AHMADU BELLO UNIVERSITY, ZARIA
DEPARTMENT OF MECHANICAL ENGINEERING

COMPUTER-AIDED DESIGN (CAD)/ COMPUTER-AIDED MANUFACTURING (CAM) AND THEIR APPLICATIONS IN NIGERIA

BY
Livinus Tyovenda Tuleun

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DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work. It has not been accepted in any previous application for higher degree. All quotations are distinguished by quotation marks and the sources of information are specifically acknowledged by means of references.



Livinus Tyovenda Tuleun.

27th October, 1983.

A B S T R A C T

This thesis is a study of computer-aided design (CAD)/computer-aided manufacturing (CAM) and their applications in Nigeria.

Computer-aided design is the design process augmented at numerous points by the use of a computer. Computer-aided manufacturing refers to the use of a computer to perform or aid in some manufacturing processes.

Basically, three stages of gradual development in the field of interactive computer graphics and its application for design and manufacturing generally have been experienced. These are: conception to birth, childhood and adolescence, with still adulthood ahead.

Basing on the present availability of appropriate computer hardware at the Iya Abubakar Computer Centre at Ahmadu Bello University, Zaria, some graphical output from Fortran programmes have been produced. An example of computer-aided design of a simple shaft has been given as an example of CAD application.

A programme for finite element method structural analysis of the designed shaft has been written, implemented and tested. For the purpose of the analysis, the stepped shaft has been assumed simply supported, with two point loads of 10N each and a uniformly distributed load of 40N/mm. Results obtained by using the programme compare favourably with analytical results for this particular case study. This programme can therefore be used for structural analysis of shafts and beams of varying dimensions.

Finally, a field study for the application of CAD/CAM in Nigeria has been carried out. It has been found that practically CAD and CAM have started to appear in Nigeria but are usually limited to few functions only. Furthermore, there are various special problems associated with the use of computers in performing some CAD and CAM functions. Among these problems are the lack of spare parts, skilled manpower, maintenance, lack of awareness of potentials of the computer, lack of interest by users concerned and the quality as well as the quantity of power supplied by the National Electric Power Authority (NEPA). Possible solutions to these problems have been highlighted.

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LIST OF SYMBOLS

(1) - (14) ..... References

E ..... Young's Modulus

F ..... Externally applied force

I ..... Second moment of area for bending

i ..... nodal point number

j ..... nodal point counter

K ..... Overall stiffness matrix

k_{pq} ..... Coefficient of the overall stiffness matrix

k_m ..... element stiffness matric

k_{rs} ..... coefficient of the element stiffness matrix

L ..... length of beam

L_m ..... length of an element

m ..... element counter

N ..... bending moment

n ..... number of modal points in a mesh

Q ..... shear force

R_m ..... vector of internal forces (and moments) applied to an element at its nodes

t ..... time

..... overall vector of unknowns such as displacements

Q_i, Q_j ..... rotations of ends of a beam element

LIST OF ABBREVIATIONS

A.B.U.	-	Ahmadu Bello University
ACM	-	Association for Computing Machinery
APT	-	Automatically Programmed Tooling
ARDS	-	Advanced Remote Display Station
CAD	-	Computer - Aided Design
CAM	-	Computer - Aided Manufacturing
CADAM	-	Computer graphics Augmented Design and Manufacturing
CADD	-	Computer - Aided Digigraphic Design
CDC	-	Control Data Corporation
CL	-	Cutter location
COGAP	-	Computer Graphics Arrangement Programme
DAC	-	Design Augmented by Computer
DNC	-	Direct Numerical Control
DPMS	-	Data Preparation Maintenance and services
DVST	-	Direct View Storage Tube
GK	-	Graphical Kernel
GM	-	General Motors
ICAM	-	Integrated Computer-Aided Manufacturing
IEEE	-	Institute of Electrical and Electronics Engineers
IPAD	-	Integrated Programme for Aerospace Vehicle Design
ITIS	-	Interactive Terminal Interface System
MIS	-	Management Information system
MIT	-	Massachusetts Institute of Technology

NASA - National Aeronautics and space Administration

NC - Numerical control

NCCG - Numerical control computer Graphics

NCGA - National Computer Graphics Association

NNPC - Nigeria National Petroleum Corporation

NCR - National Cash Register

SIGRAPH - Special Interest Group for Graphics

UCLA - University of California, at Los Angeles

WRECA - Water Resources Engineering Construction Agency

LIST OF PROGRAMME VARIABLE NAMES

D ..... diameter

DELTA ..... unknowns such as displacements

E ..... Young's Moduli

ESTIFF ..... Coefficients of element stiffness matrix

F ..... Coefficients of the vector of overall externally applied forces

I ..... nodal point counter

ICE ..... column counter for element stiffness matrix

ICOL ..... column counter for full (square) overall stiffness matrix

IRE ..... row counter for element stiffness matrix

IROW ..... row counter for overall stiffness matrix

J ..... nodal point counter

M ..... element counter

NEL ..... number of elements in a mesh

NEQN ..... number of equations to be solved

NNP ..... number of nodal points in the mesh

NPI, NPJ .... Numbers assigned to the nodes of the elements

OSTIFF ..... coefficients of overall stiffness matrix

X, Y ..... global cartesian co-ordinates of the nodal points

CHAPTER ONE

INTRODUCTION AND OBJECTIVES

1.1. INTRODUCTION:

Since the inception of computers, they have been used for a wide variety of applications.

This exists throughout the whole range of scientific and engineering fields as well as the commercial fields.

Initially, the main use of the computer in the area of science[1] was for the performance of complex and/or repetitive scientific calculations. Later on, the computer became used increasingly in the scientific and engineering fields as well as businesses and many other areas. The use of computers in most other areas was limited to the functions for which initially slide rules, calculators, cash registers and other mechanical devices had previously been used. Before very long, however, it was realized that such a powerful tool could be used for more than calculating. It could even be used to process information. Thus anything which can be stored in books or other written documents, on film or recording tape, can be stored in the computer. Moreover, access to this information can be very rapid; instead of having to hunt, physically, for the appropriate book or file, one can ask the computer for it. The computer will then display the information as

required, on a screen.

It is thus clear that the need for increased understanding of computers is obvious. We are crossing the threshold of a new era in which the integration of computer-based information with industrial processes and machinery can be expected to alter the technological landscape dramatically. Mechanical engineers are already using electronic aids to ease or eliminate tedious, repetitive tasks. As earlier mentioned in the preface, computers can be counted on to improve productivity and reduce the time from design concept to execution and manufacture. In manufacturing operations, the engineer can, with the aid of computer facilities, use numerical control, classification, coding, robotics, and manipulators to cut production costs and time.(2)

Hence there is need to study CAD/CAM and to assess to which extent it is being applied in Nigeria.

1.1.1. Computer-Aided Design (CAD)

Briefly, engineering design is the creation of manufacturing instructions, in the form of drawings or tabulated orders, for machines, structures, systems or processes which are required to perform some particular function. It is an intellectual activity involving the synthesis of many branches of knowledge.

The design process may be broken down to include the following steps:(3)

(i) The recognition of a need. This is the stage at which the problem becomes defined.

(ii) The generation of different schemes for solving the problem and from this the selection of one or more for detailed study; the main feature here would be feasibility studies backed up by any special research needed.

(iii) Preliminary design. This established the overall features of the machine, system or process and makes it possible to specify the major components.

(iv) Complete detail design.

It is in stage (ii) that the designer is predominant as a creator and at this stage his imagination and ingenuity should be given full play; in the following stages he uses his ability to synthesize the amount of information presented to him by his colleagues.

Computer-aided design (CAD) therefore is the design process augmented at numerous points by the use of a computer.

On the other hand, CAD is a human-computer interaction system, where the graphic display terminal replaces the drawing board, reference books, and the slide rule.[2] The designer is able to "converse" with the computer and receive a direct response from it. This two-way conversation may be graphical or

pictorial in nature. For example, the designer may generate a picture on the graphic display terminal by using a light pen. As a result of previous programming the computer "understands" the picture, makes calculations (for instance, stress analysis), based on it, and presents answers or a revised picture to the designer within a few seconds.

The computer can carry out vast amounts of detailed work, tirelessly and without error. It can evaluate the consequences of an endless series of design alterations, performing both the engineering calculations and the graphical manipulations, and can file away each alternative for future reference. Remembering things is a task at which the computer excels. Optimum solutions for some problems cannot be obtained in closed form, thus requiring the designer to resort to a tiresome trial-and-error process. For such problems, the computer can be instructed to implement a set of parameters and generate a family of solutions, from which the optimum one can be eventually selected.

The effort of achieving this close coupling between the designer and computer has four important benefits:[2]

(i) Designers can immediately see and correct any gross errors in their drawings or input statements.

(ii) Designers can monitor the progress of a problem solution and terminate the run or modify the input data as required.

(iii) The designer can make subjective decisions at critical branch points which guide the computer in a continuation of the problem solution.

(iv) The graphic display may present data that cannot be readily understood or interpreted in a computer output listing or even in plotted output. Through clever programming, a computer-driven display can present multiple views, moving pictures, blinking lines, dashed lines, and lines of varying intensity.

A light pen and function keyboards are some of the main input devices used by designers. Designers gain a distinct feeling of direct and personal control over the entire system because of the actions they perform with the light pen. The function keyboards make available at the touch of a key, functions for creating lines, points, circles, erasing, reversing an image, and so on. Upon designating their choice with the light pen, an acknowledgement message is displayed. Users will also receive tutorial messages at the edge of the screen, reminding them of the next step they must take and the choice of actions (menus) available to them. Caution

notices, such as illegal entry, impossible geometry, and capacity limit approaching, may also be displayed.

The view function enables the derivation of a third (or auxiliary), or oblique, or perspective, or isometric view. In addition, one view (or any part of it) can be quickly transferred to any other drawing, with the scale or the orientation changed at will. The group function enables the instant translation of any group of lines or notes to any point on that particular drawing and also sets it up for transfer to another drawing in the same manner as a complete view.

Working in this way the engineer can perform his task and view the results quickly; if the results are unsatisfactory, he can perform some editing function and try another approach.

1.1.2. Computer-Aided Manufacturing (CAM)

Briefly, manufacturing process is a chain of activities aimed at meeting a set of objectives defined by management. The objectives are mainly concerned with the production of tangible goods, and the activities are, as a rule, specified by the engineering profession. The engineer in order to specify the required activities must consider many parameters and alternatives, and reach decisions as to how, what, where and when. The more alternatives and parameters considered, the better the design finally devised.

The process of decision making will, however, take more time.

Computer-aided manufacturing (CAM), on the smallest extreme,[2] refers to the use of a computer just to run a programme such as for example, the Automatic Programmable Tool (APT) for programming numerical control(NC) machine tools, while on the largest extreme, it refers to a computer-integrated manufacturing system that controls all phases of the industrial enterprise: product design (CAD), process planning, flow of material, production planning, positioning of materials, automatic production, assembly and testing, automatic warehousing, and shipping. Leading ultimately to a completely automated (computerized) factory (sometimes referred to as un-manned factory !). No such complete system exists today, however, numerical control (NC) machines, robots, computerized inspection machines, computerized assembly lines, etc., are built recently to cover most types of processing and the general line of progress is evident.

Since the manufacturing process is a dynamic one, conditions are constantly changing and decisions have to be made within a short space of time. Since the computer can store and manipulate a large quantity of data in a short period of time, it can be employed to narrow the gap between the conflict demands of time and

decision. Today, computers are used in many industrial activities. They are being utilized more and more to perform the controlling and logistic functions of machines.

In the production phase of the manufacturing process, there probably is not a single activity that does not really need the utilization of computer. The company log book, book-keeping, inventory, purchasing and personal records and many more have long been managed by computers at many companies and additional activities are continuously being added to this list.

1.2. OBJECTIVES:

The prime objectives of this work are as follows:-

(i) To carry out briefly, a study of historical background, present status and trends for future development of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM).

(ii) To design, implement and test computer programmes capable of performing some basic CAD functions.

(iii) To investigate theCAD/CAM activities occurence in Nigeria and their scope.

CHAPTER TWO

HIGHLIGHTS OF DEVELOPMENT OF INTERACTIVE COMPUTER GRAPHICS AND COMPUTER AIDED DESIGN AND MANUFACTURING

2.1. INTRODUCTION:

Basically, three stages of gradual development in the field of interactive computer graphics and its application for design and manufacturing have been experienced. They are:[3,4] conception to birth, childhood and adolescence, with still full adulthood ahead. As usual in technology, conception to birth has a rather long gestation period which in this particular case is from the mid 1950s through 1963. Childhood takes the period from 1954 to 1970. From about 1970 to now is the adolescence period. This is the period during which the interactive computer graphics industry established its position, asserted its independence, and prepared itself for adulthood, which is now at hand. The three stages of gradual development will now be considered separately.

2.2. THE BIRTH OF INTERACTIVE COMPUTER GRAPHICS:

Interactive graphics, at the initial stage involved, in fact, very little interaction.[3,4] There was no time-shared computation at that time and because of the high cost of hardware, single users were not given dedicated time. There was no utility and appli-

cation software generally available and system reliability was poor. That is not particularly surprising because the use of electronic computation was, itself, in its infancy. The scientists of the day, in spite of such limitations, could see the trends and were predicting the improvements in computer technology that would set the stage for the many virtues of computer graphics. There were many bits and pieces of computer technology that were being explored in military systems in the United States of America (USA). There was also some level of advanced thinking in industry and at the Universities both in the USA and in Europe. All of this was the experience foundation which formed the basis for significant industrial development during the 1960s.

2.2.1. The Mid-1950s:

During the mid-1950s, cathode ray tubes (CRTs) were being used in the display of military command and control problems. However, such displays were generally passive in nature, that is, there was no interaction between man and display. However, there is evidence that the "light pen" emerged in that time period.[3,4] Thurber Moffett of the Convair Division of General Dynamics had been trying to find ways to computerize drawings.

In 1956, Moffett met with Robert Cortney, who was

with IBM. They were interested in exploring ways to deal with documentation in a more formalized sense. This led to the computerized treatment of drawing data such as parts lists, file up dates, title blocks, and alphanumerics, but the treatment of the graphic elements of drawing had not yet been defined. The management of drawing data was known as configuration management, a concept still used today. It was first employed on the Air Force's Atlas Missile Weapon System in U.S.A.

2.2.2. The Beginning Of Automatically Programmed Tooling (APT)

During the late 1950s, a number of computer programmes was being developed to define sketches and to produce output in the form of refined plots.(3,4) A programme of particular note at Massachusetts Institute of Technology (MIT) Lincoln Laboratory was Automatically Programmed Tooling(APT). The principal architect of the language known as APT II in 1957, was Douglas T. Ross, now Chairman of the Board of a consulting company named Softech. (APT I apparently, was not completed). This system afforded a programmer the capability to programme both part geometry and the cutter path and eventually produce the punched tape which a numerically controlled (NC) machine would follow to fabricate the part. Programming was done at that moment entirely off-line (that is the programme was not interactive, but processed on batch-mode). The

tape could be obviously used to replicate the part as often as desired.

In 1961,[3,4] an 11-month project was formed with eight participating aerospace companies. The project was conducted at Convair, San Diego, in U.S.A., under the direction of E. Bates, and sponsored by the Aerospace Industries Association (AIA). Out of the project APT III was produced. It is a very significant step towards achieving what is today's CAM.

Also during the mid-1950s, many people gave thought to the use of existing CRT's, keyboards, typewriters, and computers, to facilitate the more automated use of graphic or visual techniques. The "light gun" or "light pen" concept was not yet conceived by most of the early developers. It seems that Dr. Everett, now President of MITRE Corporation created the first light pen in the mid-1950s at MIT.

There were other happenings in the late 1950s that set the stage for interactive computer graphics. It was during this period that Stromberg Carlson produced a SC 4020 system, which would process computer data from tape and produce a graphical image on a special CRT, on sensitized paper, or on film. Of course, this was not interactive in nature; but passive graphics systems such as the earlier mentioned military systems. APT and the SC 4020 helped to establish early concepts

of imagery that would be the graphics portion of interactive graphics for CAD/CAM application.

2.2.3. The "Light Pen"Concept:

Also in the late 1950s, at MIT's Lincoln Laboratory, a military-oriented project SAGE, the Semi-Automatic Ground Environment System,[3,4] was being developed under Dr. Norman Taylor. It was during this period that there was a thought, "Would it not be nice to simply point to two entities on the screen and have the computer automatically make a linkage?" This was a natural requirement or specification for the light pen. The light pen would receive light through a fiber optic system as the light was generated on a CRT display from its computer source. Thus the light pen would send a signal back to the computer that "said" in effect, that it was receiving light at the same location on the display where the computer system was providing information - a point, a line, a curve, a character, a geometric entity, a symbol, a menu item, or whatever. This is the basis of the light pen of today.

It was recognized in this time period that if two points could be designated using a light pen or some other medium or if points could be displayed from computer output through some analytical process, then straight lines could be drawn by the CRT to connect pairs of points. Thus it was understood that curves, objects, and general

geometric forms could be portrayed through the linearization of geometry; e.g. a circle could be adequately represented for display by a polygon consisting of a modest number of points. Furthermore, the internal preservation of the mathematical formula, such as that for a circle, afforded as high a level of accuracy in computation as would be designed.

In the 1966 to 1969 time period, Tom Ellis and Bill Sibley[4] developed one of the earliest graphic languages, Grail-Graphics Input Language.

2.2.4. Itek's System:

At about 1960 or 1961, Norman Taylor left MIT to become Vice-President of Itek Corporation. Itek's main products were the design of optical systems[3,4] - optical lenses, high-resolution photography for reconnaissance aircraft, reconnaissance satellites, etc. Norman Taylor had convinced Mr. Linsey, President of Itek, that a practical industrial product could be made from the results of the earlier mentioned project, SAGE. It took about six months from Itek's design team using an IBM 7094 to respond to the proposal.

In late 1962 or early 1963, Moffett[3,4] suggested to Linsey and to Taylor that the Itek System could have significant impact on design technology in general, and on the Aerospace Industry, in particular. Moffett proposed that he formed an aerospace consortium of a

a few companies that would use the Itek equipment to assess the system potential for the aerospace industry. Itek would benefit from hardware (hardware refers to the physical items which are combined together to form the basic computer configuration), and software (software is used to describethe programmes which control the activities on the computer), specifications that would result from the study. In late 1962 or early 1963, Taylor negotiated with Norris, President of Control Data Corporation (CDC) for the sale of the Itek system and the corresponding patents to CDC. The system at Itek had been known as the Electronic Drafting Machine. Shortly before it went to CDC, the system's name was changed to Digigraphics.

2.2.5. General Motor's (GM) Early Activity:

Apart from the Itek/CDC[3,4] activity, there were other significant activities at IBM, GM, MIT, Lockheed and McDonnel-Douglas. About 1959, General Motors (GM) began to explore the potential for interactive graphics under Edward Jaek, Head of Research, and George Ryckman, Head of Corporate Operations. GM had developed hardware specifications and requested bids from computer companies to perform the development tasks. It is not certain how many companies submitted responses to the GM request for proposals, but IBM was selected. IBM had been having, at that time, their troubles with the Justice Department; since they had

about 80 per cent of the computer market, the government alleged that IBM was a monopoly and wanted to break them up. Finally, an accommodation was negotiated called the "consent decree" whereupon IBM could not divulge to anyone any of their ongoing projects or their plans until they literally announced a product with detailed price list. This is still their present marketing practice. Thus, in a general way IBM could not participate toward the philosophy and projections for interactive graphics. Also, GM did not care to disclose their work in the 1960s. However, GM had several projects to develop software for three-dimensional (3-D) boundary curves, surfaces, and analysis which led to their Design Augmented by Computers System (DAC-1).

