIGITAL-TO-ANALOG (D-A) CONVERSION - Production of an analog signal, whose instantaneous magnitude is proportional to the value of a digital input.

DIGITIZE - To obtain the digital representation of a measured quantity or continuous signal.

DISK - A device on which information is stored.

DISK MEMORY - A non-programmable, bulk-storage, random-access memory consisting of a magnetizable coating on one or both sides of a rotating thin circular plate.

DISPLAY - Lights, annunciators, numerical indicators or other operator output devices at consoles or remote stations.

DISCRETE - State of being separate or distinct, as opposed to a continuously varying state or condition.

DISTRIBUTED COMPUTER NETWORK - A collection of computers which can communicate with each other.

DISTRIBUTED PROCESSING - The processing of information on a distributed computer network in such a manner as to improve the overall efficiency of the task.

DNC (Direct (distributive) numerical control) - Numerical control of machining or processing by a computer.

DOCUMENTATION - The group of techniques necessarily used to organize, present and communicate recorded specialized knowledge.

DOUBLE PRECISION - The use of two computer words to represent a number.

DOWN TIME - The interval during which a device is inoperative.

DRUM PLOTTER - Plotter which draws an image on paper or film which is mounted on a drum.

DUMP - To copy the present contents of a memory onto a printout or auxiliary storage.

E

EBCDIC - Extended binary coded decimal interchange code.

EDIT - To modify a programme or alter stored data prior to output.

EDITOR - A computer programme which provides the ability to edit.

EIA STANDARD CODE - Any one of the Electronics Industries Association standard codes for positioning, straight-cut and contouring control systems.

EMULATOR - A device or programme which behaves like another system and produces identical results.

ENCODER - An electromechanical transducer which produces a serial or parallel digital indication of mechanical angle or displacement.

ERROR DETECTING - A data code in which each acceptable term conforms to certain rules, such that if transmission or processing errors occur, false results can be detected.

EXECUTE - To carry out an instruction or run a programme.

EXECUTIVE - Software which controls the execution of programmes in the computer, based on established priorities and real-time or demand requirements.

F

FEEDBACK - The signal or data fed back to a commanding unit from a controlled machine or process to denote its response to the command signal. The signal representing the difference between actual response and desired response that is used by the commanding unit to improve performance of the controlled machine or process.

FEEDBACK CONTROL - Action in which a measured variation is compared to its desired value, with a function of the resulting error signal used as a corrective command.

FEEDBACK DEVICE - An element of a control system which converts linear or rotary motion to an electrical signal for comparison to the input signal.

FEEDBACK LOOP - A closed signal path, in which outputs are compared with desired values to obtain corrective commands.

FEEDBACK RESOLUTION - The smallest increment of dimension that the feedback device can distinguish and reproduce as an electrical output.

FEEDBACK SIGNAL - The measurement signal indicating the value of a directly controlled variable, which is compared with a set point to generate a correction command.

FEED FUNCTION - The relative motion between the tool or instrument and the work due to motion of the programmed axis or axes.

FINITE ELEMENT MESH GENERATION - Engineering method for determining the structural integrity of a mechanical part by mathematical simulation. Automatic mesh generation automatically creates grid points and elements for specific regions of a model allowing creation of data necessary for finite element analysis programmes.

FLATBED PLOTTER - Plotter that draws an image on paper or film which is mounted on a flat table.

FLOPPY DISC - A flexible disc which is used for storing information.

FONTS-LINE - Repetitive pattern used to give meaning to a line, e.g. solid, dashed or dotted.

FONTS-TEXT - A complete set of one character set.

FOREGROUND PROCESSING - Execution of real-time or high-priority programmes which can pre-empt the use of computing facilities.

FORMAT - The arrangement of data.

FORMAT CLASSIFICATION - A means, usually in an abbreviated notation, by which the motions, dimensional data, type of control system, number of digits, auxiliary functions etc. for a particular system can be denoted.

