The economics of the use of numerically controlled machine tools and program development

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THE ECONOMICS OF THE USE OF

NUMERICALLY CONTROLLED MACHINE TOOLS AND

PROGRAM DEVELOPMENT

by

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A B S T R A C T

Brief History

The introduction of numerically controlled machine tools into the manufacturing industries and design considerations for their technological progress.

Classification

Considered from three aspects: type of control, the machine tools with which they are combined and the procedure involved in machining.

Programming

The preparatory work which must be carried out before components can be machined in an N.C. machine tool. This includes planning and encoding the information into the input medium, using manual or computer assisted methods.

N.C. Economics

The number and type of N.C. machines in use in the U.K. are shown, plus an indication of their cost. This emphasises the fact that justification must be on economic grounds.

Cost Analysis

Comparison of N.C. and conventional methods. Examination of justification calculations shows the danger of using short cut methods.

The method of discounting estimated future returns is used to show that accurate forecasting and alternative methods of investment must be considered before a decision can be made.

Consideration of Batch Size

A rational method of assessing batch size and component complexity is shown. Graphical results of several methods of manufacture are used to indicate the economic advantages and disadvantages of each process.

Economic Considerations of Programming

Analysed under two headings: planning and programming, the latter being considered under the headings of manual and computer assisted.

The cost of preparing a control tape ready for prove out is examined and an analysis of special and general purpose systems has been carried out.

Comparison of Methods

The relative merits of in-house or computer bureau service have been analysed and a decision process outlined to assist in the correct system selection.

Program Development

Cost and levels of tape verification are considered, plus the essential facts of producing an accurate control tape.

Methods of eliminating setting errors are considered.

Program format is illustrated and an error checking program developed, using Fortran.

Appendix A   Fortran program description (T.E.S.P.)

"   B   Module table calibration chart

"   C   Graph plotter output.

C O N T E N T S

Except where specific acknowledgement is made
to other works, the content of this thesis is
entirely the work of the author.

GLOSSARY OF TERMS

ACCESS TIME

The time required to locate and retrieve a unit quantity of data from
a store.

ACCURACY

The accuracy of a numerical-control system is measured by the difference
between the actual position taken up by the machine slide and the position
demanded. This difference will not be identical every time the same
position is demanded and, like repeatability or reproducibility, accuracy
is expressed in statistical terms. It is clear that the accuracy of a
system can never be better than the repeatability.

ADAPT

Air Material Command Developed APT. A development of APT with a limited
vocabulary, which can be employed on some small-to-medium sizes of
American computers.

ADDRESS

In numerical-control programming, a symbol which indicates the significance
of the information immediately following. For example, in the instruction
X 1575, X is the address signifying the word 1575 as a co-ordinate on
the X axis.

APT

Automatically Programmed Tools. A universal computer-assisted program
system for multi-axis contouring work. Needs a large computer. The
current version, APT III, is administered by the Illinois Institute of
Technology Research Institute.

AUXILIARY FUNCTIONS

The functions, other than positioning controls, which have to be set
to ensure correct operation of a machine tool. These functions include
stop, start, selection of the machining cycle, tool selection, feeds and

speeds, coolant on or off etc.   They also include the visual display
of information on the state of the machine.

BIT

An abbreviation for a binary digit.

BLOCK

A group of words containing all the instructions for one operation.
In a positioning system, a block will include the co-ordinates of the
position, together with all the instructions for auxiliary functions
necessary to complete an operation.   One block is distinguished from
the next by an end-of-block character.

2 CL

2 Continuous, 1 Linear control axes.   A language developed at the
National Engineering Laboratory, East Kilbride, and mainly used in
Great Britain.   In many respects similar to EXAPT.

COMPILER

A program for a computer to translate an autocode program into its
own machine code.

CONTOURING SYSTEM

A system in which motion has to be controlled on more than one axis
continuously and simultaneously.   This system, which is also known as
a continuous-path system, is typically used in milling, turning, die-
sinking, grinding and draughting machines.

DATA-PROCESSING

The performing of a systematic series of calculations or other logical
operations or information, in order to extract further information from
them, or to put them into a form suitable for controlling a numerically
controlled machine or other equipment.

DATUM

The reference position of the machine members when the measuring system
indicates zero.

DOWNTIME

Time during which equipment is out of action because of faults.

EIA

The Electronic Industries Association in U.S.A. A trade association
representing manufacturers of electronic equipment which issues standards
documents. Address: 2001 Eye Street NW, Washington DC.

END-OF-BLOCK CODE

An agreed code which indicates the completion of a block of input inform-
ation on punched tape. This code usually also causes a line feed
operation on a tape-operated typewriter. Thus one block of information
is printed on one line by the typewriter.

FEEDRATE

The rate, in mm/min or in./min, at which the cutting tool is advanced
into the workpiece. For milling and drilling, the feedrate applies to
the reference point on the end of the axis of the tool. For turning,
it applies to an agreed reference point on the tool.

FORMAT

An agreed order in which the various types of words will appear within
a block, and thus also along the length of a magnetic or punched tape.

FORTRAN

FORmula TRANslation. A universal computing language or autocode
developed by I.B.M. and used for describing numerical processes in such
a way that they can be understood both by human beings and by computers.
For computers to accept programs in FORTRAN, it has to have a compiler
to translate FORTRAN programs into machine code. In the APT system,

mathematical or logical calculations not catered for in the APT program can be programmed in FORTRAN.

INTERPOLATION

The joining up of programmed points to make a smooth curve by computation. If the segments joining the points are straight lines, the process is called linear interpolation; if they are arcs of circles or parabolas, it is known as circular or parabolic interpolation respectively.

ISO CODE

Like the EIA standard code, the ISO (International Standards Organization) code is also an 8-hole tape system.

LEAD TIME

The time between the issue of a drawing from the drawing office and the start of actual machining.

MANUSCRIPT

A planning chart of part-program containing all the information about the geometry of the part and the machining conditions (feeds, speeds, etc.) necessary to make it, written in correct order, and ready for transfer to an input medium.

PARITY CHECK

A means of minimizing errors in coding on tape, etc. All characters in a code are made either odd or even. In the EIA Standard Code for eight-track tape, for example, all characters are represented by an odd number of holes. This is ensured by using one of the eight tracks for a parity digit, the presence of a character with an even number of holes causing the parity check to fail and indicate an error in punching. The incorporation of a parity-check feature makes it possible to stop the machine automatically when a program error is detected.

PART-PROGRAMMER

The person responsible for the preparation of the manuscript.

PICNIC

Pera Instructional Code for Numerical Control. Intended to fill the
gap between simple manual programming and complex computer programming.
PICNIC has been designed expressly for programming point-to-point
machines for such operations as drilling, boring, tapping and milling.

SOFTWARE

The information fed to a computer or control system, as distinct from
their hardware.

SUB-ROUTINE

A discrete part of a computer program which carries out a particular
function and can be used at any time in conjunction with information
generated in another part of the program.

TAB SEQUENTIAL

A tape-programming method for positioning systems, in which the
instructions are always punched in the same sequence, but the TAB
character is punched at the beginning of each word. If the particular
instruction(word) remains unchanged, it need not be punched, and the TAB
character is punched again to begin the next word.

VERIFIER

A feature of tape-preparation equipment specially designed for checking
the accuracy of a punched card or punched tape by producing a second card
or tape from the original data. The two versions are then compared in
the equipment and, if there is any lack of agreement between the second
punching and the first, indicating an error, the equipment automatically
stops.

WORD

A group of characters referring to a unit of information. In numerical
control, words include characters specifying co-ordinate positions and
also such auxiliary functions as feeds, speeds, and coolant on or off.

NUMERICALLY CONTROLLED MACHINES

INTRODUCTION

The first NC machine tools were designed and developed in response to a definite user demand in the early 1950's for the machining of complex shapes. During the following fifteen years most of the NC development work was undertaken by machine tool manufacturers in advance of a known market requirement and, therefore, without particular reference to the needs of the user.

The first generation of NC machines followed, in the main, conventional machine tool design. In most cases they were in effect adaptations of existing machine tools and, because of this, suffered from a variety of inherent defects, including:-

- short life of bearing surfaces due to more intensive utilization;

- accuracy limited by "stick-slip";

- little or no attention to positioning drive dynamics leading to limited drive response;

- spindle position and spindle axis orientation suitable for manual operation, but not necessarily most suitable for NC;

- the position of the feed-back transducers could introduce dimensional errors and often made them liable to interference by dirt and swarf.

Fig. 1 shows a diagrammatic representation of a typical first generation machine. Early in the 1960's machines of the second generation were produced, fig. 2. These were machine tools designed from the outset for NC and included one or more of the following features:-

- horizontal spindle permitting greater machine rigidity and easier clearance of swarf. (It was no longer necessary for the operator to have a continuous view of the cutting tool);

- wearing parts were given special attention, e.g. hydrostatic slideway fig. 3, lubrication and recirculating ball screws were commonly utilised fig. 4;

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- programmed selection of spindle speed;

- feedback transducers integral with the machine;

- automatic tool-changing;

- pallet loading;

- programmed work-table indexing.

Some of these second generation machines were described as "Machining Centres" and introduced a new concept in batch-production metal-working. By having a machine capable of undertaking a range of operations from simple drilling to complex milling and by providing automatic changing of pre-set tools, automatic work-table indexing and pallet loading, it has become possible to carry out a large number of operations at a single
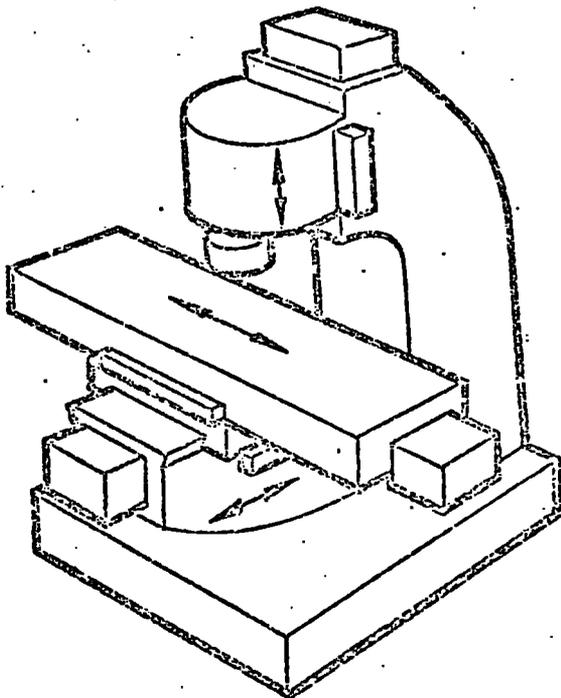
1st Generation N.C. Machine

Fig. 1
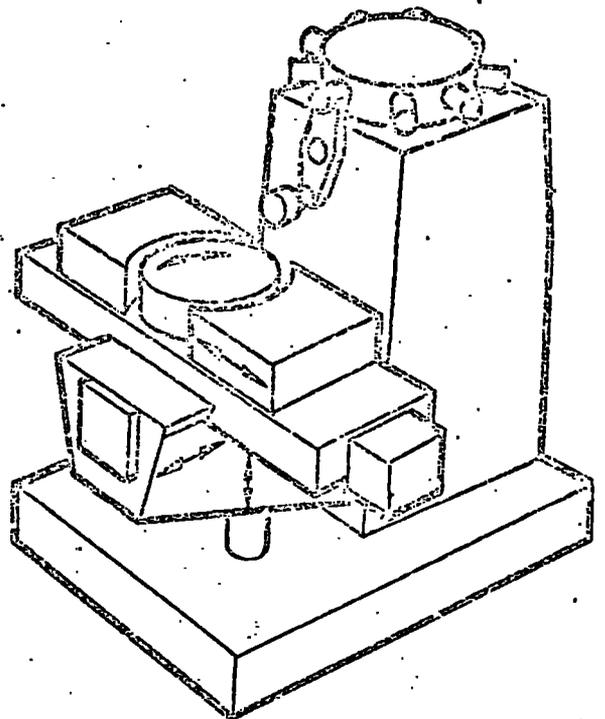
2nd Generation N.C. Machine

Fig. 2

setting of the piece-part. This has permitted much higher utilisation of the machine and considerably shorter lead times and lower work in progress. In many cases these factors have given economic advantages which have offset the much higher capital cost of the machine. An important advantage as the basis for justifying the purchase of NC machine tools must be, in broad terms, an economic one.

Reservoir

Slideway

Section of
Corner Oilway

☐ Bearing Source Area   Reservoir

▨ Oil Exhaust Grooves
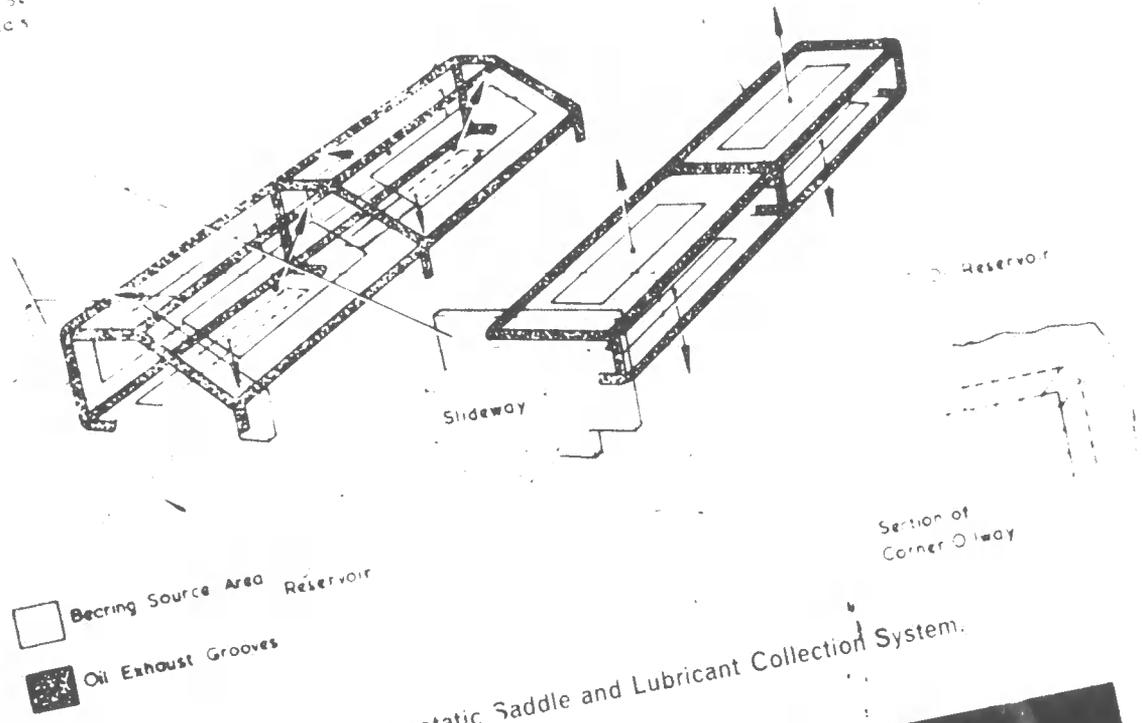
-View of Hydrostatic Saddle and Lubricant Collection System.
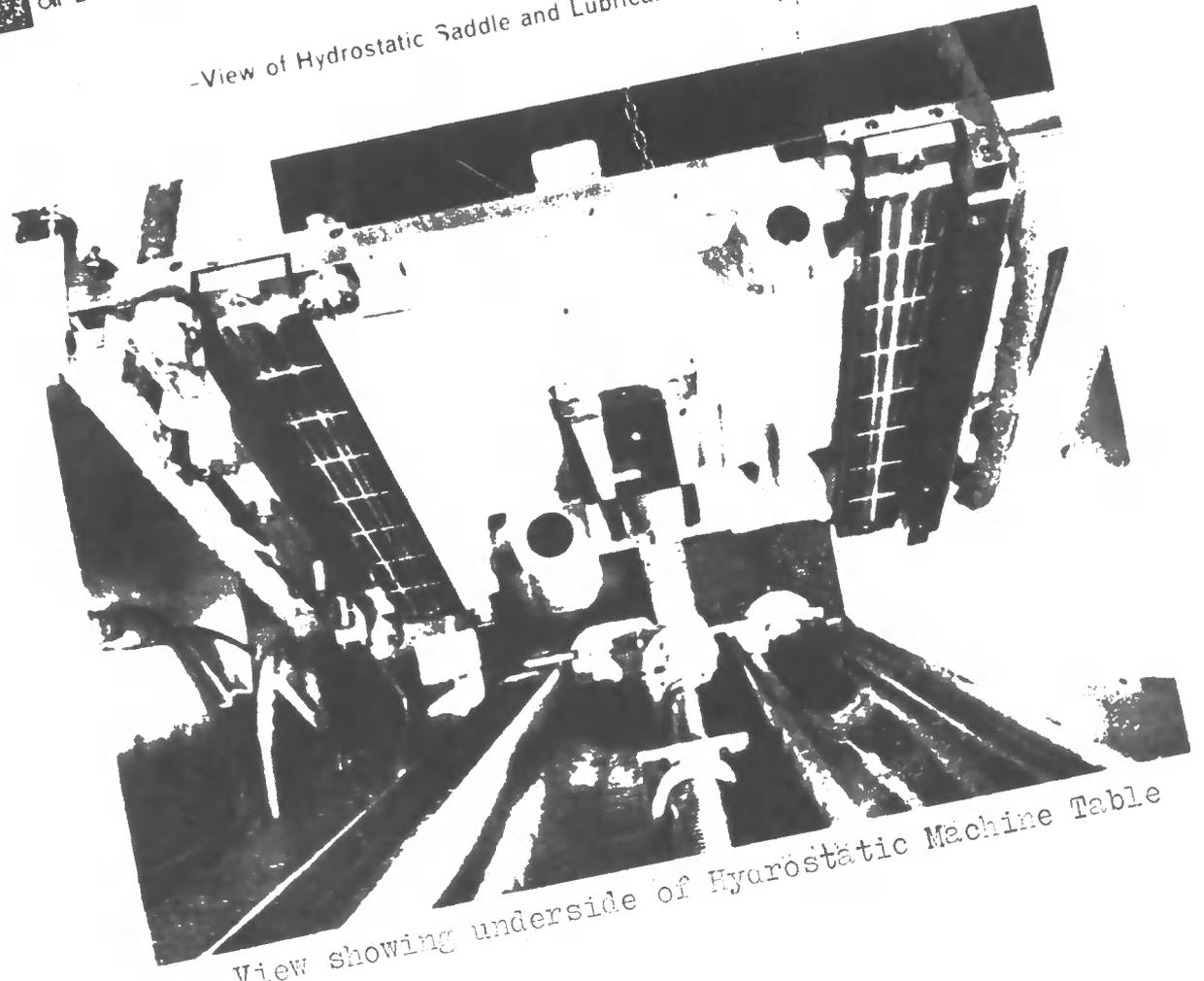
View showing underside of Hydrostatic Machine Table

Fig.3

4
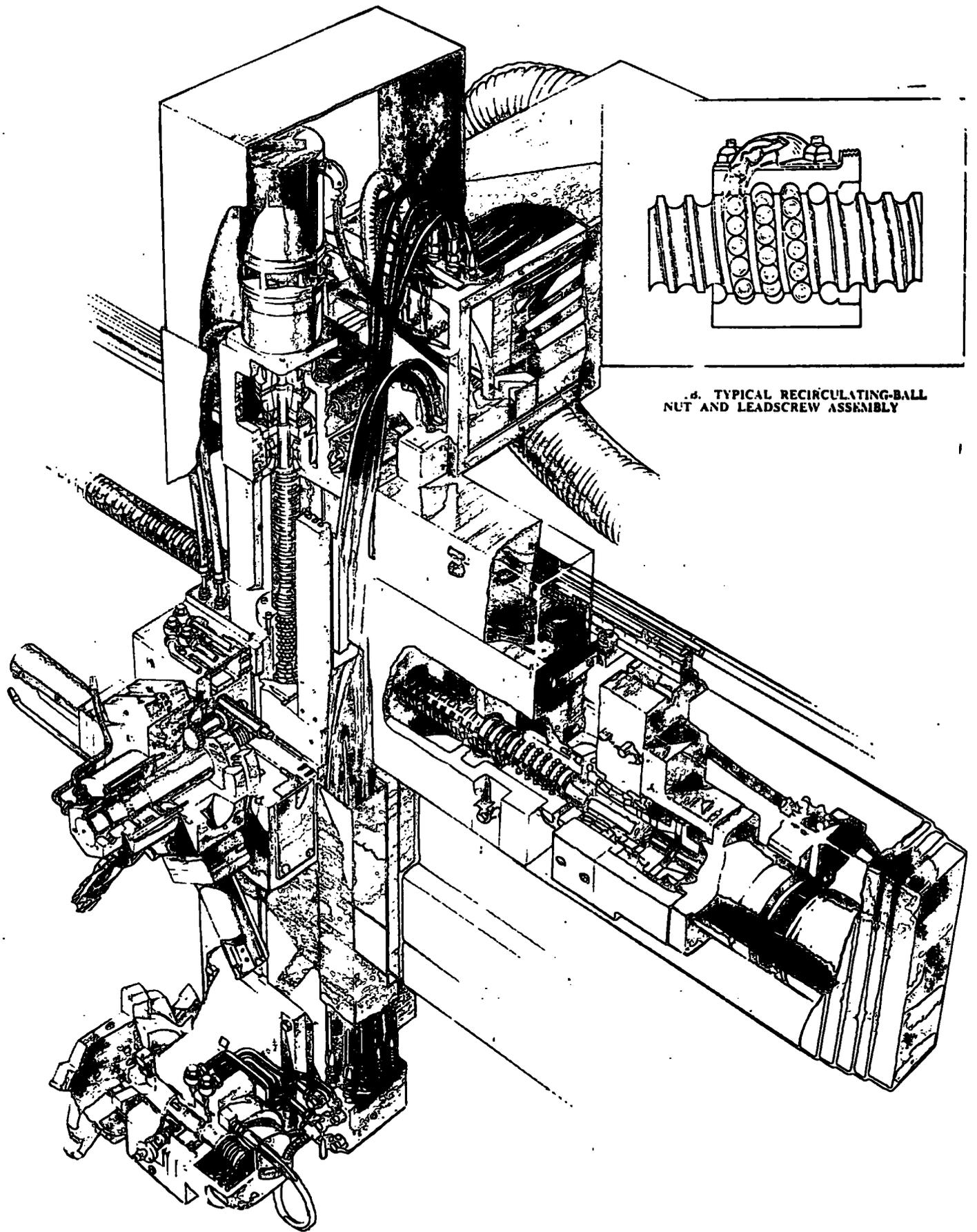
.B. TYPICAL RECIRCULATING-BALL
NUT AND LEADSCREW ASSEMBLY

Indexing and Clamping System

Fig 4

CHAPTER 2   CLASSIFICATION OF NUMERICALLY CONTROLLED

MACHINE TOOLS

This can be considered from three aspects.

1.   The degree and type of control systems which are available.

2.   The type of machine tools with which they are combined.

3.   The procedure involved in continuous path machining and in
      co-ordinate setting operations.

(1) Control Systems

These can be divided into two main categories,

a) positional control, and b) continuous contour control.

a)   Positional Control

The machining and positioning functions are performed separately.
The control system provides the position at which one or more machining
operations are to be carried out.   Thus operations which may be performed
are dependent upon the available tooling.   The cutter path during the
positioning (non-machining) part of the cycle is immaterial, although
the shortest distance would be desirable to minimise time for positioning.

Positional control can include the facility for machining whilst
traversing on one of the controlled axes.   This facility, usually
employed in the form of straight-line milling, necessitates positioning
the component so that the faces to be so machined lie parallel with the
slideway axis of the machine.   This is termed "paraxial" control.   As
a further refinement, the diagonal or "zig-zag" control facility enables
machining to take place under power feed on more than one axis, and hence
at an angle to the slideway axis of the machine.   However, both par-
axial and diagonal machining control are still basically positional,
but with the incorporation of suitable power feeds.

b)   Continuous Contour Control

During the machining operation the cutter is controlled in more
than one axis simultaneously, thus providing relative movement in any

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desired direction. With three-axis control any workpiece shape may be readily and accurately produced (observing certain restrictions due to finite cutter diameter, work-holding devices, etc.).