2.2.6. Sketchpad:

In the early 1960s, Ivan Sutherland was working at MIT's Lincoln Laboratory on the TX-2 computer on a project he called Sketchpad. He presented a paper on Sketchpad at the Fall Joint Computer Conference in 1963.[3,4] The demonstration of drawing and the alterations of objects on a CRT was a dramatic event to the computer industry. In effect, Sketchpad was the first presentation of interactive graphics to the general public in the United States of America. Many people believe, for this reason and others that Ivan Sutherland is the human catalyst that started practical interactive

graphics. Lockheed-Georgia in 1964, set up one of the first industrial teams (other than GM's) to pursue interactive graphics. Thus the stage was set for the next major phase of growth.

2.3. THE "CHILDHOOD" OF INTERACTIVE COMPUTER GRAPHICS

In early 1964, there was virtually no industrial activity in computer graphics other than the classified work at General Motors.[3,4] However, short courses were organized and sponsored by universities. For example, the University of Michigan sponsored a course entitled "Application of Computers to Automated Design."[4] Also in 1966, Dr. Bentram Herzog from the University of Michigan developed a short course entitled "Computer Graphics for Designers".

2.3.1. Lockheed-Georgia Activity

The term Computer-Aided Design or CAD came out of MIT about early 1964.[3,4]

Applications including numerical control and circuit design were developed at Lockheed-Georgia while Lockheed-Burbank initiated its Computer Graphics Augmented Design and Manufacturing (CADAM) activities in 1965.

In late 1965, Lockheed-Georgia produced its first part from its prototype Numerical Control Computer Graphics (NCCG) parts programming application. This was one of the first industrial applications and probably the first Numerical Control (NC) application via computer

graphics.

2.3.2. Time-Shared Computer Graphics And GM's DAC-1

In early 1966, Lockheed-Georgia installed its first multiterminal time-shared computer graphics system. It was dedicated to NC parts programming. The graphics time-shared software was developed by Jim Kennedy.

At almost the same time, GM installed a multi-terminal IBM 360/40 system for its DAC-1. The DAC-1 system was the forerunner of much GM work which significantly affects the design and riding comfort of today's automobiles.(3,4)

2.3.3. Mc-Donnell's Computer-Aided Digigraphic Design (CADD)

There were many other(3,4) activities of note in the explosive era for Computer Graphics (CG) of the mid-1960s. The CDC Digigraphic project team produced CG products known today as CADD, Uni-graphics, and FASTDRAW. CADD was originally intended for in-house use, but it is now marketed by MCAUTO (a Division of McDonnell-Douglas).

2.3.4. Lockheed's CADAM

In 1965, the CADAM (Computer Graphics Augmented Design and Manufacture) system was initiated(3,4) at Lockheed-Burbank under the direction of Thurber Moffett, who had just joined the company, and Bill Gunn.

CADAM was initially intended only for in-house use and was tailored strictly to IBM hardware. The application was primarily that of multiview detailed drafting with NC, finite element, and many other programmes appended. Today, this system is now marketed by IBM and is used at all IBM in-house divisions. IBM assisted Lockheed in the 1960s at Burbank under a classified arrangement. This early project produced a graphic package to assist the graphics programmes (GPAC).

2.3.5. Project DEMAND

In late 1965 or early 1966, a number of U.S. large companies such as, IBM, Lockheed, McDonnell, North American Rockwell, and Rolls-Royce,[3,4] formed a classified project called DEMAND. This project lasted until 1969. Its objectives were to set forth graphics requirements in an IBM environment.

2.3.6. CC Activity Expands

As the 1960s wore on, higher levels of activity, particularly in the automotive, aerospace, and to some extent, the oil industries, were experienced. Most of the academic work emanated from MIT, University of Michigan, University of Illinois, and a build up of activity at the University of Utah under Dave Evans.

2.3.7. Geometric Modelling Concept

In 1964 at Lockheed-Georgia, there was some of the earliest surface development technology. Also

in 1967, Lockheed-Georgia had a contract from the Naval Ship Engineering Centre to develop Computer Graphics Arrangement Programme.[3,4](COGAP). This contract required the definition of ships' surfaces in order to partition the ship and to create 3-D objects for positioning them into the various ships' compartments. The project was headed by Bert Bowers and Albert Anderson. COGAP was developed using one of the first "computer independent" languages. That was Interactive Terminal Interface System (ITIS). It was primarily a set of FORTRAN graphics commands which were common to many systems once an interface had been programmed.

2.3.8. Advent Of The Storage Tube And "Turnkey" Systems

The first storage tube emerged about 1965[3,4] Bolt, Beranck, and Newman produced a 5-in tube. About 1968, Computer Displays marketed their Advanced Remote Display Station (ARDS) terminal and Computek marketed their 400 series. They used 6 x 8 in Tektronix tubes. The storage tube, sometimes referred to as a DVST - direct view storage tube - has certain properties that are important to computer Graphics. They electronically maintain a picture of any density that is created on the screen. (What was rather difficult to achieve for the earlier refresh displays for high density pictures, without blinking). Storage tubes have been also appreciably less expensive than the

refresh displays. It is probable that this prompted the entrepreneurs to develop storage tube-based "turn-key" CAD-Systems (drafting systems) beginning in 1968 or 1969.

Among the initial "turnkey" vendors who packaged the hardware/software/applications systems were Calma in 1968, and Applicon and Computer-Vision in 1969. Several well known vendors of displays also started up in that period. Adage began in 1965 while E and S, Imlac, Lunday, and Vector General began in the 1968 to 1970 time period.

2.4. COMPUTER GRAPHICS' ADOLESCENCE:

This period is of greatly expanding knowledge, technical developments, and implementation.(4) Many of the early pioneers have seen the fruits of their labour take shape during this period. Today, most of the professionals believe that computer graphics has now reached adulthood with a prosperous life ahead. The events cited below are more or less isolated and are in approximate chronological order.

2.4.1. 1970

At Brunel University, Uxbridge, England, a conference was held called, "Computer Graphics' 70". The proceedings were published in a text entitled, COMPUTER GRAPHICS MANAGEMENT.

2.4.2. 1971

A book entitled, INTERACTIVE GRAPHICS FOR COMPUTER-AIDED DESIGN, was authored by M. David Prince and was published by Addison-Wesley. This book was highly regarded because it was one of the first of its kind.

Also during this period, a first short course entitled "Applied Interactive Computer Graphics" was organized at the University of Tennessee Space Institute. It has been offered annually to the present time.

2.4.3. 1972

During this time period, NASA's (National Aeronautics and Space Administration) Integrated Programme for Aerospace Vehicle Design (IPAD) project, headed by Bob Fulton, was begun.

Also during this period, USA/Japan Computer Graphics Conference was held in Tokyo, sponsored by the Institute of Electrical and Electronics Engineers (IEEE) and the Department of Commerce, USA.

2.4.4. 1973

A short course entitled, "Applied Interactive Graphics" was organized at the University of California, at Los Angeles (UCLA). This course has been offered continuously with plans for its tenth year in 1982. It is now offered three times annually, twice on the West Coast and once at the University of Maryland.(4)

Also a text entitled, PRINCIPLES OF INTERACTIVE COMPUTER GRAPHICS, co-authored by Newman and Sproull, was published by McGraw-Hill. It was revised in 1979.

2.4.5. 1974

There was a Special Computer Graphics issue - IEEE Computer Magazine, and the guest editor was Bert Herzog.

A special conference on Surface Modelling was held at the University of Utah.

Also at this period, a first National Special Interest Group for Graphics (SIGGRAPH), under the Association for Computing Machinery (ACM) conference was held in Boulder.(4) SIGGRAPH was initiated in 1969.

The objective of producing a standard graphic language was initiated at ACM SIGGRAPH workshop on machine independent graphics held at the National Bureau of Standards. Bert Herzog and Bob Dunn submitted a report of accomplishments, issues, and problems in 1977.

2.4.6. 1975

The Air Force's Integrated Computer-Aided Manufacturing (ICAM), project was begun. This project has been constituted of many individual projects, each of which is manned by a team from several companies.

S. H. Chasen presented a paper entitled "Economic

Principles for Interactive Graphic Applications" at the National Computer Conference. This paper was the basis for developing the concepts of the formalized relationship between productivity and economic benefits. This was later articulated in THE GUIDE FOR THE EVALUATION AND IMPLEMENTATION OF CAD/CAM SYSTEMS, co-authored by Chasen and Dow.(4)

Subsequent SIGGRAPH Conferences remained about the same in attendance through 1976 with a growth to over 600 in 1977, about 1,000 in 1978, about 2,000 in 1979, and about 2,500 in 1980.(4) Exhibits were initiated in 1976.

2.4.7. 1976

Raster graphics technology began to emerge, including colour. Raster or TV graphics offered the low-priced features of high density drawings, colour, etc. However, at lower accuracy of the pictures than the reflesh display or storage tube.

A book entitled, MATHEMATICAL ELEMENTS FOR COMPUTER GRAPHICS, authored by Dave Rogers and Alan Adams of the U.S. Naval Academy, was published by McGraw-Hill.

2.4.8. 1977

In late 1977 or early 1978, Richard Schullman formulated and chartered the National Computer Graphics Association (NCGA) to provide(4) a broad range of practical services to computer graphics users and potential users.

2.4.9. 1978

A book entitled, GEOMETRIC PRINCIPLES AND PROCEDURES FOR COMPUTER GRAPHIC APPLICATIONS, authored by S. H. Chasen was published by Prentice Hall.

2.4.10. 1979

During this period, plans were laid at SIGGRAPH 1979, for the first National Computer Graphics Association (NCGA)Conference.

There was also a first Massachusetts Institute of Technology (MIT) Conference on Computer Graphics in CAD/CAM systems.(4)

An Interactive Graphics Exchange System (IGES) - a proposed standard for computer graphics in U.S.A - was initiated in September, 1979, at a Department of Defence Manufacturing Technology Advisory Group meeting.

At about the same time, European efforts of standardization of computer graphics started in the form of Graphical Kernel (GK) Standard. Principal inputs were from the Air Force's ICAM project and NASA's I PAD project.

2.4.11. 1980

The first NCGA Conference was held in Washington, D.C.

Also during this period, S. H. Chasen and J.W. Dow authored, THE GUIDE FOR THE EVALUATION AND IMPLEMENTATION OF CAD/CAM SYSTEMS.(4)

2.4.12. 1981

There was a second NCGA Conference which included an excellent technical programme on CAD/CAM, and business graphics as well as the general Computer Graphics theme.

Through the past decade, some computer graphics software has begun to trickle into the market from several companies. One of these is AD 2000, which is a general[4] purpose graphics software, tailored by Pat Hanratty's Company, to operate on a number of different hardware configurations (it has recently been upgraded to a system named ANVIL-4000).[4] Other software systems have given special attention to solid (geometrical) modelling, three-dimensional (3-D), colour, hidden line removal, texture, etc. Such systems now include Romulus from Shape Data, Cambridge, England;[4] Synthavision from MAGI and PADL from the University of Rochester, etc.

It is impossible to cover the many branches of computer graphics besides Computer-Aided Engineering that are now expanding in many directions. Exciting new applications are being discovered and others are being developed in such areas as space movies, advertising, engineering, medicine, business, environment, etc.

CHAPTER THREE

GENERAL PROBLEMS OF COMPUTER-AIDED DESIGN

SYSTEM ORGANIZATION AND FUNCTIONING

3.1. INTRODUCTION - THE DESIGN SYSTEM IN GENERAL:

The purpose of this chapter is to analyse some fundamental problems in the structure of CAD systems.

The basic outline of the design system is given in Figure 3.1.[5,6]

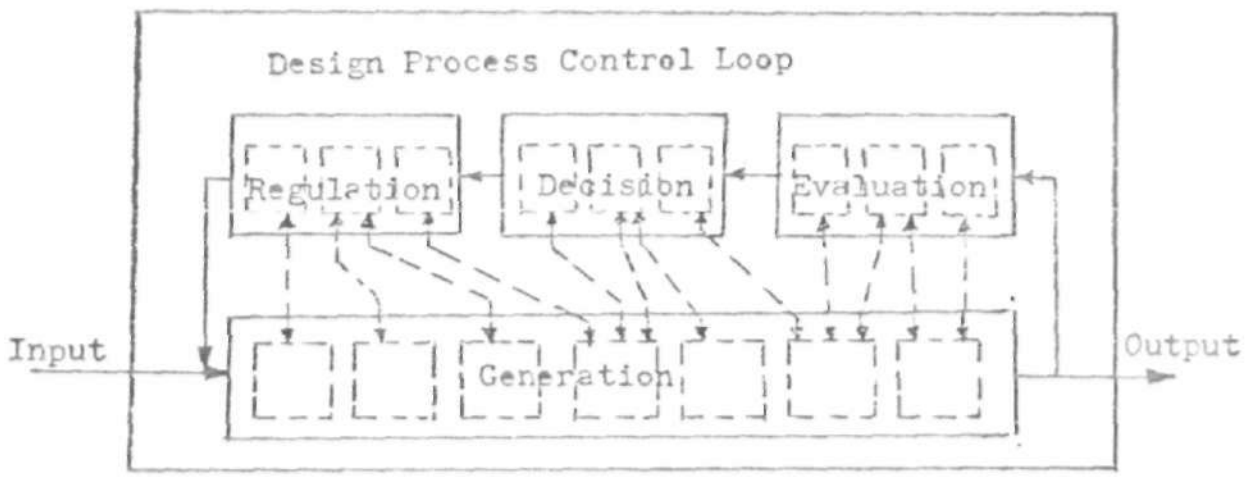


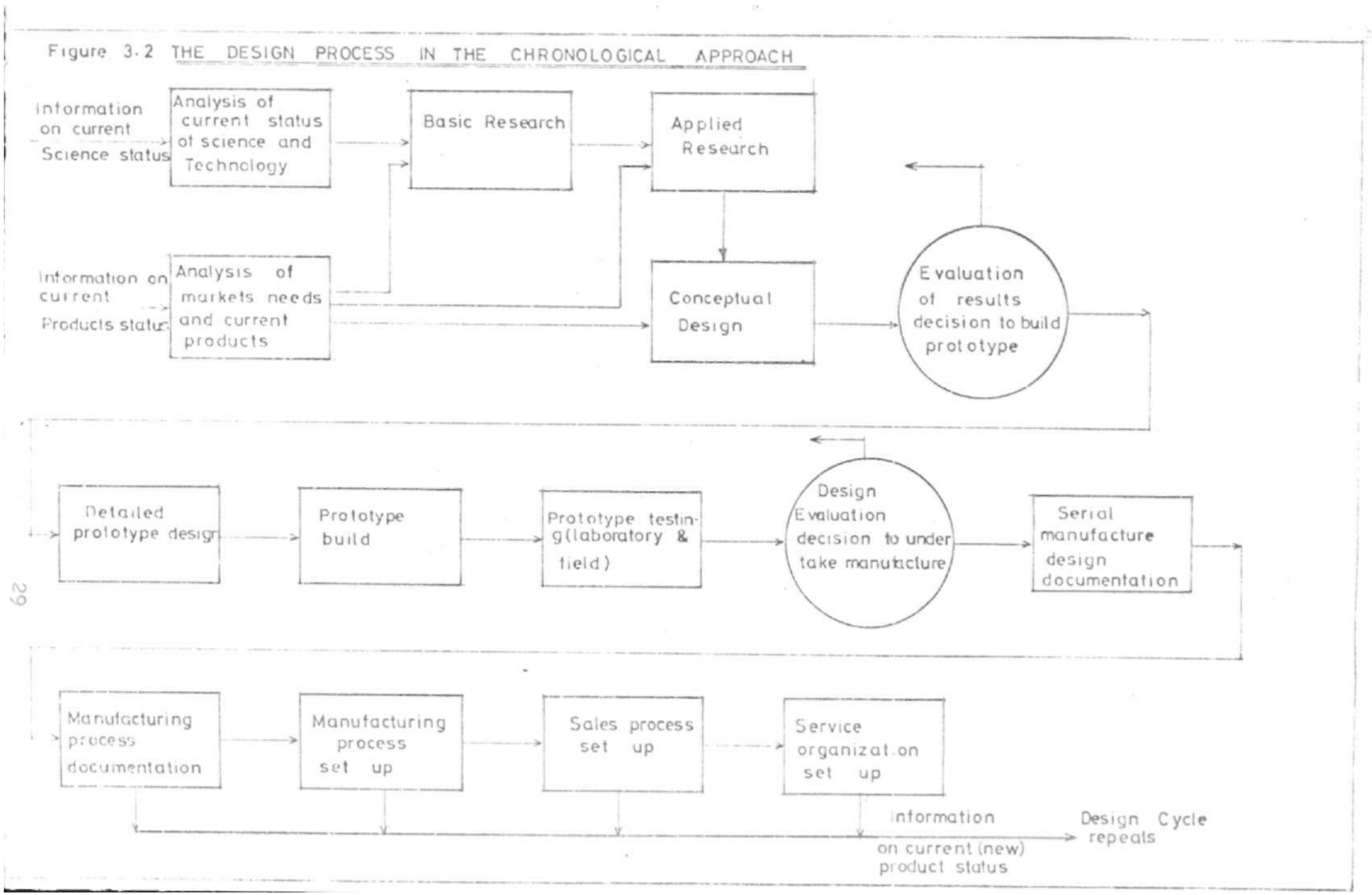
Figure 3.1: The Design System in its General Pattern

The design process is a transformation of some input information into output. Roughly, the Design Functions performed in the course of that transformation may be divided into Generation and Control. The control in turn may be specified in a little more detail as the

sequence: Evaluation-Decision-Regulation. It has to be observed that the functions may be only rather vaguely specified. All the basic four Design Functions comprise of numerous subfunctions. Multiple information flows and control operations occur directly between these subfunctions (subsystems). However, the divisions between subfunctions and the pattern of the internal information flows differ from one design organization to another and from one product to another. This makes the problem of preparing comprehensive computer aids of general applicability to become a very complex one, and the existing solutions either pertain to some particular well defined fragments of the system only, or - if the CAD solutions happen to be more comprehensive and try to cover the entire field - they immediately become single user and one-family-of-products solutions, not transferable easily to other organizations and other products. This makes the CAD systems design and manufacture a very complex task and the existing CAD "turn-key" systems, obtainable from various manufacturers, are usually not more than drafting systems - this being, in fact, one of the less important (although laborious) subfunctions.

Figure 3.2 gives the "flow diagram" of the Design Process (i.e. the chronological succession of events).[5,6] For the process to be executed smoothly

Figure 3.2 THE DESIGN PROCESS IN THE CHRONOLOGICAL APPROACH



and the control to be applied effectively - to achieve a good product - the designer has to have access to numerous data and tools. In fact, the amount of necessary data and procedures is tremendous and if the company aims at a modern, integrated concept of the design process, it cannot be realized without the use of computers.