FORMAT DETAIL - Describes specifically which words of what length are used by a specific system in the format classification.

FIRMWARE - Programmes or instructions stored in read only memories.

FIRST GENERATION - (1) In the NC industry, the period of technology associated with vacuum tubes and stepping switches; (2) the period of technology in computer design utilizing vacuum tubes, electronics, off-line storage on drum or disc and programming in machine language.

FORTRAN - Acronym for Formula Translator, an algebraic-procedure-oriented computer language designed to solve arithmetic and logical programmes.

FULL DUPLEX - Allows the simultaneous transmission of information in both directions.

FUNCTION KEY - Specific key which causes a predefined function to be requested of the system whenever the key is depressed.

G

GAIN - The ratio of the magnitude of the output of a system with respect to that of the input (the conditions of operation and measurements must be specified, e.g., voltage, current or power).

GENERAL-PURPOSE COMPUTER - A computer designed and capable of carrying out a wide range of tasks.

GKS - Graphics Kernal System, a standard for graphics software.

GRAPHICS - The use of a computer to interactively create a drawing displayed on a terminal.

GRAPHICS TABLET - A surface through which coordinate points can be transmitted by identification with a cursor or stylus.

GRID - Network of uniformly placed dots on an input device used for locating position.

GROUP TECHNOLOGY - The grouping of machines and of parts based on similarities in production requirements such that the parts may be produced more efficiently.

H

HALF DUPLEX - Allows the transmission of information one way at a time.

HARD COPY - Any form of computer-produced printed document. Also sometimes punched cards or paper tape.

HARDWARE - Physical equipment.

HIDDEN LINES - Line segments that would be obscured from view in the display of a solid three-dimensional object.

HIGH-LEVEL LANGUAGE - A programming language that generates machine codes from problem- or function-oriented statements. Fortran and Cobol are commonly used high-level languages. A single high-level statement may translate into a series of instructions in machine language, in constrast to a low-level language in which statements translate on a one-for-one basis.

HOST COMPUTER - Computer attached to a network providing services such as computation, data base management and special programmes.

HOUSEKEEPING - The general organization of programmes stored to ensure efficient system response.

I

IEEE - Institute of Electrical and Electronic Engineers (United States).

IGES - International Graphics Exchange Standard.

INCREMENTAL DIMENSION - A dimension expressed with respect to the preceding point in a sequence of points.

INCREMENTAL SYSTEM - Control system in which each coordinate or positional dimension is taken from the last position.

INHIBIT - To prevent an action or acceptance of data by applying an appropriate signal to the appropriate input.

INITIALIZE - To cause a programme or hardware circuit to return a programme, a system, or a hardware device to an original state or to selected points within a computer programme.

INPUT - A dependent variable applied to a control unit or system.

INSTRUCTION - A statement that specifies an operation and the values or locations of its operands.

INSTRUCTION SET - The list of machine language instructions which a computer can perform.

INTEGRATED CIRCUIT (IC) - A combination of interconnected passive and active circuit elements incorporated on a continuous substrate.

INTEGRATOR - A device which integrates an input signal, usually with respect to time.

INTELLIGENT TERMINAL - A terminal which has its own local processing power.

INTERACTIVE GRAPHICS - Ability to carry out graphics tasks with immediate response from the computer.

INTERFACE - (1) A hardware component or circuit for linking two pieces of electrical equipment having separate functions, e.g., tape reader to data processor or control system to machine; (2) a hardware component or circuit for linking the computer to external I/O device.

INTERLOCK - To arrange the control of machines or devices so that their operation is interdependent in order to assure their proper coordination.

INTERLOCK BY-PASS - A command to temporarily circumvent a normally provided interlock.

INTERPOLATION - (1) The insertion of intermediate information based on assumed order or computation; (2) a function of a control whereby data points are generated between given coordinate positions to allow simultaneous movement of two or more axes of motion in a defined geometric pattern, e.g., linear, circular and parabolic.