Three-dimensional shapes may also be produced with a somewhat less costly system, having two axes with continuous contour control and one with positional control. Thus with the cutter set at discrete heights on the third axis, the form is generated by continuous control of the other two.

The continuous contour control systems possess a complexity, and cost, considerably higher than positional control. One of the first considerations therefore, must be to investigate the range and extent of the work to be performed in order to decide which type of control is needed.

The basic difference between positioning and contouring control systems can be seen, at least in part from the arrangements for feedback of the necessary information. Fig. 5 shows a positioning system in which position feedback is all that is required. For contouring, however, both position and velocity must be under control, and hence feedback of both is required, as shown in Fig. 6.

(2) Machine Tool Systems

Most basic forms of machine tool, such as the drill, mill, borer, lathe, etc. are now available with one or more types of control. It has been shown by Marshall (1) that the drill with positional control is the most commonly used of all, and milling machines with paraxial or continuous contour control, are a close second. These two general types together still account for something like two-thirds of numerically controlled machine tools in use today.

Machine tools with positional or paraxial control may be broadly categorised in order of increasing sophistication and cost as follows:-

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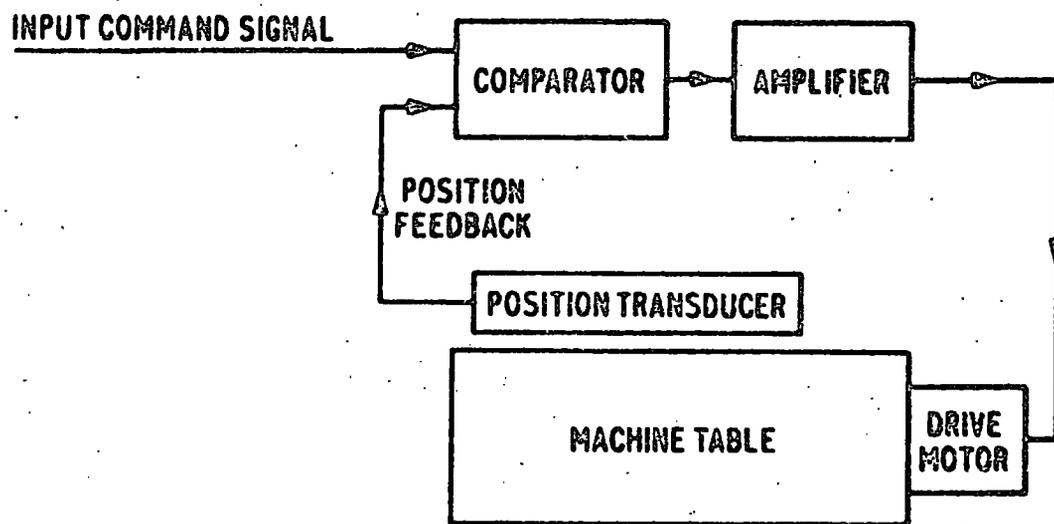
Fig. 5　　　　　　　　　　　Positioning System
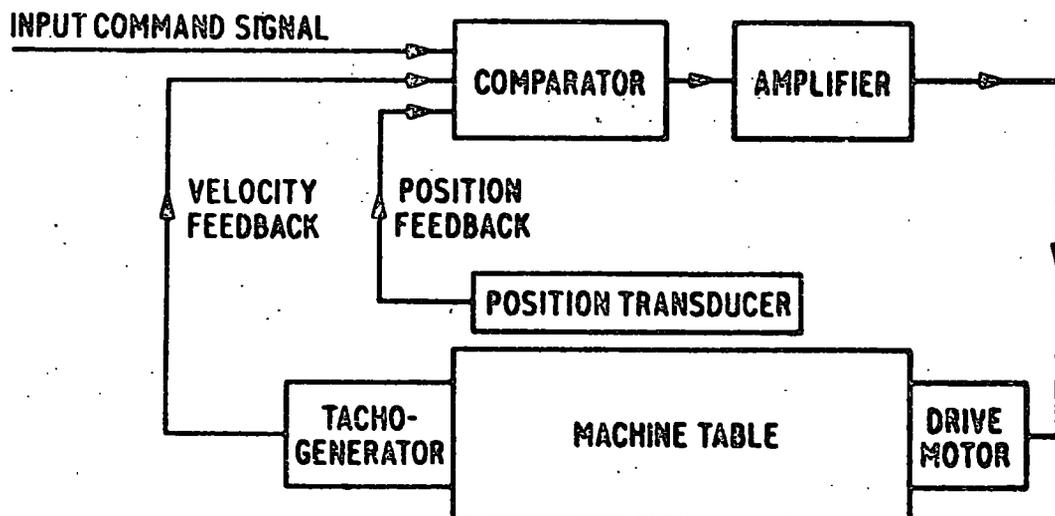
Fig. 6　　　　　　　　　　　Contouring System

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a) Converted conventional machines fitted with a two-axis positioning table. Feed and speed changing and other machine operations remain the duty of the operator, who would, therefore, be hard pressed to handle an additional machine. The control system merely takes over the responsibility for positioning.

b) Single spindle with two-axis positional control. Usually the basic machine functions also (spindle speed, feed, etc.) may be programmed; simple machining cycles may thus be made automatic. Tool changing, however, must be performed by an operator. Depth of penetration (in the third axis) may usually be set by adjustable trips, but the number of these is limited.

c) Turret drills with two-axis positional control permits a fully automatic cycle, depending upon the maximum number of turret stations provided, possibly up to six or more. The operator's principal concern is now the loading of the machine, and he should be capable of handling more than one.

d) Boring and milling machines. Here accuracy and consistency of working are of great importance, and the potentialities of numercial control offer considerable advantages. Cutting times are inclined to be lengthy, so that positioning speeds, already favourable compared with an operator, proceeding cautiously, are not a critical factor. The third axis may be controlled, or may be semi-automatic; this is a matter of balancing utility against cost.

Various types of control system are available with this class of machine. Many have paraxial, as well as positional control facilities.

Machines with continuous contour control employ the control system for the primary form generation process; the form of the cutter used for such operations, although fulfilling the requirements of practical convenience, is quite secondary. These machines will normally also perform the positioning role, and can be used for drilling, boring, etc., with normal tooling. Whilst it would be obviously uneconomic to employ
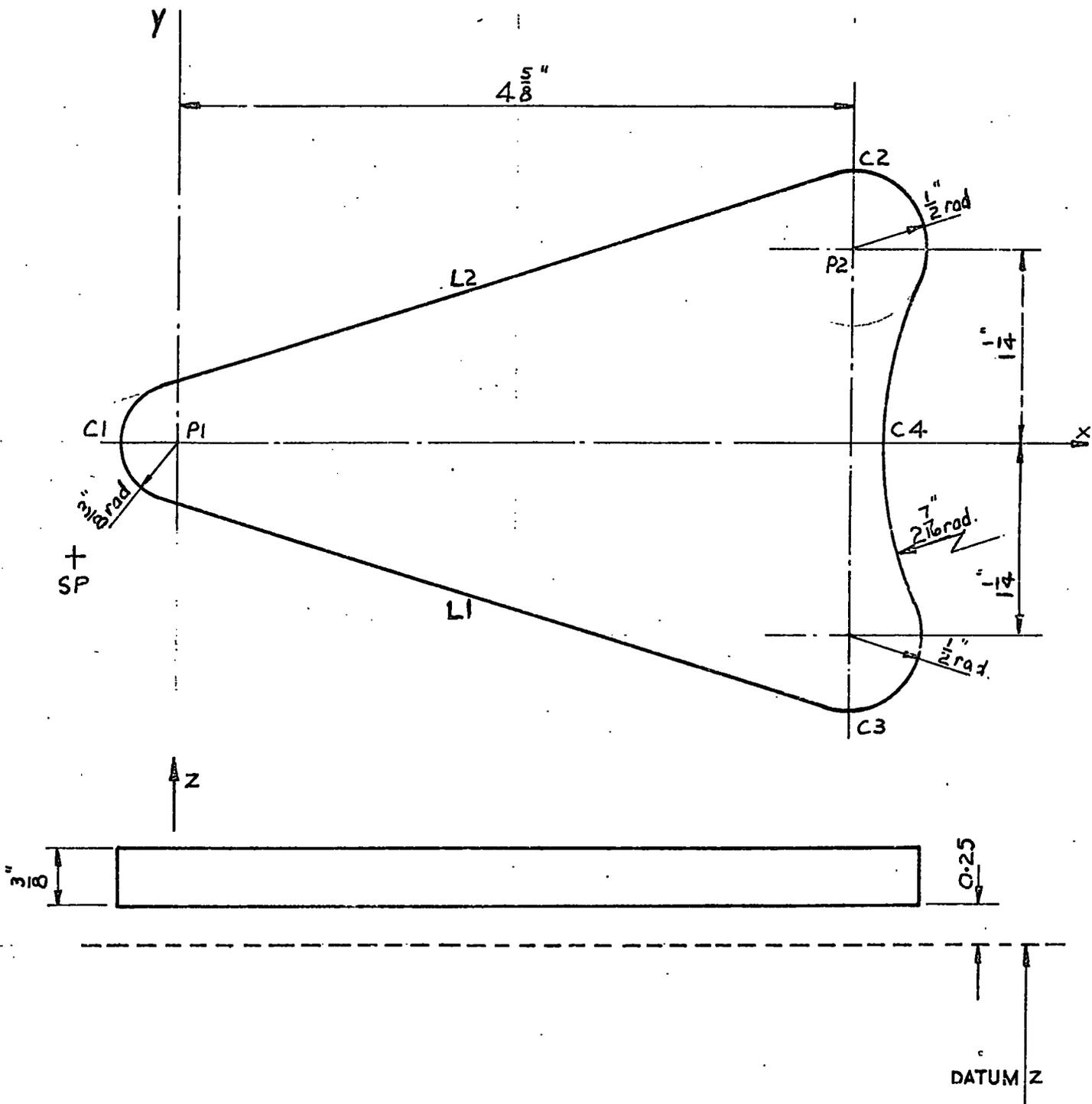
Fig. 7   STOP PLATE

such machines excessively upon work that could equally well be carried out by the positional or paraxial control types, the great versatility of these machines is evident.

3. Procedure Continuous Path Machining

The procedure involved in machining, on a vertical milling machine, the outer contour of a workpiece such as that shown in Fig. 7 is as follows:

The shape of the workpiece is adequately defined in its simplest form on a drawing. This is achieved by using a suitable datum point, Polar and Cartesian co-ordinates and by specifying non-linear shapes in mathematical terms. (Fig. 12).

The cutter path is computed, either manually or automatically, in conjunction with auxiliary information such as cutter diameter, feed rates, etc., and recorded in numerical form on a suitable data storage medium such as punch paper tape or magnetic tape.

The tape is fed into the control equipment, situated alongside the machine tool, which translates the "language" on the tape into a form acceptable to the servomechanisms controlling the movements of the machine slides. The machining proceeds without operator intervention until the operation is completed.

Procedure Co-ordinate Setting Operations

For producing the holes in a workpiece such as that shown in Fig. 8 the procedure involved is given below.

The position of the holes are suitably specified on a drawing, usually in the form of Cartesian co-ordinates from a suitable datum point.

Generally, there are two methods of operation in the control unit, by decade switches, or encoded punched cards; or punched paper tape. The decade switches would be set by the machine operator to correspond with the hole positions.

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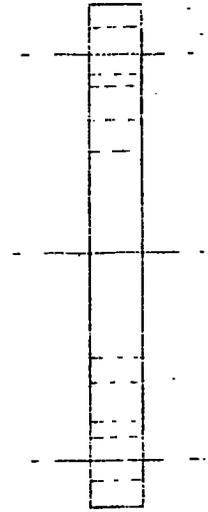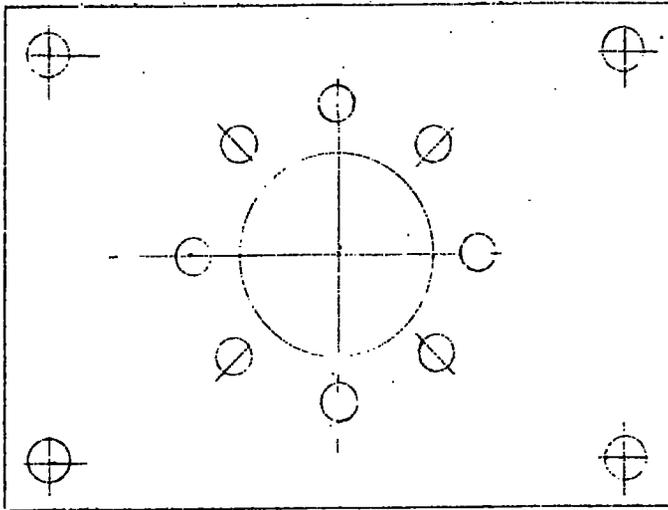
Fig. 8 Component drilled with co-ordinate
setting equipment
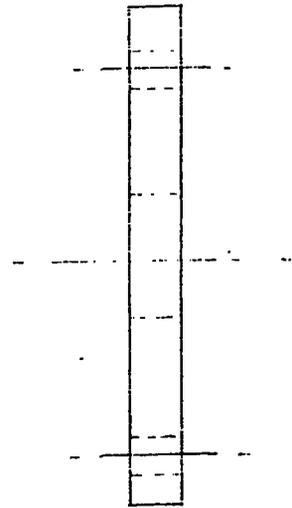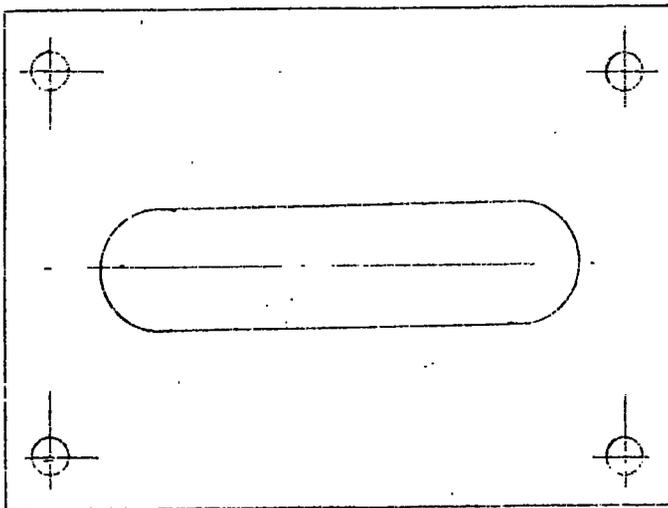
Fig. 9 Component machined with paraxial
control equipment

Using punched cards or paper tape the co-ordinates would be encoded onto these. The cards or tape would then be inserted into the control unit.

When decade switches are used the procedure (that of setting the switches) is repeated for each individual machine setting. A facility that is economically very useful for one-off jobs, due to the cost savings in tape preparation and machine setting time. For a machine tool coupled to a positional control system with the facility for paraxial control, the operation procedure is the same as that for co-ordinate setting operations, with the exception that coding will need to include the facility for bringing in the suitable power feeds. The type of component produced is shown in Fig. 9.

Information Transfer and Coding

It has been shown by Brewer (2) that machine command information will comprise both the numerical specification of co-ordinate positions and machines functional commands, such as "start of operation" and "change of tooling". The machine responds to suitably coded information, normally in binary form. Non-numerical information must also be coded, such as alphabetical letters and other symbols for delete and end of block codes. These are required for the machine function command, according to the instructions which a particular machine may require.

For positional (point-to-point) control systems, such instructions would refer to the initiation of machining operations, and specification of speeds and feeds to be used, change of tooling, etc.

In continuous control (contouring) applications the paper tape normally constitutes the implicit instructions, i.e. the shorthand specification of contours by centre locations and radii of curves, intersections with straight lines, etc. The tape thus contains data on co-ordinates and instructions on cutter path sequence, the precise speci -

fication of cutter path subsequently being computed in terms of a large
number of individual points.

Irrespective of programming languages, the tape codes have become
standardised, broadly into two systems, both of which employ eight hole
punched paper tape. The E.I.A. (Electronics Industries Association)
and I.S.O. (International Standards Organisation) (See Fig. 10).

An advantage of the I.S.O. code is its compatability with computer
codes, particularly when the latter are used for contouring control which
require certain symbols not available in the E.I.A. code.

It was this limitation which led to the development in the U.S.A.
of the ASCll code, from which the I.S.O. code was derived. A further
advantage of the I.S.O. code will arise when the international tele-
typewriter network becomes available, which will be based upon the
I.S.O. code.

Information can be stored (when coded in the manner mentioned above)
in the form of punched cards, magnetic tape, or punched paper tape.
Other methods are known, but the present trend towards standardisation
has consolidated the former three systems of storage.

CHAPTER 3   Program Preparation

The preparatory work which must be carried out before components
can be machined on a Numerical Control machine tool can be divided into
a number of separate tasks:

1)   Selection of a suitable method of mounting the unmachined component
     on the worktable of the NC machine, including the design of any
     required jigs and fixtures.

2)   Selection of the tools and cutters required to machine the component
     to the specified final condition.

3)   Selection of suitable cutting speeds and feed rates for these tools,
     taking into account both the workpiece material and also any

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Left table (a) — EIA code, column headers: 8 7 6 PARITY 4 · 3 2 1

EIA CHARACTER
0
1
2
3
4
5
6
7
8
9
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
. (FULL STOP)
, (COMMA)
/
+
—
DELETE
END OF BLOCK
END OF RECORD
TAPE FEED

(a)

Right table (b) — ISO code, column headers: PARITY 64 32 16 8 · 4 2 1

CODE No.	ISO CHARACTER
48	0
49	1
50	2
51	3
52	4
53	5
54	6
55	7
56	8
57	9
61	=
65	A
66	B
67	C
68	D
69	E
70	F
71	G
72	H
73	I
74	J
75	K
76	L
77	M
78	N
79	O
80	P
81	Q
82	R
83	S
84	T
85	U
86	V
87	W
88	X
89	Y
90	Z
127	DELETE (IGNORED)
8	BACK SPACE
9	HORIZONTAL TAB (SEPARATES WORDS)
10	LINE FEED (END OF BLOCK MARKER)
13	CARRIAGE RETURN (IGNORED)
32	SPACE
36	$
40	(
41	)
42	*
43	+
44	,
45	—
46	.
47	/ (OPTIONAL BLOCK SKIP)
37	% (START OF PROGRAM)
58	: (ALIGNMENT, OR REWIND STOP)
0	NULL (NORMALLY IGNORED)

(b)

Codes for 8-Hole, 1 inch wide punched paper tape, showing (a) the standard EIA code and (b) the ISO code. In the ISO code, the functions specific to numerical control are given in brackets.

Fig. 10

special features such as thin sections in castings etc. which may
make it necessary to reduce the normal values of speed and feed.

4)   Writing a description of the movements operations and functions
which the machine tool must carry out, in the order it must perform
them, to machine the component to the required finished condition.
And, where programming is carried out manually, this set of
instructions must be written in the special language used by the
machine tool control system.

5)   Encoding this set of instructions onto the input medium used by
the control system.

These tasks, with the exception of item 5, which is usually carried
out on a tape typewriter are all inter-related and all require, as a
pre-requisite, a detailed study of both the unmachined and finished com-
ponent drawings, and are all, therefore, usually carried out by the same
man and collectively referred to as "programming". However, the first
three of these tasks are no different from those normally carried out
in the planning office for manufacture on conventional machines were
detailed production planning is applied. Thus, task 4 alone is correctly
described as programming an NC machine tool.

If we now consider the two main classes of NC machine tools mentioned
previously.

1)   Continuous Path Machines, which can be used for cutting complex
shapes such as aerofoil sections, dies, etc.

2)   Point to Point Machines, which are intended to move to a pre-
determined point and there carry out some specified task such as
drilling a hole.

Due to the need to calculate vast numbers of intermediate points
round the curved paths to be machined, most continuous path NC machines
are programmed with the assistance of a computer using a programming
system such as APT, ADAPT or 2C,L. But currently the majority of point

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machines are programmed by manual methods.

However, with the increased versatility of point to point NC machines - many of which can do boring, tapping and milling parallel to the machine axis, in addition to drilling and also the machining of more complex components, manual programming becomes a laborious and lengthy task.

It will be realised from the statements above that programming can be an expensive process and will be referred to in the section dealing with economics.

Programming Procedure

It is evident that the two major alternative roles, i.e. positioning and contouring, are differentiated most particularly by the requirements for the specification of machining operations. For positional control, only the locations at which operations are to be performed, and the instructions for the auxiliary functions of the machine, are required to carry out even very complex cycles and sequences of machining. The information needed is thus not basically complex, and programming can be performed manually.

By comparison, a contouring operation may require a great number of co-ordinate values to define adequately the relative cutter path. Thus, the amount of information needed by the machine is very considerable and is virtually outside the scope of an unaided manual programmer.

Manual Programming

The illustrations in Fig. 11 show the process involved in manual programming. Details of feed, speed and tools to be used and cuts to be taken are first established by the programmer. A programme sheet is then prepared in accordance with them. Using a tape punch, the information on the programme sheet is typed onto this tape (which is the control medium for the machine) to the previously determined code. This method of

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X AXIS

Z AXIS

SAFE PLANE

10.0 dia.

9.6 dia.

8.8 dia.

0.1

B

A

TOOL TIP

0.040R TIP

0.2R

C

5+0.1−0.2+0.040=4.94

0.2

D

E

4

5
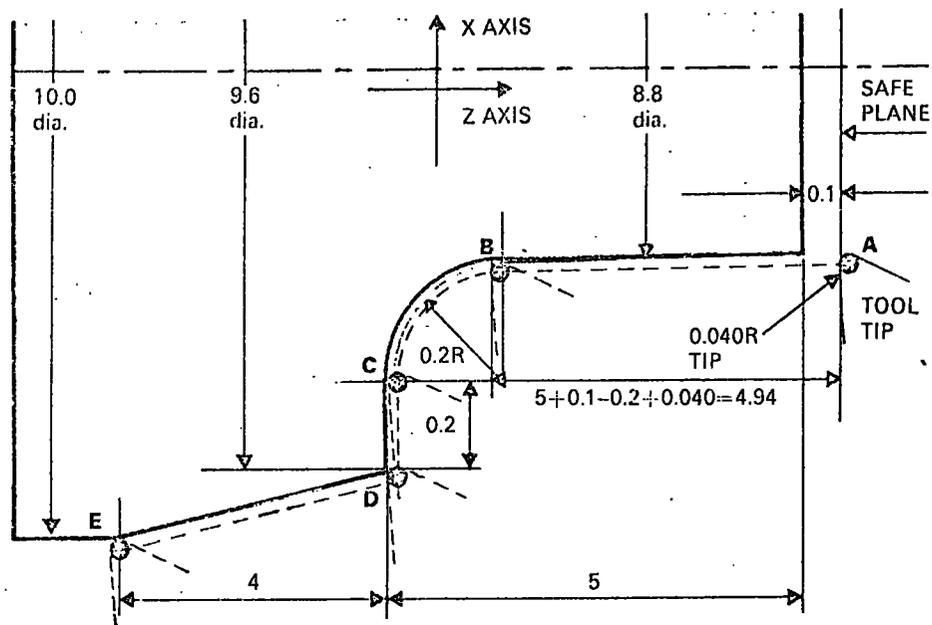
Fig. 11

The portion of the Programme Sheet corresponding to the above cut.