The information flows in the Design Process occur basically in the chronological fashion envisaged, but there are simultaneously numerous formal and organized, as well as informal and spontaneous flows between various, sometimes remote blocks. Furthermore, the process shown in Figure 3.2 shows the design of one model of a machine only, and customarily there is a sequence of such processes in time at the company, as well as a number of design processes running in parallel for various machine types and/or models. There is also a large amount of computations and data processing internally, in most of the blocks.

3.2. THE DESIGN FUNCTIONS AND THE DESIGN DATA BASE INTEGRATION:

In the course of the Design Process, several Design Functions are performed, usually for a number of times (repetitively, with a varying degree of detailness).[5,6]

The picture given in Figure 3.3 shows an ideal version of how the main Design Function, grouped in the four basic groups mentioned earlier should operate: integrated through the interaction with a common design data base. This ideal picture is very seldom found in practice. There has not been found as yet a single, well defined, clear method of describing digitally the product of the design activity in such a way that all design functions could be performed upon the stored data once their basic set is established, and that data resulting from subsequent action of new functions could be added to the basic set without significant human intervention.

In fact, at present, not all the design functions shown in Figure 3.3 are customarily considered as the elements of CAD. The generation group is most frequently identified with CAD, as well as some functions of the evaluation group. It is less clear whether some of the regulation functions should be considered as CAD, although some of them (such as searching for information) are frequently computerized and others could benefit easily from such approach.

The decision functions are certainly the ones which are not computerized at all at present. The decision-making processes - which occur mainly at the locations of the design process depicted with circles

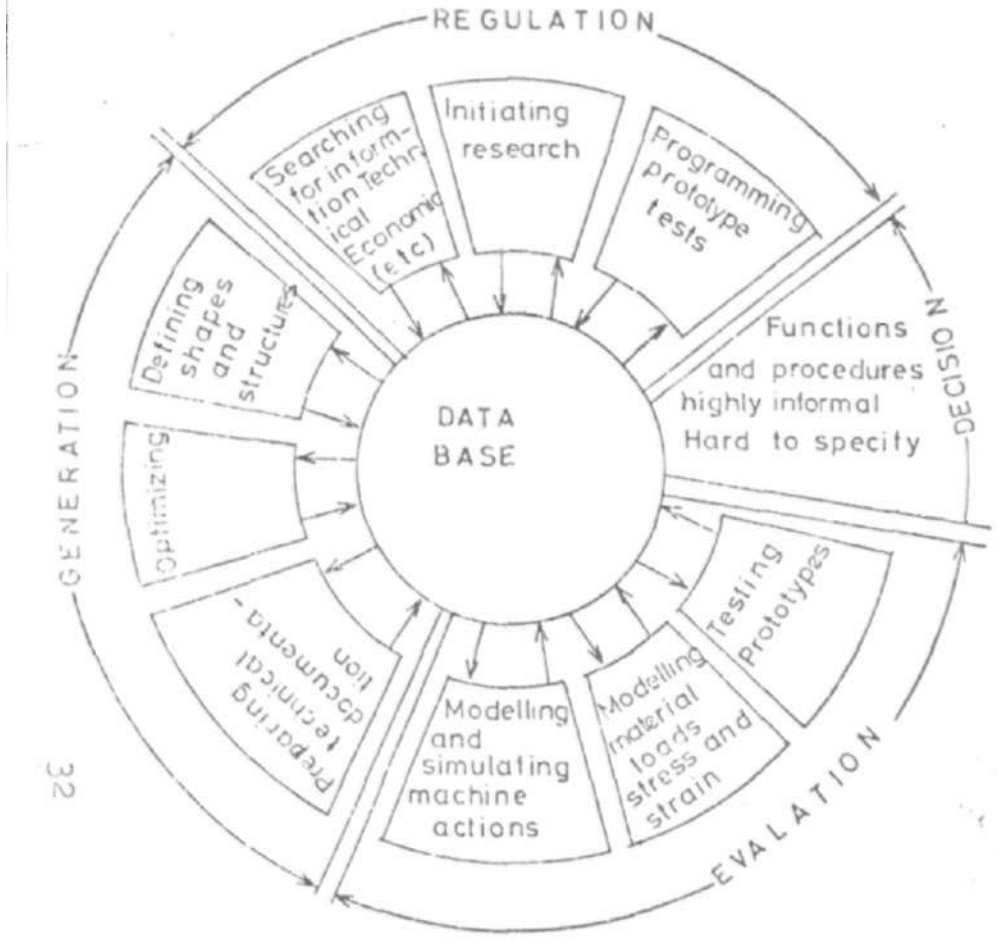


FIG. 3.3 MAIN DESIGN FUNCTIONS INTEGRATED THROUGH THE DESIGN DATA BASE

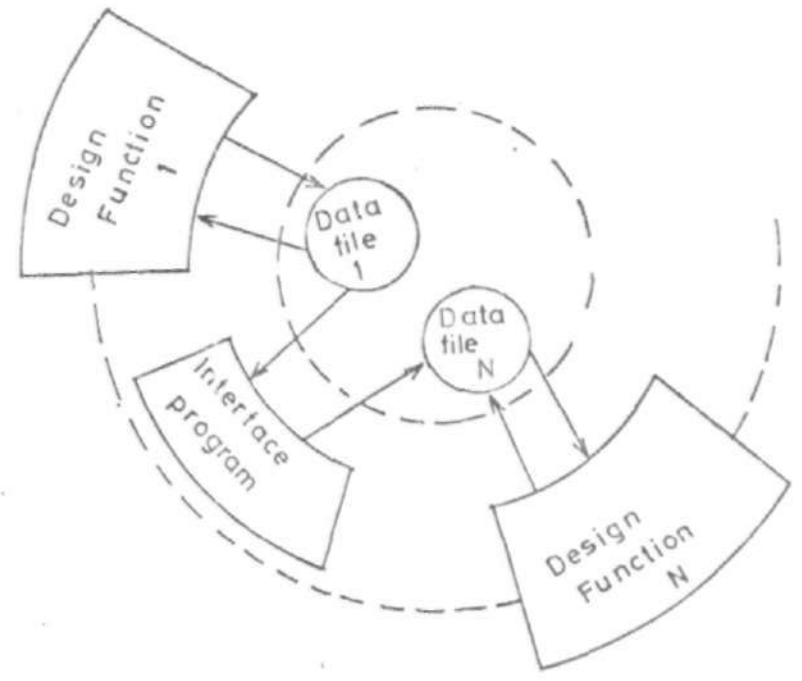


FIG. 3.4 PRESENT DAY PRACTICAL REALIZATION OF DESIGN FUNCTIONS OPERATION AND DATA INTEGRATION

in Figure 3.2 - are usually highly informal; the exact procedures and criteria are hard to specify; general experience and intuition of the engineers and managers plays the main role and it is hard to envisage these processes as subject to the assistance of the computer playing any role other than that of a simple, quickly accessible data file.

In spite of all these doubts and difficulties, the integrated approach and the integrated data base seem to be the goal of all those working in the CAD area. Even more, there are thoughts today about integrated CAD-CAM-Management Information Systems and attempts have been made at building them. This has not been yet fully achieved anywhere in the industrial practice.(5,6)

The real-life picture of the Design Functions operation and their integration procedures is given in Figure 3.4. Each separate functional module operates upon its separate data file and every file is converted into another one with the aid of Interface Programmes.

A typical example of an interface programme will be a finite element method mesh generator which converts the graphical part description (or the geometric model description) into the finite element description. The main problem with Interface Programmes lies in the fact that various functions are customarily performed

with various large software packages, usually well established and mastered within the company - the packages which usually were not designed deliberately to be integrated with something else in the future. To write Interface Programmes is thus a laborious and conceptually difficult task. As the Interface Programmes couple some specific package to perform one function with another specific package for the other function - they (Interface Programmes) are not of general applicability, numbers of their possible variants are very high, and thus their design is usually not interesting for professional software houses or computer manufacturers. Thus they have to be, and usually are, in fact, written (or at least tailored from something ready-made) by the users; their preparations constituting, in fact, a very heavy work-load upon a company's CAD department, at these companies which had decided to integrate their CAD or CAD-CAM-MIS activities.

Finally, it is important to note that usually, in industries, the volume of the "alive" documentation is rather large. The number of design drawings is high plus a lot of associated textual information: machine testing protocols, manufacturing processes ducumentation, etc.[5,6] The documentation can be stored in digital form or on microfilms. However, for large

documentation in the digital form, the necessary memory will be in the range of several thousands of Megabytes. (The amount of memory available on any computer device is referred to in terms of words of Bytes, 1 megabyte = 2^{20} bytes). Thus, both the size and the rather infrequent access to a specific drawing, or document once it is approved and the part is being manufactured, suggest sequential type of storage organization for the data base in this case.

Independent of whether the data would be in digital or microfilmed form, the storage and access have to be organized in a very special way, taking into account the multiplicity of users' requirements, of access of purposes and of the ways in which queries may be formulated.

Two considerations of a general nature have to be taken into account:

(i) A random access Master file may be necessary. This is because of sequential organization (and, frequently, in fact, non-computerized nature) of the basic data (drawings), the role of this file being to enable locating quickly a drawing (other document) or a set of these according to various requirements of the design engineers.

(ii) It is most probable that a typical Data Base Management System may not serve the role adequately. Thus, the Data Base Management System has to be specific for the engineering application and for a particular case.

CHAPTER FOUR

THE DESIGN-MANUFACTURE-MANAGEMENT TOOLS AND CAD-CAM-MIS INTEGRATION

4.1. DESIGN-MANUFACTURE-MANAGEMENT TOOLS:

For the design (the functions of which are briefly discussed in the preceding chapter), manufacture and management functions to be performed, one has to have support of numerous tools. Following Zgorzelski,(5) they are shown in Figure 4.1 and roughly can be assembled in four groups:

- hardware
- software
- organization
- know-how.

The last two groups exist within every conventional (i.e. non-computerized) system. Emphasis here, however, will be given more to the tools which have been influenced significantly by the impact of computer techniques. A closer look at each of the groups, as they look today will be taken.

In computer hardware the conflict between the trend of some to use large computer installations and computer networks and the tendency of others to use stand alone minis and desk top computers is still in existence.

Fig. 4.1 DESIGN - MANUFACTURE - MANAGEMENT TOOLS

DESIGN						MANUFACTURING					MANAGEMENT		
Research Labs	Technical Information Dept.	Design Dept.	Design Analysis Dept.	Materials Engineering Dept.	Prototype Build & Test Dept.	Manuf'g Engineering Dept.	Planning and Control Dept.	Stocks	Production Dept.	Quality Control Dept.	Management	Financial Dept.	Marketi Dept
ORGANIZATION													
	Computers with Graphic In put and Out put	Drafting Equipments	Micro-and Repro-Graphic Equipment	Prototype Tests stands and Measuring Apparatus	Prototype Manufacturing Devices	N C Machine Tools	Computer Controlled Transport Devices	Computer Controlled Inspection Machines	Robots and Automated Assembly Lines	Office Automation Equipment	Interactive Computer Terminals		
HARDWARE													
Data Base Management Systems	Information Storage & Retrieval Systems	Digital Shape Description Systems	Computer Graphics System	Machine Simulation & Optimization Systems	Structural Strength & Dynamics Analysis Systems	Experimental data Processing and Simulation Systems	N.C Machine Tool Programming Aid Systems	Computer Aided Process Planning Systems	Production Planning And Control Systems	Stock Control Systems	Order Processing Systems	Financial Control Systems	Payroll Systems	Simulation Systems
SOFTWARE													
Specialized (for particular Industry branch) Designers Data base	Design Criteria Continuously Actualized and Registered	Computational Design Analysis Methods	Value Analysis Methods	Experiment Planning and Evaluation Methods	Design Manufacturability Analysis Methods	Design Reliability and Maintainability Analysis Methods	Optimal Production Allocation Methods	Quality Control Techniques	Operating Research Techniques	Statistical Techniques	Forecasting Techniques	Simulation Techniques		
KNOW - HOW														
DESIGN						MANUFACTURING			MANAGEMENT					

This is because of the rapid growth of the capabilities of digital computers (ranging from small to large, commercially available. Most of the relatively small machines are capable now of performing even the most demanding (in terms of the necessary computer power) tasks, such as the finite element analysis of complicated structures or large non-linear optimization problems. It is important to note that, with the recent emergence of powerful mini computers, the "large" computer is wholly unnecessary for CAD-CAM-MIS purposes. This is because large packages could be easily implemented on these machines. It seems thus that CAD-CAM-MIS users will have to refer to large computer centres only in cases where they need access to some very large and proprietary data bases and/or some proprietary specialized analysis systems.

The computer software seems to lag a little behind hardware. In some areas, great progress has been made and firm establishment of certain techniques may be assessed. An example is the finite element method for structural analysis or techniques for numerical description of sculptured surfaces. In other fields the progress is not as fast as could be expected a few years ago, as for example, in the case of simulation and optimization techniques.

A quick look at the software group in Figure 4.1 reveals that each of the fields comprising it may be

filled in by several (sometimes more) software systems or packages. Most of them have cost hundreds of man-years of analysts' and programmers' work. An industrial organization trying to use CAD-CAM-MIS in its everyday practice, has to purchase these packages from various sources and they are not in any way matched with each other; and due to their size and complication - specifying and writing interfacing programmes and trying to build out of them the integrated CAD-CAM-MIS environment is an extremely difficult task. Thus, the architect of a company's CAD or CAM or MIS systems is really in a very difficult position: the system must be tailored to the typical needs and procedures of the company, but the software fragments which have to be tailored are extremely difficult to work with.

Analysis of the implications of CAD-CAM-MIS techniques upon numerous other Design-Manufacture-Management Tools visible in Figure 4.1 will not be carried out in a work like this. However, mention will be made of one, which is the presence of NC machine tools in the hardware group of the tools and should not be overlooked. This is because NC machinery is very well suited both for established production purposes, as well as for prototype manufacturing, provided that very advanced programming and graphical verification aids are at the research and development prototype workshop. This is,

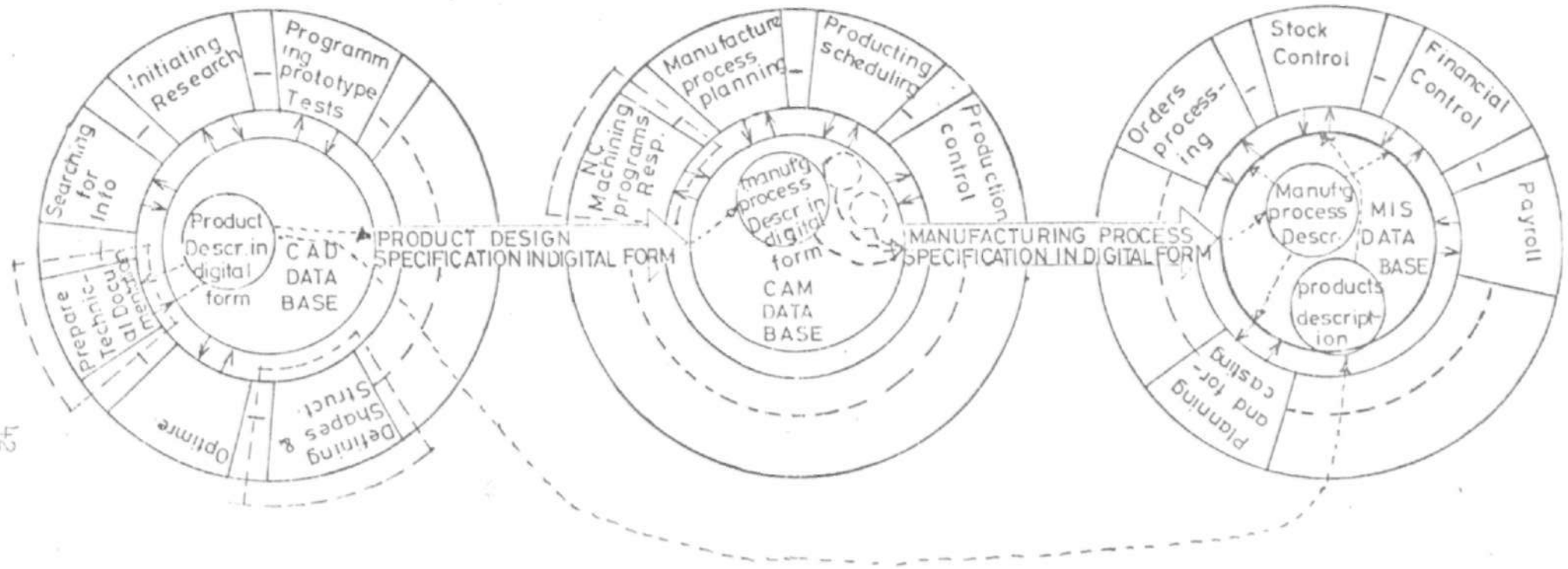
however, the only way in which accuracy and stability of the prototype can be achieved; and this is also the point where CAD-CAM-MIS integration begins.

It is important to note that the full set of Design-Manufacture-Management tools given in Figure 4.1 is rather expensive and difficult to complete. In particular, organization and know-how groups, contrary to hardware and software, cannot be easily bought and an industrial organization needs a lot of effort to complete these groups.

4.2. CAD-CAM-MIS INTEGRATION

As earlier mentioned above, NC machine tools play a particularly important role in the integration of CAD-CAM-MIS systems. This can be[7,8] seen clearly in Figure 4.2, which shows in examplary form, the integration of the systems with the consideration of only few functions per system. The CAD data base is shown interlinked with CAM and MIS data bases, with some of their corresponding functions also shown. Most of the functions carried out in CAD are stored in the CAD data base in digital form. The product design specifications in digital form, stored in CAD data base can be transferred to CAM data base and used for manufacturing processes. In particular, NC machine tool programmes may be prepared practically automatically from them. Similarly, the manufacturing process specifications in digital form can be transferred to MIS data base for

FIG. 4.2 CAD - CAM - MIS INTEGRATION



management functions. For example, manufacturing process description in digital form can be used for planning and forecasting, and also for financial control. It should be noted also that the product description in digital form from CAD data base could be transferred directly to MIS data base and used for instance, for stock control purposes and other functions as well. Thus the three systems' data bases may be interlinked, one with another, mainly through the NC machine tool technique.

The CAD-CAM-MIS integration will be eventually achieved within the fully automated (unmanned) factory, being the ultimate goal and reason for automation. As the unmanned factory is not the solution to be fast applied in the developing countries, usually possessing significant reserves of manpower, the question arises whether speaking about CAD-CAM-MIS integration makes any sense in the context of the conditions of the developing countries. However, there are deeper reasons for integration than the most obvious reduction of personnel costs through automation. The most important reasons are:(8)

. (i) the enforcement of technological discipline within the manufacturing organization (as all the computer systems involved usually require very orderly data inputs, strict engineering procedures, etc.);

(ii) the assurance of highly accurate and faultless manufacturing of even very complicated parts (as a part described by the designer with the computer aid in the CAD subsystems may then be programmed automatically for the NC machine tool manufacture and machined faultlessly without human errors introduced in the process);

(iii) the assurance of faultless and exact data acquisition for the management information systems (MIS) (as the NC part programmes and their execution upon the NC machine tools can be used as the most reliable source of data on machining times, number of manufactured parts, etc.);

(iv) the introduction of greater flexibility into the manufacturing system. That is improving its ability to adapt quickly and effectively to engineering changes, varying market demands and new product designs (the lead time for new production preparation in integrated systems is much shorter than in conventional systems and the flexibility relies mainly upon the NC technique which assures manufacture of complicated parts without previous long and tedious learning process of the machine operators and is, in fact, independent of the operators' skills);[8]

(v) the improvement of manufacturing systems, economical effectiveness, through better planning (possibility of forecasting and load balancing,

optical production allocation upon machine tools, etc.).