INTERRUPT - A break in the execution of a sequential programme or routine, to permit processing of high priority data.

I/O (Input/Output) - Input or output or both.

ISO - International Standards Organization.

ITERATION - A set of repetitive computations, in which the output of each step is the input to the next step.

J

JCL - Job control programme.

JOB - An amount of work to be completed.

JOYSTICK - A data entry device for manually entering coordinates in specific XYZ registers.

K

KEYBOARD - The keys of a teletypewriter which have the capability of transmitting information to a computer but not receiving information.

L

LAN - Local Area Network.

LAYER - Logical concept to distinguish subdivided groups of data within a given drawing. May be thought of as a series of transparencies which may be displayed in any order.

LAYOUT - A visual representation of a complete physical entity usually to scale.

LIGHT PEN - A photosensing device similar to an ordinary fountain pen which is used to instruct CRT displays by means of light-sensing optics.

LINEAR INTERPOLATION - A function of a control whereby data points are generated between given coordinate positions to allow simultaneous movement of two or more axes of motion in a linear (straight line) path.

LINE PRINTER - A printing device that can print an entire line of characters all at once.

LINKAGE - A means of communicating information from one routine to another.

LOG - A detailed record of actions for a period of time.

LOG OFF - The completion of a terminal session.

LOG ON - The beginning of a terminal session.

LSI - Large-scale integrated circuit.

M

MACHINE LANGUAGE - A language written in a series of bits which are understandable by, and therefore instruct, a computer. The "first-level" computer language, as compared to a "second-level" assembly language or a "third-level" compiler language.

MACRO - A scurce language (q.v.) instruction from which many machine language instructions can be generated.

MAGNETIC DISK STORAGE - A storage device or system consisting of magnetically coated metal disks.

MAGNETIC TAPE - A tape which is constructed from plastic and coated with magnetic material which is used to store information.

MAIN FRAME - See central processing unit.

MANUAL DATA INPUT (MDI) - A means of inserting data manually into the central system.

MANAGEMENT INFORMATION SERVICE (MIS) - An information feedback system from the machine to management and implemented by a computer.

MASS PROPERTIES - Calculation of physical engineering information about a part, e.g. perimeter, area, volume, weight and moments of inertia.

MASS STORAGE - Auxiliary or bulk memory that can store large amounts of data which is readily accessible to the computer.

MEMORY - A device or medium used to store information in a form that can be understood by the computer hardware.

MEMORY PROTECT - A technique of protecting stored data from alteration, using a guard bit to inhibit the execution of any modification instruction.

MENU - Input device consisting of command squares on a digitizing surface. It eliminates the need for input keyboard for common instructions.

MICROPROCESSOR - A single integrated circuit which forms the basic element of a computer.

MICROPROGRAMMING - A programming technique in which multiple instruction operations can be combined for greater speed and more efficient memory use.

MIRRORING - A graphics construction aid - the ability to create a mirror image of a graphic entity.

MNEMONIC - An alphanumeric designation, designed to aid in remembering a memory location or computer operation.

MODEL - A geometrically accurate and complete representation of a real object stored in a CAD/CAM data base.

MODEM - A contraction of modulator demodulator. The term may be used with two different meanings: (1) the modulator and the demodulator of a modem are associated at the same end of a circuit; (2) the modulator and the demodulator of a modem are associated at the opposite ends of a circuit to form a channel.

MODULE - An independent unit which may be used on its own or in conjunction with other units to form a complete entity.

MONITOR - A device used for observing or testing the operations of a system.

MOUSE - A manual device for use in information input and in accessing differing portions of a screen.

MULTIPLEXER - A hardware device which handles multiple signals over a single channel.

N

NETWORK - Two or more central processing units which are interconnected.

NOISE - An extraneous signal in an electrical circuit capable of interfering with the desired signal. Loosely, any disturbance tending to interfere with the normal operation of a device or system.