	N	G	X	Z	I	K	F	T	S	M	EOB
Select 679 rev/min	N014	G04	X02						S30	M04	
Turn A to B	N015	G01		Z-49 4			F02				
B to C	N016	G03	X-016	Z-016	1016		F4				
C to D	N017	G01	X-024				F4				
D to E	N018		X-02	Z-404			F025				

N block number
G preparatory function
X movement in X axis
Z movement in Z axis
I auxiliary function of X (e.g. distance of centre of arc to starting point in X direction)
K auxiliary function of
F feed rate

T tool number
S spindle speed number
M miscellaneous functions
EOB end of block

18

programming is particularly suited to small batch production using point to point machines, and can offer considerable economic advantage over conventional methods, particularly to the smaller user.

Computer Aided Programming

Computer aided programming was originally developed to assist in the problems involved in preparing control tapes for making parts having very complex geometry. The eventual outcome of this being the APT programme, now widely used in the U.S.A. It soon became evident that a computer could be used not only to make geometrical calculations but, given tooling and material data, to calculate speeds, feeds, roughing cuts required, repositioning movements etc. as well. This is known as "technology".

Though the computer can be used to assist in point to point programming, where it can be economically justified (see Programming Economic Considerations), the greatest advantage is in contour control and multi axis machines.

The following example is a typical computer aided part-programme using National 2CL language. For the component shown in Fig. 7 instructions written into the part-programme comprises several different types, e.g.:-

    a)   Heading statements

    b)   Geometric statements

    c)   Motion statements

    d)   Machine function statements

    e)   Arithmetic statements

    f)   Special facility statements, such as "area clearance" for cutting pockets and recesses.

```
Partno      Stop Plate (Drg. No.AJ001X5)

Remark      Heading Statements Follow

            Machin/Nelmil

            Cutter/1

            Spindl/350

            Toler/0.003

            Fedrat/5

Remark      Geometric Statements Follow

    P1      Point/0,0,0.25

    P2      Point/4.625,1.25,0.25

    P3      Point/4.625,-1.25,0.25

    C1      Circle/Center,P1,Radius,0.375

    C2      Circle/Center,P2,Radius,0.5

    C3      Circle/Center,P3,Radius,0.5

    L1      Line/Right,Tanto,C1,Right,

            Tanto, C3

    L2      Line/Left,Tanto,C1,Left,Tanto

            C2

    C4      Circle/XLarge,Out,C2,Out,C3,

            Radius,2.4375

    SP      Point/-1,-1,1

    PL1     Plane/P1,P2,P3

Remark      Motion Statements Follow

            From/SP

            GO/TO,L1,TO,PL1

            GORGT/L1,Tanto,C3

            GOFWD/C3,Tanto,C4

            GOFWD/C4,Tanto,C2

            GOFWD/C2,Tanto,L2

            GOFWD/L2,Tanto,C1

            GOFWD/C1,Tanto,L1
```

GOTO/SP

STOP

FINI

PROGRAMME WRITTEN IN 2 C.L.

In the part programme the cutter is instructed to move from a convenient start point (SP) clear of the workpiece, and proceed to line L1. Line L1 is defined as being tangential to (TANTO) circles C1 and C3, which, in turn, have been respectively defined as being centred as points P1 and P3, with the appropriate radii. The MOTION STATEMENT then instructs GORGT/L1, TANTO, C3, i.e. go right along L1 to the point of tangency (blend point) with circle C3. In effect L1 has been specified by its common tangency to C1 and C3. This is not yet a complete specification, as four possibilities exist, as shown in Fig. 12. Hence the modifiers RIGHT in the GEOMETRIC STATEMENT L1 = LINE/RIGHT, TANTO, C1, RIGHT, TANTO, C3 eliminate all but the desired common tangent, i.e. tangent I.

The mathematical programming implications can be seen from Fig. 12. These are intended to illustrate the general principles, rather than specifically to represent any particular programming language. All four possible common tangents (I to IV) can be defined by their respective blend points with C1 and C3. The blend point co-ordinates are given below, in which suffices 0 and b refer to the co-ordinates of the circle centres and blend points respectively, and suffices 1 and 3 to the circles C1 and C3 respectively. Hence,

Tangent I
$$
\begin{cases}
X_{b1} = X_{01} + r_1 \cos(\alpha + \beta) \\
Y_{b1} = Y_{01} - r_1 \sin(\alpha + \beta) \\
X_{b3} = X_{03} + r_3 \cos(\alpha + \beta) \\
Y_{b3} = Y_{03} - r_3 \sin(\alpha + \beta)
\end{cases}
$$

Tangent II
$$
\begin{cases}
X_{b1} = X_{01} + r_1 \cos(\beta - \alpha) \\
Y_{b1} = Y_{01} + r_1 \sin(\beta - \alpha) \\
X_{b3} = X_{03} + r_3 \cos(\beta - \alpha) \\
Y_{b3} = Y_{03} + r_3 \sin(\beta - \alpha)
\end{cases}
$$

Tangent III
$$
\begin{cases}
X_{b1} = X_{01} + r_1 \cos(\alpha + \gamma) \\
Y_{b1} = Y_{01} - r_1 \sin(\alpha + \gamma) \\
X_{b3} = X_{03} + r_3 \cos(\alpha + \gamma) \\
Y_{b3} = Y_{03} + r_3 \sin(\alpha + \gamma)
\end{cases}
$$

$$
\text{Tangent IV}
\begin{cases}
X_{b1} = X_{01} + r_1 \cos (\gamma - \alpha) \\
Y_{b1} = Y_{01} + r_1 \sin (\gamma - \alpha) \\
X_{b3} = X_{03} + r_3 \cos (\gamma - \alpha) \\
Y_{b3} = Y_{03} - r_3 \sin (\gamma - \alpha)
\end{cases}
$$

where $\alpha = \tan^{-1} \dfrac{Y_{03} - Y_{01}}{X_{03} - X_{01}}$

$$\beta = \frac{\pi}{2} + \sin^{-1} \frac{r_3 - r_1}{(Y_{01} - Y_{03})^2 + (X_{03} - X_{01})^2}$$

$$\gamma = \cos^{-1} \frac{r_3 + r_1}{(Y_{01} - Y_{03})^2 + (X_{03} - X_{01})^2}$$

It will be noted that the co-ordinates of the blend points are all given by expressions of the general form:

$$X_b = X_0 + r \cos \theta$$

$$Y_b = Y_0 + r \sin \theta$$

The blend points appropriate to any of the common tangents could be specified by the appropriate signs, and by values of θ, such as those given in Table I, for the common tangents I to IV shown in Fig. 12. Thus, each "sign-and-angle" convention would be allotted an appropriate modifier code in the part-programming language, so that the form of common tangent required by the programmer would be unambiguously specified as the cutter path.

The blend points of line L1 with circles C1 and C3 now establish its position; it is now possible to evaluate any required number of co-ordinate points along its length from the equation:-

$$Y = \left(\frac{Y_{b3} - Y_{b1}}{X_{b3} - X_{b1}} \right) X + \frac{Y_{b1} \, Y_{b3} - Y_{b3} \, Y_{b1}}{X_{b3} - X_{b1}}$$

However, the blending of circles C3 & C2 with circle C4 involves eight possibilities, as shown in Fig. 13. Thus, in the line:-

$$
\begin{aligned}
&C4 = \text{CIRCLE/X LARGE, OUT, C2, OUT, C3,} \\
&\qquad\qquad \text{RADIUS } 2.4375
\end{aligned}
$$

the modifier X LARGE eliminates possibilities (1) to (4), and OUT, C2, OUT, C3 eliminates possibilities (5) to (7), leaving the desired form (8).
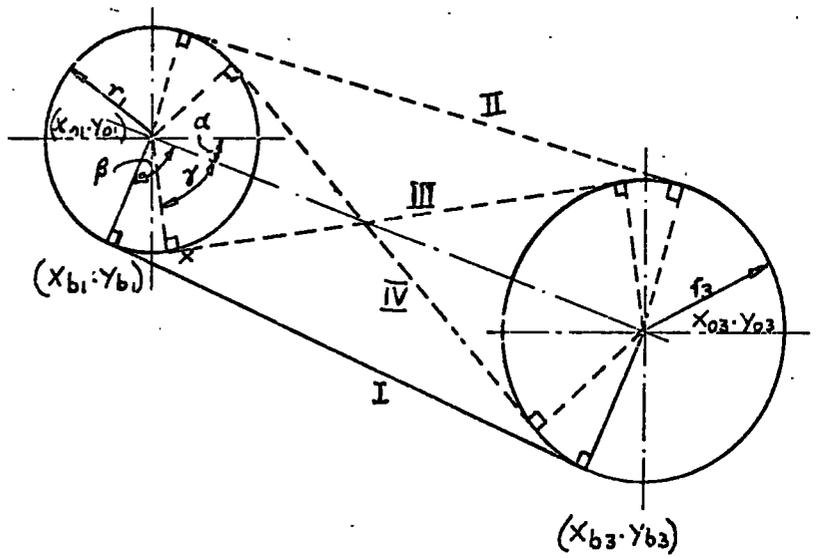
FIG.12 THE FOUR POSSIBLE COMMON TANGENTS TO TWO CIRCLES
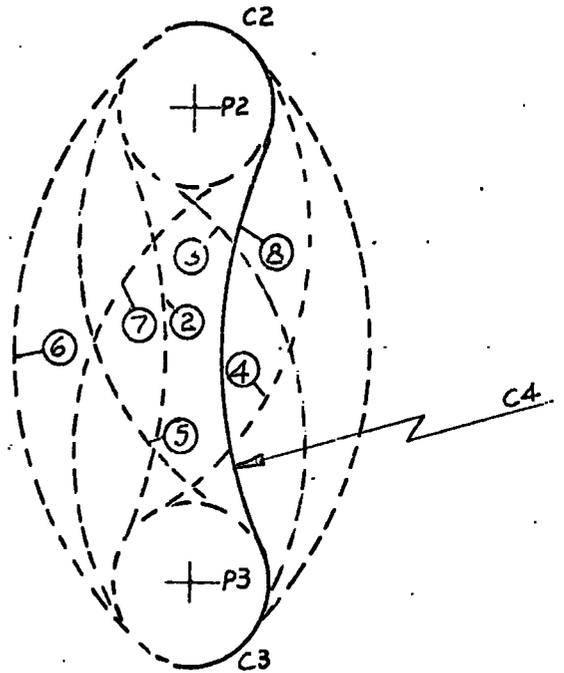
FIG.13 THE EIGHT POSSIBILITIES OF BLENDING THREE CIRCULAR ARCS

As has already been mentioned, once the component profile has been established, the computer must now calculate the cutter path, taking into account the radius of the cutter to be used. When cutting at point P (see Fig. 14) i.e. at co-ordinates (x,y), the centre of the cutter axis will be at Q, with co-ordinates (x ± δx, y ± δy), where δx = Rsinφ, δy = Rcosφ, R = cutter radius and tanφ = dy/dx at P. Hence, when cutting a straight line such as L1 in Fig. 7, the cutter path is also a straight line (Fig. 14) and can be computed from an expression of the general form

$$y = mx + c \pm R\sqrt{1 + \tan^2\phi}$$

When cutting a circular arc, the cutter axis also moved around a circle of radius r + R, and so that the general equation for its path is

$$(x - xo)^2 + (y - yo)^2 = (r \pm R)^2$$

In each case the alternative signs ± are resolved by a modifier which conveys the sense of the cutter path, e.g. whether it is an external or internal shape which is being machined.

Performed manually, these calculations, if not particularly difficult, are lengthy and tedious, and are subject to the inevitable occasional errors which, however low the level of incidence with a careful programmer, are bound to arise. Not least among the benefits of using a computer is the lead time saved in obtaining the machine control tape. It is therefore generally considered to be virtually essential to use a computer for the programming of contouring operations

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LOCUS OF
CUTTER
CENTRE

PROFILE TO
BE CUT

ϕ

$P(x,y)$

δx

δy

BLEND POINT
(x_b, y_b)

r

y

x

$\tan \phi = \dfrac{dy}{dx}$
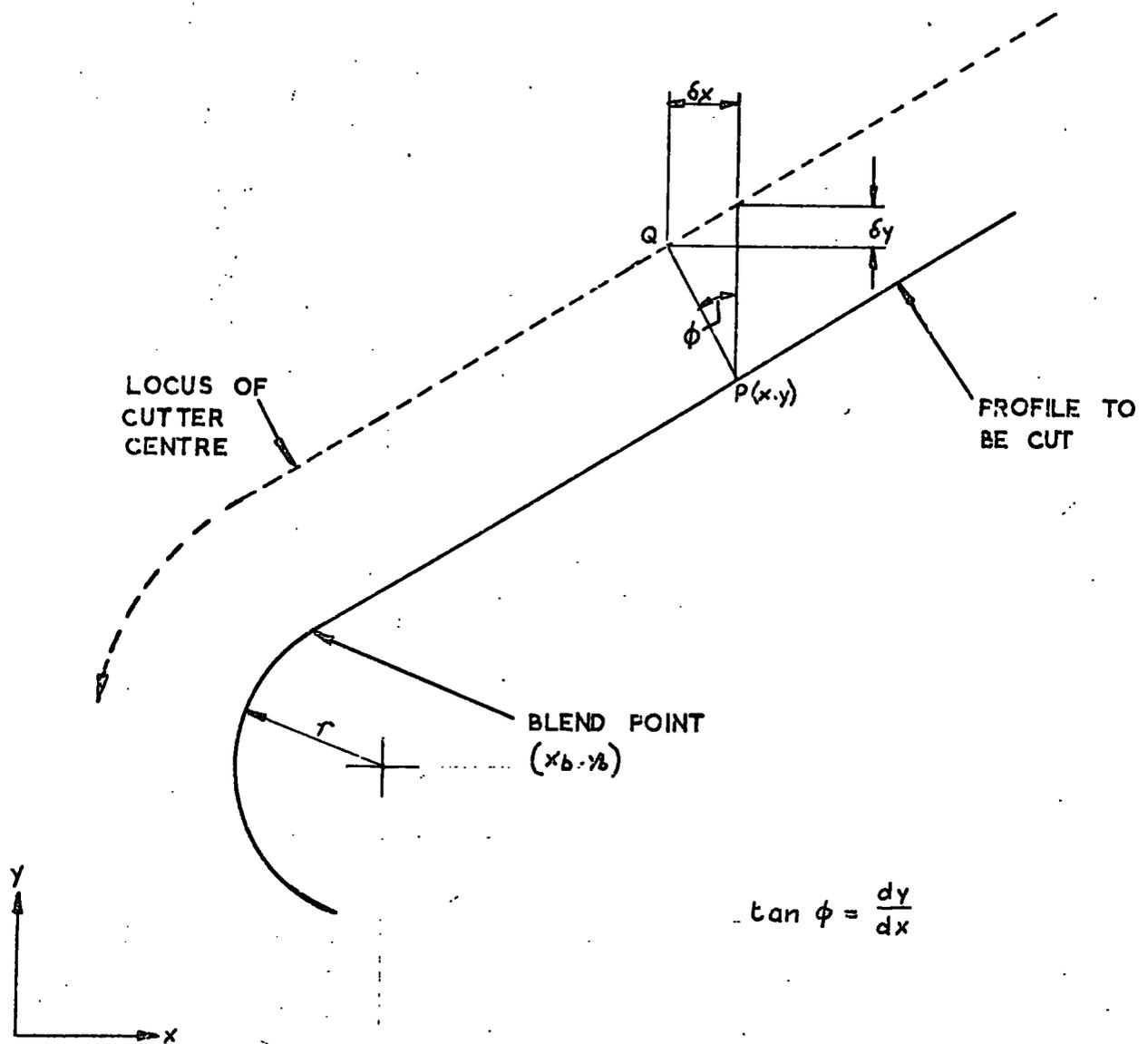
Fig. 14   Derivation of Locus of Cutter Centre

TABLE I   SIGNS AND ANGLE CONVENTIONS

	Tangent Type / Circle No.	I	II	III	IV
Angle θ	C1 and C3	$\alpha + \beta$	$\beta + \alpha$	$\alpha + \gamma$	$\gamma - \alpha$
x co-ordinates	C1	+	+	+	+
	C3	+	+	+	+
y co-ordinates	C1	−	+	−	+
	C3	−	+	+	−

The number of NC machine tools in use in U.K. industry is now
approaching 2,500 and although this number is still only about 0.2%
of the total, (about $1\frac{1}{4}$ million) NC is now an accepted part of the
manufacturing scene.   The major problems of marrying mechanical and
electronic systems together to form a satisfactory working unit have
now been generally overcome - although standards of reliability still
show considerable scope for improvement - and the potential NC machine
user can make his choice from a total of some 500 machine/system
combinations.   The following graph shows the number of NC machines being
used by a typical advanced engineering company.

Installation of numerically controlled machine tools 1958/70
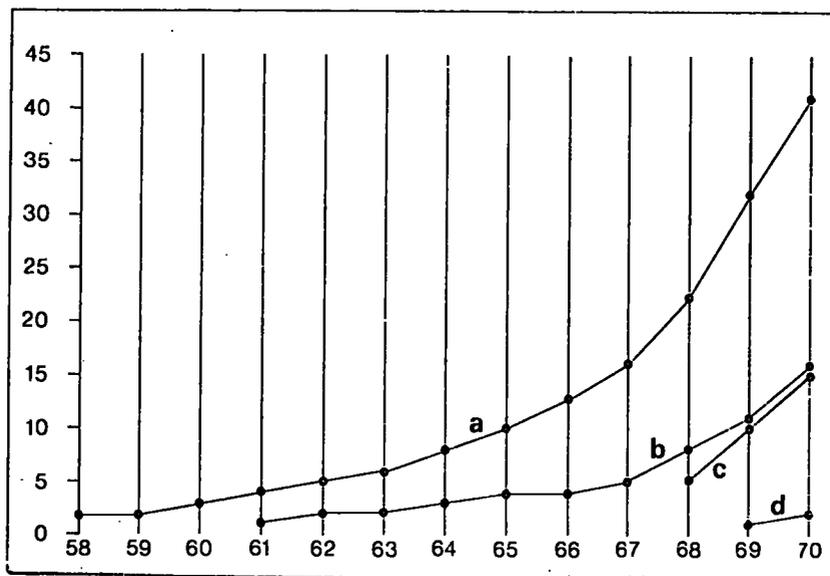
A point to point B continuous path C turning D machining centres

It would seem that the technological step forward which numerical
control represents is now fully appreciated, and the main stumbling block
to the more widespread use of NC over the past few years has concerned
the selection and economic justification of the 'right' machine to meet
the needs of individual users.   The basic cost of NC hardware, i.e. the
machine tools, is undoubtedly high by comparison with conventional machines,
and this fact coupled with the general lack of techniques which enable a
would-be-user to evaluate the advantages of NC in terms of pounds, shillings
and pence has proved a fairly severe deterrent to many companies.

Numerically controlled machines cost approximately $1\frac{1}{4}$ to 4 times as

such as their conventional counterparts, and therefore to justify their use a manufacturer must first satisfy himself that some overall saving, either direct or indirect, is going to result.

When considering the purchase of a numerically controlled machine as opposed to a conventional machine, the following factors need to be considered.

Direct Charges

Capital cost of machine including installation charges,

Power Consumption,

Maintenance Charges (Labour and Spares),

Tooling Costs,

Programming and Tape Preparation, Planning,

Factory Overheads (Supervision, Labouring, Inspection,

Building depreciation, Lighting, Heating, Rent, Rates and Insurance),

Machining Costs.

Indirect Costs and Factors

Jigs, Fixtures and Special Tooling:-

These can often be eliminated completely by the use of NC machines with the resultant liberation of design, storage, handling and maintenance facilities.

Against this we have the cost of storing the data input media, i.e. Punched Cards and/or Tapes.

Operations:-

Reductions. Marking out can be dispensed with completely and, as con-fidence grows, inspection will decrease substantially.

Increases Time is taken proving tapes, by common practice, on the machine.

Consistency of performance

Once input data has been verified as "correct", scrap, resulting from those operations removed from operator control, will be eliminated.

Assembly considerations

In order to avoid incurring the cost of complicated jigs, assemblies

are often planned on the basis of "Holes transferred on assembly". Other advantages to be considered under this heading are:-

1. Machining time which is much easier to control than fitting time.

2. Interchangeability between parts because of machining accuracy.

3. Modifications quickly introduced by simple editing of the master tape.

4. Due to more operations being carried out on NC machines, material handling is sharply cut, thus making valuable floor space available

Positioning times

By NC these are dramatically decreased and will be reflected as a substantial part of the saving of machining time. Assuming that rapid traverse rates are equal and considering final positioning only, it is not uncommon for allowances of 1-2 minutes to be made per hole for this operation on Non-NC machines, whereas the NC machine will steer itself into position in something in the order of $1\frac{1}{2}$ seconds.

In addition, rapid traverse is often faster on NC machines in that the control is tailored to the transmission inertias such that acceleration and deceleration, relative to the final position, are automatically programmed with regard to the rapid traverse rate, to avoid damage. On Non-NC machines one often finds that low "rapid traverse" rates are used to avoid troubles.

Work in Progress

The elimination, combination and shortening of operations reduces Lead time and consequently reduces the volume of work in progress. This related to Bank Charges alone will show tangible savings, there are savings in Labouring, (transportation of parts between operations), Progressing, Inspection and Storage.

Reduction in operator involvement

NC releases the operator from direct involvement with the operation for longer periods and his time can be directed to tasks such as:-
Controlling a number of machines,

30

Setting up a second component during machining of the first

Tool organisation/maintenance

Inspection duties.

The above factors can be used to compile a balance sheet for relative costs of manufacture by NC as opposed to Non-NC, but the following factors, at least equally significant in benefits, are difficult to allocate convincing costs to.

Intangibles

Operator Fatigue

There is no doubt that NC takes a lot from the shoulders of the operator particularly with accurate and intricate work and this can show itself as reduction of scrap from those functions which he still controls.

Cutting Tools

Retrospective analysis of Cutting Tool costs will show that a reduction has occurred due to the disciplined use of Tools under NC.

Production Flow

Constant speeds, feeds and a smooth production flow are ensured with NC. These should improve as more optimisation of speeds is introduced into computer programming.

Modifications

A modification to a tape or the replacement of some punched cards simplifies this need as compared to the physical alteration of a jig.

Flexibility

NC methods and facilities allow production to be switched, between machines or even factories with only the inconvenience of transferring tapes, cards and planning layouts and with the assurance of consistency or productivity and accuracy. The alternative to the transfer of tapes would be the costly and complex removal of machines.

There are no hard and fast rules to determine when numerical control should be used, but consideration of the factors discussed and the justification examples to follow, should give useful guidance to potential users.

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These factors may be classified into four sections as follows:-

1. A cost analysis of the factors discussed.

2. Typical component cost comparison.

3. Systematic method to calculate the justification of Numerical Control.

4. Programme cost considerations.

Cost analysis of a numerically controlled Turret Lathe having a dimensional continuous path control operating from punched paper tape. The machine having - 24 in diameter swing; 30 H.P. motor; hydraulic chuck; two four positions automatically indexing turrets; pre-set tooling; 24 speeds from 36 R.P.M. to 2400 R.P.M. in either direction; and a rapid feed rate of 200 inches per minute.

Instead of the purchase of:-

A No. 7 combination Turret lathe.

The study is carried out on a basis of preparation (set up) and operation time for average batch size of 25 components.   (Data supplied by Newall Engineering Co. Peterborough).

Preparation: Set-up time

This includes selection and setting of tools and equipment and a contingency for starting and finishing a batch. The study shows that for the purchase of one NC machine

$$\frac{\text{Preparation Time for NC machine}}{\text{Preparation Time for manual machine}} = \frac{8}{10}$$

This ratio could drop to 4/10 if several NC machines were purchased to justify a man being employed to preset tools and prepare following batches.

N.B.   The average manual preparation time per batch was found to be three times the average operation time.

(These factors were obtained by averaging the details of a number of studies).

Operation Time

Floor to floor time (including contingencies) shows the NC machine 2.4 times as fast as the manual machine.