Points (ii) and (iv) above, should be considered as the ones most important in the case of developing countries. The manufacture of complicated, modern machinery is, in fact, impossible using conventional (i.e. manual, non-NC) techniques, particularly under the conditions when there is lack of very highly skilled machine tool operators, with long industrial tradition in high technology manufacturing.

Finally, what seems extremely important as earlier mentioned, is the fact that integration may be performed solely and only via the NC technique.

The NC machine tool application, which here in Nigeria is in its infancy, should thus be strongly promoted and enhanced in the near future.

CHAPTER FIVE

GRAPHICAL OUTPUT FROM FORTRAN PROGRAMMES AND AN EXAMPLE OF COMPUTER-AIDED DESIGN OF A SIMPLE SHAFT

5.1. GRAPHICAL OUTPUT FROM FORTRAN:

For the graphical output from FORTRAN programmes at the Iya Abubakar Computer Centre, Ahmadu Bello University, a CALCOMP Electromechanical Plotter (Drum type) is used, which is the only type of graph plotter available at the Centre. The type of graphic software used is the Basic Software. This is the lowest level of software used in producing a plot. This software consists of a set of subroutines which allow a programmer to perform elementary plotting operations such as drawing lines, annotation, selecting pens, scaling the plot, etc.

For design purposes, this level of software is not sufficient. This is because the user of the Basic Software has to programme many commonly used graphic functions, while in a higher level of software, there are subroutines which plot figures such as circles, arcs, spirals, etc.

Still higher level of software can be used for mechanical engineering drawing, with typical functions such as dimensioning, projection drawing, etc., automated.

This type of software is, however, at present not available at the Iya Abubakar Computer Centre. Furthermore, specialized graphical terminals are available today, together with software for design purposes, in the form of turn-key draughting systems.

In the lack of these facilities, the present chapter presents an attempt at using the basic CALCOMP Software to produce useful output from FORTRAN programmes in the form of an engineering drawing of a simple shaft.

To use the CALCOMP graph plotter, one needs the basics of co-ordinate geometry. That is how to plot points on the X and Y axis. Necessary also is the basics of a FORTRAN programming language. The following statements are important for any FORTRAN programme intended for graph plotting:

(i) Programme name (input, output, tape 5 = input, tape 6 = output, tape number).
This is always the first statement, where tape number is the logical output device number of the plotter.

(ii) Call Plots (0.0, 0.0, number).
This statement performs initialization. 0.0, 0.0, are maintained only for compatibility.

(iii) Call Factor (Fact).
Fact is the ratio of the desired plot size to

the normal plot size. If a factor entry is not desired, this statement is ommitted. From here, many equations and subroutines can be included as may be desired.

(iv) Call Plot (0.0, 0.0, 999).
This is always the last call plot statement. It advances the pen beyond the current plotting area, writes a terminating record, and closes the plot output device.

(v) Stop.

(vi) End.
These last two statements are the formal end of all FORTRAN programmes.

5.1.1. Basic Software Subroutines

The basic software subroutines are[9] as follows:

(a) Plot Subroutine:

The calling sequence has three arguments:

Call Plot (x,y, + ipen)

x,y - are the x,y coordinates in centimetres from the current reference point (origin), of the position to which the pen is to be moved.

± ipen-is a signed integer which controls pen status (up or down), and origin definition. If the ipen = 2, the pen is down during movement, thus drawing a visible line. If ipen = 3, the pen is up during movement. If ipen =

-2 or -3, a new origin is defined at the terminal position after the movement is completed.

(b) Symbol Subroutine:

This subroutine produces plot annotation at any angle and in practically any size. There are two symbol Call Formats:

(i) the "standard" call, which can be used to draw text such as titles, captions, and legends; and

(ii) the "special" call, which is used to draw special centred symbols such as box, triangle, angle-head, etc., for plotting data points.

The "Standard" Call is:

Call Symbol (x,y, Height, 1bcd, Angle, ± Nchar)

x,y - are the coordinates in centimetres, of the lower left-hand corner of the first character to be produced. The pen is up while moving to this point.

Height - is the height, in centimetres of the character to be plotted.

1bcd - is the text, in internal computer representation, to be used as annotation.

Angle- is the angle, in degrees from the x-axis, at which the annotation is to be plotted.

+Nchar - is the number of characters to be plotted from 1bcd.

The "Special" Call is:

Call Symbol (x,y, Height, 1nteq, Angle, - 1code)

x,y and Angle - are the same as described for the "Standard" Call. If the symbol to be produced is one of the centred symbols, x,y represent the geometric centre of the character produced.

Height - is the height, in centimetres of the centred symbol to be drawn.

1nteq - is the integer equivalent of the desired symbol. For example, the integer equivalent of an arrow-head is 6.

- 1code - is negative and determines whether the pen is up or down during the move to x,y, when - 1code is:
-1, the pen is up during the move, after which a single symbol is produced.
-2, or less, the pen is down during the move, after which a single symbol is produced.

(c) Number Subroutine:

This subroutine plots a number in the FORTRAN F-type format.

The number subroutine is:

Call Number (x,y, Height, FPN, Angle, ± Ndec).

x,y, Height and

Angle - are the same as those arguments described for subroutine symbol. The continuation feature, where x or y equals 999.0 may also be used.

FPN - is the floating-point number that is to be converted and plotted.

± Ndec - controls the precision of the conversion of the number FPN. If the value of Ndec ➢ 0, it specifies the number of digits to the right of decimal point that are to be converted and plotted, after proper rounding.

(d) Scale Subroutine:

This subroutine is used to examine the data values in an array and to determine a starting value (minimum or maximum) and a scaling factor.

There are four arguments in the calling sequence:

Call Scale (Array, Axlen, Npts, ± inc)

Array- is the first element of the array of data points to be examined.

Axlen- is the length of the axis to which the data is to be scaled.

Npts - is the number of data values to be scanned in the array.

± 1nc- is an integer whose magnitude is used by SCALE as the increment with which to select the data values to be scanned in the array.

(e) Axis Subroutine:

This subroutine is used for axis lines and scales to indicate the orientation and values of the plotted data points. When both x and y axes are needed, axis is called separately for each one. The calling sequence is:

Call Axis (x,y, 1bcd, ± Nchar, Axlen, Angle,
Firstv, Deltav).

x,y - are the coordinates, in centimetres, of the axis line's starting point.

1bcd - is the title, which is centred and placed parallel to the axis line.

± Nchar - the magnitude specifies the number of characters in the axis title, and the sign determines on which side of the line the scale marks and labelling information shall be placed.

Axlen - is the length of the axis line, in centimetres.

Angle - is the angle in degrees, at which the axis is drawn.

Firstv - is the starting value which will appear at the first tick mark on the axis.

Deltav - represents the number of data units per centimetre of axis.

(f) Line Subroutine:

This subroutine produces a line plot of the pairs of data values in two arrays (x and y).

The calling sequence is:

Call Line (xarray, yarray, Npts, 1nc, ± Lintyp, 1nteq).

xarray - is the name of the array containing the abscissa (x) values and the scaling parameters for the x-array.

yarray - is the name of the array containing the ordinate (y) values and the scaling parameters for the y-array.

Npts - is the number of data points in each of the two arrays just mentioned.

1nc - is the increment that the line subroutine is to use in gathering data from the two arrays.

± Lintyp - is a control parameter which describes the type of line to be drawn through the data points. The magnitude of Lintyp determines the frequency of plotted symbol.

1nteq - is the integer equivalent of the special plotting symbol centred at each data point.

5.2. COMPUTER-AIDED DESIGN OF A SIMPLE SHAFT:

An example of a suitably programmed combination of the above subroutines to produce the technical drawing of a simple shaft is given in Appendix A.

The drawing of the shaft is shown in Figure 5.1. An additional example of a technical drawing from FORTRAN, of a guide in isometric view is also shown in Figure 5.2.

From the length of the programme given in Appendix A, for the drawing of a simple shaft, it is clear that the basic software is not sufficient for design purposes and higher level software for technical drawing purposes should be acquired to produce drawings more effectively.

It is important, however, to notice that the form of mechanical part (i.e. shaft) description used here for drawing purposes can be easily transformed into a set of commands to manufacture the part upon a numerically controlled (NC) machine tool.

The NC process can be briefly described as follows:[2]

1. The "Part Programmer" prepares a manuscript (the part programme), describing the part geometry, machine geometry, and cutting instructions, using a language predefined to the computer. The most common language for this purpose is APT. The commands of APT are somewhat similar to the Plotter

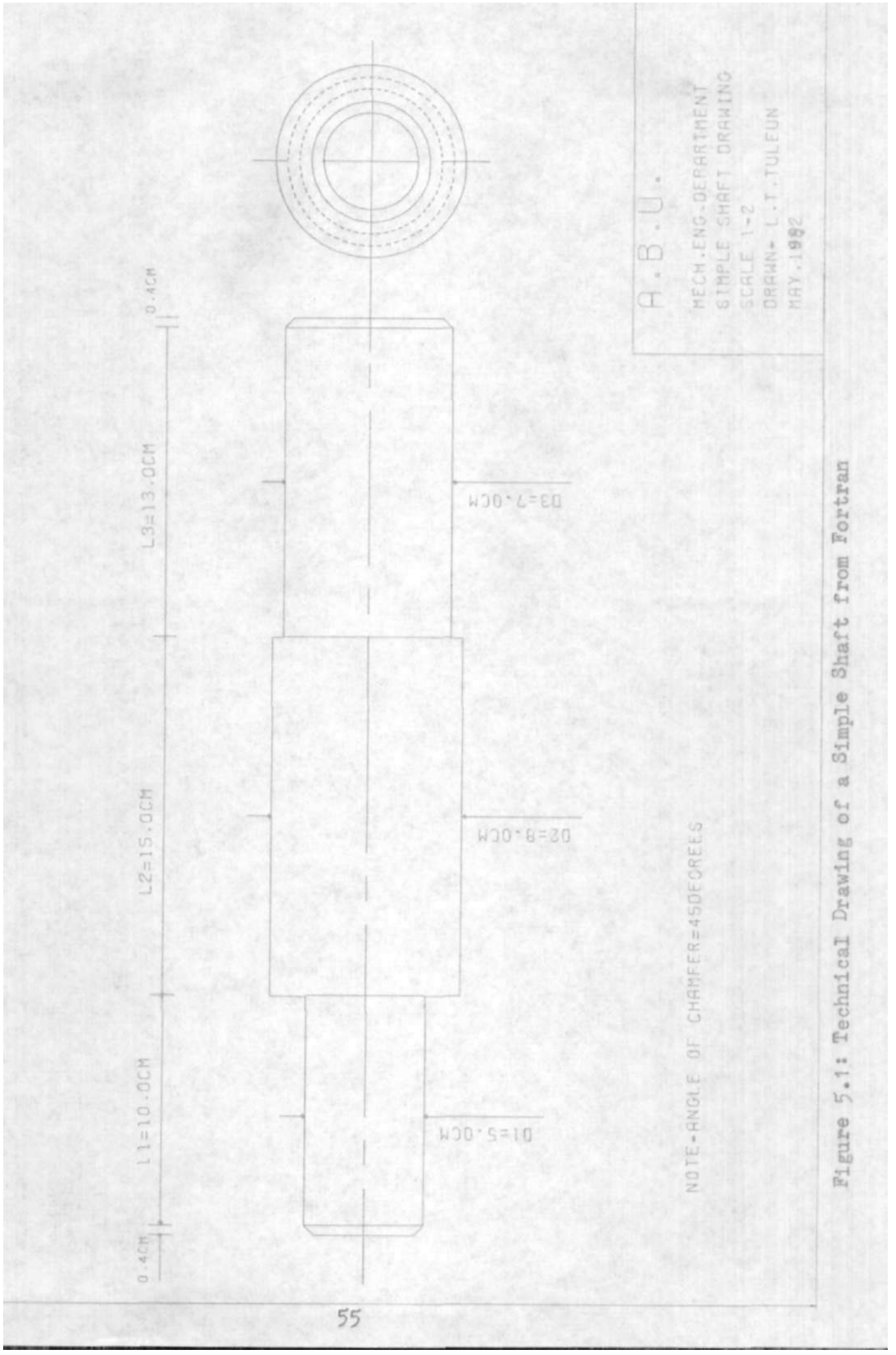


Figure 5.1: Technical Drawing of a Simple Shaft from Fortran

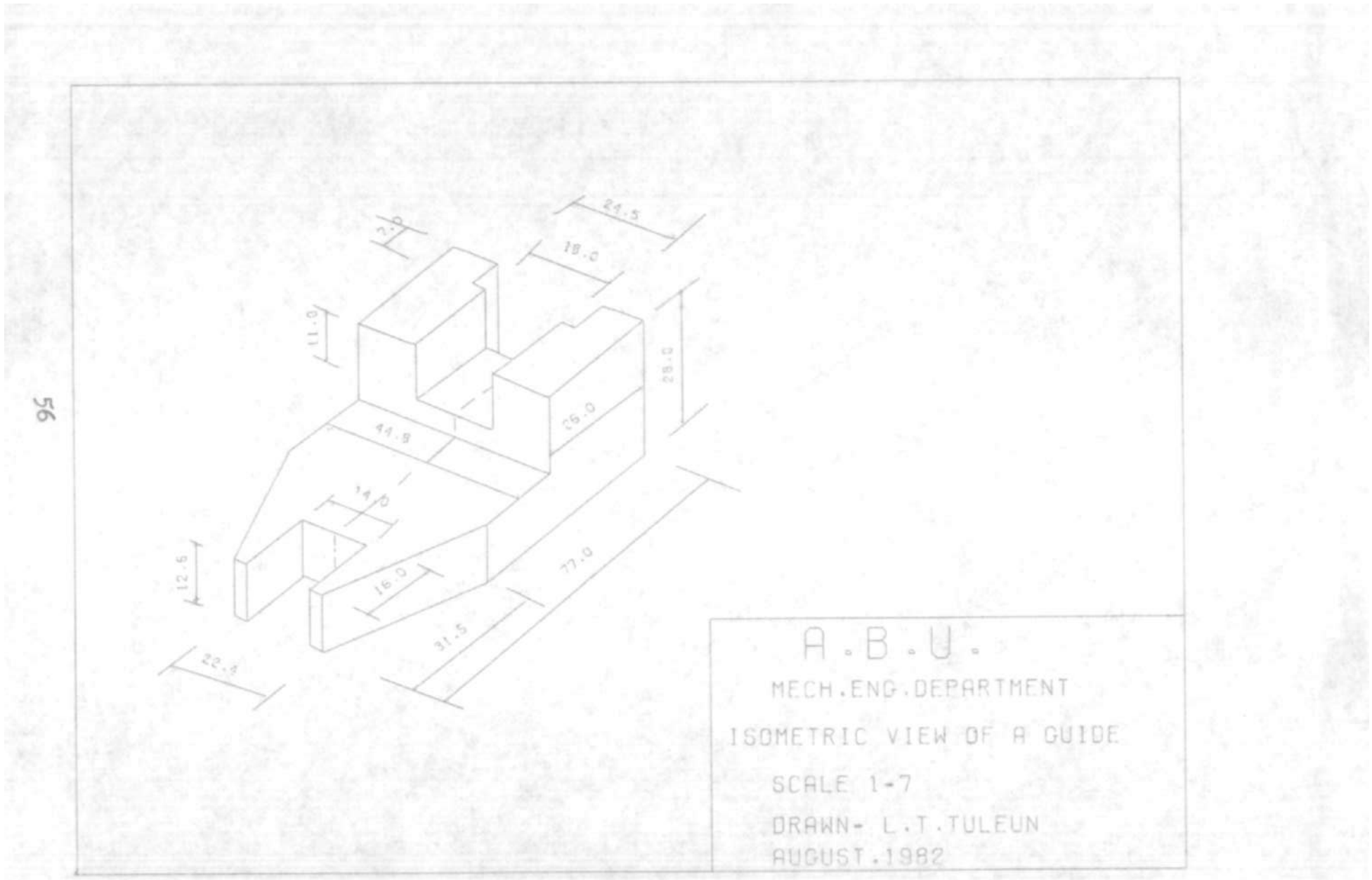


Figure 5.2: Technical Drawing of a Guide in an Isometric View from Fortran

commands described previously and used for the shaft drawing programme given in Appendix A. The part programmer regards this language as a dictionary of words, symbols, and rules for writing instructions that describe the part or rather the tool motions necessary to produce it. The computer has programmes that allow recognition of these written instructions, and these programmes are called APT processors. The processors produce a general solution to the machining problem. This solution is called the Cutter Location (CL) file.

2. The computer uses the CL file as input to a second computer programme called the post processor; this programme relates general CL data to the format required by the particular NC machine tool control unit.
3. The processed control data is output to the machine, usually on punched tape, sometimes on magnetic tape, or by direct cable (direct numerical control, DNC).

The generation of part programmes can be done as a component part of the CAD (or rather CAD/CAM) process. The geometric data base constructed in the computer by an interactive CAD system can be used to generate tool paths with a few extra commands. This minimizes the total design-to-production time, increases engineering efficiency, and improves quality control.

Checking of NC programming is aided by animation of the tool path on the graphic display terminal or on a plotter. This enables the programmer to visualize tool motion.

Thus CAD integrates directly with CAM and can result in increasing productivity of both engineering and production personnel by factors of up to an order of magnitude or more, while improving quality control and reducing the design-to-production time.

CHAPTER SIX

COMPUTERIZED STRUCTURAL ANALYSIS OF A SIMPLE SHAFT USING FINITE ELEMENT METHOD

6.1. INTRODUCTION TO FINITE ELEMENT METHOD:

Many practical problems in engineering are either extremely difficult or impossible to solve by conventional analytical methods. Such methods involve finding solutions to mathematical equations which define the required variables. For example, the distribution of stresses and displacements in a solid component or of pressure and velocities in the flow of a fluid, might be required. It was a common practice in the past to simplify such problems to the point where an analytical solution could be obtained which, it was hoped, bore some resemblance to the solution of the real problem.

However, large 'factors of safety' had to be introduced because of the uncertainties involved in such a procedure.

With the present high-speed electronic digital computers, the emphasis in engineering analysis has moved towards more versatile numerical methods. One class of such methods has been given the name of finite element methods. Briefly, finite element methods originated in the field of structural analysis and were widely developed and exploited in the aerospace industries during the 1950s and 1960s.(10) Such methods are

established firmly in civil and aeronautical engineering. Finite element methods are also used widely by mechanical engineers, particularly for the structural analysis of solid components. Finite element methods are not commonly used for problems in fluid mechanics and heat transfer. Possibly, this is because such problems are not so much made difficult by geometric complexities as by the nature of the physical processes involved.

All finite element methods involve dividing the physical systems, such as structures, solid or fluid continua into small sub-regions or elements. Each element is an essentially geometrically simple unit, the behaviour of which can be readily analysed. The complexities of the overall systems are accommodated by assembling large numbers of simple elements, rather than by resorting to the sophisticated mathematics required by many analytical solutions. One of the main attractions of finite element methods is the ease with which they can be applied to problems involving geometrically complicated systems.