NUMERICAL CONTROL (NC) - A technique of operating machine tools or similar equipment, in which motion is developed in response to numerically coded commands.

NUMERICAL DATA - Data in which information is expressed by a set of numbers that can only assume discrete values.

O

OBJECT PROGRAMME - The coded output of an assembler or compiler.

OCTAL - A characteristic of a system in which there are eight elements, such as a numbering system with a radix of eight.

OFF-LINE - Operating software or hardware not under the direct control of a central processor, or operations performed while a computer is not monitoring or controlling processes or equipment.

ON-LINE - A condition in which equipment or programmes are under direct control of a central processor.

OPEN LOOP - A signal path without feedback.

OPEN LOOP SYSTEM - A control system that has no means of comparing the output with the input for control purposes (no feedback).

OPERATING SYSTEM - Software which controls the execution of computer programmes and the movement of information between peripheral devices.

OPTIMIZE - To establish control parameters which maximize or minimize the value of performance.

ORIGIN - A reference position whose coordinate values are zero.

OUTPUT - The transfer of information out of a computer; it may be output to punched tape or magnetic tape, to another computer, etc.

OUTPUT DEVICE - A device for producing output, e.g., printer, plotter or paper tape punch.

OUTPUT SIGNAL - A signal delivered by a device, element or system.

OVERLAY - A technique of repeatedly using the same area of computer store when handling different stages of a problem.

P

PAN - To move an image on a display to the left, right, up or down.

PARALLEL - The simultaneous transfer and processing of all bits in a unit of information.

PARAMETER - A characteristic of a system or device, the value of which serves to distinguish various specific states.

PARAMETRICS - High level graphical applications language used to build variable geometric constructions and solve problems.

PARITY CHECK - A test of whether the number of ones or zeros in an array of binary digits is odd or even to detect errors in a group of bits.

PART PROGRAMME - Specific and complete set of data and instructions written in source languages for computer processing or written in machine language for manual programming for the purpose of manufacturing a part on an NC machine.

PART PROGRAMMER - A person who prepares the planned sequence of events for the operation of a numerically controlled machine tool.

PASSWORD - A word the operator must supply in order to meet the security requirements and gain access to the computer.

PATCH - Temporary coding used to correct or alter a routine.

PERIPHERAL EQUIPMENT - The auxiliary machines and storage devices which may be placed under control of the central computer and may be used on-line, e.g., card reader and punches, magnetic tape feeds, high-speed printers, CRTs and magnetic drums or discs.

PHOTOPLOTTER - Device used to generate artwork photographically.

PLOTTER - A device used to make a drawing of a display.

POINT-TO-POINT CONTROL SYSTEM - An NC system which controls motion only to reach a given end-point but exercises no path control during the transition from one end-point to the next.

POLAR COORDINATES - A mathematical system for locating a point in a plane by the length of its radius vector and the angle this vector makes with a fixed line.

POSITION READ-OUT - A display of absolute slide position as derived from a position feedback device normally attached to the lead screw of the machine.

POSITION SENSOR - A device for measuring a position, and converting this measurement into a form convenient for transmission.

POST-PROCESSOR - The part of the software which converts all the cutter path coordinate data (obtained from the general-purpose processor and all other programming instructions and specifications for the particular machine and control) into a form which the machine control can interpret correctly.

PRECISION - The degree of discrimination with which a quantity is stated, e.g., a three-digit numerical value discriminates among 1,000 possibilities. Precision is contrasted with accuracy, i.e., a quantity expressed with 10 decimal digits of precision may only have one digit of accuracy.

PREPARATORY FUNCTION - An NC command on the input tape changing the mode of operation of the control (generally noted at the beginning of a block by "G" plus two digits).

PREPROCESSOR - A computer programme which prepares information for processing.

PREVENTIVE MAINTENANCE - Maintenance specifically designed to identify potential faults before they occur.

PROCESSOR - A computer programme which processes information.