Lost Time NC machine

Electronic breakdown $= 1\frac{1}{2}\%$ of total operating time

Mechanical   " $= 2\frac{1}{2}\%$ "   "   "   "

Tape proving time	= 4% of total operating time.	
Shortage of operators	= 2% " " " "	
	10% of total operating time	

Lost Time - Manual Machine

Shortage of operators   = 2% of total operating time.

Labour

One man per machine.

Operator rate - NC.	= 10/2 per hour
Operator rate - Manual	= 11/3 per hour

Alternative methods of working

40 hours + 4½ hours overtime at 1.1/3

or

40 hours nights at 1.1/3 + 4 hours overtime at 1½ plus 40 hours +

4½ hours overtime at 1.1/3

or

Three equal shifts of 38 hours but each paid for 45 hours.

N.B.   1 year = 48 working weeks.

Fixed Charges	NC Machine	No. 7 Comb. Lathe
Capital cost of machine	£20,600	£4,500
Installation charge	140	20
Programming and tape preparation costs	1,000 p.a.	-
Power consumption	130 p.a.	44 p.a.
Indirect Labour charge (Supervision, Inspection, Labouring, etc.)	700 p.a.	640 p.a.
Maintenance engineers salaries etc.	220 p.a.)	80 p.a.
Including Spares	150 p.a.)	
Tooling	250 p.a.	250 p.a.
General overheads based on floor area:-		
Building depreciation & maintenance	130 p.a.	90 p.a.
Light and heat	25 p.a.	18 p.a.
Rent, rates and Insurance.	180 p.a.	126 p.a.

Calculation of Fixed Charges

NC Machine £		Manual Machine £
20,600	Capital cost of machine	4,500
140	Installation Charges	20
20,740		4,520
2,074	Written down over 10 years	452
1,000	Tape preparation	-
130	Power	44
700	Indirect Labour	640
220	Maintenance)	80
150	Spares)	-
250	Tooling	250
130	General overheads - Building	90
25	Light and heat	18
180	Rent, Rates and Insurance	126
4,859		1,700
4,859	Wages - total per annum:-	1,700

Total weekly hours x weeks/year x hourly rate.

40

$4\frac{1}{2}$ x 1.33   105.33 x 48 x   10/2 NC

                                                          11/3 Manual

40 x 1.33

4 x 1.5   = 2576 NC

| 2,576 | TOTAL = 105.33 hrs.   2848 Manual | 2,848 |
| 7,435 | Total expenses per annum. | 4,548 |

∴ Cost ratio = Total expenses/annum

$$\frac{NC}{Manual}$$ £7,435

          £4,548

Cost Ratio = 1.64

Two Shift Working   Productivity Ratio

	NC	Manual
Possible Weekly Hours	$88\frac{1}{2}$	$88\frac{1}{2}$
Lost time	10% = 8.85	2% = 1.77
Actual hours available	79.7	86.7
Average Batch size	25	25
No. of components lost due to preparation	3 x 0·8 = 2.4	3
Effective Batch size for productivity purposes	27.4	28

Production time lost to
Preparation per week:-

$$\frac{\text{actual hours available x no. of components lost due to preparation}}{\text{Effective batch size}}$$

$$= \frac{79.7}{27.4} \times 2.4 \quad = \quad 7 \qquad \frac{86.7}{28} \times 3 = 9.6$$

Actual hours spent machining

$$79.7 - 7 \quad = \quad 72.7 \qquad 86.7 - 9.6 = 77.1$$

Machining hours available

$$72.7 \times 2.4 = \quad 174.4 \qquad\qquad 77.1$$

$$\text{Productivity Ratio} = \frac{\text{NC(Effect.) Hours available}}{\text{Manual hours available}} = \frac{174.4}{77.1}$$

Comparison of effective machining hours assuming that the capital

invested in NC had been spent on Manual machinery:-

    NC   - Effective machining hours available = 174.4

    Manual - Effective machining hours x Cost Ratio

$$77.1 \times 1.64 \quad = \quad 126.3$$

Therefore, extra hours available due to investment
    in NC per week   = 48.1

Related to Operator Wages at 10/2 per hour
    annual saving 48.1 x 10/2 x 48   = £1172

Related to annual expense savings

$$\frac{48.1}{77.1} \times £4,548 \qquad\qquad\qquad\qquad\qquad = £2830$$

Single Shift Working

Repeating the above calculations for single shift

Hours.

NC   Effective machining hours available   = 87.6

Manual - Effective machining hours x Cost Ratio

$$39 \times 2.04 \qquad = 78.1$$

Extra hours available due to investment
in NC per week.   = 9.5

Annual Savings $9.5 \times 10/2 \times 48$ = £232

plus $\dfrac{9.5}{77.1} \times £4,548$ = £559

The following list compares conventional machining time, with those taken on a 3 axis continuously Controlled Milling Machine data supplied by Messrs. Rolls Royce, Derby.

	Quantity/ Annum	Average Machining Time	
		Contimatic	Conventional
Glass plates for Inspection	460	$1\frac{1}{4}$ hours	5 hours
Profile and former plates	143	9 hours	30 hours
Electrodes	244	5 hours	20 hours
Blade Forms (for Foundry dies)	23)		
(for Production dies)	22)	15 hours	70 hours
(for Experimental dies)	17)		
Cam Plates	97	3 hours	10 hours

From the details shown above:-

Total hours on Conventional machine = 16,780

Saving (Hours)   = 12,477

Example II By employing NC Messrs. Rolls Royce have cut the lead time for Turbine Blade Production from 12 weeks to 72 hours and reaped a "significant intangible". A retrospective modification was required to the compressor of an engine already in production. Engines were being produced at the rate of 2 per week and, as production could not be halted,

the modification had to be applied to all engines already produced - at a cost of £5,000 per engine to Rolls Royce.

The shortened Lead Time for the introduction of the modification saved 23 x £5,000 = £115,000.

The original purchase price for the machine was £43,000.

Details of old and new procedures employed:-

Blade Forms

Conventional Method

Blade design

Die block design

Conventional machining (4 stages) of Master Die Block

Proof Inspection of master die block

Production of Blades

With the installation of the Contimatic and the computerisation of blade design, the technique at present is:-

Blade Forms

Contimatic Method

Blade design and automatic generation of magnetic tapes, for master die block and inspection profile plate

NC machining of master die block

Simplified inspection of die block

Production die manufacture

Production of Blades.

Cost comparison of component produced on a centre lathe and on the N.C. P5 lathe.

Cost values and production times for figs. supplied by Churchill Redman Ltd. (4)

EXPERIMENTAL COMPONENT

	SETTING		CUTTING		PLANNING	
	C.L.	N.C.	C.L.	N.C.	C.L.	N.C.
TIME	25 mins.	10 mins.	80 mins.	4½ mins.	30 mins.	90 mins.
COST	12/6	10/-	40/-	4/6	15/-	45/-

Costs Planning   30/- per hour

       Centre Lathe   30/- per hour

       N.C. P5 Lathe 60/- per hour

Average Production Time Per Component

	BATCH SIZE		
	1	6	10
Centre Lathe	105 mins.	84¹/6 mins.	82½ mins.
N.C. Lathe	14½ mins.	6¹/6 mins.	5½ mins.
Saving per component	90½ mins.	78 mins.	77 mins.
% Saving	86.2 %	92.8 %	93.3 %

COST PER COMPONENT

	1st Batch			Repeat Batch		
Batch Size	1	6	10	1	6	10
Centre Lathe	67/6	44/7	42/9	52/6	42/1	41/3
N.C. Lathe	59/6	13/8	10/-	14/6	6/4	5/6
Saving per Comp.	8/-	30/11	32/9	38/-	35/9	35/9
% Saving	11.8%	69.6%	76.7%	72.3%	85.2%	86.7%

NOTE. The centre lathe cutting time shown for this component is an estimated one assuming cutting in 2 operations.

      The N.C. cutting is for end driving the component, eliminating one set up.

COUPLING BOLT

	SETTING		CUTTING		PLANNING	
	C.L.	N.C.	C.L.	N.C.	C.L.	N.C.
TIME COST	40 mins. 20/-	15 mins. 15/-	52 mins. 26/-	15 mins. 15/-	60 mins. 30/-	180 mins. 90/-

Costs   Planning   30/- per hour

        Centre Lathe   30/- per hour

        N.C. P5 Lathe   60/- per hour

Average Production Time Per Component

	BATCH SIZE		
	1	6	10
Centre Lathe N.C. Lathe	92 mins. 30 mins.	$58\frac{2}{3}$ mins. $17\frac{1}{2}$ mins.	56 mins. $37\frac{1}{2}$ mins.
Savings per Comp.	62 mins.	$41^{1}/6$ mins	$39\frac{1}{2}$ mins.
% Saving	67.3%	70%	70.5%

COST PER COMPONENT

	1st Batch			Repeat Batch		
Batch Size	1	6	10	1	6	10
Centre Lathe N.C. Lathe	76/- 120/-	34/4 32/6	31/- 25/-	46/- 30/-	29/4 17/6	28/- 16/6
Saving per Comp.	Loss of 44/-	1/10	5/6	16/-	11/10	11/6
% Saving	- 57.8%	5.4%	17.7%	34.8%	40.4%	41.2%

NOTE: This component is in fact normally produced on a copy turning lathe
        and not a centre lathe. No account has been taken in costing out
        the first batch of the cost involved in producing the template.
        The machine hour rate would also be higher when using a copy turning lathe.

In this example a detailed study has been carried out into the complete proposed machine load as follows.   Initial data was obtained from the Newall Engineering Co. (5).

Machine Hour Rate

	Conventional M/C.	N/C Machine
Capital Cost	£10,000	£18,000
Floor Area	100 sq. ft.	150 sq. ft.
Labour	£ 1,000	£ 1,000
Depreciation at 20%	£ 2,000	£ 3,600
Insurance at 1%	£ 20	£ 36
Power	£ 20	£ 50
Maintenance	£ 50	£ 150
Factory Overheads allocated to shop: (a) Material (b) Engineering Services (c) General Maintenance (d) Shop Expenses (e) Personal Services (f) Admin. Expenses	£ 1,500	£ 1,500
Total Yearly Expenses	£ 4,590	£ 6,336
Machine utilisation	90%	80%
Utilisation hours/year	1,800	1,600
Machine hour rate	51. 0d.	79. 3d.

Piece-part Cost Analysis.
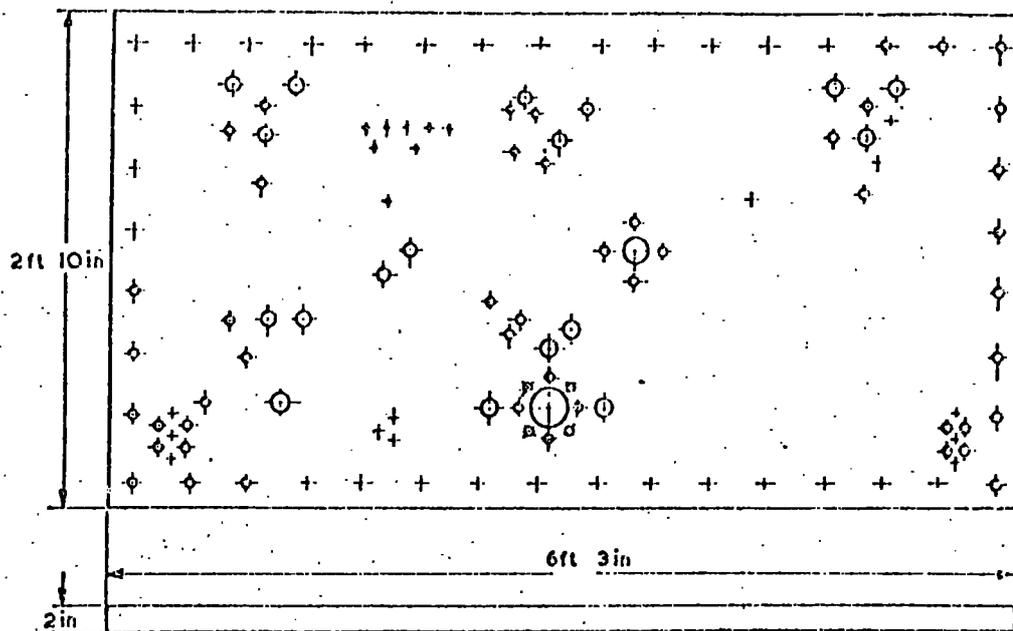
Workpiece Steel Door	Material Mild Steel
Numerically Controlled Method	Portal frame drilling machine
Conventional Method	Radial drilling machine
Operations	Drill, tap & C'bore 3/16 - $1\frac{3}{4}$ in dia. 137 holes
Production Quantity	60 per batch; 12 batches per year

Production Details	Numerical Control					Conventional				
	Time		Cost			Time		Cost		
	hr.	min.	£.	s.	d.	hr.	min.	£.	s.	d.
Programming/Planning Data Preparation	8	0	6.	0.	0.	–		–		
Jig & Tool Design & Manf.	20	0	15.	0.	0.	220	0	250.	0.	0.
Pre-Production Time/Cost	28	0	21.	0.	0.	220	0	250.	0.	0.
Marking-off & Setting Up Machining	3	15	12.	18.	0.	2	45	7.	0.	0.
Inspection	Similar for both methods									
Handling	–		–			–		–		
Fitting and Assembly	24	0	24.	0.	0.	40	0	40.	0.	0.
Processing Time/Cost	27	15	36.	13.	0.	42	45	47.	0.	0.
Total for 720	19648	0	26568.	0.	0.	31000	0	33840.	0.	0.

Examples of actual savings incurred by using N.C.

Part No. 38211-250 Spindle Drive Pulley   FιG ιS

Average Batch Size   12

Average Time taken on Conventional Machine - 1 hour 33 min. each.

Average Time taken N.C.   - 52 min. each.

Part No. 31861-541 Gear Change Bracket   FιG ι6

Average Batch Size   6

Average Time taken on Conventional Machine - 3 hours 56 min. each.

Average Time taken N.C.   - 1 hour each.

Part No. 38861-314 - holes in front and rear faces.   FιG ι7

Average Batch Size   6

Average Time taken - Manual Jig Borer   - 10 hours 10 mins.

Average Time taken - N.C. Borer   - 2 hours 45 mins.

ALL DIMENSIONS SHOWN
IN MILLIMETERS

MACHINE ALL OVER

TO BE STATICALLY AND
DYNAMICALLY BALANCED

PART Nº 38211-250
SPINDLE DRIVE PULLEY
SCALE :- FULL SIZE

HK.

117·5 DIA

3·45°

36° INCL.

73

14·25 14·25
14·25

1·5-45°

16·5
4

16·5
4

16·5

3-45°

63·5 DIA

114 DIA

140 DIA

158·75 P.C.D.

171·5 DIA

4 HOLES DRILL 6·75 DIA.
COUNTER BORE -10·25 DIA.
x6·35DEEP 6·35
EQUI-SPACED ON 76·25 P.C.D.

FIG 15

44
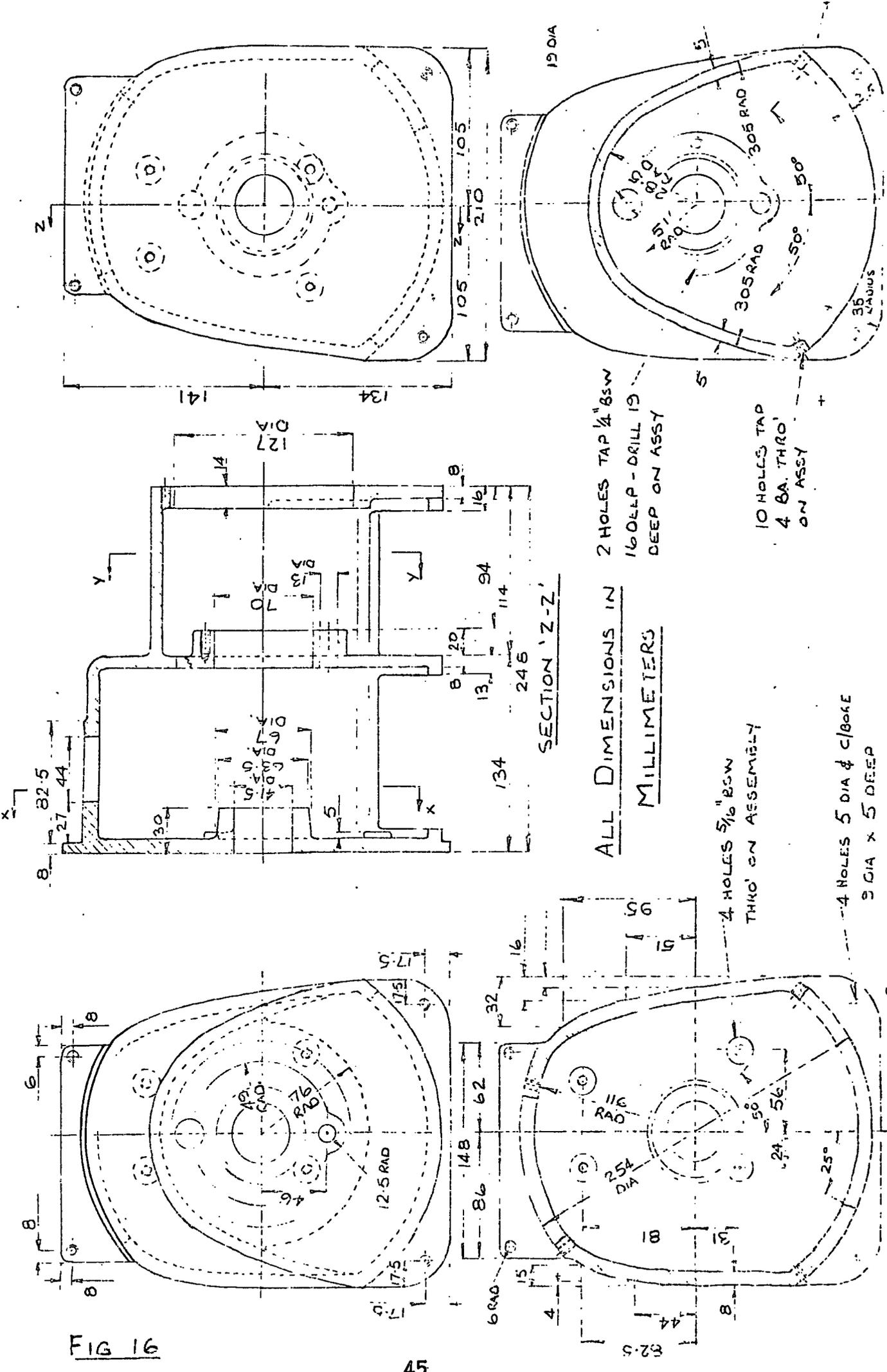
FIG 16

Section on 'Y-Y'

All Dimensions in Millimeters

Section 'Z-Z'

'X' Gear Change Bracket

Section 'X-X'

2 HOLES TAP ¼"BSW
16 DEEP - DRILL 19
DEEP ON ASSY

10 HOLES TAP
4 BA. THRO'
ON ASSY

4 HOLES 5/16"BSW
THRO' ON ASSEMBLY

4 HOLES 5 DIA & C/BORE
8 DIA × 5 DEEP

19 DIA
305 RAD
305 RAD
35 RADIUS
50°
50°

127 DIA
70 DIA
13 DIA
94
114
246
134
20
13
82·5
44
27
30
41·5
33·5
65 DIA
10 DIA
5
8
8
16

141
134
105
210
105

17·5
17·5
8
8
8
6
62
148
86
12·5 RAD
76 RAD
46
4 RAD
17·5

95
51
16
32
56
18
31
44
82·5
116 RAD
254 DIA
24
56
25°
50°
6 RAD
5
4
8

45

R.H. TRANSFER PLATE

58861 - 314

FIG. 17

Justification Calculations

To determine whether N.C. or conventional methods are the more economic in given circumstances, the calculation made must take into account all the factors which have been discussed. Information supplied by machine tool manufacturers, of which the following example is typical, can be misleading. In addition, methods which have been shortened to make these calculations less tedious can prove to be inaccurate. If the following example is examined, this fact becomes evident.

Cost comparison with N.C. lathe.

Component   P5.C.5328, shown in Fig. 19.

Existing Method   Centre lathe (5 in rad. sphere not cut).

	Setting		Cutting		Pre-Production Planning	
	Existing Method	N.C.	Existing Method	N.C.	Existing Method	N.C.
Cost per hour	£1.75	£3.5	£1.75	£3.5	£1.75	£1.75
Time (Hrs.)	1.0	0.39	1.0	0.24	1.0	1.0
Cost	£1.75	£1.36	£1.75	£0.84	£1.75	£1.75

Average production time for each component when produced in batch sizes shown.

$$\frac{\text{Setting Time} + (\text{Cutting Time} \times \text{Batch Size})}{\text{Batch Size}}$$

Batch Size	1	5	10	20
Existing Method	2.0	1.2	1.1	1.05
N.C.	0.63	0.32	0.8	0.24
Saving in Time	1.37	0.88	0.82	0.81
% Saving	69%	73%	75%	77%

Cost for each component
when produced in batch
sizes shown.

$$\text{1st Batch} = \frac{\text{Setting Cost} + (\text{Cutting Cost} \times \text{Batch Size}) + \text{Planning Cost}}{\text{Batch Size}}$$

Repeat batch is without planning cost.

	1st Batch				Repeat Batch			
Batch Size	1	5	10	20	1	5	10	20
Existing Method	£5.25	£2.45	£2.10	£1.92	£3.5	£2.1	£1.93	£1.83
N.C.	£3.45	£1.46	£1.15	£1.0	£2.2	£1.1	£0.98	£0.91
Saving per component	£1.30	£0.99	£0.95	£0.92	£1.3	£1.0	£0.95	£0.92
% Saving	25%	40%	45%	48%	37%	48%	49%	50%

<u>Cost Saving in (1 year Single Shift)</u>

	Existing Method (1)	N.C. (2)
Batch Size	5	5
Total Production Time Setting and Cutting	6.0 hrs.	1.6 hrs.
Cost	£10.5	£5.6

Cost (1) £10.5 - Cost (2) £5.6 = £4.9 saving in 1.6 N.C. hours.