For the examplary numerical analysis of a simple shaft, the method of formulation is first considered in the next sub-topic, following Fenner.(10)

6.2. COMPUTERIZED STRUCTURAL ANALYSIS OF A SIMPLY SUPPORTED BEAM USING THE FINITE ELEMENT METHOD:

Consider a simply supported beam of variable cross-section, shown in Figure 6.1.

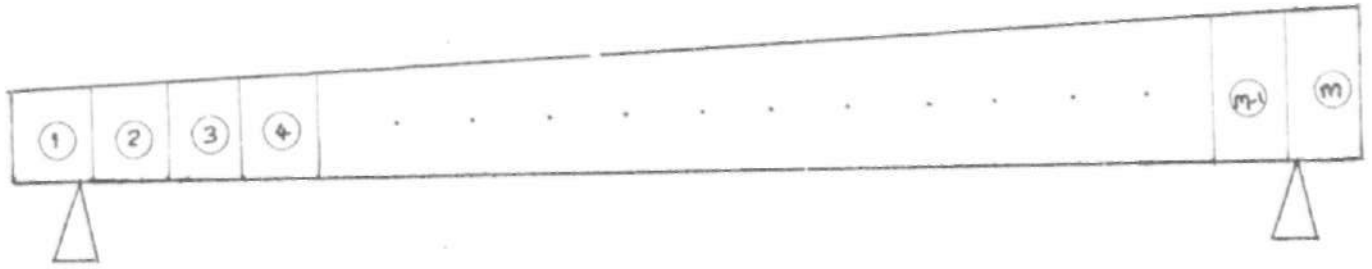


Figure 6.1: A Simply Supported Beam

Provided the length of the beam is large compared with its depth, it can be divided into a number of simple uniform cross section beam (finite) elements of the type shown in Figure 6.2. The analysis begins with the examination of the behaviour of individual elements. Local co-ordinates x and y are chosen to be respectively along and normal to the neutral axis of the typical element as shown in Figure 6.2.

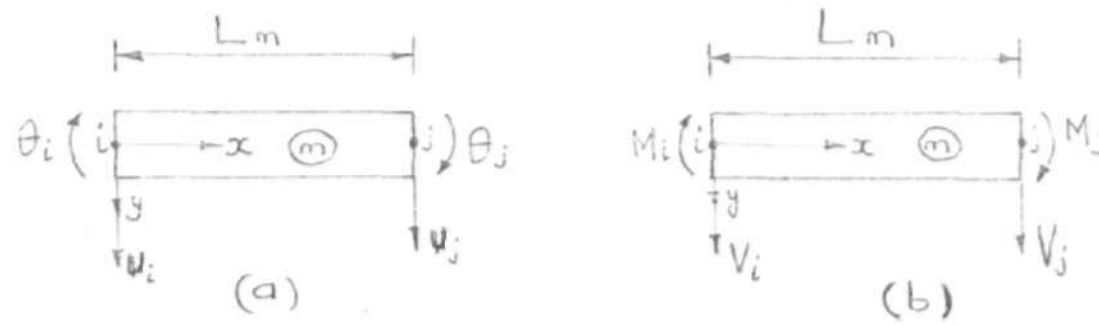


Figure 6.2: A simple beam element:

(a) Displacements and rotations

(b) Forces and moments.

All the elements of the beam are numbered. The number of this element is m. Its length, second moment of area for bending in the x-y plane and Young's Modulus are Lm, Im and Em respectively. The element is joined to its immediate neighbours via 'nodes' at its ends which are numbered i and j.

When the structure is loaded, the displacement in

the y-direction and clockwise rotation of the typical point i are U_i and θ_i, and the corresponding force component and moment applied to the element are V_i and M_i.

To proceed with the analysis, a suitable form of variation is assumed for the displacement in the y-direction along the element. That is,

$$U(x) = C_1 + C_2x + C_3x^2 + C_4x^3 \text{ ----------(6.1)}$$

where C_1 and C_4 are constants for the particular element.

It is convenient to choose a polynomial function, and a cubic form allows the following modes of motion and deformation of the element.

(1) Rigid body translation ($C_1 \neq 0$)

(2) Rigid body rotation ($C_2 \neq 0$)

(3) Bending strain ($C_3 \neq 0$)

(4) Shear strain (due to shear forces in the y-direction ($C_4 \neq 0$)

The use of a function involving four parameters allows their values to be found in terms of the four nodal points displacements U_i, θ_i, U_j and θ_j.

The clockwise rotation (θ) at any position along the element is found by

$$\theta = \frac{dU}{dx} = C_2 + 2C_3x + 3C_4x^2 \text{ ----------(6.2)}$$

Hence

$$U_i = U(o) = C_1 \text{ ----------(6.3)}$$

$$\theta_i = \theta(o) = C_2 \text{ ----------(6.4)}$$

$$u_j = u(L_m) = C_1 + C_2 L_m + C_3 L_m^2 + C_4 L_m^3 \text{ ---(6.5)}$$

$$\theta_j = \theta(L_m) = C_2 + 2C_3 L_m + 3C_4 L_m^2 \text{ --------(6.6)}$$

The values of C_1 and C_2 are given directly by equations (63) and (6.4), those of C_3 and C_4 being obtained from equations (6.5) and (6.6) as follows:

$$C_3 = -\frac{3u_i}{L_m^2} - \frac{2\theta_i}{L_m} + \frac{3u_j}{L_m^2} - \frac{\theta_j}{L_m} \text{ ----------(6.7)}$$

$$C_4 = \frac{2u_i}{L_m^3} + \frac{\theta_i}{L_m^2} - \frac{2u_j}{L_m^3} + \frac{\theta_j}{L_m^2} \text{ ----------(6.8)}$$

From the simple theory of bending, the hogging bending moment N and shear force Q defined as in Figure 6.3 are given by:

$$N = E_m I_m \frac{d^2u}{dx^2} = E_m I_m (2C_3 + 6C_4 x) \text{ ---------(6.9)}$$

$$Q = \frac{dN}{dx} = 6 E_m I_m C_4 \text{ ----------(6.10)}$$

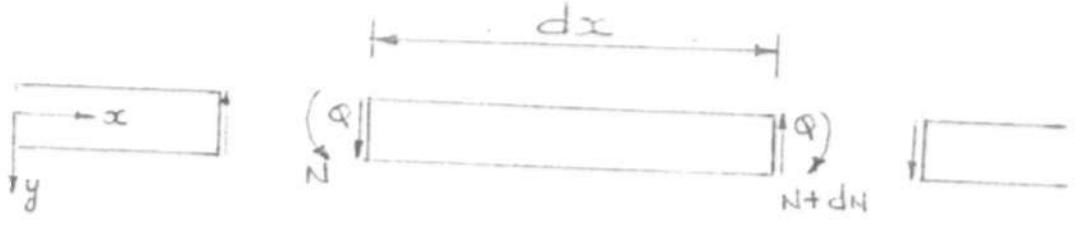


Figure 6.3: Bending moment and shear force in the simple bending of a beam

The forces and moments applied to the element at its

nodes may therefore be expressed in matrix form as follows:

$$\begin{bmatrix} V_i \\ M_i \\ V_j \\ M_j \end{bmatrix} = \begin{bmatrix} Q(o) \\ -N(o) \\ -Q(L_m) \\ N(L_m) \end{bmatrix} = E_m I_m \begin{bmatrix} 0 & 6 \\ -2 & 0 \\ 0 & -6 \\ 2 & 6L_m \end{bmatrix} \begin{bmatrix} C_3 \\ C_4 \end{bmatrix} \qquad \text{----------(6.11)}$$

Using equations (6.7) and (6.8) for C_3 and C_4

$$\begin{bmatrix} V_i \\ M_i \\ V_j \\ M_j \end{bmatrix} = \frac{E_m I_m}{L_m^3} \begin{bmatrix} 12 & 6L_m & -12 & 6L_m \\ 6L_m & 4L_m^2 & -6L_m & 2L_m^2 \\ -12 & -6L_m & 12 & -6L_m \\ 6L_m & 2L_m^2 & -6L_m & 4L_m^2 \end{bmatrix} \begin{bmatrix} v_i \\ \theta_i \\ v_j \\ \theta_j \end{bmatrix} \qquad \text{---(6.12)}$$

That is,

$$R_m = K_m \delta_m \qquad \text{----------(6.13)}$$

where R_m and δ_m are the element force and displacement vectors and K_m is the element stiffness matrix, which is symmetric.

The next stage in the analysis is to add together the force-displacement characteristics of the individual elements to determine the behaviour of the overall structure. For problems of the straight beam type, it is possible to proceed immediately with the assembly process. Since the elements are connected at the nodes, the displacements (both linear and rotational) of a particular node are the same for every element connected

to it. Also the conditions for equilibrium of the structure may be expressed in words and symbols as:

$$\begin{bmatrix}\text{Externally applied forces}\\ \text{and moments at the nodes}\end{bmatrix} = \sum \begin{bmatrix}\text{Forces and moments on these}\\ \text{the elements of/nodes}\end{bmatrix}$$

$$F = \{ R_m = \sum K_m \delta_m = K \quad \text{----------(6.14)}$$

where K is the overall stiffness matrix, and the vectors F and δ contain the externally applied forces and moments, and the corresponding linear and rotational displacements. For example, if there are n nodes, δ contains v_1, θ_1, v_2, θ_2 ..., v_n, θ_n, in this order. The summation in equation(6.14) is for all the elements in the structure, and the coefficients of the overall stiffness matrix are assembled from those of stiffness matrices of the individual elements. The matrix K is 'sparse' (having relatively few nonzero coefficients) because not more than two elements are connected to any one nodal point.

To solve the linear equations (6.14) for displacements, the restraint conditions appropriate to the particular problem must be applied.

In some problems members are subjected to loads distributed along their lengths. Such loadings cannot be accommodated exactly by the present method which assumes the cubic displacement function given by equation (6.1). If the differential element shown in

Figure 6.3 is subject to a uniformly distributed vertical load of q per unit length, then

$$q = \frac{dQ}{dx} = E_m I_m \frac{d^4 v}{dx^4} \qquad \text{----------(6.15)}$$

which would be zero.

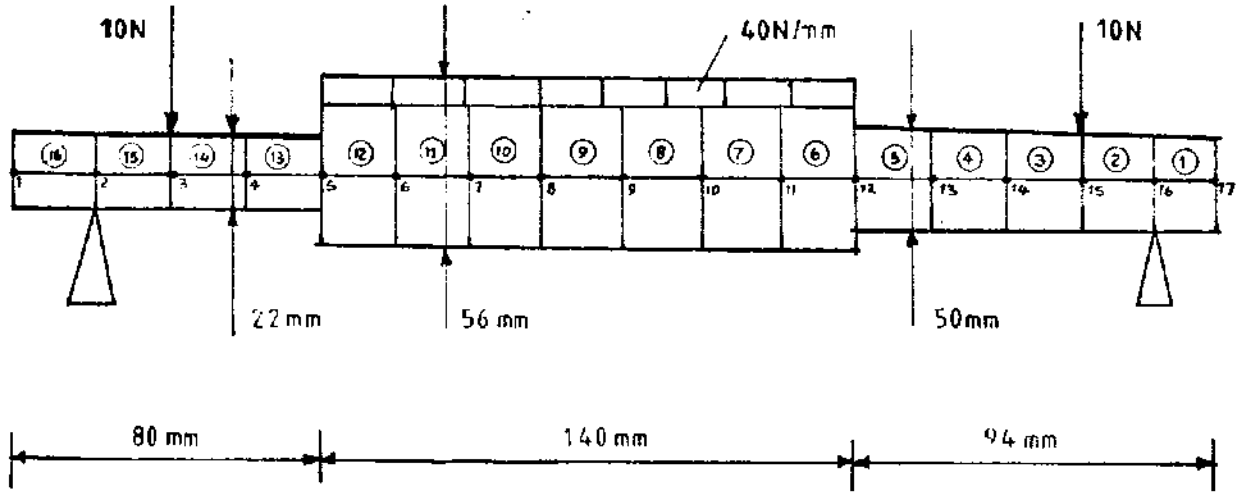
Such a uniformly distributed load can be accommodated approximately, however, by taking the total load applied to an element, qL_m, and dividing it equally between its two nodes as point loads.

6.3. NUMERICAL ANALYSIS OF A SIMPLE SHAFT:

Appendix B shows a FORTRAN programme for analysing the bending behaviour of a simple shaft shown in Figure 6.4. The shaft is loaded with two point loads of 10 N each and a uniformly distributed load of 40 N/mm, as shown in the figure. The method of formulation is that described in Section 6.2, and the resulting set of simultaneous linear algebraic equations is solved by gaussian elimination in a subprogramme named ELIMIN.

For the purpose of analysis, the shaft is divided into 16 elements. The nodal points index i goes from 1 to 16 and j goes from 2 to 17. The nodal point loads for the section of the shaft uniformly loaded, are got by taking the total load applied to an element, and dividing it equally between its two nodes as point loads. An arbitrary number of elements is chosen for this case study, however, the developed programme for the structural analysis of beams or shafts (Appendix B) allows

Figure 6.4 A Simply Supported Shaft.



for beams involving up to 50 elements and 51 nodal points to be analysed.

RESULTS:

Figure 6.5 shows the results obtained with the specified data and the element arrangement shown in Figure 6.4. The printed results show the nodal numbers, modulus, second moment of area and length. For each of the seventeen nodal points, the restraint condition number, co-ordinate, applied force, deflection, applied moment and rotation are printed. Also printed are the nodal points' numbers, the constants $C_3(m)$ and $C_4(m)$, bending moment Mb(i) and Mb(j), stress (i) and stress (j) for the nodal points. It should be noted that higher accuracy is obtained by increasing the number of elements.

The main purpose of this case study is to serve as an introduction to the formulation and programming of finite element methods. Clearly, this approach can be extended to more complex structural elements, subjected to forces and moments in all three co-ordinate directions.

Generally, the programme given in Appendix B, for the structural analysis of a simple shaft, is applicable also to shafts of fixed and varying dimensions (length, cross-section), as well as to arbitrary loading and support pattern.

The programme can also be used to determine for a given permissible stress, the size of the cross-section of the shaft.

Figure 6.5:Results From Shaft Bending Analysis Programme.

STRUCTURAL ANALYSIS OF A SIMPLE SHAFT

M	I	J	C3(M)	C4(M)	MB(I) [N-MM]	MB(J) [N-MM]	STRESS(I) [N/MMXMM]	STRESS(J) [N/MMXMM]
1	16	17	•1384E+18	0	•1344E-07	•1344E-07	•1095E-11	•1095E-11
2	15	16	•4303E+06	•7172E+08	•5334E+05	•2688E-07	•4346E+01	•2190E-11
3	14	15	•8591E+06	•7145E+08	•1065E+06	•5334E+05	•8677E+01	•4346E+01
4	13	14	•1268E+05	•7145E+08	•1596E+06	•1065E+06	•1301E+02	•8677E+01
5	12	13	•1588E+06	•7145E+08	•1968E+06	•1596E+06	•1604E+02	•1301E+02
6	11	12	•1241E+05	•3857E+08	•2420E+06	•1968E+06	•1403E+02	•1142E+02
7	10	11	•1390E+05	•2490E+08	•2711E+06	•2420E+06	•1572E+02	•1403E+02
8	9	10	•1457E+05	•1123E+08	•2842E+06	•2711E+06	•1649E+02	•1572E+02
9	8	9	•1443E+05	•4445E+09	•2814E+06	•2842E+06	•1632E+02	•1649E+02
10	7	8	•1346E+05	•1612E+08	•2625E+06	•2814E+06	•1523E+02	•1632E+02
11	6	7	•1167E+05	•2979E+08	•2276E+06	•2625E+06	•1320E+02	•1523E+02
12	5	6	•9264E+06	•4346E+08	•1768E+06	•2276E+06	•4028E+01	•5187E+01
13	4	5	•2538E+04	•2112E+08	•1179E+06	•1768E+06	•1128E+03	•1691E+03
14	3	4	•1271E+04	•2112E+06	•5906E+05	•1179E+06	•5550E+02	•1128E+03
15	2	3	•2992E+16	•2119E+06	•1396E+06	•5906E+05	•1330E-09	•5650E+02
16	1	2	•1735E+17	•5150E+18	•8059E+08	•1516E+06	•7709E-11	•1450E-09

M	I	J	MODULUS [N/MMXMM]	2ND MOM AREA	LENGTH [MM]
1	16	17	•2020E+06	•3068E+06	•2000E+02
2	15	16	•2020E+06	•3068E+06	•2000E+02
3	14	15	•2020E+06	•3068E+06	•2000E+02
4	13	14	•2020E+06	•3068E+06	•2000E+02
5	12	13	•2020E+06	•3068E+06	•1400E+02
6	11	12	•2020E+06	•4827E+06	•2000E+02
7	10	11	•2020E+06	•4827E+06	•2000E+02
8	9	10	•2020E+06	•4827E+06	•2000E+02
9	8	9	•2020E+06	•4827E+06	•2000E+02
10	7	8	•2020E+06	•4827E+06	•2000E+02
11	6	7	•2020E+06	•4827E+06	•2000E+02
12	5	6	•2020E+06	•4827E+06	•2000E+02
13	4	5	•2020E+06	•1150E+05	•2000E+02
14	3	4	•2020E+06	•1150E+05	•2000E+02
15	2	3	•2020E+06	•1150E+05	•2000E+02
16	1	2	•2020E+06	•1150E+05	•2000E+02

Figure 6.5 (Contd.)

I	REST	X [MM]	LOAD [N]	DEFLN [MM]	MOMENT	ROTATION
1	0	0	0	.4321E-01	0	.2161E-02
2	1	.2000E+02	0	.3208E-15	0	.2161E-02
3	0	.4000E+02	-.1000E+02	.4152E-01	0	.1906E-02
4	0	.6000E+02	0	.7287E-01	0	.1144E-02
5	0	.8000E+02	-.4000E+03	.8392E-01	0	-.1243E-03
6	0	.1000E+03	-.8000E+03	.8103E-01	0	-.1658E-03
7	0	.1200E+03	-.8000E+03	.7723E-01	0	-.2161E-03
8	0	.1400E+03	-.8000E+03	.7235E-01	0	-.2718E-03
9	0	.1600E+03	-.8000E+03	.6634E-01	0	-.3298E-03
10	0	.1800E+03	-.8000E+03	.5917E-01	0	-.3868E-03
11	0	.2000E+03	-.8000E+03	.5090E-01	0	-.4394E-03
12	0	.2200E+03	-.4000E+03	.4164E-01	0	-.4844E-03
13	0	.2340E+03	0	.3457E-01	0	-.5246E-03
14	0	.2540E+03	0	.2362E-01	0	-.5676E-03
15	0	.2740E+03	-.1000E+02	.1198E-01	0	-.5934E-03
16	1	.2940E+03	0	.3206E-16	0	-.6020E-03
17	0	.3140E+03	0	-.1204E-01	0	-.6020E-03

6.3.1. Comparison Of The Numerical Results With Analytical Solutions:

Briefly, simplified analytical solutions are found here simply for comparison purposes. The analytical values of bending moments, deflections and stresses are found at arbitrary cross-sections along the shaft, corresponding to some nodal points for easy comparison with the numerical results.

6.3.1.1. Analytical Solutions:

Figure 6.6 shows the same problem specification as given in Section 6.3 above.