PRINTED CIRCUIT - A circuit for electronic components made by depositing conductive material in continuous paths from terminal to terminal on an insulating surface.

PROGRAMME - A plan for the solution of a problem. A complete programme includes plans for the transcription of data, coding for the computer and plans for the absorption of the results into the system. The list of coded instructions is called a routine. Thus, programming consists of planning and coding, including numerical analysis, systems analysis, specification of printing formats, and any other functions necessary for the integration of the computer into the system.

PROGRAMMABLE - Capable of being set to operate in a specific manner, or of accepting remote set point or other commands.

PROTOCOL - Set of rules governing message exchange between two devices.

PUCK - Manually operated directional control device used to input coordinate information.

PUNCHED CARD - A piece of lightweight cardboard on which information is represented by holes punched in specific positions.

PUNCHED PAPER TAPE - A strip of paper on which characters are represented by combinations of holes.

R

RANDOM ACCESS MEMORY (RAM) - A storage unit in which direct access is provided to information, independent of memory location.

RASTER DISPLAY - A display in which the entire display surface is scanned at a constant refresh rate.

RASTER SCAN - Line-by-Line sweep across the entire display surface to generate elements of a display image.

READ - To acquire data from a source. To copy, usually from one form of storage to another, particularly from external or secondary storage to internal storage. To sense the presence of information on a recording medium.

READER - A device capable of sensing information stored in an off-line memory medium (cards, paper tape, magnetic tape) and generating equivalent information in an on-line memory device (register, memory locations).

READ-ONLY MEMORY (ROM) - A storage device generally used for control programs whose content is not alterable by normal operating procedures.

REAL TIME CLOCK - The circuitry which maintains time for use in program execution and event initiation.

REAL TIME OPERATION - Computer monitoring, control, or processing functions performed at a rate compatible with the operation of physical equipment or processes.

REFRESH - CRT display technology which requires continuous restroking of the display image.

REPAINT - Redraws a display on a CRT to reflect its current status.

REPEATABILITY - The closeness of agreement among multiple measurements of an output, for the same value of the measured signal under the same operating conditions, approaching from the same direction, for full-range traverses.

REPRODUCIBILITY - The closeness of agreement among repeated measurements of the output for the same value of input, made under the same operating conditions over a period of time, approaching from either direction.

RESOLUTION - (1) The smallest distinguishable increment into which a signal or picture etc. is divided in a device or system; (2) the minimum positioning motion which can be specified.

RESOLVER - (1) A mechanical to electrical transducer whose input is a vector quantity and whose outputs are components of the vector; (2) a transformer whose coupling may be varied by rotating one set of windings relative to another. It consists of a stator and rotor, each having two distribution windings 90 electrical degrees apart.

ROLLER BALL - A manual data input device.

ROBOT - An automatic device which performs functions ordinarily ascribed to human beings.

ROUTINE - A series of computer instructions which performs a specified task.

RUBBER BANDING - A technique for displaying geometry which has one end fixed and the other end following a stylus or some other device.

RUN - The execution of a programme on a computer.

S

SCALE - To change a quantity by a given factor, to bring its range within prescribed limits.

SCALE FACTOR - A coefficient used to multiply or divide quantities in order to convert them to a given magnitude.

SCHEDULE - A programme or timetable of planned events or of work.

SCULPTURED SURFACE - A mathematically described surface.

SCROLL - To move an image on a display to the left, right, up or down.

SECURITY - Prevention of unauthorized access to information or programmes.

SENSITIVITY - The ratio of a change in steady state output to the corresponding change of input, often measuring in percentage of span.

SERIAL - The transfer and processing of each bit in a unit of information, one at a time.

SIGN - The symbol or bit which distinguishes positive from negative numbers.

SIGNAL - Information conveyed between points in a transmission or control system, usually as a continuous variable.

SIGNIFICANT DIGIT - A digit that contributes to the precision of a numeral. The number of significant digits is counted beginning with the digit contributing the most value, called the most significant digit, and ending with the one contributing the least value, called the least significant digit.