Saving in 2000 hours (1 year single shift) = £6,130   (3)

	Existing Method	N.C.
Capital Expenditure	£5,000	£30,000
20% grant	£1,000	£ 6,000
Total	£4,000	£24,000

N.C. - Existing Method = £20,000   (4)

Return on Investment of (4) £20,000 = £6,130   (3)

% Return Investment per year $= (\frac{3}{4})$ $\frac{£6,130}{£20,000}$ x 100

$$= 30.5\%$$
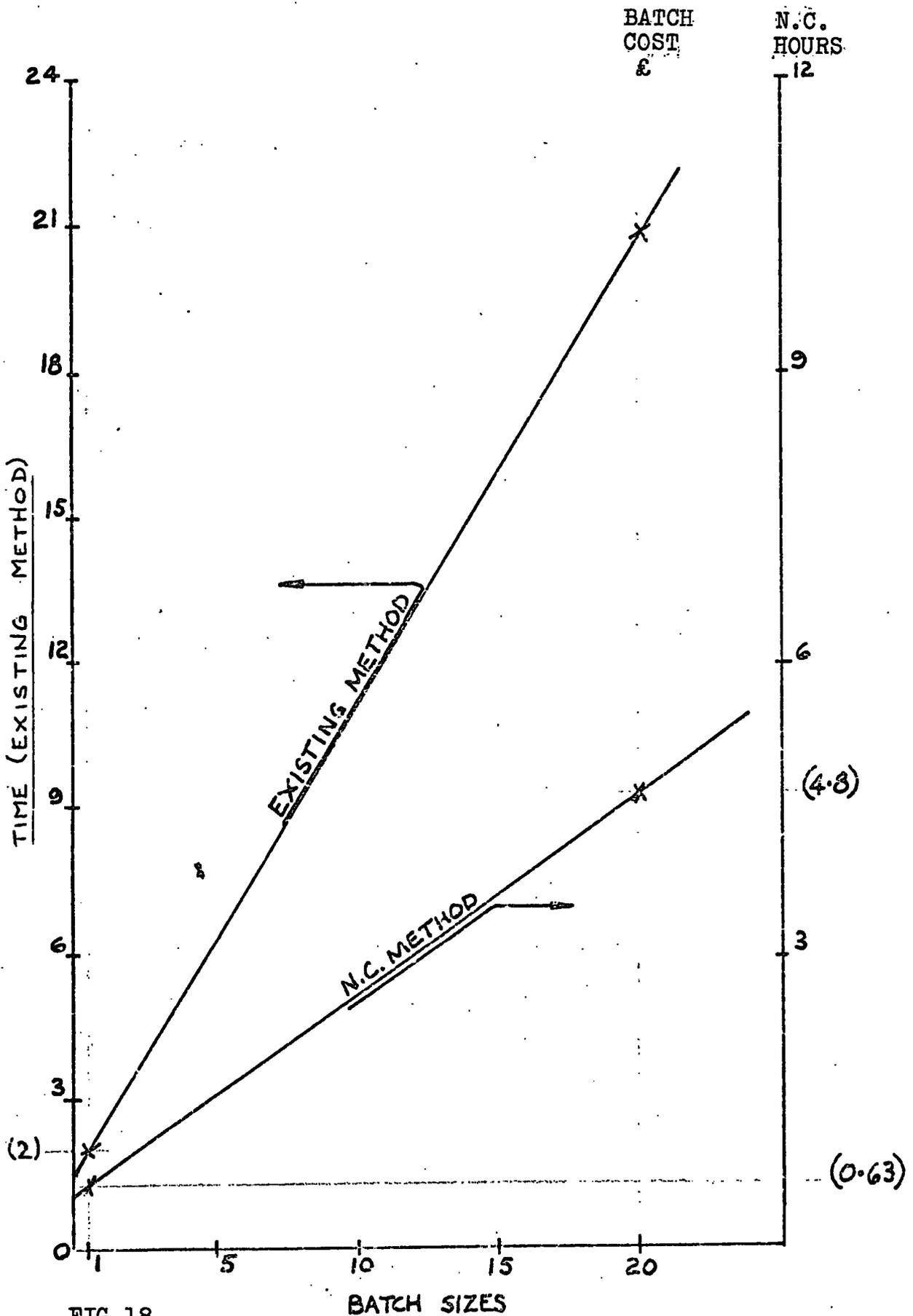
FIG.18

GRAPH OF BATCH COST AND TIME

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FIG. 19
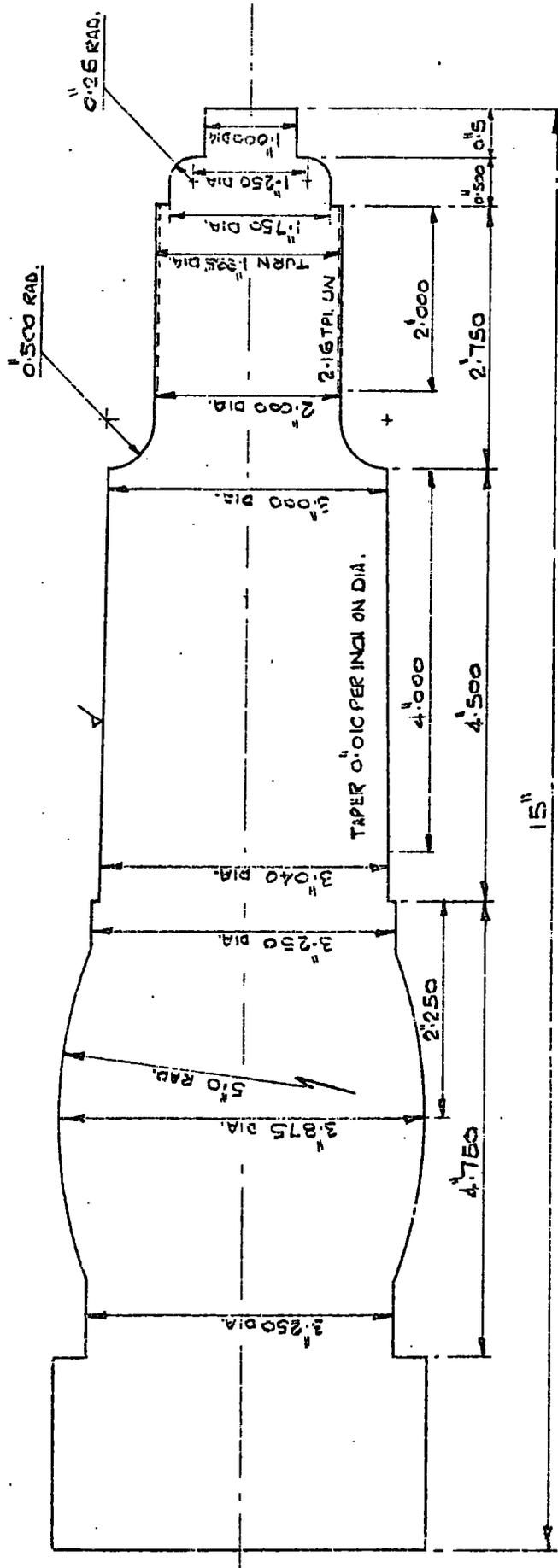
TEST COMPONENT.

MATERIAL:- 4" DIA E.N.8.

P5. C. 5328   HX

ALL DIMENSIONS TO 3 DECIMAL FIGURES
TO BE ± 0·001

MACHINING SYMBOL ▽

There are instances where pre-production costs for both numerical control and conventional methods are equal,* therefore, if the data above is used in the calculation shown below then this method becomes void, and is therefore in opposition to Marshall (1).

* (see page 47).

Break-even Quantity q

The cost C for producing q components is given by

$$C = T + q(tM + A);$$ (1)

where T = pre-production cost, i.e. cost of programming, planning,

design and manufacture of jigs and tools.

t = maching time (floor-to-floor).

M = machine hour rate (i.e. depreciation rate, plus labour rate

plus overhead rate).

A = cost per component, of inspection (off the machine),

fitting and assembly.

Let the suffixes c and n indicate conventional and numerically controlled methods respectively.

Then for conventional production:

$$C_c = T_c + q(t_c M_c + A_c);$$ (2)

and for production by numerically controlled methods

$$C_n = T_n + q(t_n M_n + A_n).$$ (3)

The break-even quantity is given by the value of q for which

$$C_c = C_n,$$

so

$$T_c + q(t_c M_c + A_c) = T_n + q(t_n M_n + A_n).$$ (4)

Therefore, q, the break-even quantity is given by:

$$q = \frac{T_c - T_n}{(t_n M_n + A_n) - (t_c M_c + A_c)}$$ (5)

Examination of this equation reveals that the numerator is the difference of the pre-production costs, and the denominator the difference of the processing cost.

If we now let $P_n = (t_n M_n + A_n)$,

and $\qquad\qquad P_c = (t_c M_c + A_c)$;

equation (5) becomes

$$q = \frac{T_c - T_n}{P_n - P_c} \qquad\qquad (6)$$

Since both $(T_c - T_n)$ and $(P_n - P_c)$ can be either positive or negative, the value of q can be interpreted in four different ways, these are:

Case 1. When the pre-production costs are greater for conventional manufacture than by numerically controlled methods, i.e. $(T_c - T_n)$ is positive; but the processing cost per part is smaller by the conventional method, i.e. $(P_n - P_c)$ is positive. Then q has a positive value below which it is more economical to produce by numerically controlled methods, and above which it is economical to use conventional means.

Case 2. When $(T_c - T_n)$ is positive, and $(P_n - P_c)$ is negative (i.e. the process cost per component is greater by conventional methods) then q is negative (i.e. less than zero) and therefore it is always more economical to produce by numerically controlled methods.

Case 3. When $(T_c - T_n)$ is negative, i.e. $T_n > T_c$, and $P_n - P_c$ is positive, i.e. $(P_n > P_c)$ then q is negative (i.e. less than zero) and it is always cheaper to produce by conventional methods.

Case 4. When $(T_c - T_n)$ is negative, i.e. $T_n > T_c$ but $(P_n - P_c)$ is negative, i.e. $P_c > P_n$, then q again has a positive value above which it is cheaper to use numerically controlled methods, and below which it is cheaper to use conventional means.

Referring to sheet 48 where savings are shown relative to capital expenditure, the following observations should be taken into account:

1.   The 20% grant system referred to has now been replaced by a system of investment allowances based on capital outlay to offset against the sum on which the company will pay tax.

This, according to a Government statement, will work out the same as the 20% grant system.

2.   As the company must make a profit to benefit from the investment allowance, the implications of the new system should be taken into account and recorded.

3.   The cost figures shown for "total production time, setting and cutting" may not be realised in practice if labour costs vary in an unpredictable way.   Similarly, the assumption that the output from 2000 hours per annum single shift working will be saleable, may be unrealistic.

It has been shown by Merrett & Sykes (7) that logical analysis alone cannot yield the complete answer to a capital investment problem, depending as it does on the successful forecasting of future events.   For this analysis to be justified despite uncertainty and imperfect estimates, it is necessary that the extra effort involved should yield a worthwhile improvement in the quality of the decision taking.

In the foregoing example, for an investment of £25,000, the return per annum is £6,130.

Discounting the series of future returns.
Where A = Annual profit (not known) applicable for n years.

   r = Rate of interest (at present 11% per annum).

   P = Present value.

53

Existing Method

Immediate outlay   £5,000

Life of machine   10 years

Future income   Annual profit A for 10 years

Present value of future income with interest r = 11% per annum

$$P = \frac{A}{(1 + r)} + \frac{A}{(1 + r)^2} \ldots \frac{A}{(1 + r)^n}$$

$$\therefore P = \frac{A\left[1 - (1 + r)^{-n}\right]}{r}$$

$$\therefore P = \frac{A\left[1 - (1.11)^{-10}\right]}{.11}$$

$$P = A\, 5.88923$$

Net gain on present value = $5.88923A - 5,000$

N.C. Method

Immediate outlay   £30,000

From above n = 10   r = 11%

$$\therefore P_1 = A\left[1 - \frac{(1.11)^{-10}}{.11}\right]$$

$$P_1 = A_1\, 5.88923$$

Net gain on present value = $A_1\, 5.88923 - £30,000$

To check which method gives the larger gain in the present value.

From sheet 48 $A_1 - A = 6130$

and N.C. Method - Existing Method:-

$\therefore$ $5.88923A_1 - 30,000 - (5.88923A - 5000)$

$\therefore$ $5.88923(A_1 - A) - 25000$

$\therefore$ $5.88923 \times 6.30 - 25000$

    = <u>£11,100</u>

If one of these methods is going to be used the N.C. method appears
to be financially the more attractive method (ignoring repair costs).
The accuracy of a cost comparison calculation of the type shown on
pages 47 - 49, therefore, depends on the following points.

1.   The length of trouble-free life of the equipment.

2.   The rate of discount employed.

3.   Accuracy of the cost saving figure.

   This latter item in turn depends upon:-

1.   Changing external economic environment invalidating much of the

   usefulness of past experience particularly in calculating the

   cost per hour of the two methods.

2.   The assumed number of hours per annum of production from which the

   cost saving figure is obtained.

3.   Bias in the data and in its assessment.

CHAPTER 6   Batch Size and Component Complexity

   The normal day-to-day work schedule will comprise components of
varying complexity in batches of varying sizes. The more complex
components may economically justify the use of numerical control over
a wide range of batch sizes, whereas the more simple types will inevit-
ably fall into one category or the other, depending upon the balance of
these two factors. Decisions have to be made, therefore, for individual
components, or types of components.

   It is also important in the economics of N.C. to find some rational
method of assessing component complexity. Long contouring operations
represent a special case in practice and justification for numerical
control can frequently be found on technological grounds. Some progress
can be made by confining considerations to multiple operations of
relatively short individual duration, i.e. positional control.

Depending on the particular application, numerical control increases manufacturing flexibility, reduces the lead time for going into production, and makes small batch production a more economical proposition.

Consideration must then be given to decide what batch size is economic for numerical control, and at what degree of complexity.

In the following calculation from data supplied by Philips of Eindhoven (6), seven possible methods of manufacture were examined and the cost of producing a range of components each requiring a different number of operations was calculated.

All the components were of simple shape, mostly in the form of a flat plate, see Fig.22, which tended if anything to favour jigging, since only cheap fixtures would be required. Factors such as storage and maintenance of fixtures, less scrap, and shorter lead time, were deliberately ignored, so that findings in favour of N.C. can be considered reliable.

Costs were calculated for components with from 5 to 30 holes involving drilling and reaming operations. The seven methods considered for determining hole positions were:-

I. Marking out.

II. Jigging.

III. Centering on a jig-borer.

IV. Manual setting of controller dials of N.C. machine.

V. Automatic tape control N.C. machine.

VI. Stop bar controlled co-ordinator table.

VII. Precision radial table.

The production cost per piece was determined for each method. This was based on machine time, wages and overheads, including capital depreciation. Preparation costs were determined and these included

the cost of jig design and manufacture, programming and tape preparation.

Selecting from data thus obtained the figures for an average component with 15 drilled and two reamed holes are given in Table 2. The costs are in Guilders which it would be misleading to convert because of wage rates and costs. The values are, however, valid as indices for comparison.

TABLE 2

Procedure	Method	Wages and overheads per piece	Preparation cost
		FL	FL
I	Marking out	5.54	7.09
II	Jigging	2.43	179.9
III	Centering in Jig borer	5.43	6.4
IV	Numerical control Manual switching	5.03	6.9
V	Numerical control with tapes	3.89	9.30
VI	Stop bar Co-ordinator table	4.21	21.4
VII	Precision radial table	4.75	12.60

Jigging is shown to be the cheapest method of production, followed by numerical control with tape. The preparation costs for jigging are nearly 20 times those for preparing tape. The following table shows the overall cost per batch.

Overall cost = cost of wages and overheads multiplied by batch size
plus preparation costs.

TABLE 3

Batch Size	METHOD						
	I	II	III	IV	V	VI	VII
20	117.8	228.5	115.0	107.4	87.1	105.6	107.63
40	228.6	277.1	223.6	208.1	164.9	189.8	202.63
60	339.4	325.7	332.2	302.7	242.7	274.0	297.63
80	450.2	374.1	440.8	409.3	320.5	358.2	392.63
100	561.0	422.9	549.4	509.9	398.3	442.4	487.63
120	671.8	471.5	658.0	610.5	476.1	526.6	582.63
140	782.6	520.1	766.6	711.1	553.9	610.8	677.63
1	12.54	182.33	11.83	11.93	13.19	25.61	17.38
2	18.08	184.76	17.26	16.96	17.08	29.82	22.10
3	23.62	187.19	22.69	21.99	20.97	34.03	26.85
4	29.16	189.62	28.12	27.02	24.86	38.24	31.60

From the graph Fig. 20 Tape control procedure (V) is cheaper than
any other method until jigging (procedure II) breaks even at 120 pieces.

In the lower range of batch sizes the graph is drawn to a larger
scale, Fig. 21, and it can be seen that centering in a jig borer
(procedure III) has a marginal advantage on one piece, but for two
pieces manual switching of the numerical control machine (procedure IV)
has the advantage. For three pieces, however, tape control (procedure
V) breaks through as the most economic method.

FIG. 20

59

FIG.21

60
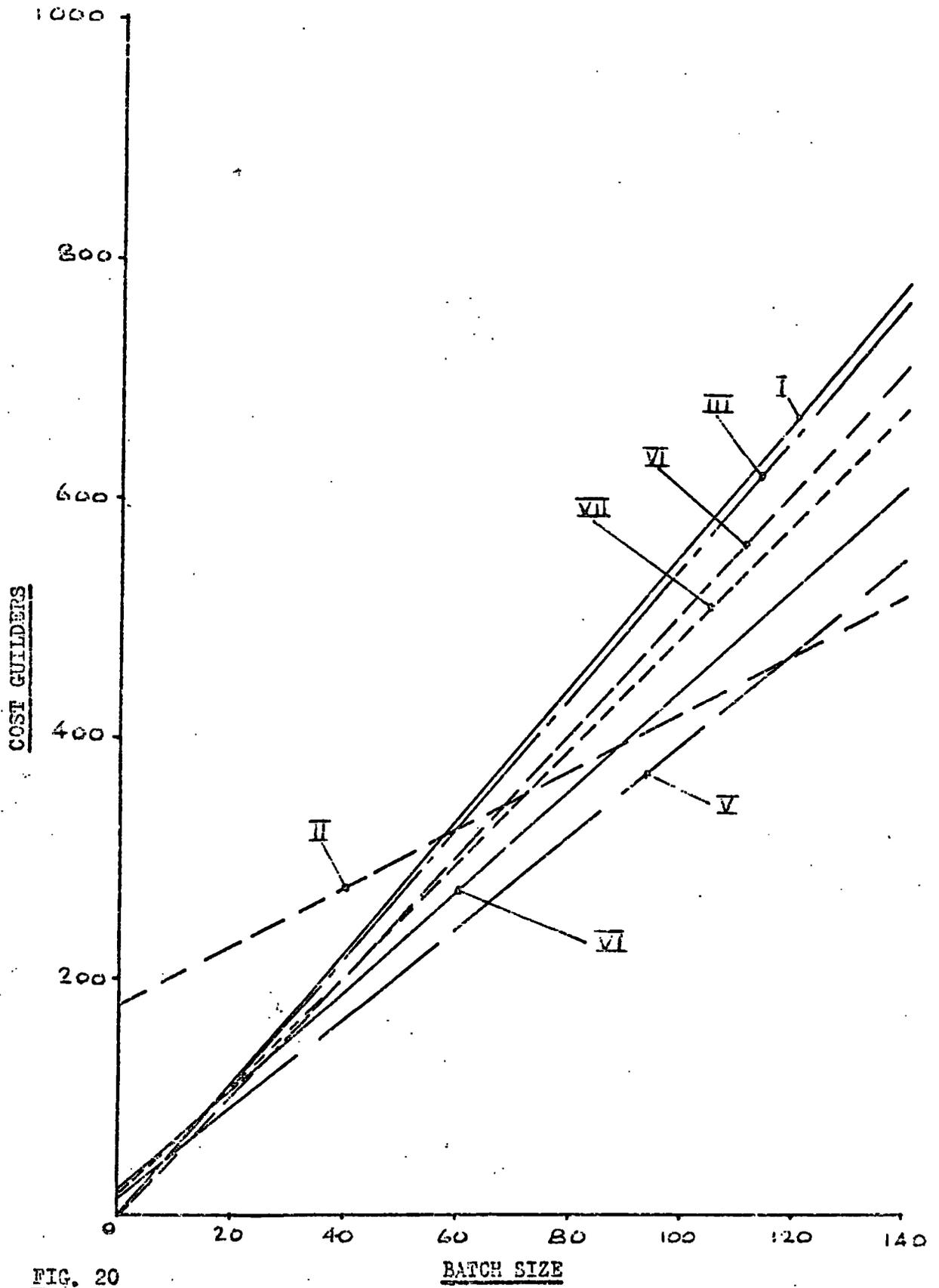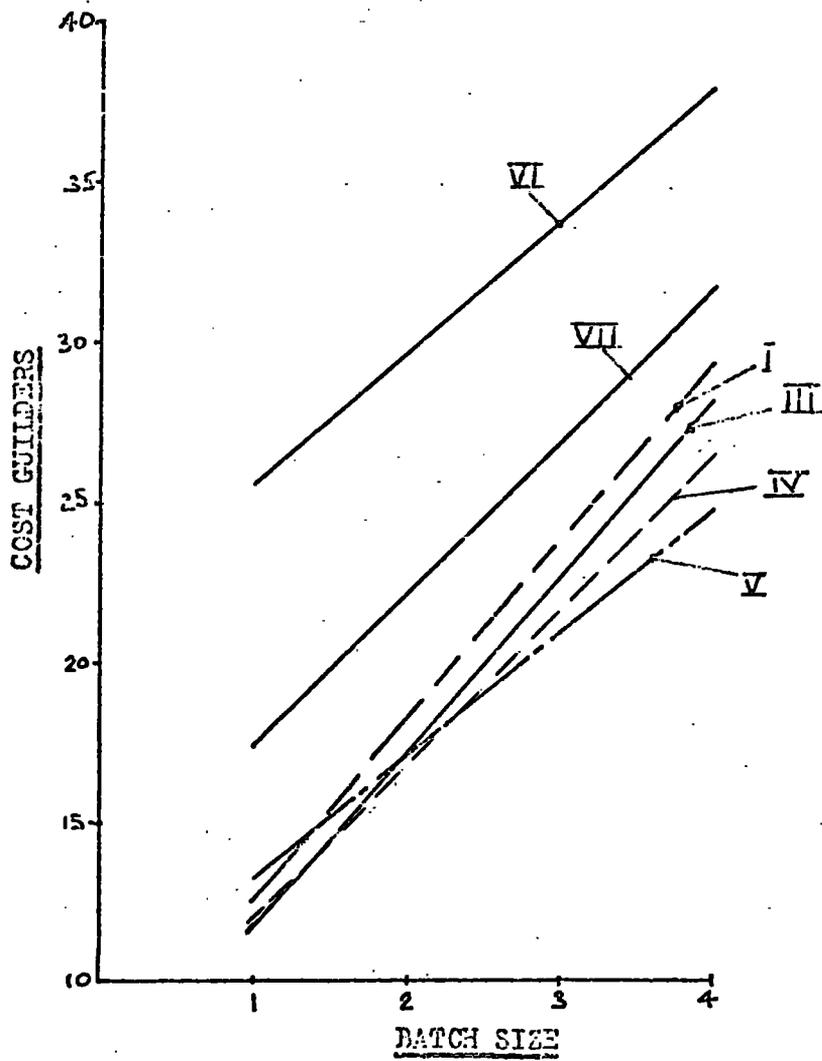
CHAPTER 7

Economics of Program Preparation

The pre-production work which must be carried out before a component

can be released for manufacture on an N.C. machine can be divided into

two areas: 1. Planning,   2. Programming.

1.   Planning

This section of the work includes fixturing, tooling, selection of

machining conditions and order of machining.   In order to utilise fully

the technological advantages of N.C. machines these must be fully

optimised.   A further essential requirement for N.C. planning is a

thorough knowledge of programming (either manual or computer aided,

depending on the facilities within the company).

Planning costs are based on man hours and examples of these can

be seen in the previous economic examples.

2.   Programming

Enquiries carried out with several major companies in the United

Kingdom, i.e. Rolls Royce, Hawker Siddely Aviation, Plessey Numerical

Controls and Philips Electrics, have shown that it is inadvisable to

quote costs, other than those arrived at in a particular company, due

to variations in programmer expertise, complexity, length of programme

required and varying computer facilities.   The following section will

deal with the factors that contribute to the costs under two separate

headings - manual and computer assisted.   In both instances, tape

costs are based on the number of tape blocks required.   This is in

agreement with Madigan (8).

Manual

The majority of N.C. machines in use in the United Kingdom are

point-to-point machines requiring less than sixteen blocks of tape per

machine minute and nearly all are programmed by completely manual methods

(often with the assistance of a desk calculating machine).   Costs can

be calculated from the following considerations:

Programming Engineers

An overall cost rate per hour derived from:

Wages   per hour (relative to the company concerned).

Plus:

Overheads per cent (in general 1.25% of hourly wage rate).

Tape Punch Operators

An overall cost rate per hour derived from:

Wages   per hour (relative to the company concerned).

Plus:

Overheads per cent (in general 1.25% of hourly wage rate).

Plus:

Depreciation recovery on tape typewriter

(usually over ten years).

A competent operator on N.C. work, using the "three-line visual" technique for verification, can punch and check about three thousand tape characters per hour. An N.C. tape block can vary from about six to sixty characters for letter address and tab sequential systems: tape blocks for fixed block-length control systems are usually between twenty and thirty characters long - a typical mean block length, regardless of system type, is about twenty-five characters. Thus, the mean cost of punching an N.C. control tape on a tape typewriter from manually prepared programme sheets remains virtually constant, regardless of program complexity and at these rates would be the overall cost rate per hour of tape punch operators divided by one hundred and twenty, to give cost per block.