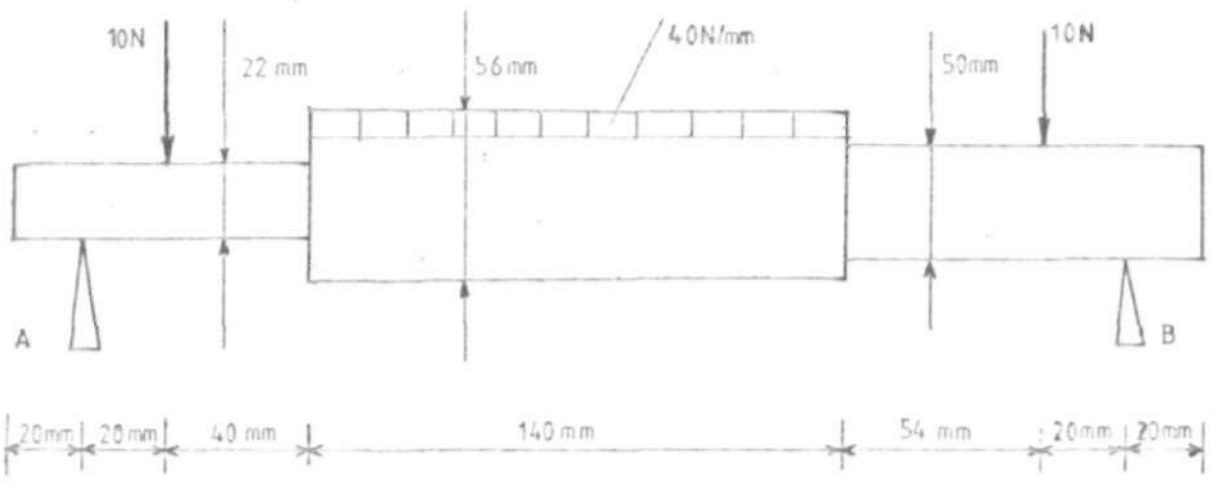


Figure 6.6: A simply supported shaft (loaded)

Sample Calculations:

For the purpose of the analysis, the uniformly distributed load have to be extended to the end of the beam, with negative loading introduced (see Figure 6.7).

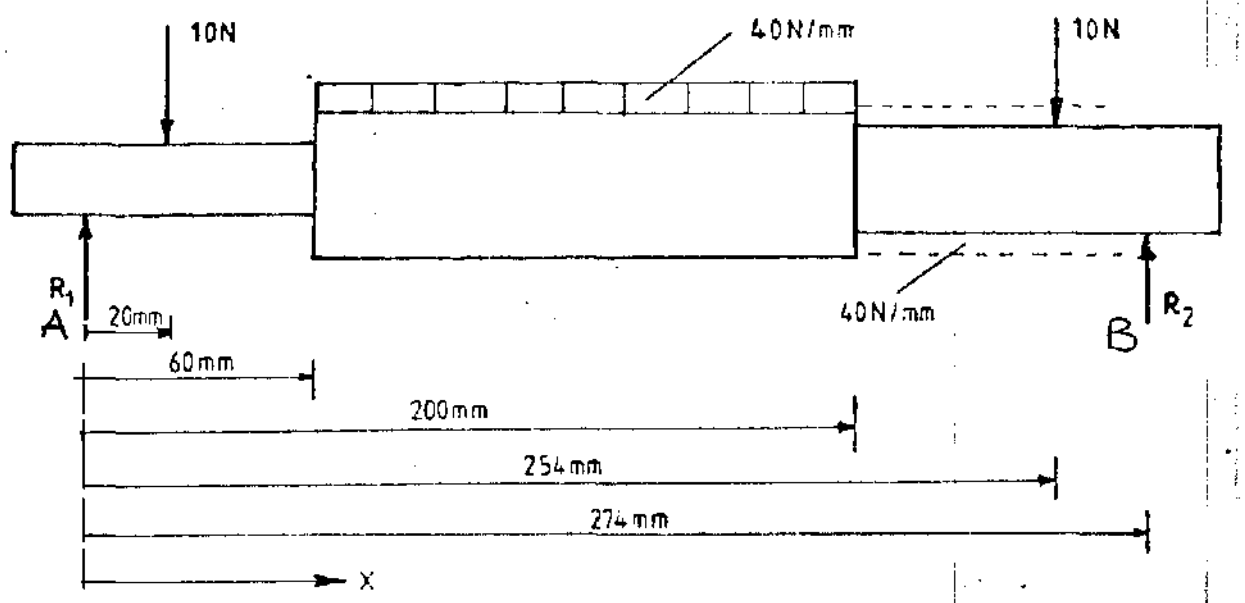


Figure 6.7

Computation of Reactions:

Let R_1 and R_2 be the reactions at the supports A and B respectively. For equilibrium,

$$R_1 + R_2 = 5620 \text{ N} \quad \text{----------(1)}$$

Taking moments about B,

$$274R_1 - 10(274 - 20) - 40(200 - 60)\left[(274 - 200) + \tfrac{1}{2}(200 - 60)\right] = 0 \quad \text{----------(2)}$$

Solving equations (1) and (2)

$R_1 = 2952.336$ N

$R_2 = 2667.664$ N.

Moments (M_x)

The bending moment at x is given by

$$M_x = R_1 x - 10\left[x - 20\right] - \tfrac{1}{2} \times 40\left[x - 60\right]^2$$

$$+ \tfrac{1}{2} \times 40\left[x - 200\right]^2 - 10\left[x - 254\right] \quad \text{------(3)}$$

Note that the square brackets denoteterms to be neglected if they are negative.

Deflections Y_x

The deflection is obtained by the integration of the second order differential equation given below.

$$EI \frac{d^2y}{dx^2} = - M$$

that is,

$$EI \frac{d^2y}{dx^2} = - R_1 x + 10\left[x - 20\right] + \frac{40}{2}\left[x - 60\right]^2$$

$$+ 10\left[x - 254\right] - \frac{40}{2}\left[x - 200\right]^2$$

Integrating,

$$EI \frac{dy}{dx} = - \frac{R_1 x^2}{2} + \frac{10}{2}\left[x - 20\right]^2 + \frac{40}{6}\left[x - 60\right]^3$$

$$+ \frac{10}{2}\left[x - 254\right]^2 - \frac{40}{5}\left[x - 200\right]^3 + C_1$$

Integrating again,

$$EIy = -\frac{R_1 x^3}{6} + \frac{10}{6}\left[x - 20\right]^3 + \frac{40}{24}\left[x - 60\right]^4$$

$$+ \frac{10}{6}\left[x - 254\right]^3 - \frac{40}{24}\left[x - 200\right]^4 + C_1 x + C_2$$

when $x = 0, y = 0 \quad \therefore C_2 = 0$

when $x = 274, \ y = 0$

$$\therefore \ 0 = -\frac{2952.3 \times 273^3}{6} + \frac{10}{6}\left[254\right]^3 + \frac{40}{24}\left[214\right]^4$$

$$+ \frac{10}{6}\left[20\right]^3 - \frac{40}{24}\left[74\right]^4 + 274\, C_1$$

giving $C_1 = 2383689.77$

$$\therefore EIy = -\frac{R_1 x^3}{6} + \frac{10}{6}\left[x - 20\right]^3 + \frac{40}{24}\left[x - 60\right]^4$$

$$+ \frac{10}{6}\left[x - 254\right]^3 - \frac{40}{24}\left[x - 200\right]^4$$

$$+ 23863689.77X \text{ ----------(4)}$$

Stresses:

The stress at x is given by

$$\text{Stress } (x) = \frac{M_x \times D_x}{2\, I_x} \text{ ----------(5)}$$

where M_x = moment (bending) at x

D_x = Diameter of shaft at x

and I_x = Second moment of area at x

When x = 160 mm,

From equation (3)

$$M = 2952.3 \times 160 - 10\left[140\right] - \frac{40}{2}\left[100\right]^2$$

$$= \underline{0.2710 \times 10^6 \text{ Nmm}}$$

From equation (4),

$$y = \left(-\frac{2952.3}{6}\left[160\right]^3 + \frac{10}{6}\left[140\right]^3 + \frac{40}{24}\left[100\right]^4 + 23863689.77 \times 160\right)/(0.202 \times 10^6 \times 0.4827 \times 10^6)$$

$$= \underline{0.0302 \text{ mm}}$$

From equation (5),

$$\text{Stress} = \frac{0.2710 \times 10^6 \times 56}{2 \times 0.4827 \times 10^6}$$

$$= \underline{15.72 \text{ N/mm}^2}.$$

The table below shows both some analytical and numerical results at the same cross-sections along the shaft.

Analytical	x (mm)	20	60	120	160	214	254
Numerical	x (mm)	40	80	140	180	234	274
Analytical	M $\times 10^5$ Nmm	0.5911	1.769	2.816	2.710	1.602	0.5399
Numerical	M $\times 10^5$ Nmm	0.5906	1.768	2.814	2.711	1.596	0.5334
Analytical	Stress N/mm^2	56.547	169.2	16.339	15.72	13.05	4.399
Numerical	Stress N/mm^2	56.50	169.1	16.32	15.72	13.01	4.346
Analytical	y mm	0.035	0.0651	0.0691	0.0302	0.0278	0.0112
Numerical	y mm	0.0415	0.0839	0.0723	0.0592	0.0346	0.01198

TABLE 1: Comparison of Analytical and Numerical Results.

From Table 1, it is clear that the bending moment, stress and deflection values obtained analytically, at some chosen points along the shaft compare favourably with the numerical values.

Basing on the above comparison and the general form of the above developed programme for the structural analysis of beams and shafts of varying dimensions (length, cross-section), as well as to arbitrary loading and support patterns, the programme is therefore recommendable.

CHAPTER SEVEN

Industrial Applications Survey in Nigeria

There is no doubt that computers are now widely used in industries. Such industries include: Steel, Chemical and petroleum processing industries. In some industrial applications, they are used to carry out continuous calculations on data obtained from process monitoring instruments. In other cases, computers are used to monitor and control one or more sub-processes. In still other cases, the computer is used to control the routine operations of the whole production plant as is common in petroleum and chemical plants. Another application of computers lies in the numerical control of machine tools, such as lathes, milling machines, drilling machines.

In Nigeria, computer applications in industries are in their infant stage. This is because most of the computers found in the industries are under-used. Most of the jobs which could be done by the computer are still done manually. The results of a survey carried out for the purpose of this thesis of some of the industries in the country are shown in Table 2. From the table, it can be observed that most of the industries surveyed use computers mainly for financial operations, inventory and stock control. Some of the industries surveyed use computers for production planning and countrol. It is evident that the oil industry in the country at present has the broadest area of computer applications. For example, in the field of exploration,

TABLE 2: Results of Industrial Applications Survey

NAME OF COMPANY/ INSTITUTION/ DESIGN OFFICE	COMPUTER TYPE	PLANS FOR FUTURE INSTALLATION	AREAS OF COMPUTER APPLICATIONS: FINANCIAL OPERATIONS	INVENTORY & STOCK CONTROL	PRODUCTION PLANNING & CONTROL	DESIGN ENGINEERING	MANUFACTURING ENGINEERING	NC MACHINE TOOLS	OTHER AREAS OF APPLICATION	PROBLEMS ARISING
Shell Petroleum Dev. Co. of Nig. Ltd. Lagos.	IBM 4341	✓	✓	✓	✓	-	-	-	Exploration, Petrol. Eng. Transport Drilling, etc.	Importation of spare Pts. maintenance from DPMS
Modelor Design Aids Ltd. Lagos	Many		✓	✓	-	-	-	-	-	Importation of spare pts. in-house maintenance
PZ Industries Ltd., Lagos	ICL/ 2903/40		✓	✓	✓	-	-	..		Lack of spare pts. & skilled manpower
Ajaokuta Steel Complex	?	✓		-	-	-	-	-	-	-
Katsina Steel Rolling Mill	?	✓		-	-	-	-	..	-	-
PAN Ltd., Kaduna	ICL 2904/50		✓	✓	—	-	-	-	-	New installation, no problem yet
Arewa Textiles Ltd., Kaduna.	NCR 8140		✓	—	—	-	-	-	-	— ditto —

TABLE 2 (continued)

Name of/ Company Institution/ Design Office	COMPUTER TYPE PLANS FOR FUTURE INSTALLATION	Areas of Computer Applications							Problems Arising
		FINANACIAL OPERATIONS	INVENTORY AND STOCK CONTROL	PRODUCTION PLANNING AND CONTROL	DESIGN ENGINEERING	MANUFACTURING ENGINEERING	NC MACHINE TOOLS	OTHER AREAS OF APPLICATION	
A.B.U., Zaria	Cyber 72	✓	–	–	✓	–	–	Offers services to various organizations	Importation of spare parts. Maintenance from Leventis
National Trucks Manufacturers Ltd., Kano	N C R 8250	✓	✓	✓	–	–	–	–	New Installation, no maintenance problems Lack of awareness of computer potentials and interest by users
OSOT Associates, consulting Engineers Kaduna	Hewlett Packard 9830A, commodore computer	✓	–	–	✓	–	–	–	Maintenance problems from time to time
Yaroson and Partners, Consulting Engineers, Kaduna	?	–	–	–	✓	–	–	–	–

petroleum engineering, transportation and drilling.
It is important to note here that an important aspect of CAD/CAM is found at Shell Petroleum Development Company of Nigeria Limited. That is the use of graphical input in the form of digitizing tables. Geological surveys at Shell Petroleum Development Company of Nigeria Limited, for example at Lagos and Warri are done in digital modes, using digitizing tables. The digitizing table is a device for the conversion of basic two-or three-dimensional graphical data into digital form, generally onto magnetic tape, paper tape, or punched cards. A digitizing system consists of a programmable controller and a flat plotting table, adjustable for rake and elevation. The digitizer enables the operator, by means of a cursor, to trace and record the details of a map or engineering drawing, with keys on the cursor or on a seperate keyboard controlling the procedure.

In some of our institutions of higher learning, for example, at Ahmadu Bello University, the Iya Abubakar Computer Centre offers computer services to almost all the departments of the University for various undergraduate, post graduate and staff projects. The faculty of engineering of the University, for example, uses the centre for various design engineering projects. Packages such as SAP4 are being used for structural analysis. The centre offers services also to organizations such as Savanna Forestry Research for their statistical calculations, Nigeria National Petroleum Corporation (NNPC) Lagos for forecasting

studies of consumption of their products and Water Resources Engineering Construction Agency (WRECA), Kano for pipe network analysis.

Two Engineering consulting and design offices have been surveyed; These are OSOT Associates Consulting Engineers (Civil and Mechanical Engineers), and Yaroson and Partners Consulting Engineers (Civil, Electrical and Mechanical Engineers).

The OSOT Associates Consulting Engineers have computers installated (The Hewlett Packard 9830A and a commodore computer). Apart from their computer facilities, they also use external IBM computer facilities at the University of Ibadan and International Institute of Tropical Agriculture, Ibadan. At present, they have the following packages to aid in their designs:-

(1) A host of structural analytic programmes

(2) Pipe network analysis

(3) Channel network analysis

(4) Hydrologic river routing analysis

(5) Hydrologic reservoir routing analysis

(6) Hydraulic water - Shed routing analysis

(7) Slip circle analysis for earth dams

(8) Earth work quantity for earth dams and road works

Edition of the above packages, which is usually carried out, depends on the type of design problem at hand. New packages are continously being developed by their engineers for various design problems.

Yaroson and Partners Associates Consulting Engineers have no computer installation. However, they make use of the Associates' computer in the United Kingdom for some of their designs. For such cases, the preliminary designs are carried out by their engineers and are sent to the United Kingdom for computational details. Apart from the Associates' computer in the United Kingdom, they also make use of the external computer facilities at Ahmadu Bello University, Zaria. At present, they make use of these facilities for frame analysis and bridge design jobs whereby variables such as stresses, bending moments and deflections are required. It follows therefore that, the programme on bending of beams and shafts of varying dimensions, presented in chapter six is very relevant to design offices in the country.

In general however, it is true that application areas such as manufacturing engineering, NC machine tools are yet to be considered in this country as CAD/CAM. It must thus be concluded that practically CAD, CAM and MIS have started to appear in Nigeria but are usually limited to very few functions only. Furthermore, no single industrial enterprise has been encountered which would attempt at building an integrated CAD/CAM/MIS system of the type described in the earlier chapters.

In almost all the industries surveyed, there are various problems experienced by them in the application of the computer. Among these problems are the lack of spare parts, skilled manpower for easy maintenance of hardware and software, lack

of awareness of potentials of the computer and the lack of interest by users concerned. These are typical problems that have led to the unfortunate situation where work-loads that could have been done more quickly and more efficiently are instead handled manually.

Users who expect to adopt engineering applications in their stride soon find that dedicated and specialist management is essential for the achievement of an efficient and continuing technical computing service.

It is important to note that for users of a particular software they should be given adequate advice and guidance; enough training in general computer use or specific software systems and appropriate hardware for the particular software to be used. There are various problems which may occur with the hardware as a result of any of the following:-

(i) Incorrect operation of equipment owing to user non-familiarity with the equipment or poor operating instructions;

(ii) Insufficient maintenance, leading to breakdowns;

(iii) Use of non-standard items resulting in a single manufacturer having a monopoly over special stationary, materials supplies, or spares;

(iv) Poor estimates of stationary, supplies, or spares requirements;

(v) The equipment proving inadequate owing to a poor initial evaluation of user requirements and hardware performance; and so on.

Most of the above problems can be solved by suitable training of various cadres of staff of the companies with computer hardware and software. User expertise takes a long time to acquire and demands initial and continuing instruction. Without the expertise, efficient use of the computer will not be realized. Thorough training, besides encouraging the engineer to use a system and promoting greater efficiency generally, can encourage progress towards CAD/CAM/MIS in this country. Individual training needs will vary enormously from organization to organization. Our industries should note that some new graduates have good basic computer appreciation and some limited knowledge of a programming language such as FORTRAN or BASIC. They are often sufficiently interested in the subject of computing to wish to gain a deeper understanding of programming. Other engineers have no concept of a computer or of its capabilities and therefore need enough basic computer appreciation to enable them realize its potential and begin to make use of it. For Nigeria's progress towards CAD/CAM/MIS, the need for training manpower at various levels is apparent. Some of the levels include basic computer appreciation, use of specific applications programmes or the use of computer terminals, system design and programming.

Types and sources of training

(a) Conferences: From a training point of view, attendance at a national or international conference rarely benefits the delegate further than the appreciation level.

(b) Seminars: One - day seminars on carefully chosen application areas or limited aspects of hardware or software can provide an excellent starting point for a user seeking solutions to specific problems.

Seminars may be sponsored by groups of users, by computer vendors or by specialist research and educational organizations, or organized internally by an individual user department.

(c) Courses: Where the requirement is in - depth knowledge, sufficient to enable an engineer or any other cadre of staff to write a programme or use an applications system or for proper maintenance, a properly structured formal training course is necessary. Some of these courses are offered locally by some computer vendors and Universities. For example, the Iya Abubakar Computer Centre, A.B.U., Zaria, offers the following courses:-

(i) Basic computing concepts;

(ii) Computing for managers;

(iii) Systems analysis and design;

(iv) Cobol programming; and

(v) Fortran programming.

The University of Ilorin offers the following data processing courses;-

(i) Computer appreciation;

(ii) Computer hardware concepts;

(iii) Computer installation management;

(iv) Data base management systems;

(v) Software design techniques; and

(vi) Operating systems.