SIMULATOR - A device or computer programme that performs simulation.

SOFTWARE - The collection of programmes, routines, and documents associated with a computer.

SOURCE LANGUAGE - The symbolic language comprised of statements and formulas used to specify computer processing. It is translated into object language by an assembler or compiler, and is more powerful than an assembly language in that it translates one statement into many items.

STABILITY - Freedom from undesirable deviation, used as a measure of process controllability.

STAND-BY POWER SUPPLY - An energy generation or storage system, that can permit equipment to operate temporarily or shut down in an orderly manner.

STATIC GAIN - The ratio of steady state output to input change.

STEADY STATE - A characteristic or condition exhibiting only negligible change over an arbitrarily long period of time.

STORAGE - A memory device in which data can be entered and held, and from which it can be retrieved.

STORAGE TUBE - A CRT which retains an image for a considerable period of time without redrawing.

STYLUS - A hand-held device by which coordinate information may be input to a display unit.

SUBROUTINE - A series of compute instructions to perform a specific task for many other routines. It is distinguishable from a main routine in that it requires, as one of its parameters, a location specifying where to return to the main programme after its function has been accomplished.

SURFACE OF REVOLUTION - Rotation of a curve around an axis through a specified angle.

SURFACE MACHINING - The ability to output 3-, 4- and 5-axis NC tool paths using 3-dimensional surface definition capabilities.

SYMBOL LIBRARY - A library of commonly used graphical symbols.

SYNCHRONOUS - A fixed rate transmission of information synchronized by a clock for both receiver and sender.

SYNTAX - The rules which govern the structure of words and expressions in a language.

T

TABLET - An input device which allows digitized coordinates to be indicated by stylus position.

TABULATED CYLINDER - The translation of a curve along a direction line with upper and lower limits on the distance of translation.

TAPE - A magnetic or perforated paper medium for storing information.

TAPE TRAILER - The trailing end portion of a tape.

TAPE LEADER - The front or lead portion of a tape.

TAPE PREPARATION - The act of translating command information into punched or magnetic tape.

TASK - A unit of work.

TERMINAL - A device by which information may be entered or extracted from a system or communication network.

TIME SHARING - The interleaved use of a sequential device, to provide apparently simultaneous service to a number of users.

TOOLPATH - The geometry of the path a tool will follow to machine a component.

TRACK - The portion of a moving storage medium, such as the drum, tape or disc, that is accessible to a given reading head position.

TRUNCATE - To terminate a computational process in accordance with some rule, e.g., to end the evaluation of a power series at a specified term.

TRUTH TABLE - A matrix that describes a logic function by listing all possible combinations of inputs, and indicating the outputs for each combination.

TUNING - The adjustment of coefficients governing the various modes of control.

TURNKEY SYSTEM - A term applied to an agreement whereby a supplier will install an NC or computer system so that he has total responsibility for building, installing and testing the system.

V

VDU - Visual display unit.

VLSI - Very large-scale integrated circuit.

W

WINCHESTER - A type of hard disk memory storage unit.

WINDOW - A rectangular area on a display screen selected by the operator.

WINDUP - Lost motion in a mechanical system which is proportional to the force or torque applied.

WIRE-FRAME - A three dimensional drawing created by the projection of the points of intersection of the geometry.

WORD ADDRESS FORMAT - Addressing each word in a block by one or more characters which identify the meaning of the word.

WORD LENGTH - The number of bits or characters in a word.

Z

ZERO - One of the two symbols normally employed in binary arithmetic and logic, indicating the value zero and the false condition, respectively.

ZERO SUPPRESSION - The elimination of non-significant zeros to the left of significant digits usually before printing.

ZERO SYNCHRONIZATION - A technique which permits automatic recovery of a precise position after the machine axis has been approximately positioned by manual control.

ZOOM - To enlarge or decrease proportionally the size of the display.