Information from the above considerations only shows the order of initial cost of preparing a control tape ready for prove-out, not the cost of a proven tape.

TEST PIECE

12 - 20mm DIA
HOLES AT 30mm
EQUAL PITCH

30mm EQUAL
PITCH

120 $^{+0.010}_{-0.010}$ mm

120 $^{+0.010}_{-0.010}$ mm

120 $^{+0.010}_{-0.010}$ mm

120 $^{+0.010}_{-0.010}$ mm

125 mm

125 mm

125 mm

125 mm

22½°

22½°

125 mm

250 mm

A

8 HOLES
10mm DIA ON
200mm P.C.D.

21 HOLES TAPPED
10mm DIA THREAD

FIG 22

SCRAP VIEW ON ARROW A

10mm

25.4mm

63

Computer Assisted Programming

Apart from small tapes the computer-produced tape is economically attractive compared with the manually produced one.

Since the manual production of tapes involves tedious calculations, the method is particularly prone to human errors. The employment of computer assistance removes the arithmetic type errors, and helps to reduce the logical errors. Also the time taken to compile the input information to the computer is considerably less than that taken to manually program part of the data.

All users of numerically controlled machine tools are faced with the problem of preparing tapes quickly and efficiently so as to ensure the successful operation of expensive machinery. Assuming that computer assistance is chosen for the production of tapes, the most suitable program system must be selected to meet the requirements of the company both technologically and economically.

During the selection of the best suited system or systems, it is important to consider all present and future technical requirements. Areas for consideration are:-

(i) The geometrical characteristics of the components to be machined and the capabilities of the machine tools available, e.g. point to point, turning, two axis milling, multi-axis contouring.

(ii) If the above yields more than one component per machine tool grouping it is necessary to consider either (a) an all-embracing program system, and (b) a group of systems. If a group system (b) is desirable then a further consideration would be:- must it contain compatible systems?

(iii) Geometrical calculations (co-ordinate positions, etc.) also technological calculations, i.e. optimum feeds, speeds, depth of cut, and automatic tool selection.

(iv) Extensions to basic central tape preparation, e.g. design functions, tool or material control and machine shop loading.

(v) The necessity of applying the system wholly or in part to

conventional operations.

General Purpose Program Systems

Perhaps the most powerful and most widely known of the computer-assisted NC programming systems is APT. Using APT the programmer describes the geometry of the part and the machining operations he wants carried out in a series of statements made up of English-like words - some of them shortened because of computer limitations - and the computer translates these statements, carries out all the calculations and then prepares the actual machine tool control tape. The APT language is virtually an international standard today and is soon to be formally recognised as such. However, the versatility and power of APT, which make it ideally suited to the aerospace type component, virtually preclude its use for the more simple components which are manufactured daily by the majority of industry. The reasons for this are:

a) APT is physically a very large computer program; therefore one central computer costing hundreds of thousands of pounds is required to run it.

b) Because APT has a continuous motion in 5-axes capability, only a small fraction of its facilities are required or can be used for programming point-to-point machines or even 2-axis continuous path machines. Thus, to use it, facilities have to be paid for which may never be employed.

c) APT output is arranged in a generalised form which must be adapted to suit a particular machine tool by means of a 'Post Processor'. And post processors are not available for a large number of the NC machines currently in service.

However, despite these serious drawbacks, the APT concept appears to be a logical and efficient way of solving the NC programming problem. Almost since its inception, simplified versions of APT aimed at specific areas of NC programming have been and are being developed; amongst these are:

1. ADAPT, developed in the U.S.A., which caters for continuous motion in 2 axes and linear path control in a 3rd axis.

2. 2C.L developed at the National Engineering Laboratory which has similar capabilities to ADAPT but with the addition of automatic "Area Clearance" milling and other features which can assist programming.

3. 2P.L which is in the final stages of development at NEL and is aimed at the point-to-point machining centre market and includes automatic tool selection.

4. EXAPT 1 which has similar capabilities to 2P.L but with the addition of "Technology" for the automatic calculation of speeds and feeds, as well as automatic tool selection.

5. AUTOSPOT developed by IBM, mainly for point-to-point work but with limited continuous path milling capability; it comes between 2P.L and 2C.L in both facilities and complexity.

6. PICNIC developed by PERA for point-to-point machines for use on small computers. A sub-set from the APT vocabulary.

Some of these programming systems are true APT "subsets" in that the input language and the generalised output are as near as possible identical to APT. Others are simply "APT-like" and vary in different degrees, as far as both input language and generalised output are concerned.

All of these systems are physically much smaller than APT and can therefore be run at a lower cost on a smaller computer; but a post processor is still needed to convert the generalised output to the tape format for a specific machine tool.

Special Purpose Program Systems

Special purpose program systems designed for a specific machine tool application. For example, if a machine tool is to be used primarily for the manufacture of cams, it may be found desirable to include design calculations for the cams, or scheduling features for transfer line applications. In manufacture the following general points should then be noted:-

a) The system should operate very efficiently in the computer as it

has been designed specifically for the job.

b)   Core store usage should be more efficient, because of the lack of extraneous calculations produced by generalisation.

c)   Restrictive in scope and adaptability.

Relating the above programming systems to the groups of machines to which they are most suitable will help to evaluate the economic benefits or otherwise.

1.   NUMERICAL CONTROL BORING MACHINES which spend most of their productive time cutting metal.   Control of speeds and feeds and the actual boring operation remains in the hands of the operator, although he is often provided with trip dogs to establish the machining depth and these may be selected from tape.   The tape only contains information to position the workpiece relative to the machine spindle.

Computer programming is unlikely to make any significant improvement to programmer productivity unless the particular component requires large amounts of geometric calculation.   The programmer is likely to be involved in nearly as much work in describing the machine in APT language as he would be in preparing the program manually.

The recently developed PICNIC program can be used effectively for this class of machining; using some 40 words from the APT vocabulary considerably simplifies programming.

2.   SIMPLE NC DRILLING MACHINES mainly for flat plate work where change over from rapid approach to drilling feed and also the final drilling depth are fixed by manually set trip dogs;   although one or more alternative sets may be selected from tape.

The situation regarding the application of computer-sided programming to this group is much the same as far Boring Machines.   However, a significantly larger part of the work available has a fairly high geometric content - boiler and heat exchanger tube plates and other flat plate components which consist essentially of through-holes in regular patterns.   Many of the machines which are mainly engaged on this

class of work are already programmed by special-purpose computer programs. For this class of work, where special purpose programs are not available, advantage can be taken of any of the APT sub-set languages.

3. SIMPLE MULTIPURPOSE MACHINES with linear path control on the table motions and trip dog control of the spindle axis. Table feed rates are generally controlled from tape as are miscellaneous functions such as a simple turret tool changer, coolant, and selection of the required canned cycles for drilling, milling, tapping and boring.

An appreciable part of the work for these machines involves multiple operations at the same point, e.g. drill and tap or drill, bore and ream. Therefore, the storage and recall facilities for points and patterns which are available with computer-aided programming can assist the programmer by reducing the change of writing errors when instructing the machine to return to the same point for a later machining operation.

4. MORE VERSATILE MULTIPURPOSE MACHINES with linear path control on the table motions and tape control of the feed change point and machining depth. Spindle speed and quill feed may also be controlled from tape.

These machines have none of the machining depth limitations which apply to the previous groups. Castings and forgings - with a considerable number of different workplanes and with a higher proportion of the work consisting of operations other than drilling - constitute the majority of the work load. These more complex workpieces involve the manual programmer in considerably more calculation; computer-aided programming can therefore improve productivity considerably.

The machines all employ computer canned cycles also, which are essentially an aid to the manual programmer. In order to use canned cycles efficiently, a considerable amount of anticipation of the next machine move is necessary when preparing the control tape.

5. THE MOST VERSATILE AND COMPLEX MULTI-PURPOSE MACHINES have three axes of motion with full linear path control, possibly either a full fourth axis in the form of a tape controlled rotary table

or alternatively a rotary table with indexing called from tape. Spindle speeds and also feed rates on all three main axes are controlled from tape; a full range of miscellaneous functions, and generally an automatic tool changer, are also controlled from tape. Canned cycles are not used.

These versatile machines which normally require between three and five blocks of tape to position and drill a single hole can benefit significantly from computer programming. Since full tape control is available on the spindle axis, the degree of anticipation available from the post processor is sufficient to ensure that computer-prepared tapes are as efficient from a machine productivity point of view as manually programmed ones.

CHAPTER 8   Comparison of methods computer assisted programming

When considering the factors which contribute to the cost of producing control tapes, the relative merits of either an in-house computer or a computer bureau service need to be analysed, under two broad headings: set-up and running costs.

Set-up Costs

Costs involved in the implementation of the computer programs, training of staff, the preparation or purchase of documentation, the creation of files and the initial re-organisation required. These costs must be borne in mind when considering the resultant cost for each tape produced by the system. The in-house user has to bear all these; the bureau user, on the other hand, is only involved in the training of part-programming staff, the creation of files, and the initial re-organisation costs (which should be considerably less than that to the in-house user). A decision as to what period of time over which to recover these costs is left to the user.

Running Costs

All the factors of costs incurred in running an NC program system, except one, are common whichever type of service is used. The exception is a cost for the in-house user of program system maintenance and updating,

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including annual subscriptions, if any, to the appropriate distributing organisation. The common factors are: part programming, supply of data sheets, data preparation, computer processing time and fault finding. The part programming and fault finding costs are comparable whether using in-house or service bureau. In general the in-house computer time cost is less than the equivalent bureau rate, in that usually the in-house computing service for an organisation is not a profit making centre; consideration must be given to the fact that the bureau user pays only for the computer time used.

When studying the costs of computer bureaux, care should be taken to note which of the above factors are included within the charges for the service. The following table shows a summary of the contributory factors to cost, indicating which costs are incurred by the user of the two types of service.

SUMMARY OF ECONOMIC ASPECTS

Set-up Costs (recovered over 3 years)	In-House	Bureau
1. Implementing of program system.	x	
2. Training of operating staff	x	
data prep. staff	x	
part programming staff	x	x
3. Preparing manuals etc.	x	
4. Setting up tool files etc.	x	x
5. Initial re-organisation	x	x/3

Processing Costs		
1. Maintaining & updating of program system.	x	
2. Part programmer time.	x	x
3. Data Sheets	x	x
4. Data Prep.	x	x
5. Computer time.	x	x
6. Fault finding.	x	x
7. Transmission.	?	Minimal.

The foregoing facts can be summarised using the following process
to assist potential users of computer assistance for the preparation
of numerical control tapes.

DECISION PROCESS

. In fig.23 a flowchart is shown representing a typical initial process
through which a potential user may go in deciding which type of service
to use.

In constructing this flowchart two broad assumptions have been made;

a) that employment of computer assistance in preparing the tapes is
   essential;

b) that there exists a program system which will be satisfactory for the
   individual users requirements.

The flowchart is not intended to indicate the final decisions which
are to be made, but rather the possibilities which must be considered
in the final analysis.

Considering the points raised in the flowchart in greater detail:

Box 1:   Study of the present tape requirements, and also the
            technical aspects of the various program systems which are
            currently available, as discussed earlier.

Boxes 2-6: All acceptable systems are considered for both in-house and
            bureau; possible systems are entered on a comparison chart,
            an example of which is shown on Page 74.

Box 7:   Consider all acceptable present systems over a three year
            period. Repeat the process for future requirements, i.e.
            the next three year period - the appropriate values are again
            entered in the comparison sheet.

Boxes 8,9   In order to eliminate the systems which are technically or
            economically unsuitable, a change of system is considered.
            The decision to change is based on the technological desir-
            ability and cost. The cost should then be added to the
            comparison chart. If a change is not acceptable all non-

continuing systems should be discarded.

Boxes 10,11: The process of boxes 8, 9 is repeated, this time considering a change in operating mode from in-house to bureau or vice versa. Again, the cost is entered in the comparison chart.

From the above data equivalent cost values are entered on the comparison chart. This is essential if such a comparison is to be of use, as the whole purpose of an exercise of this sort is to help to determine how to manufacture goods within a specified timescale and quality at minimum cost.

The comparison chart represents a system which will enable the different options to be radically reduced in number.

COMPARISON CHART DETAILS

Item 1: Identification of the system.

Item 2-7: The financial case for the system to cater for present needs is considered, successively, by: operating mode (bureau or in-house); sum of set-up costs; costs per average control tape; and total number of tapes; giving a sum of running costs and hence a total cost of the system.

Item 8: The cost of change, if any, from system to system or in-house to bureau.

Item 9: A repeat of the present requirements items 2-7 for future requirements, resulting in a total cost of a system to cover these requirements.

Item 10: The present system cost, cost of change, and future system cost are summed to give a total overall cost.

Item 11: In order to allow for desirability of system and any side benefits, it is suggested that a cost value be added. Examples of possible areas for consideration are turnround, technical suitability, optimisation of tool usage, and auxiliary facilities available.

Item 12: Overall cost.

START

Study Present Requirements 1
and List Acceptable Systems

Choose System; 2
Have all Systems been cons'd

All Systems Considered

Are in-house Resources 3
available for chosen system

Yes

Mark system possible for 4
in-house, and enter cost

No

No

Is preferred system 5
available at a bureau

Yes

Mark system possible for 6
bureau, and enter cost

Repeat steps 1 to 6 for 7
future requirements

Study desirability of 8
a change in system

Not Acceptable

Discard all systems not 9
available now and in the
future

Acceptable

Study desirability of 10
à change in operating mode

Not Acceptable

Discard all systems which 11
split operating mode

Acceptable

END

Fig. 23

COMPARISON CHART

Present - 3 years

1. System identification.

2. Bureau or in-house.

3. Set-up cost.

4. Cost per ave. tape.

5. Total number of tapes expected.

6. Running costs.

7. Total present cost of system.

8. Cost of change.

9. These items should be considered on the basis of the present

    three years, and then repeated for the following three years.

    In both cases the costs of in-house and bureau should be compared.

10. Total cost.

11. Cost value.

12. Overall cost.

Present - 3 years

The costs calculated from the statements shown at the beginning of
this section, assume that the planning work which was carried out before
programming commenced was correct in every detail.   As this is virtually
impossible, nearly the whole of some programming tasks may have to be
repeated so that time and costs given would need to be doubled.   The
expertise of N.C., like any other technique, increases with experience
in that particular field.

Initial proving of a completely new tape, by most users of point-
to-point machines, consists of a block at a time run through the tape
to check that the encoded machine functions are correct.   Users of
complex and expensive N.C. machines often follow this by a further stage
of prove-out with the machine operating continuously but either cutting
fresh air or a dummy component made of polystyrene, balsawood, etc.
Step-by-step prove-out will generally take two to five times as long as
a normal metal cutting run through the same tape.

When a company uses bureau computer assistance for producing control
tapes, the following prices published by ICSL (10) illustrate how prohibit-
ive prove-out costs can be; allowing for the fact that the figures shown
are for one run only, whereas several runs may be needed before a proven
tape is accomplished.

Error charges, previously based on a machine time wasted basis have
also been standardised in formulae related to the size of the tape
ultimately produced and the section of the system, i.e. the geometry,
technology or post-processor phase, within which the error occurs.   The
charge per error is thus:

    Geometry: £2 + 5p. per 10 output blocks

    Technology: £2 + 10p. per 10 output blocks

    Post-processor: £2 + 15p. per 10 output blocks.

From the economic facts covered earlier, it is evident that if
programming could be developed to ensure the production of control tapes

on which all information is correct, thus enabling component production to commence without loss of time, the economic advantages would be considerable.

It is not always practical or economical to rely entirely on the N.C. machine tool to check out encoded information. The machine may be so heavily scheduled that it cannot be spared for a long slow prove-out cycle, or the hourly cost of machine and operator time may be so high that this method of prove-out is uneconomic, particularly as the programmer is usually monitoring the operation.

The method and level of verification needed to check the encoded machine functions are correct will depend upon the complexity of the machining program, and in certain cases the value of the component.

Existing methods of prove-out for encoded information can be grouped to show the various levels at present available in the following manner. In many cases, particularly with contouring information, several methods would be used starting with one or more of the lower levels of verification.

Levels of Verification

I. Manually programmed tapes can be checked by a duplicate typing operation on a Flexowriter. The punched tape is inserted into a verifying unit connected to the Flexowriter. The program is then retyped. The verifier automatically compares each character with that on the original tape. If they do not match, the keyboard locks. The operator determines which tape is wrong and makes the correction.

It has been shown by B.L. Soloway (11) that the recently developed Soval system, using fibre optics, enables an operator to produce control tapes identical to the manuscript, thus saving a verification process using a second operator. These methods assume the manually written program to be correct.

For N.C. systems that use computer and punched cards from data implementation, accuracy of card coding can be determined by a key-

punch verifying machine. This process requires that the operator place the previously coded cards in the verifier. The entire program as outlined in the manuscript would then be retyped. The verifying unit automatically scans the card coding for accuracy of the original punching operation. If there is a mismatch, the incorrect card is rejected. A replacement would then be punched.

The process checks whether the punched cards correspond with the written manuscript. Also that the program language and motion instructions are in the prescribed format.

In general purpose program systems such as APT, both format and language are rigidly prescribed. A grammatical error in punctuation or language could make the statement unintelligible to the computer and thus unprogrammable. Other types of discrepancies include instructions that violate previous instructions.

With APT computer processing the validity of the input program and motion instructions are checked by special screening programs that are part of the soft-ware system. At its present stage of development, the error analysis program for APT can detect about 160 different errors in programming procedure. The location of the error in the program is printed out along with a diagnostic statement of the defect. Not every error can be diagnosed specifically. In some cases the programmer must analyse the problem himself.

II. Consists of examining the pattern of the punched holes to see that they are properly spaced and aligned according to established standards.

Irregularities can occur in the hole pattern because the tape fails to track squarely through the tape punch, particularly in high-speed punches. Some spacing errors occur because of slight deviations in spacing of the sprocket holes.

Improper alignment, skewed or elongated holes and similar irregularities can cause the tape reader in the NC machine to misread data, causing an erratic tool motion or complete machine stoppage.

The punched holes should at least be spot-checked before the tape is put on the NC machine. Both punched cards and tapes can be checked using a simple template and though it is difficult to check an entire tape, the first 2 to 4 metres should be checked.

A more sophisticated gauge can be built to check an entire tape automatically. It is similar to the punched-tape readers used on standard NC machine control units. It employs a photo-electric scanning mechanism coupled with error-detection circuitry. The verifier can rapidly examine the entire tape for conformance to channel and sprocket-hole standards. If deviations are sensed by means of a partial or full cutoff of transmitted light, the machine will automatically stop.

III. This form of verification consists basically of plotting the cutter-centre path or the series of tool positions on a sheet of standard drafting material. For a continuous-path program, the plot will show if the tool path is in correct relation to the part outline.

Graphic techniques can only depict coordinate information. They cannot predict how accurately the actual machined part will correspond to the desired shape. Final results depend on the variable effects of cutter deflection, speeds and feeds, and the dynamic response of the machine tool during the cutting cycle. Plotting techniques, however, are useful for visualising the basic accuracy of the programmed tool movements.

The most accurate way to depict coordinate information graphically is with a numerically controlled drafting machine. It will plot the tool path with an accuracy of 0.050 mm./0.3 metres. The accurate detail from a drafting machine is limited to the motions of X, Y, and Z axis operations. Tool path data involving additional axes, such as swivel and tilt motions, can be plotted to show only excessive errors.

The control tape for the drafting machine is obtained from the computer using a post processor appropriate to the drafting machine. There would be considerable advantages in using the same tape as the one

operating the machine tool.   Chapter 9   shows an example of this level
of verification and indicates the accuracy expected.

IV.   The approaches that can be used for checking aspects of the programmed
machining cycle cannot be readily visualised by plotting tool path or
position, include a machine tool simulation, a universal measuring machine
and a simulation run in the machine tool itself (providing the latter is
economically justifiable, see first paragraph).   They also take into
account machine and work set up.

A machine tool simulator is a working mock-up that can duplicate the
full range of motions of the actual NC machine on which it is patterned.
Vernier scales are used for checking the positions of simulated motions
of the movable elements of the machine.   To check out an entire program
using this technique would be tedious, the main purpose is for spot-
checking critical or doubtful parts of the program.

A measuring or inspection machine can also be used in much the same
way as a machine tool simulator.

These inspection machines consist essentially of a work-mounting
surface and stylus movable in three axes.   The coordinate location of
the stylus with respect to any selected reference point is shown in
numerical form on a readout panel.

To check a program, an accurate part or master is set up on the
machine.   After being zeroed against a reference point, the stylus is
moved to a succession of coordinate locations as called for in the program
to check tool position and possible interference problems.

Most users of NC machines still carry out a dry run on the machine
tool itself using the actual control tape and a wooden or plastic stylus
of the same length and diameter as the cutter.   This will prevent damage
to the work or machine in case of an impact.

V.   The ultimate verification is to machine an actual workpiece.   The
cycle will positively check the dimensional accuracy of the tape.   It
will also reflect the numerous unpredictable factors that arise only during
an actual machining cycle and whether they will affect the acceptability

of the part.

The high investment in NC machines and the value of these machines
as short run production tools place a premium on accurate control tapes.
A considerable effort to correct a new tape before it reaches the machine
is essential. The degree of effort and the type of equipment used depends
on balancing the cost of a potential scrapped component or machine down
time against the cost of verification.

When numerical control is applied in an organisation the process
of controlling the machine tool is largely removed from the shop floor
and placed in the planning office, where the part programming operation
is carried out.

Most of the factors governing the choice of tools are the same as·
for manually controlled machines. However, the advantages of using
tools with a long cutting life and optimum cutting speeds are more
significant, since otherwise a disproportionate amount of machine time
may be spent on replacing tools. When large batches of components are
being made, a tool inspection and replacement schedule should be associ-
ated with the part programme. This eliminates having to scrap components
because of undetected deterioration due to tool wear or breakage.

Drill speeds and feeds etc. are also determined as in manually
controlled drilling, even when they are programmed on the tape and sel-
ected automatically, but with more emphasis placed on optimum settings
to give maximum machine output efficiency. The sequence of operations
should be that requiring minimum travel from hole to hole. Wherever
possible, movements between successive holes should be in the direction
of increasing co-ordinate. To eliminate any lost motion, the mechanism
travels beyond the point required in the negative direction and reaches
final position in a positive direction. Therefore the time required to
position in a positive direction is less than in a negative direction.

Where a machine is fitted with a turret and some holes require several operations with different tools, it is usual to carry out all the work making use of one tool before going on to the next stage. However, if the distances between holes are large or if the turret indexing mechanism is very fast, it may be quicker to carry out all the operations on one hole before going on to the next one. It may sometimes be found expedient to follow the same course when the position of two successive tools over a hole are required to be concentric within a very close tolerance.

The specification of such factors as tolerance takes on a different aspect, as in the final analysis they are now a function of the machine control system chosen to carry out the machining operation. Additional errors, arising from the machining process itself, must be added to the combined machine-control system errors.

Tooling for NC is closely related to programming since it involves the choice of size, shape of cutters, and their proper setting in standard holders to match the plan envisaged by the programmer. It is customary for the program to include tool specifications so that the machine operator can get the complete set of tools for a given part without initially having to work out the required list. The programmer must provide the tool room with all the data required for setting up all the tools needed for a given job on a given machine. The tool room must see to it that the tools are correctly ground and held in place so that no unnecessary time is lost correcting tool settings on the NC machine.

As shown by S.J. Martin (3) setting time can be reduced and maximum accuracy maintained by using preset tooling. The effect is to set the tooling from a drawing or chart away from the machine to a specified accuracy, whilst a different batch is being produced. The reduction in machine idle time has to be balanced therefore against the capital cost of the equipment and the increase in the total time spent setting the tools.