Apart from the above courses offered by some of our universities, certain operational programming and key - punch courses are offered by some computer vendors in the country. For example, Data Preparation Maintenance and Services Ltd (DPMS), Lagos and National Cash Register (Nigeria) Ltd (NCR), Lagos offer some of these courses. N C R, for example has established a school specially for this purpose at Apapa, Lagos. It is important to mention also that to help t ckle the maintenance problems, most computer vendors, for example, NCR, have established re-work centres in most parts of the country. For most of the courses where in-depth knowledge is needed, especially maintenance of the hardware, the training of personnel should be done abroad due to poor facilities in the country. Some of the organizations abroad that offer these courses are hardware manufacturers, research and development organizations and software suppliers.

It should be noted that in most of our industries, where computer use is well established and the training of personnel in the use of applications software or hardware devices is a recurring need, experienced users can carry out the training function as an internal service. The choice between internal or external training should be guided by the training facilities available.

As to hardware support and maintenance problems, organizations using computer installations should consult

other users to obtain their views on materials. They should also consult representatives of various suppliers and be aware of alternative products, and if possible should use samples of each alternative in order to choose the most economical product. This is because peripherals such as teletypewriters, line printers, card readers, magnetic tape units, are standardised and this allows the user to choose from a range of supplies from several different sources. The quantities of printer paper and punched cards, which an installation will consume make it essential for the most reliable supplier to be found. Breakdowns caused by inferior items, all decrease the efficiency of the installation.

Where the cost of maintenance agreement may be too high for an industry, it can prove more economical to purchase a reasonable amount of spares for the essential parts of the equipment, so that replacement of parts can be made as soon as a part needs changing. Purchasing options for this type of user - maintenance may be specifically provided for by the manufacturer.

It is hoped that if computer vendors, institutions of higher learning and industrial organizations with computer installations in this country, co-operate fully along the lines suggested above and most importantly, with the co-operation of the Federal Government, for example, on issuance of import licences to computer venders, application of CAD/CAM/MIS which is at present facing serious problems will significantly give a positive impact to our economy.

Finally, it is rather unfortunate that one of the major setbacks to this survey is the lack of co-operation given to the surveyor by most of the organizations visited. Some of them became suspicious of the surveyors' character even with a full identity. As a result much of the detailed information needed was not made available to him on the grounds that such information was confidential.

CHAPTER EIGHT

RESULTS, DISCUSSIONS AND CONCLUSIONS

8.1. RESULTS AND DISCUSSIONS

In general, CAD/CAM as is well known today, is a vast topic and it is obviously impossible to cover extensively all its branches and aspects that are now expanding in many directions, in a study like this. Nevertheless, two of CAD functions have been considered, treated and implemented successfully, to some extent, within this thesis. The consideration of the two functions selected was based purely on the present availability of appropriate computer hardware and software at the Iya Abubakar Computer Centre. The two functions selected were: computer-aided drafting of a simple mechanical part and computer-aided stress analysis of the same.

The general programme developed for the simple shaft drawing (given in Appendix A), turned out to be laborious in nature. However, if numerous similar shafts of various dimensions are to be designed and drawn, it pays. This is because only the dimensions of the shaft are needed to be entered as data, for the shaft to be drawn automatically, once the programme was designed.

Similarly, the programme for the finite element method structural analysis of shafts and beams of varying

dimensions (given in Appendix B), is recommendable for massive structural analysis of similar parts. A significant ease in performing these two functions (as well as others, in fact), could be achieved in case more advanced, higher level software for computer graphics and finite element structural analysis was acquired for the Iya Abubakar Computer Centre.

Following the exemplary implementation of the two CAD functions, the central issue of CAD data bases has been presented. A brief analysis of some fundamental problems in the design of CAD data bases was carried out. The crucial problems associated with the integration of data (for various functional applications) in the base are briefly presented.

For the computerized design, manufacture and management functions to be performed, one has to have support of numerous tools. A brief description of these is also given in the thesis. The CAD-CAM-MIS integration, which is the ultimate goal of all present efforts in these fields is also described. What seems extremely important here is the fact that integration may be performed solely via the numerical (NC) technique. The NC machine tool application, which here in Nigeria is in its infancy, should thus be strongly promoted and enhanced in the near future, because of this reason as well as numerous others, outlined in the thesis (see Chapter 4, Section 4.2).

In a more general context, from the work done, on the historical background, it is clear that CAD/CAM really started long ago, in the 1950s, and in developed countries much has been achieved, and in fact, computers are presently used extensively to aid design, manufacturing and management in numerous ways.

However, in Nigeria, as the Survey carried out within this thesis shows (See Table 2), CAD/CAM is still in its infancy. Some Engineering Consulting and Design Offices have started to use computers for most of their design functions. Many Companies in the country now have computers installed and are at present making use of them for various functions. At the same time new computer applications in CAD/CAM are being planned.

Some institutions of higher learning in the country, for example, Ahmadu Bello University, Zaria, University of Lagos and University of Ilorin use their computer installations for various under-graduate, Post-graduate and staff projects in design engineering and manufacturing engineering. They also offer computer services to engineering consulting and design offices and other organisations in the country.

As computers are a relatively new tool, many companies, institutions of higher learning and design offices that use them have some problems. Skilled manpower for easy maintenance of hardware and software, power supply and quality of telecommunications constitute the greatest ones

in Nigeria. In some cases, progress is held back also by the production staff, who in most cases lack understanding of the full potential of computers in these highly advanced application areas.

In others, progress is held back partly by lack of Senior Management awareness of the accounts of satisfactory computer installations.

In most cases, after the decision to use a computer in an industry has been made, the task of installation and/or system development is left to computer professionals who rarely have any knowledge of day-to-day design and production processes and do not appreciate the problems of the users from these areas of applications.

As already mentioned in Chapter Seven, there are various ways of tackling some of these problems. These include adequate advice and guidance to hardware and software users, suitable training of various cadres of staff.

Some types and sources of training are: Conferences, Seminars and Courses. Some of these are organized or offered locally by institutions of higher learning and computer vendors in the country.

For most of the courses where in-depth knowledge is needed, especially maintenance of the hardware, the training of personnel should be done abroad due to poor facilities in the country.

Most importantly, during the system design stage, it is the responsibility of the management to make sure that the system designer maintains a very close contact with the user departments, so that their requirements are

incorporated into the system. If the system does not satisfy the user requirements, then it should be judged to be a failure.

It is obvious that this country lags seriously in the area of CAD/CAM. However, it should be noted that the computer as a problem-moving tool in the manufacturing process is not different from the other tools that most industries in this country have already adopted and utilized so well to improve productivity. As usual, introduction of a new tool into manufacturing practice usually has some initial problems which are, however, later on, solved. For example, the introduction of the conveyor belt into assembly lines solves the problem of transferring work pieces from one work station to another; although initial problems such as line balancing, maintenance, etc., were experienced, solutions have been ultimately found.

It should also be noted that the use of a new tool merely to solve an immediate problem or to serve an immediate need without examining its effect on the overall manufacturing process and without adjusting the procedures accordingly is a waste and missuse of it.

It has to be remembered that the development of CAD or CAM even in the developed countries, has faced some difficulties. Some of these usually have been caused by low quality of available computer hardware and - particularly - software. (Though presently, the hardware seems to be advancing far ahead of the software). Also the question of human factors has always been a problem (for example,

individual engineers tend to worry about their status threatened by the introduction of new techniques such as CAD/CAM). A sound conviction of the top management of the organization that CAD and CAM are really the tools that the organization needs is thus essential to their successful introduction. For a success of the introduction of any new tool, a continuous and patient support of the management is a vital factor.

It is hoped that if computer vendors, institutions of higher learning and industrial organizations with computer installations in this country, co-operate fully along the lines suggested above and most importantly, with the co-operation of the Federal Government, for example, on issuance of import licences to computer vendors, application of CAD/CAM/MIS which is at present facing serious problems will significantly give a positive impact to our economy.

Finally, it should be noted that the future may be really bright but events will be most frustrating if a proper environment is not established. There is still much further to go in the future, in this country. It is a rare opportunity to participate in a real industrial revolution like this. However, it should be handled with the utmost care and attention it deserves.

8.2. CONCLUSIONS:

Basing on the work done, the following conclusions have been made.

1. CAD/CAM really started long ago, in the 1950s and has grown to an adolescence stage, with still full adulthood ahead. In fact, presently, computers are being

used extensively to aid design, manufacturing and management in numerous ways.

2. In an industry, the amount of necessary data and procedures is tremendous such that if a company aims at a modern, integrated concept of the design and manufacturing processes, it cannot be realized without the use of computer for data storage. In practice, each separate design or manufacture function operates upon its separate data file. The storage and access of the data have to be organized in a very special way, taking into account the multiplicity of users' requirements.

3. The CAD-CAM-MIS integration which is the ultimate goal of all present efforts in these fields, may be performed solely via the numerical (NC) technique. Because of this reason as well as numerous others outlined in the thesis (see Chapter 4, Section 4.2), the NC machine tool application, which, here is Nigeria, is in its infancy, should thus be strongly promoted and enhanced in the near future.

4. The programme developed for the simple shaft drawing, given in Appendix A, is general and efficient, in that only the dimensions of the shaft are needed as data for the shaft to be drawn automatically to scale. More especially, it pays if numerous similar shafts of various dimensions are to be designed and drawn.

5. Similarly, the programme for the finite element method structural analysis of shafts and beams of varying dimensions is general and has proved to be efficient.

As is shown in Table 1, Chapter 6, results obtained by using this programme compare favourably with analytical solutions for a case study given in the chapter. This programme can be used for massive structural analysis of similar parts.

6. Results of the field study for the application of CAD/CAM in Nigeria have shown that CAD/CAM is still in its infancy in Nigeria.

Comapnies, institutions of higher learning and Engineering consulting and Design Offices, tend to use computers for such applications as for example, payroll, inventory and stock control, production planning and control, Design engineering and manufacturing.

Some of them have plans on the way for new computer applications in CAD/CAM.

7. Finally, it should be noted that we are crossing the threshold of a new era in which the integration of computer-based information with industrial processes and machinery can be expected to alter the technological landscape dramatically. Engineers, Managers, etc., are already using electronic aids to ease or eliminate tedious repetitive tasks. With expanded use, computers can be counted on to improve productivity. Generally, thus it would be desirable that the manufacturing companies which have already installed computers or are planning to install them soon should seriously consider CAD/CAM applications, besides the more conventional ones already in existence.

CHAPTER NINE

RECOMMENDATIONS FOR FURTHER WORK

1. Judging from the nature of the topic CAD/CAM, a more comprehensive literature review could be done.

2. Some more work on computer graphics could be done. However, with significant ease if more advanced, higher level software for computer graphics, such as a functional software package for technical drawings, could be acquired for the Iya Abubakar Computer Centre.

3. The approach used in the formulation and programming of finite element methods for the structural analysis of beams and shafts of varying dimensions, can be extended to more complex structural elements, subjected to forces and moments in all three co-ordinate directions.

CHAPTER TEN

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APPENDIX A:A SIMPLE SHAFT DRAWING PROGRAMME

```
C  THIS PART OF THE PROGRAM WRITES THE ANGLE OF CHAMFER
C     AND DRAWS THE CENTER LINE FOR THE SHAFT

      CALL SYMBOL(5.2,5.1,.15,32HNOTE:ANGLE OF CHAMFER=45DEGREES,0.,31)
      Y=(7+31.1)/2
      CALL PLOT(1.0,Y,3)
      CALL PLOT(5.0,Y,2)
      CALL PLOT(6.0,Y,3)
      CALL PLOT(7.0,Y,2)
      CALL PLOT(8.0,Y,3)
      CALL PLOT(16.0,Y,2)
      CALL PLOT(17.0,Y,3)
      CALL PLOT(18.0,Y,2)
      CALL PLOT(19.0,Y,3)
      CALL PLOT(28.0,Y,2)
      CALL PLOT(29.0,Y,3)

      CALL PLOT(30.0,Y,2)
      CALL PLOT(31.0,Y,3)
      CALL PLOT(37.5,Y,2)
      CALL PLOT(38.5,Y,3)
      CALL PLOT(39.5,Y,2)
      CALL PLOT(40.0,Y,3)
      X1=X-2.0
      CALL PLOT(X1,Y,2)

C  THIS PART OF THE PROGRAM DRAWS PART OF THE END VIEW OF THE SHAFT

      IF(D1.LT.D2.AND.D2.LT.D3) GO TO 7
      IF(D1.LT.D2.AND.D1.GT.D3) GO TO 11
      IF(D1.GT.D2.AND.D2.GT.D3) GO TO 19
      IF(D1.GT.D2.AND.D2.LT.D3) GO TO 25
      IF(D1.LT.D2.AND.D2.GT.D3) GO TO 11
       IF(D1.GT.D2.AND.D1.LT.D3) GO TO 25
      R=D1/2.0
    7  CALL CIRCLE(X2,Y,R,1D)
       R=D2/2.0
       CALL CIRCLE(X2,Y,R,1D)
       R=D3/2.0
       CALL CIRCLE(X2,Y,R,1D)
       GO TO 200
      R=D1/2.0
   11  CALL CIRCLE(X2,Y,R,1D)
       R=D2/2.0
       CALL CIRCLE(X2,Y,R,1D)
```