A further means of maintaining maximum accuracy and reducing setting time is the use of a module table shown in fig. 24, the purpose being to provide a reference area onto which components may be clamped at known positions for machining. Zero setting positions can be programmed directly. All that is then required is that the operator places the component against the stops in a position pre-determined by the programmer. This dispenses with the need for accurate manual setting. Repositioning errors are eliminated and setting time is reduced very considerably.

Time and trouble in programming is saved if drawings and tables are supplied with ordinates that coincide with the grid positions of the module table. Also the design should allow access to as many faces of the component as possible at a single location on the machine table. The versatility of the numerically controlled machine tool can then be fully exploited.

Design considerations (module table).

The table must be large enough to cover the total travel of the machines axes and must comply to the same design characteristics as the conventional machine bed.

Particular attention should be paid to the accuracy of the grid position bores, location stops, and to the geometric tolerances allocated to them. In all combinations the latter should be within the accuracy capability of the machine.

Calibration

Bores and location stops were accurately calibrated and all data processed using a Fortran program to give:

1. taper per unit length

2. location bore centre distances

3. bore centre to location face distances.

TYPICAL SECTION - X - X

25.00 ± 0.001 M.M.

18 M.M., 18 M.M.

32 M.M.

5/16" B.S.F.

31 M.M., 25 M.M.

DIM 'A' =
50.000 ± 0.00

MODULE

TABLE

X

'A' 'A' 'A' 'A' 'A' 'A' 'A'

X

458 M.M.

54 M.M.

377 MM

63.5 MM

'A' 'A' 'A' 'A' 'A' 'A' 'A'

Fig. 24

83
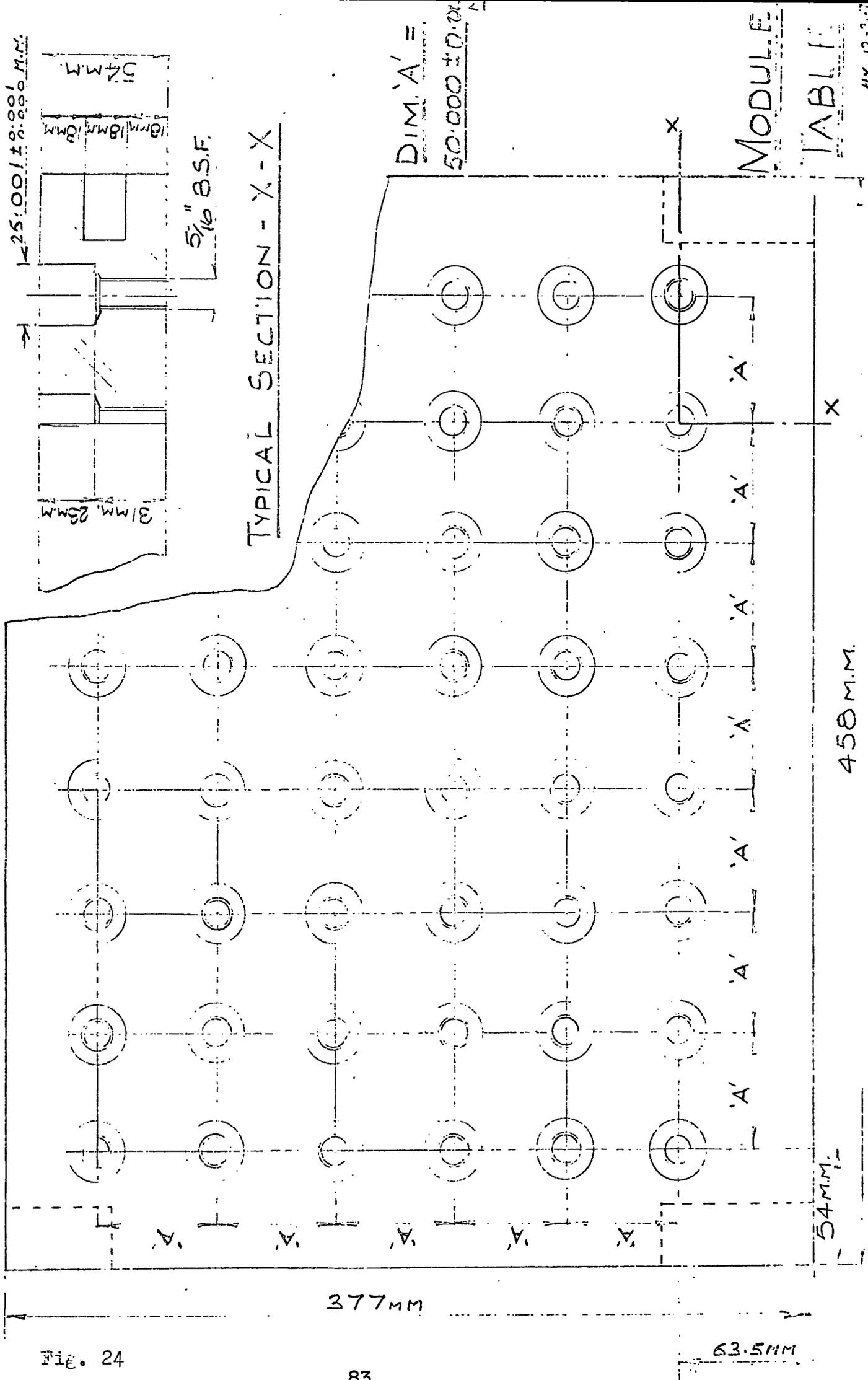
A coding system was used to ensure accuracy of location.stops in all combinations of their positions in the module table.

The dimensional accuracy obtained can be seen in appendix B where an extract from the line printer output is shown.

Error Elimination (Manual Programming)

As previously stated in programming economic considerations, the majority of N.C. machines in use in the United Kingdom, estimated at 75% by W.H.P. Leslie (9), are point-to-point, programmed by completely manual methods.

It must be acknowledged that numerical control alters the practice and system of manufacture and unless an accurate control medium, at present in the form of punched or magnetic tape, can be produced its full potential will not be realised.

With the latter thought in mind, the following program has been developed to check format errors during the production of a control tape. Also to ensure the programmed instructions are accurate and in a form that will enable a machine tool to produce an acceptable part.

Equipment

Newall 1520   Auto Positioning Boring and Milling Machine.

The 1520 is of column type design, with open table access.

Table movement can be controlled automatically or manually.

Quill head control is manual only.

Table and cross-slide are mounted on widely spaced vee and flat sideways.   Clamps are also incorporated to prevent table movement.

Measurement systems, automatic by Airmec AEI N410, manually by the Newall linear system.

N.C. System Airmec - AEI N410

The control system operates by comparing the programmed position and the position of the machine axis, the table being driven towards the programmed position by a positioner unit measuring absolute angle, until the two positions coincide.

Accuracy is maintained by the use of a very accurate leadscrew, any errors in position being corrected by a cam in the drive gear box.

Backlash is eliminated by ensuring the approach to the final position is always in the same direction.

The required table co-ordinates may be selected in two ways:

a)   Manual control panels in which the co-ordinate values and machine functions can be dialled in.

b)   A punch tape reader.

The tape reader mechanism embodies a toothed sprocket drum which engages with and supports the tape.   Each indexing pulse transmitted to the reader causes the sprocket to move one pitch.   Tape reading speed 12 characters per second.

COMPUTER FACILITIES

TYPE	ICL 1902/A
STORE	16,000 words.
	24 bits per word.
	Cycle 1.8 sec.
HARDWARE	Floating point arithmetic unit.
MULTIPLEXER	8 channels.
LANGUAGE	ALGOL
	FORTRAN IV
	COBOL
	NICOL
	PLAN
	SLANG
ELLIOTT 803	Simulator and Mercury Simulator.
	Limited multiple on line processing
	2 Disc Transports
	6 discs each and 10 surfaces per transport
	8,250,000 per transport.

1 Line Printer (300 L/m)

                    1 Paper Tape Reader (1000 Ch/s.)

                    1   "   "   Punch (110 Ch/S.)

                    1 Card Reader   (300 cards/m).

METHOD OF PROGRAMMING

All the tape control data was coded into paper tape, one line of control data being represented by one block of coded characters.   The blocks were separated by a block marker which enabled the Autoset to identify the beginning and end of each block.

The following table shows the headings of the columns that a layout sheet must have.   The words that may be programmed are also given, showing their letter address if any, and the number of digits that each word must have.

PROGRAMME FORMAT

Operation Code No.	Coordinates	Machine Functions	Sequence No.
(1)	x(6) y(6)	t(3)	n(3)

A block of control data may contain one or all of the above control words.   Any words that are programmed must be punched on to the tape in the order as shown.

OPERATION CODE NUMBER

A single digit; no letter address.   Operation code numbers are effective only for the block in which they are programmed.

Their purpose is to modify the normal function of the equipment when a slightly different mode of operation is more suitable for a particular operation.

Each operation is effected by operating the auto start button.

At the start of a programme the tape reader of the Autoset reads

the first block of information and any commands in that block are init-
iated; the tape reader continues to read forward the next block up to
the 't' code, therefore any 'x' and 'y' numerical data is read in advance,
and stored.   Except when milling mode is called (by the appropriate t
code) positioning will not take place until the quill is fully retracted
to top limit.

On operating the auto start button again, any stored 'x' and/or 'y'
commands are effected immediately and the machine moves to bring the
positioners to balance with no delay for tape reading; while positioning
is taking place any programmed 't' words and 'n' words are read and the
reader continues again to read any 'x' or 'y' information in the next
block as before.

The operation code numbers and their effect on the normal function
of the Autoset applied to this machine are as follows.   Note that they
apply only to the block in which they are programmed.

1.   STOP PROGRAMME.   After all the commands in the block have been
     carried out the tape reader is halted, i.e. inhibits the tape reader
     reading forward.   Reset when the auto start button is operated.

2.   OMIT MACHINING.   Signifies that no head cycle is required for that
     block, therefore, after all the commands in the block have been
     completed the next block is initiated without the need to operate
     the autostart button, i.e. the next block is linked to make a
     continuous cycle.   Normal function is resumed when all linked blocks
     have been completed.

3.   OMIT MACHINING AND STOP PROGRAMME.   Signifies that no head cycle
     is required but that after all the commands in the block have been
     carried out the tape reader is halted.   Reset when the autostart
     button is operated.

TEST PIECE PROGRAM   (For component used see fig. 22).

OP. CODE	Coordinates		Seqn. No.	Instruction
	X	Y	N	
	X035000	Y125000	N001	Centre Drill
	X065000		N002	
	X095000		N003	
	X125000		N004	
	X155000		N005	
	X185000		N006	
	X215000		N007	
	X125000	Y215000	N008	
		Y185000	N009	
		Y155000	N010	
		Y095000	N011	
		Y065000	N012	
1		Y025000	N013	
	X018935	Y018935	N014	Load Tap Drill
	X040148	Y040148	N015	
	X061361	Y061361	N016	
	X082574	Y082574	N017	
	X103787	Y103787	N018	
	X146213	Y146213	N019	
	X167426	Y167426	N020	
	X188639	Y188639	N021	
	X209852	Y209852	N022	
	X231065	Y231065	N023	
	X018935		N024	
	X040145	Y209852	N025	
	X061361	Y188639	N026	
	X082574	Y167426	N027	
	X103787	Y146213	N028	
	X146213	Y103787	N029	

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OP. CODE	Coordinates		Seqn. No.	Instruction
	X	Y	N	
	X167426	Y082574	N030	
	X188639	Y061361	N031	
	X209852	Y040148	N032	
1	X231065	Y018935	N033	
	X086732	Y032612	N034	Load 10 MM
	X163268		N035	
	X217388	Y086732	N036	
		Y163268	N037	
	X163268	Y217388	N038	
	X086732		N039	
	X032612	Y163268	N040	
1		Y086732	N041	

PROGRAMMING ERRORS

Considered under two headings; (a) Format errors, (b) geometric or dimensional errors.

(a) Format Errors

Generally known as alpha-numeric errors, can occur both in the language, and the sequence in which they are written. Any deviation from the prescribed coding constitutes an error.

(b) Dimensional Errors

Usually arise from mistakes in the coordinate data, and can still exist when program format is correct.

FORTRAN ERROR SEARCH PROGRAM

General Description

The following program has been developed primarily to check format errors, and in the latter stage, dimensional errors using a graph plotter.

The technique employed in the program is to feed in a single block of data to the computer. Having then established the validity of the block the answer will appear in line printer output, for visual checking by the programmer. Tape output can also be used for dimensional error checking using a graph plotter.

Appendices A and C show the pattern of N.C. machine tool data being checked for format and dimensional errors respectively using the Fortran error search program.

PROGRAM OPERATION   (see fig. 25)

1.   The Fortran program T.E.S.P. in disc form is presented to the compilers and fed in.   The compiler is now ready to accept the N.C. control tape data.

2.   Machine tool data on the control tape is received by the compiler a block at a time into a storage area.

3.   The main program now begins.   The data in the block being sorted and identified into numbers and letters.

4.   Starting at the beginning of each block and working through, each section is identified and sent to sub sections for checking.

5.   Each section of a block is tested for relevance in these sub sections.

6.   When the series of checks are completed the answers are sorted and directed.

7.   If an error has been found the error message is called and a visual message on line printer out-put is provided for the programmer.   The block containing an error is then abandoned and new one read in.

8.   If the information is correct, the data it represents may be presented for visual display in line printer out-put and also tape out-put for use with a graph plotter for dimensional error checking.

9.   The program will then either return to the block of information in store (2) to process the next section of data, or may proceed to (1) to read in the next block of data from the control tape.

GENERAL FLOW DIAGRAM

PROGRAM INPUT.

T.E.S.P.
1

COMPUTER STORE

N.C. DATA TAPE.
2

SORT DATA INTO LETTERS AND DIGITS ³

②

RECOGNISING INFORMATION TO BE EXAMINED. ⁴

①

| ⁵ OPERATION CODE. | ⁵ X CO-ORD DATA | ⁵ Y CO-ORD DATA | ³ T FUNC-TIONS | ⁵ N LABEL SECTION |

HAS AN ERROR BEEN FOUND ⁶

No — YES

TAPE OUTPUT FOR PLOTTER ⁸

OUTPUT CORRECT DATA ⁸

OUTPUT ERROR AND BLOCK ⁷

IS BLOCK CHECK COMPLETE ⁹

No — YES

RETURN TO READ IN NEW BLOCK OF DATA

Fig. 25

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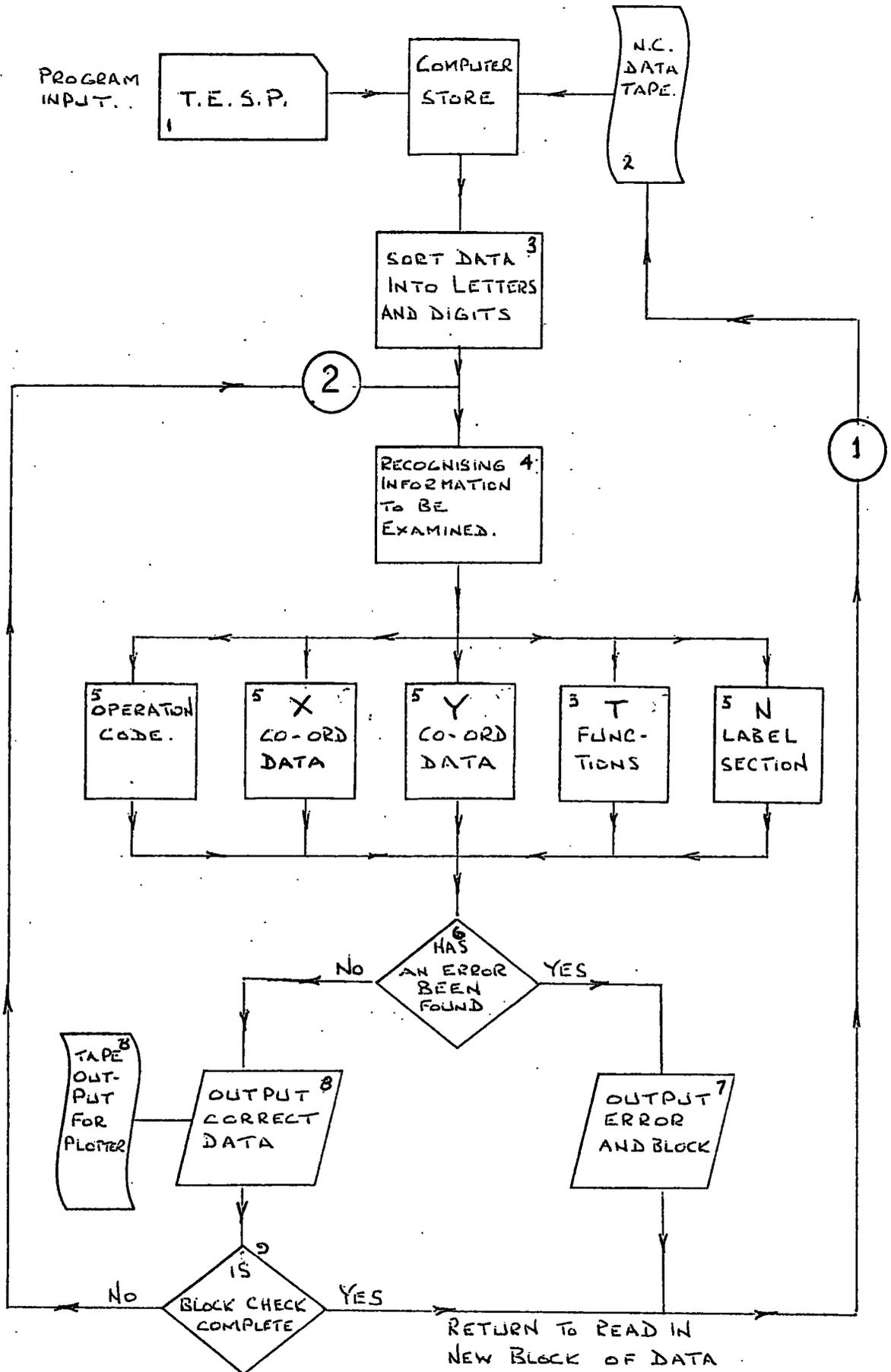
Using the Fortran error search program 120 blocks of information
on line printer output can be produced in two minutes, and any existing
format errors shown on the line printer output can be located immediately.

Checking carried out by an experienced programmer for the equivalent
number of blocks would take fifteen minutes. Also this line by line
method of checking is extremely tedious and there is no guarantee of
accuracy.

It must be borne in mind that a core store of 5K is required to use
the error search program. There are, however, many companies in the
U.K. using manual programming methods for short batch production, who do
have this facility. Therefore the error search program could be used
to considerable advantage when manually programming N.C. machine tool
data.

CHAPTER 10   CONCLUSIONS AND RECOMMENDATIONS

The economic justification of numerically controlled machine tools will depend upon careful consideration of the following facts:-

Direct Savings

The direct savings, which can be expressed in terms of time and money, may occur in the pre-production stage by the simplification or elimination of jigs, fixtures and special tooling. At the production stage, savings are due to the exclusion of marking out, and reduction in setting, machining, handling and inspection times. As a result of improved product quality, fitting and assembly times are reduced at the assembly stage.

Savings achieved in the pre-production, production assembly and fitting stages are determined, to varying degrees, by component complexity and batch size. These facts are illustrated in chapter 6 table 3, and from the graphs (figures 20 and 21) it can be seen that for batch sizes from three to one hundred and twenty, tape control is economically advantageous. Numerical control can be readily justified for complex components over a much wider range of batch sizes. Long contouring operations represent a special case in practice and numerically controlled methods can usually be justified technologically.

Indirect Savings

Indirect savings, which can be attributed to the introduction of numerical control, should involve the following considerations.

Jigs, fixtures and special tooling can be eliminated, therefore, considerable savings can be made, due to the liberation of design, manufacture, maintenance and storage of these items.

Production operations, such as marking out, can be dispensed with and inspection reduced. Savings in these areas are not total as time is taken proving control tapes on the machines.

Machining errors are reduced under numerical control once input
data has been verified as correct; a fact that may be of overriding
importance where the component value is high, due to expensive machining
operations.

An important asset of numerically controlled methods is the ease
with which a program can be altered in order to accommodate design change.
Where jigs have been used conventionally, modification was a lengthy
and expensive process. Savings in transportation of parts between
operations, progressing, inspection and storage due to the elimination
and shortening of operations thus creating a reduction in lead time,
which consequently reduces the volume of work in progress.

Machine operators can be directed to such tasks as controlling a
number of machines, inspection duties and tool organisation, as direct
involvement with the operation is considerably reduced.

Intangible savings are difficult to assess but can show quite
significant benefits in the following areas: operator fatigue causing
scrap, particularly where the work is of an accurate and intricate
nature; reduction in cutting tool costs, due to their more disciplined
use; production can be switched between machines or factories with an
assurance of consistency, (the alternative to the transfer of control
tapes is the costly and complex removal of machines).

The cost analysis (pages 33-37) based on the factors discussed,
show a saving on one machine of £559 per annum for single shift working
and £2,830 when working a two shift system. A further example (page
42) based on component quantity, shows a saving of £7,272 per annum.

Justification calculations of the type mentioned in the previous
paragraph are essential when considering the introduction of numerical
control. This fact is emphasised when data obtained from the use of

numerically controlled machines is used in a short cut calculation
(page 51). The facts obtained from the latter method would be a
deterrent to potential users of numerical control.

The analysis of capital investment, Chapter 5, has shown that
accurate forecasting and alternative methods of investment must be
considered to yield the quality of decision necessary for investment
in numerical control. From the example calculated, numerical control
proves to be financially the more attractive method, providing the
factors affecting the following points are considered:

(a) the rate of discount employed and (b) the accuracy of the cost
saving figure.

Programming Economics

In order to decide which is the better method of programming, it is
essential to take into account, primarily, the economic factors. Assum-
ing that computer assistance is chosen for the production of control
tapes, the most suitable program system must be selected to meet the
requirements of the company, both technologically and economically.
Furthermore, the relative merits of either an in-house computer or a
computer bureau service need to be analysed.

The latter considerations are summarised in Chapter 7. Provided
the decision has been made that computer assistance in preparing control
tapes is essential, also that a program system exists which is satis-
factory, the decision process outlined can be used. If the data
obtained from using the decision process is entered on a comparison
chart, as described, the many different options will be reduced in number
and a logical conclusion arrived at.

It is an established fact that manual programming is the most
widely used method of preparing control tapes and the initial cost

calculated only takes into account a control tape ready for prove-out. The prohibitive costs required to ultimately produce a correct tape emphasises the urgent need for program development to include an error checking facility in this area of control tape production.

The program developed using Fortran IV shows considerable benefit in time saved checking manually programmed data away from the machine, therefore, reducing downtime.

Direct savings would be due to profit from continued production, using a machine of high capital value at the rate of £10 per hour. This would be an additional saving to costs incurred by prove out runs on the same machine. A further saving would be the time taken by a planning engineer to check the equivalent amount of data. Against these savings there is, of course, the cost of running the program on the computer.

Intangible savings from such facts as no guarantee of accuracy from manual checking, resulting in scrap work and no accurate knowledge of the number of proving runs required to produce an acceptable part,

Using the subroutine at the end of the error checking program, tool position can be checked to an accuracy dependent upon the type of graph plotter used. This can be as low as 0.02 mm. and it is, therefore, quite feasible to note dimensional errors visually of this magnitude, if the chart is used on an optical projector.

The error checking program now available on disc in the Computer Department of the Polytechnic will be offered as a checking service to industry in the region, using the same program format.

Further advantage can be gained from using preset tooling and module tables, as shown in Chapter 9. The magnitude of the errors which occur in this area are usually in the order of 0.02 mm., and are often not

located until the component assembly stage.

Every possible effort should be made to eliminate errors from the control tape without creating machine downtime, therefore, the advantages gained from using the type of tooling mentioned above should be fully exploited.