288804

```
C THIS PART OF THE PROGRAM WRITES THE ANGLE OF CHAMFER
C   AND DRAWS THE CENTER LINE FOR THE SHAFT

      CALL SYMBOL(5.,5.,.2,3HANGTH('ANGLE OF CHAMFER=45DEGREES',1.,0.,23)
      Y=(T+3.)/2
      CALL PLOT(2.,Y,3)
      CALL PLOT(5.,Y,2)
      CALL PLOT(6.,Y,3)
      CALL PLOT(7.,Y,2)
      CALL PLOT(8.,Y,3)
      CALL PLOT(16.,Y,2)
      CALL PLOT(17.,Y,3)
      CALL PLOT(18.,Y,2)
      CALL PLOT(19.,Y,3)
      CALL PLOT(28.,Y,2)
      CALL PLOT(29.,Y,3)

      CALL PLOT(30.,Y,2)
      CALL PLOT(31.,Y,3)
      CALL PLOT(37.5,Y,2)
      CALL PLOT(38.5,Y,3)
      CALL PLOT(39.5,Y,2)
      CALL PLOT(41.,Y,3)
      X1=X+2.0
      CALL PLOT(X1,Y,2)

C THIS PART OF THE PROGRAM DRAWS PART OF THE END VIEW OF THE SHAFT

      IF(D1.LT.D2.AND.D2.LT.D3) GO TO 7
      IF(D1.LT.D2.AND.D1.GT.D3) GO TO 11
      IF(D1.GT.D2.AND.D2.GT.D3) GO TO 13
      IF(D1.GT.D2.AND.D2.LT.D3) GO TO 25
      IF(D1.LT.D2.AND.D2.GT.D3) GO TO 11
       IF(D1.GT.D2.AND.D1.LT.D3) GO TO 25
    7 R=D1/2.0
      CALL CIRCLE(X2,Y,R,ID)
      R=D2/2.0
      CALL CIRCLE(X2,Y,R,ID)
      R=D3/2.0
      CALL CIRCLE(X2,Y,R,ID)
      GO TO 31
   11 R=D1/2.0
      CALL CIRCLE(X2,Y,R,ID)
      R=D2/2.0
      CALL CIRCLE(X2,Y,R,ID)
```

```
            ID=2
            R=D3/2.1
            CALL CIRCLE(X2,Y,R,ID)
            GO TO 111
 19         R=D1/2.0
            CALL CIRCLE(X2,Y,R,ID)
            ID=2
            R=D2/2.1
            CALL CIRCLE(X2,Y,R,ID)
            R=D3/2.1
            GO TO 111
 25         R=D1/2.1
            CALL CIRCLE(X2,Y,R,ID)
            ID=2
            R=D2/2.1
            CALL CIRCLE(X2,Y,R,ID)
            R=D3/2.1
            CALL CIRCLE(X2,Y,R,ID)
C
C   THIS PART OF THE PROGRAM DRAWS THE FRONT VIEW OF THE SHAFT
C
 111     CONTINUE
           Y42=Y+5.3
         CALL PLOT(X2,Y+2,3)
         Y+3=Y+3.5
         CALL PLOT(X2,Y+3,2)
         Y44=Y+2.1
         CALL PLOT(X2,Y44,3)
         Y45=Y+2.1
         CALL PLOT(X2,Y45,2)
         Y46=Y+3.1
         CALL PLOT(X2,Y46,3)
          Y47=Y+5.8
         CALL PLOT(X2,Y47,2)
         Y2=Y-D1/2.0+0.4
         CALL PLOT(3.0,Y2,3)


         Y7=Y2+D1+0.8
          CALL PLOT(3.3,Y7,2)
          Y8=Y7+1.4
          CALL PLOT(3.4,Y8,2)
          X9=3.0+L1
          Y9=Y8
          CALL PLOT(X9,Y9,2)
          Y10=Y9+(D2-D1)/2.0
          X10=X9
          CALL PLOT(X10,Y10,2)
          Y11=Y11
          X11=X11+L2
```

```
      CALL PLOT(X11,Y11,2)
      Y12=Y11-(D2-D3)/2.0
      X12=X11
      CALL PLOT(X12,Y12,2)
      Y13=Y12
      X13=X12+L3
      CALL PLOT(X13,Y13,2)
      X14=X13+0.4
      Y14=Y13-0.4
      CALL PLOT(X14,Y14,2)
      X15=X14
      Y15=Y14-D3+0.8
      CALL PLOT(X15,Y15,2)
      X16=X13
      Y16=Y15-0.4
      CALL PLOT(X16,Y16,2)
      CALL PLOT(X13,Y13,2)
      CALL PLOT(X16,Y16,3)
      X17=X12
      Y17=Y12-D3
      CALL PLOT(X17,Y17,2)
      X18=X17
      Y18=Y17-(D2-D3)/2.0
      CALL PLOT(X18,Y18,2)
      X19=X18
      Y19=Y18-D2
      CALL PLOT(X19,Y19,2)
      X20=X19
      Y20=Y19-(D2-D1)/2.0
      CALL PLOT(X20,Y20,2)
      X21=3.4
      Y21=Y8-D1
      CALL PLOT(X21,Y21,2)
      CALL PLOT(3.4,Y8,2)
      CALL PLOT(3.4,Y21,3)
      CALL PLOT(3.0,Y2,2)
      CALL PLOT(X20,Y20,3)
      CALL PLOT(X3,Y8,2)
      CALL PLOT(X12,Y12,3)
      CALL PLOT(X17,Y17,2)
C
C  THIS PART OF THE PROGRAM DRAWS (HORIZONTAL) DIMENSIONAL LINES
C
      Y22=Y+T
      CALL PLOT(3.0,Y22,3)
      Y23=Y22+1.0
      CALL PLOT(3.0,Y23,2)
      CALL PLOT(3.4,Y22,3)
      CALL PLOT(3.4,Y23,2)
      CALL PLOT(X1,Y22,3)
      CALL PLOT(X1,Y23,2)
      CALL PLOT(X11,Y22,3)
```

```
      CALL PLOT(X11,Y23,2)
      CALL PLOT(X14,Y22,3)
      CALL PLOT(X14,Y23,2)
      CALL PLOT(X13,Y22,3)
      CALL PLOT(X13,Y23,2)
      CALL PLOT(X14,Y24,3)
      X73=X1442,3
      CALL PLOT(X73,Y24,2)
      Y24=Y22+0.5
      CALL PLOT(X13,Y24,3)
      CALL PLOT(3.4,Y24,2)
      CALL PLOT(3.3,Y24,3)
      CALL PLOT(1.3,Y23,2)
C
C     THIS PART DRAWS ARROW HEADS FOR DIMENSIONING
C
      CALL SYMBOL(3.5,Y24,1.2,5,90.0,-1)
      CALL SYMBOL(2.9,Y24,[.2,5,270.0,-1)
      X24=X11[.1
      CALL SYMBOL(X24,Y24,[.2,5,270[.[,-1)
      X25=X10+0.1
      CALL SYMBOL(X25,Y24,[.2,5,90[.0,-1)
      X26=X11-0.1
      CALL SYMBOL(X26,Y24,[.2,5,270[.[,-1)
      X27=X11+0.1
      CALL SYMBOL(X27,Y24,[.2,5,90[.0,-1)
      X28=X13+0.1
      CALL SYMBOL(X26,Y24,[.2,5,270[.[,-1)
      X74=X14+0.1
      CALL SYMBOL(X74,Y24,[.2,5,90.0,-1)
C
C     THIS PART WRITES THE HORIZONTAL DIMENSIONS
C
      X29=3.[+L1/4.
      X51=X29+4.3
      CALL SYMBOL(X29,Y23,[.5,4HL1=,0.[,4)
      CALL NUMBER(999.,999.,0.5,L1,0.0,1)
      CALL SYMBOL(X51,999.,.3.5,24HC[,[,2)
      X30=3.[+L1+L2/4.
      X52=X30[+4.[
      CALL SYMBOL(X30,Y23,0.5,4HL2=,0.0,4)
      CALL NUMBER(999.,999.,[.5,L2,.[,1)
      CALL SYMBOL(X52,999.,.[.5,24HC[,[,2)
      X31=3.[+L1+L2+L3/4.[
      X53=X31+4.0
      CALL SYMBOL(X31,Y23,[.5,4HL3=,0.[,4)
      CALL NUMBER(999.,999.,[.5,L3,[.0,1)
      CALL SYMBOL(X53,999.,.[.5,24HC[,[,2)
```

```
C
C  THIS PART DRAWS (VERTICAL) DIMENSIONING LINES WITH
C     ARROW HEADS AND PUTS THE DIMENSIONS
C
      X32=3.4+L1/2.0
      Y32=Y8+1.0
      CALL PLOT(X32,Y32,3)
      CALL PLOT(X32,Y2 ,2)
      Y33=Y8+0.1
      CALL SYMBOL(X32,Y33,0.2,5,180.0,-1)
      CALL PLOT(X32,Y22,3)
      Y34=Y22+5.0
      CALL PLOT(X32,Y34,2)
      Y35=Y22+0.1
      CALL SYMBOL(X32,Y35,0.2,5,0.0,-1)
      X33=X32+0.3


      Y34=Y34+3.5
      CALL SYMBOL(X33,Y34,0.5,4H D1=,0.0,4)
      CALL NUMBER(999.,999.,0.5,D1,90.0,-1)
      CALL SYMBOL(999.,Y34,0.5,24HM,90.0,2)
      X34=3.0+L1+L2/2.0
      Y36=Y11+1.0
      CALL PLOT(X34,Y35,3)
      CALL PLOT(X34,Y12,2)
      Y37=Y11+0.1
      CALL SYMBOL(X34,Y37,0.2,5,180.0,-1)
      CALL PLOT(X34,Y19,3)
      Y38=Y19+5.0
      CALL PLOT(X34,Y38,2)
      Y39=Y19+0.1
      CALL SYMBOL(X34,Y39,0.2,5,0.0,-1)
      X35=X34+0.5
      Y35=Y38+3.5
      CALL SYMBOL(X35,Y39,0.5,4H D2=,0.0,4)
      CALL NUMBER(999.,999.,0.5,D2,90.0,1)
      CALL SYMBOL(999.,Y35,0.5,24HM,90.0,2)
      Y39=Y12+1.0
      X36=3.0+L1+L2+L3/2.0
      CALL PLOT(X36,Y39,3)
      CALL PLOT(X36,Y12,2)
       Y40=Y12+0.1
       CALL SYMBOL(X36,Y41,0.2,5,180.0,-1)
       CALL PLOT(X35,Y17,3)
      Y41=Y17.5+0
      CALL PLOT(X35,Y41,2)
      Y36=Y17.0+0.1
      CALL SYMBOL(X36,Y36,0.2,5,0.0,-1)
      Y36=Y41+3.5
     X37=X36+0.5
      CALL SYMBOL(X37,Y41,0.5,4H D3=,90.0,4)
     CALL NUMBER(999.,999.,0.5,D3,90.0,2)
      CALL SYMBOL(999.,Y36,0.5,24HM,90.0,2)
     Y76=Y24+0.5
      CALL SYMBOL(1.0,Y76,0.4,54HA-A,0.0,5)
      X77=X14+0.2
      CALL SYMBOL(X77,Y76,0.4,54HA-A,0.0,5)
```

```
C   THIS PART COMPLETES THE END VIEW
C
          <=D1[[[[
          R=K/2[[
          CALL CIRCLE(X2,Y,R,ID)
          <=D3[[[[
          ID=2
             R=K/2[[
           CALL CIRCLE(X2,Y,R,ID)
            CALL PLOT([.[,[.[,999)
          STOP
          END
C
C  A SUBROUTINE TO DRAW BOTH BROKEN AND FULL CIRCLES
C   WHEN  ID=1,  DRAWS FULL CIRCLE,OTHERWISE BROKEN CIRCLE
C
C
        SUBROUTINE CIRCLE(X2,Y,R,ID)
         IF(ID.EQ.2) GO TO 20
        CALL PLOT(X2,Y,3)
          CALL PLOT(X2,Y,[3)
          Q=44.[/(3[.[*7.[)


          X4=R*SIN(Q)
          Y4=R*[OS(Q)
          CALL PLOT(X4,Y4,3)
          DO 3[[ M=2,36[
          Q1=44.[*M/(36[.[*7)
          X5=R*SIN(Q1)
          Y5=R*[OS(Q1)
          CALL PLOT(X5,Y5,2)
 300      CONTINUE
          RETURN
 20       CALL PLOT(X2,Y,3)
          CALL PLOT(X2,Y,[3)
          Q=44.[/(36[.[*7)
          X6=R*SIN(Q)
          Y6=R*[OS(Q)
          CALL PLOT(X6,Y6,3)
          N=5
          DO 4[[ M=2,35[,5
          Q3=44.[*M/(36[.[*7)
          X2=R*SIN(Q3)
          Y2=R*[OS(Q3)
          CALL PLOT(X2,Y2,2)
          Q4=6.282*N/36[.[
          X3=R*SIN(Q4)
          Y3=R*[OS(Q4)
          CALL PLOT(X3,Y3,3)
          N=N+5.[
 4[[      CONTINUE
          RETURN
          END
```

```
      MNF,L=BEAM1.
000001B           PROGRAM BEAM1 (FEMDAT1,OUTPUT,TAPE5=FEMDAT1)
                C  PROGRAM FOR STRUCTURAL ANALYSIS OF A SIMPLE SHAFT.
                C
                C
003121B           REAL MB
003121B           DIMENSION  NREST(51),X(51),NPI(50),NPJ(50),E(50),SMA(50),
                1     ESTIFF(4,4),OSTIFF(102,103),DELTA(102),VTH(2,51),F(102),
                1     STRESS(20),MB(20),C3(20),C4(20)
003121B           REAL  L(50),LOAD(2,51),D(20)
003121B           EQUIVALENCE  (F(1),LOAD(1,1)),(DELTA(1),VTH(1,1))
                C
                C  INPUT AND TEST THE NUMBER OF ELEMENTS.
003121B    1      READ(5,51) NEL
030777B    51     FORMAT(I5)
030777B           IF(NEL.GT.0.AND.NEL.LE.50) GO TO 2
031002B           STOP
031003B    2      PRINT 61
031006B    61     FORMAT (1H1,*       STRUCTURAL ANALYSIS OF A SIMPLE SHAFT  *//)
                C
                C  INPUT THE NODAL POINT DATA.
031007B           NNP=NEL+1
031007B           READ(5,52) (I,NREST(I),X(I),LOAD(1,I),LOAD(2,I),J(I),N=1,NNP)
031035B    52     FORMAT(2I5,F10.0,2E15.5,F5.2)
                C
                C  INPUT THE ELEMENT DATA.
031035B           READ(5,53) (M,NPI(M),NPJ(M),E(M),SMA(M),N=1,NEL)
031056B    53     FORMAT(3I5,2E15.5)
                C
                C  PREPARE TO SUM THE STIFFNESS COEFFICIENTS.
031056B           NEQN=2*NNP
031056B           DO 3 IROW=1,NEQN
031061B           DO 3 ICOL=1,NEQN
031063B    3      OSTIFF(IROW,ICOL)=0.
031073B           DO 6 M=1,NEL
                C
                C  FORM THE STIFFNESS MATRIX FOR EACH ELEMENT.
031075B           I=NPI(M)
031075B           J=NPJ(M)
031077B           L(M)=X(J)-X(I)
031101B           FACT=E(M)*SMA(M)/L(M)**3
031140B           ESTIFF(1,1)=FACT*12.
031105B           ESTIFF(1,2)=FACT*6.*L(M)
031111B           ESTIFF(1,3)=-ESTIFF(1,1)
031111B           ESTIFF(1,4)=ESTIFF(1,2)
031112B           ESTIFF(2,1)=ESTIFF(1,2)
031114B           ESTIFF(2,2)=FACT*4.*L(M)**2
031117B           ESTIFF(2,3)=-ESTIFF(2,1)
031120B           ESTIFF(2,4)=FACT*2.*L(M)**2
031122B           DO 4 ICE=1,4
031125B    4      ESTIFF(3,ICE)=-ESTIFF(1,ICE)
031132B           DO 5 ICE=1,3
031133B    5      ESTIFF(4,ICE)=ESTIFF(ICE,4)
031137B           ESTIFF(4,4)=ESTIFF(2,2)
                C
                C  ADD ELEMENT STIFFNESS TO OVERALL STIFFNESS.
031141B           DO 6 IRE=1,4
031142B           DO 6 ICE=1,4
031144B           IF(IRE.LT.3) IROW=2*(I-1)+IRE
031152B           IF(IRE.GE.3)IROW=2*(J-1)+IRE-2
031156B           IF(ICE.LT.3)ICOL=2*(I-1)+ICE
031162B           IF(ICE.GE.3)ICOL=2*(J-1)+ICE-2
031167B    6      OSTIFF(IROW,ICOL)=OSTIFF(IROW,ICOL)+ESTIFF(IRE,ICE)
                C
                C  APPLY THE RESTRAINTS.
031204B           DO 9 I=1,NNP
031206B           IF(NREST(I).EQ.0) GO TO 9
031210B           DO 8 N=1,2
031211B           IF(NREST(I).NE.N.AND.NREST(I).NE.3) GO TO 8
031216B           IROW=2*(I-1)+N
```

```
031220B          DO 7 ICOL=1,NEQN
031222B    7     IF(IROW.NE.ICOL) OSTIFF(IROW,ICOL)=0.
031230B          LOAD(N,I)=0.
031232B    8     CONTINUE
031235B    9     CONTINUE
           C
           C  EXTEND THE OVERALL STIFFNESS MATRIX TO INCLUDE THE FORCE VECTOR.
031240B          DO 10 IROW=1,NEQN
031242B   10     OSTIFF(IROW,NEQN+1)=F(IROW)
           C  SOLVE THE LINEAR EQUATIONS.
031246B          CALL ELIMIN(OSTIFF,DELTA,NEQN,102,103,DET,RATIO)
031251B           PRINT  75


031253B   75       FORMAT(*     M      I      J        C3(M)        C4(M)                MB(I)
          1              MB(J)                STRESS(I)          STRESS(J)    *  )
031253B           PRINT  81
031256B   81       FORMAT(*                                                              [N-MM]
          1              [N-MM]                [N/MMXMM]          [N/MMXMM]    */)
031256B           DO 200 M=1,NEL
           C COMPUTE BENDING MOMENT
031260B           I=NPI(M)
031261B           J=NPJ(M)
031262B           C3(M)=-(3.0*VTH(1,I)/L(M)**2)-(2.0*VTH(2,I)/L(M))
          1+(3.0*VTH(1,J)/L(M)**2)+(VTH(2,J)/L(M))
031301B           C4(M)=(2.0*VTH(1,I)/L(M)**3)+(VTH(2,I)/L(M)**2)
          1-(2.0*VTH(1,J)/L(M)**3)+(VTH(2,J)/L(M)**2)
031315B           MB(I)=E(M)*SMA(M)*2.0*C3(M)
031317B           MB(J)=E(M)*SMA(M)*(2.0*C3(M)+6.0*C4(M)*L(M))
           C COMPUTE STRESSES
031325B           STRESS(I)=(MB(I)*D(I))/(SMA(M)*2.0)
031331B           STRESS(J)=(MB(J)*D(I))/(SMA(M)*2.0)
031334B           PRINT 70,(M,I,J,C3(M),C4(M),MB(I),MB(J),STRESS(I),STRESS(J))
031360B   70      FORMAT(1X,3I5,2E12.4,4E17.4)
031360B   200      CONTINUE
           C
           C  OUTPUT THE RESULTS.
031362B          PRINT 62,  (M,NPI(M),NPJ(M),E(M),SMA(M),L(M),      M=1,NEL)
031406B
031406B   62    FORMAT(*      M     I     J  MODULUS [N/MMXMM]      2ND MOM AREA
          1  LENGTH [MM]*//  (1X,3I5,3E17.4))
031406B           PRINT 63,  (I,NREST(I),X(I),(LOAD(N,I),VTH(N,I),N=1,2),
          1  I=1,NNP)
031435B   63    FORMAT(*      I    REST       X [MM]          LOAD [N]          DEFLN [MM]
          1     MOMENT     ROTATION*     //    (1X,2I5,2E15.4,3E13.4))
031435B           GO TO 1
031435B           END


000011B          SUBROUTINE  ELIMIN(A,X,NEQN,NROW,NCOL,DET,RATIO)
           C
           C  SUBPROGRAM FOR SOLVING SIMULTANEOUS LINEAR EQUATIONS BY GAUSSIAN
           C  ELIMINATION WITH PARTIAL PIVOTING.
           C
000011B          DIMENSION  A(NROW,NCOL),X(NROW)
000011B          NEQN=NEQN
000011B          IF(NEQN.LE.NROW.AND.NEQN.LE.NCOL-1) GO TO 1
000006B          PRINT 61
000011B   61    FORMAT(33HOSTOP - DIMENSION ERROR IN ELIMIN)
000011B          STOP
           C
           C  FIND MEAN COEFFICIENT MAGNITUDE.
000012B    1     AMEAN=0.
000012B          DO 2 I=1,NEQN
000015B          DO 2 J=1,NEQN
000017B    2     AMEAN=AMEAN+ABS(A(I,J))
000026B          AMEAN=AMEAN/FLOAT(NEQN*NEQN)
           C
           C  COMMENCE ELIMINATION PROCESS.
000030B          JMAX=NEQN+1
000031B          NEQNM1=NEQN-1
000031B          DO 6  IEQN=1,NEQNM1
```

```
C
C  SEARCH LEADING COLUMN OF THE COEFFICIENT MATRIX FROM THE DIAGONAL
C  DOWNWARDS FOR THE LARGEST ELEMENT AND MAKE THIS THE PIVOTAL ELEMENT.
000034B          IMIN=IEQN+1
000034B          IMAX=IEQN
000035B          DO 3 I=IMIN,NEQN
000042B        3 IF(ABS(A(I,IEQN)).GT.ABS(A(IMAX,IEQN))) IMAX=I
000057B          IF(IMAX.EQ.IEQN) GO TO 5
000061B          DO 4 J=IEQN,JMAX
000062B          AA=A(IEQN,J)
000065B          A(IEQN,J)=A(IMAX,J)
000070B        4 A(IMAX,J)=AA
C
C  ELIMINATE X(IEQN) FROM EQUATIONS (IEQN+1) TO NEQN,FIRST TESTING FOR
C  NONZERO PIVOTAL ELEMENT.
000074B        5 IF(ABS(A(IEQN,IEQN)/AMEAN).LT.1.E-8) GO TO 10
000074B          DO 6 I=IMIN,NEQN
000106B          FACT=A(I,IEQN)/A(IEQN,IEQN)
000112B          DO 6 J=IMIN,JMAX
000117B        6 A(I,J)=A(I,J)-FACT*A(IEQN,J)
C
C  SOLVE THE UPPER TRIANGULAR SET OF EQUATIONS BY BACK SUBSTITUTION.
000135B          IF(ABS(A(NEQN,NEQN)/AMEAN).LT.1.E-8) GO TO 10
000144B          X(NEQN)=A(NEQN,JMAX)/A(NEQN,NEQN)
000152B          DO 8 L=2,NEQN
000154B          I=NEQN+1-L
000155B          SUM=A(I,JMAX)
000161B          IP1=I+1
000162B          DO 7 J=IP1,NEQN
000164B        7 SUM=SUM-A(I,J)*X(J)
000173B        8 X(I)=SUM/A(I,I)
C
C  EVALUATE DETERMINANT OF COEFFICIENT MATRIX AND COMPARE WITH
C  ORIGINAL COEFFICIENTS
000213B          DETA=1.
000213B          DO 9 I=1,NEQN
000215B        9 DETA=DETA*A(I,I)
000211B          DET=DETA
000211B          RATIO=DETA/AMEAN**NEQN
000221B          RETURN
000224B       10 DET=0.
000224B          RETURN
000227B          END
```

APPENDIX B (Contd.)

The DIMENSION statement in the above programme allows for beams involving up to 50 elements and 51 nodal points to be analysed. The arrays F, OSTIFF and DELTA,store the externally applied nodal point forces and moments, the coefficients of the overall stiffness matrix, and the linear and rotational displacements of the nodal points, respectively. It should be noted that OSTIFF is allowed an extra column so that it can be extended to include the nodal point forces and moments, as required by ELIMIN. While F and DELTA are single subscript form, for some purposes double subscripts are more convenient: one for the nodal point number and the other to indicate translation or rotation. Hence, arrays LOAD and VTH are introduced and refer to the same storage register as F and DELTA by virtue of the EQUIVALENCE statement. For example, the variables VTH (1, i) and VTH (2, i) store the values of V_i and Θ_i, respectively, where i is the value of the counter I.

The array X is used to store the co-ordinates of the nodal points, while NREST stores integer numbers which define the type of restraint condition applied to each point. A zero value of NREST(i) means that the point whose number is given by the value of i is unrestrained, while values of one, two or three mean

that either the linear, rotational or both displacements of the point are prescribed as zero. The arrays NPi and NPj are used to store the numbers of the nodal points at the ends of the elements, while SMA, E and L store the element second moments of area, Young's moduli and lengths. The array ESTIFF is used to store the coefficients of the element stiffness matrices. The variables NEL, NNP and NEQN are used to store the number of elements, nodal points and equations, respectively, while the counters I and J are used for nodal point numbers, and M for element numbers. IROW and ICOL are used for row and column numbers in the overall stiffness matrix, while IRE and ICE serve the same purpose for the element stiffness matrices.