The decision to invest in numerical control should only be taken after making an economic appraisal, centred on the relative economics of numerically controlled equipment compared with existing manufacturing methods, embracing all the facts discussed in this thesis.

PROGRAM DESCRIPTION T.E.S.P.

    This is a Numerically Controlled Machine Tool Tape Error Search Program (T.E.S.P.). It is designed to examine 8 channel tape that has been prepared for an N.C. point-to-point jig boring machine.

    The program is written in Fortran IV and is available on disc in the Polytechnic's ICL 1902A computer.

PROGRAM DESCRIPTION SEGMENT

Input

    The tape reader unit is used to input the N.C. tape to the computer, the program will read this tape a block at a time until the end of the tape is reached.

Output

    The program is designed to give two forms of output: (1) Line printer paper, (2) Paper tape.

(1) Line printer output (see Appendix A, page 123 for layout) gives visual representation of the processed N.C. tape information. The status of each block of N.C. data will be shown by the printout position on the page. Errors are made easily visible by the format of the script.

(2) The tape output is used on the Elliott 803 computer to drive the graph plotting machine and give a visual co-ordinate representation.

MASTER SEGMENT DESCRIPTION

    Every Fortran IV program needs a defined master segment for the program to be operational. The master segment in this program is given the initial letters of the program title, i.e. T.E.S.P.

    At the beginning of the program, instructions are given that define the mode in which the program is going to be operated. Constants are set up and the preparations for the program to run effectively are made.

M1.12 This statement brings into the computer the first and each block
of N.C. data to be processed. Because the nature of each character in
the block of data is initially unknown, a counter is set up, M1.14 and
a loop of program performed with each character in the block, to establish
whether it is a number or a letter, and also to store it in its correct
representation. This is performed in the section M1.15 to M13.10. It is
done by comparing the store value within the computer with known store
values for specific numbers, and hence it is possible to attain their real
value.

When this first sort of the block data into a more handlable form is
complete, the program segment must examine block data in detail to decide
which section of the data is to be checked.

In M3.11 a variable (JJ) is set up which throughout the program will
check by testing against constants to ensure that the data has been presented
in the correct order.

The correct data presentation order can start with an Operation Code.
So the loop of program MS3.12 to MS7.14 comprises the sorting of the data
starting with operation codes first into the correct SUB-ROUTINE so that
each section may be checked for errors.

At the entry of this loop the first value of block data is taken and
it proceeds through the contents of the loop until the section is identified.
Non-identification constitutes an error. Then after this data and any
further characters of the block data which may be called for has been processed,
the NEXT character in the stored block data will follow the same path through
the loop.

With the first data an operation code is looked for in MS3.15 and, if
found, the appropriate subroutine is called MS3.16. Should this section
be used at the beginning of a block it cannot be used again. The findings

of the subroutine are directed at MS3.18 onward to the ERROR SUBROUTINE.

Section MS4.10 - MS4.15 decides whether the data being examined is coordinate data for the X section by deciding whether the data presented is a letter X or not. This uses a FORTRAN LIBRARY SUBROUTINE CALL COMP which will compare one set of data against a fixed set and alter a variable value accordingly. A test on this variable value provides the answer to the question of whether the examined data is an X or not. If the answer is yes the SUBROUTINE for the X section is called, if not the data passes on for further examination by the same technique for the Y, T, and N sections.

After examination in the X subroutine for errors, the error section may be called if any have been found, or otherwise the data count is updated, and the process continues with a new piece of data from the block stored.

This is repeated in the other sections.

At the end of this loop the size of the count is monitored to see if the end of the block of data is reached. MS3.18. If this is so the program returns to the beginning of the master segment and a new block of data is read in.

SUBROUTINE DESCRIPTIONS

SUB NUMBERS

In this subroutine the value of the operation code will be checked. To get as far as this subroutine a number between 0 and 9 must have been found at MS3.15, therefore it remains for this subroutine only to check the size and also the position in the block of the data.

If the number has appeared in the block after an X section has already been checked then it constitutes an error. This will be found by the test

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of the size of JJ at Sn1.12. The acceptable size of an operation code

for the machine tool system we are dealing with requires it to be a

whole number greater than O and less than or equal to 4. This is checked

at SN1.14. Depending on the answers to the checks, the subroutine will

write out the checked output (1) or recommend an error signal.

SUB TEST X and SUB TEST Y

The methods employed in these two subroutines are identical, only

the variable names are changed with also the different value of one

constant.

The subroutines start on a check, of the order of calling up the

section SX1.11.

Next the data for the next six characters is read in from the stored

block and each one checked for validity as a number. SC1.14. After

this the numbers are assembled into the coordinate value by raising the

number to the power of ten, descending from 6 by 1 for each value read in.

Each complete number is assembled by using a program loop. The size

of this data is checked at SX2.10 to ensure the coordinate size is below

the max. machine size of travel.

The coordinate numbers are stored in variable stores for use with

the graph plotter tape output (2). If the checks have been carried,

without any errors found, the section will print out the sections on

output (1) or conversely the error subroutine will be called.

SUBROUTINE TEST T

This subroutine is basically the same as the X and Y described above.

The main difference being that the check is carried out for the milling

sequence numbers which can be between 100 and 400 inclusive.

SUBROUTINE TEST N

Again the subroutine is very similar to the previous ones, especially in the main construction. At the latter stages of the subroutine it has a check for the number size, i.e. is the label less than 999.

The last section involves the calling of special library subroutines for the correct output of the paper tape for graph plotting. These are in this position because the correct last section of a block of information is an N section, and here where they are correctly punched out. If there is a previous error, this is missed and hence errors of this kind show in plotting.

REFERENCE LABELLING SYSTEM

301   Position labels

500's

400-1   Master segment DO loop labels

 11   "   "   internal. DO loop label

12-15   Subroutine. DO loop labels

2011   Program switching and comparison routines

201   Labels

211

231-3   Numbers. subroutine labels

241-9   Test X subroutine labels

251-9   Test Y subroutine labels

261-9   Test T subroutine labels

271-9   Test N subroutine labels

666   Call Error subroutine label

901-999 Format labels

LIST OF CONSTANTS IN T.E.S.P.

CONSTANT	USE
LLL	Gives the Block size to master segment loop which processes the block information.
JJ	A progressing constant which is updated after each function subroutine and prevents order errors.
KK	A constant of 2 values which is switched depending whether an operation code has been found or not.
LL	The value of LL which may be 1, 2, 3, will determine a route the program is to follow usually proceeding or call error
J	This constant is the constant of comparison for the library subroutine named CALL COMP
M	A constant that will update the loop count on the program checks function by function through the block of information
NNOS	A no. which will govern the order sequence for the NOS subroutine
NX	A no. which will decide upon the order sequence being used in the SUBROUTINE TEST X
NY	" " " SUBROUTINE TEST Y
NT	" " " SUBROUTINE TEST T
NN	" " " SUBROUTINE TEST N

START

YY = 0
XX = 0
MSI·11

GRAPH PLOTTER DATUM SET

301

Read
R(I) 1-36
MI·12

READ IN THE BLOCK OF INFORMATION IN 'A' FORMAT

Write
MI·13

NEW LINE ON PRINTER

I = 1
MI·14

B

IS
R(I) < 0
MSI·15

R(I) = R(I)
PL 501
MI·16

401

IS
R(I) = 328720
MI·17

R(I) = 1
PL 502
MI·18

401

IS
R(I) = 590864
MI·19

R(I) = 2
PL 503
MI·20

401

IS
R(I) = 853008
MI·21

R(I) = 3
PL 504
MI·22

401

IS
A

A

MS2.10
IS R(I) = 1115152 — YES — MS2.11 R(I) = 4 — 401

MS2.12
IS R(I) = 1377296 — YES — MS2.13 R(I) = 5 — 401

MS2.14
IS R(I) = 1639440 — YES — MS2.15 R(I) = 6 — 401

MS2.16
IS R(I) = 1901584 — YES — MS2.17 R(I) = 7 — 401

MS2.18
IS R(I) = 2163728 — YES — MS2.19 R(I) = 8 — 401

MS2.20
IS R(I) = 2425872 — YES — MS2.21 R(I) = 9 — 401

MS2.22
IS R(I) = 66576 — YES — MS2.23 R(I) = 0 — 401

MS2.24
IS R(I) = 4260880 — YES — MS2.25 LLL = I, I = 36 — 401

666

(401)

IS MS3.10

(B) —No— I > 36 ---- DO LOOP COUNTER

YES

JJ = 2 MS3.11
KK = 1
I = 1

MS3.12
(C) — I = I+1

MS.313
LL = 1

MS3.14
IS
KK = 1 —No 2— (202) ---- COMPUTED GOTO WHICH SEARCHES THE OPERATION CODE

1 YES

MS3.15
R(I)>08 <9 —No— (202) ---- TEST FOR OPERATION CODE NUMBERS

YES

MS3.16
KK = 2 ---- PREVENTS A RETURN TO THIS PART OF THE PROGRAM.

MS3.17
CALL DIGITS ---- FORMAT ERROR TESTING SUBROUTINE.

(400)

YES

IS
(C) —No— I >LLL-1 —2— IS MS3.18
LL >2 OR <2 —1— (202)

(11) (666) 3

202

KK = 2   MS4.10

CALL
COMP
X   MS4.11

IS
J = 1   MS4.12   No → E

YES

CALL
TEST
X   MS4.13

IS
LL ≤ 2   MS4.14

No ←   → YES

666

I = I+M

PL 211

11
To MS3

E

MS5.10

J = 1

MS5.11

CALL
COMP
Y

MS5.12

IS
J = 1

No → F

YES

MS5.13

CALL
TEST
Y

MS5.14

IS
LL < 2

666 ← No

YES

MS5.16

I = I + M

PL 211

11

F

MSG.10

J = 1

MSG.11

CALL
COMP T

IS   MSG.12

J = 1   No   G

Yes

MSG.13

CALL
TEST .T.

IS   MSG.14

666   LL < 2

MSG.15

I = I + M

11
To MS3

G

MS7.10

J = 1

MS7.11

CALL
COMP N

IS MS7.12
J = 1

No

Yes

MS7.13

CALL
TEST N

666

IS MS7.14
LL < 2

Yes

MS7.15

I = I+M

11
MS3

666

CALL
ERROR

400

IS
JK = 1000

NO

JK = JK+1

301

STOP.

```
        ( TEST X )
             |
             |          SX1.10
      +--------------+
      |  LL = 1      |
      |  NX = 4      |
      +--------------+
             |
             |        SX1.11
            / IS  \
           / JJ< NX \-------------( 249 )
            \       /
             \     /
              | YES
              |      SX1.12
      +--------------+
      |  VAR = R(1)  |
      +--------------+
              |
              |        SX1.13
      +--------------+
      |  M = G       |
      |  I SUMX=0    |
      +--------------+
              |
      +------>|
      |       |        SX1.14
      |      / IS      \
      |     / R(I+K)>O AND \----( 249 )
      |      \    <9     /
      |       \        /
      |        |
      |        |      SX1.15
      |  SX1.16                  +----------------+
      | +----------+            | ISUMX = ISUMX+ |
      | | K = K+1  |            |      R(I+K)    |
      | +----------+            |   *10(KI-M).   |
      |        ^                +----------------+
      |        |                        |
      |        |     No         / IS     \
      +--------+---------------/  K < M    \
                               \         /
                                | YES
                                |     SX1.18
                         +--------------+
                         |  XX = ISUMX  |
                         +--------------+
                                |
                              (  H  )
```

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H

249

IS Sx2·10

XX>375000 — YES — 249

No

Sx2·12

Sx2·11

WRITE VAR
I SUMX

SX2·13

JJ = JJ+3

Sx2·14

RETURN.

```
                    ( TEST Y )
                         |
                         v
                   +-----------+
                   |  LL = 1   |
                   |  NY = 8   |
                   +-----------+
                         |
                         v
                       / IS  \
                      / JJ<NY \------No------( 259 )
                      \       /
                       \     /
                         |
                        Yes
                         v
                   +-----------+
                   | VAR = R(I)|
                   +-----------+
                         |
                         v
                   +-----------+
                   |   M = 6   |
                   | I SUMY=0  |
                   +-----------+
                         |
          +------------->v
          |            / IS  \
          |           /R(I+K)>0\------No-----> ( 259 )
          |           \ AND<9 /
          |            \     /
          |              |
          |              v
    +-----------+   +-----------+
    | K = K + 1 |   | ISUMY=I   |
    +-----------+   | SUMY+R(I+K)|
          ^         | X 10^(K-M)|
          |         +-----------+
          |              |
          |              v
          |            / IS  \
          +----No------/ K≤M  /
                       \     /
                         |
                        Yes
                         v
                   +-----------+
                   | YY=ISUMY  |
                   +-----------+
                         |
                         v
                       (  J  )
```

```
                    ( J )
                      |
                      v
                     IS
                  / YY>265000 \ ---YES---> ( 259 )
                  \           /               |
                      |                        v
                     No                  +-----------+
                      |                  |  LL = 2   |
                      v                  +-----------+
             / WRITE VAR /                     |
            /  I SUMY   /                      |
           +-----------+                       |
                      |                        |
                      v                        |
             +-----------+                     |
             | JJ = JJ+7 |                     |
             +-----------+                     |
                      |                        |
                      |<-----------------------+
                      v
                ( RETURN. )
```

```
        ( TEST. T. )
             │
             ▼
        ┌──────────┐
        │  LL = 1  │
        │  NT = 16 │
        └──────────┘
             │
             ▼
          IS
        ╱ JJ < NT ╲──── No ───▶ ( 269 )
        ╲         ╱
             │
            YES
             ▼
        ┌──────────┐
        │ VAR = R(I) │
        └──────────┘
             │
             ▼
        ┌──────────┐
        │  M = 3   │
        │ ISUMT = 0│
        └──────────┘
             │
             ▼
          IS
        ╱ R(I+K)>0 & ╲── No ──▶ ( 269 )
        ╲   < 9      ╱
             │
            YES
             ▼
┌─────────┐   ┌──────────────┐
│ K = K+1 │   │ ISUMT =      │
└─────────┘   │ ISUMT +      │
              │ R(I+K)×10^(M-K)│
              └──────────────┘
                   │
                   ▼
                 IS
      No ◀──── ╱ K < M ╲
              ╲        ╱
                   │
                  YES
                   ▼
                 IS
              ╱ ISUMT>100 ╲──── ▶ ( 269 )
              ╲  < 400    ╱
                   │
                   ▼
                 ( K )
```

$ISUMT = ISUMT + R(I+K) \times 10^{(M-K)}$

K

269

WRITE VAR
I SUM T

LL = 2

JJ = JJ+15

RETURN

```
        ( TEST N )
             │
             ▼
     ┌───────────────┐
     │  LL = 1       │
     │  NN = 32      │
     └───────────────┘
             │
             ▼
          ◇ IS
         JJ < NN ──── No ───▶ ( 279 )
             │
           Yes
             ▼
     ┌───────────────┐
     │  VAR = R(I)   │
     └───────────────┘
             │
             ▼
     ┌───────────────┐
     │  M = 3        │
     │  ISUMN = 0    │
     └───────────────┘
             │
             ▼
          ◇ IS
        R(I+K) > 0 &  ──── No ───▶ ( 279 )
          < 9
             │
           Yes
             ▼
     ┌───────────────┐
     │  ISUMN =      │
     │  ISUMNN +     │
     │  R(I+K)×10^(M-K) │
     └───────────────┘
             │
             ▼
          ◇ IS
         K SM ──── No ───▶ K = K + 1
             │
           Yes
             ▼
           ( L )
```

$$ISUMN = ISUMNN + R(I+K) \times 10^{(M-K)}$$

```
       INPUT10=CR0
       INPUT20=TR0
       OUTPUT30=LP0
       OUTPUT40=TP0
       TRACE2
       END

       MASTER TESP
       INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
       COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
       DATA X,Y,T,N  /1HX, 1HY, 1HT, 1HN /
       YY=0
       XX=0
301    DO 400 JK=1,1000
       READ(20,921)(R(I),I=1,36)
921    FORMAT(36A1)
       WRITE(30,922)
922    FORMAT(1H )
       DO 401 I=1,36
       IF(R(I).LT.0)GOTO 501
       IF(R(I).EQ.328720)GOTO 502
       IF(R(I).EQ.590864)GOTO 503
       IF(R(I).EQ.853008)GOTO 504
       IF(R(I).EQ.1115152)GOTO 506
       IF(R(I).EQ.1377296)GOTO 507
       IF(R(I).EQ.1639440)GOTO 508
       IF(R(I).EQ.1901584)GOTO 509
       IF(R(I).EQ.2163728)GOTO 510
       IF(R(I).EQ.2425872)GOTO 511
       IF(R(I).EQ.66576)GOTO 512
       IF(R(I).EQ.4260880)GOTO 513
       GOTO 666
502    R(I)=1
       GOTO 401
503    R(I)=2
       GOTO 401
504    R(I)=3
       GOTO 401
506    R(I)=4
       GOTO 401
507    R(I)=5
       GOTO 401
508    R(I)=6
       GOTO 401
509    R(I)=7
       GOTO 401
510    R(I)=8
       GOTO 401
511    R(I)=9
       GOTO 401
512    R(I)=0
       GOTO 401
501    R(I)=R(I)
       GOTO 401
513    LLL=I
       I=36
       GOTO 401
401    CONTINUE
```

```
                    JJ=2
                    KK=1
      ----->    DO 11 I=1,(LLL-1)
                    LL=1
                    GOTO (2011,202)KK
      2011     IF(R(I).GE.0.AND.R(I).LE.9)GOTO 201
                    KK=2
                    GOTO 202
       201     KK=2
                    CALL NUMBERS
                    GOTO(202, 11,666)LL
       202     J=1
                    CALL COMP(J,R(I),1,X,1)
                    IF(J.EQ.1)GOTO 203
                    J=1
                    CALL COMP(J,R(I),1,Y,1)
                    IF( J.EQ.1)GOTO 204
                    J=1
                    CALL COMP(J,R(I),1,T,1)
                    IF(J.EQ.1)GOTO 205
                    J=1
                    CALL COMP(J,R(I),1,N,1)
                    IF( J.EQ.1)GOTO 206
                    GOTO 666
       203     CALL TESTX
                    GOTO(211,666)LL
       204     CALL TESTY
                    GOTO(211,666)LL
       205     CALL TESTT
                    GOTO(211,666)LL
       206     CALL TESTN
                    GOTO(211,666)LL
       211     I=I+M
        11     CONTINUE
                    GOTO 400.
       666     CALL ERROR
       400     CONTINUE
       901     FORMAT(I1,1A1,6I1,1A1,6I1,1A1,3I1,1A1,3I1)
                    STOP
                    END


      END OF SEGMENT, LENGTH    611, NAME   TESP
                    SUBROUTINE NUMBERS
                    INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
                    COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
                    LL=1
                    NNOS=2
                    IF(NNOS.EQ.JJ)GOTO 231
                    LL=3
                    GOTO 233
       231     VAR=R(I)
                    IF(VAR.LE.4)GOTO 232
                    GOTO 233
       232     WRITE(30,902)R(I)
                    LL=2
                    JJ=JJ+1
       233     RETURN
       902     FORMAT(1H+,2X,I1)
                    END


      END OF SEGMENT, LENGTH    87, NAME   NUMBERS
```

```
      SUBROUTINE TESTX
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NX=4
      IF(JJ.LT.NX)GOTO 241
      LL=2
      GOTO 249
  241 VAR=R(I)
      M=6
      ISUMX=0
      DO 12 K=1,M
      IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 242
      LL=2
      GOTO 249
  242 ISUMX=ISUMX+R(I+K)*10**(M-K)
   12 CONTINUE
      XX=ISUMX
      IF(XX.LE.375000)GOTO 243
      GOTO 249
  243 WRITE(30,903)VAR,ISUMX
      JJ=JJ+3
  249 RETURN
  903 FORMAT(1H*,5X,1A1,1X,I6)
      END
```

END OF SEGMENT, LENGTH   174, NAME   TESTX

```
      SUBROUTINE TESTY
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NY=8
      IF(JJ.LT.NY)GOTO 251
      LL=2
      GOTO 259
  251 VAR=R(I)
      M=6
      ISUMY=0
      DO 13 K=1,M
      IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 252
      LL=2
      GOTO 259
  252 ISUMY=ISUMY+R(I+K)*10**(M-K)
   13 CONTINUE
      YY=ISUMY
      IF(YY.LE.250000)GOTO 253
      LL=2
      GOTO 259
  253 WRITE(30,904)VAR,ISUMY
      JJ=JJ+7
  259 RETURN
  904 FORMAT(1H+,15X,1A1,1X,I6)
      END
```

END OF SEGMENT, LENGTH   179, NAME   TESTY

```
              SUBROUTINE TESTT
              INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
              COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
              LL=1
              NT=16
              IF(JJ.LT.NT)GOTO 261
              LL=2
              GOTO 269
          261 VAR=R(I)
              M=3
              ISUMT=0
              DO 14 K=1,M
              IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 262
              LL=2
              GOTO 269
          262 ISUMT=ISUMT+R(I+K)*10**(M-K)
           14 CONTINUE
              IF(ISUMT.GE.100.OR.ISUMT.LE.400)GOTO 263
              LL=2
              GOTO 269
          263 WRITE(30,905)VAR,ISUMT
              JJ=JJ+15
          269 RETURN
          905 FORMAT(1H+,25X,1A1,1X,I3)
              END


END OF SEGMENT, LENGTH   181, NAME  TESTT

              SUBROUTINE TESTN
              INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
              COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
              LL=1
              NN=32
              IF(JJ.LT.NN)GOTO 271
              GOTO 279
          271 VAR=R(I)
              M=3
              ISUMN=0
              DO 15 K=1,M
              IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 272
              LL=2
              GOTO 279
          272 ISUMN=ISUMN+R(I+K)*10**(M-K)
           15 CONTINUE
              IF(ISUMN.LT.999)GOTO 273
              LL=2
              GOTO 279
          273 WRITE(30,906)VAR,ISUMN
              A=FLOAT(XX)
              B=FLOAT(YY)
              CALL ELPRINT(A/1000.,4)
              CALL ELPRINT(B/1000.,4)
              CALL ELNEWLINE(1)
          279 RETURN
          906 FORMAT(1H+,32X, 1A1,1X,I3)
              END


END OF SEGMENT, LENGTH   194, NAME  TESTN
```

126

```
      SUBROUTINE ERROR
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      WRITE (30,999)(R(I), I=1,36)
      RETURN
  999 FORMAT (1H+,50X,5HERROR,5X,36A1)
      END
```

END OF SEGMENT, LENGTH   33, NAME   ERROR

      FINISH

END OF COMPILATION - NO ERRORS

S/C SUBFILE: 38 BUCKETS USED

CONSOLIDATED BY XPCK 11C   DATE   30/03/71   TIME 12/46/56

PROGRAM BJEL
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE   6144


```
              SEG      TESP
              SEG      NUMBERS
              SEG      COMP
              SEG      TESTX
              SEG      TESTY
              SEG      TESTT
              SEG      TESTN
              SEG      ERROR
              SEG      FLOAT
              SEG      ELPRINT
              SEG      ELNEWLINE
              ENT      FTRAP
              ENT      FRESET
    X   35000  Y 125000          N   1
    X   65000  Y 125000          N   2
    X   95000                    N   3
    X  125000                    N   4
    X  155000                    N   5
    X  185000                    N   6
    X  215000                    N   7
    X  125000  Y 215000          N   8
               Y 185000          N   9
               Y 155000          N  10
               Y  95000          N  11
               Y  65000          N  12
               Y  35000          N  13
```

X		Y		N	
X	18935	Y	18935	N	14
X	40148	Y	40148	N	15
X	61361	Y	61361	N	16
X	82574	Y	82574	N	17
X	103787	Y	103787	N	18
X	146213	Y	146213	N	19
X	167426	Y	167426	N	20
X	188639	Y	188639	N	21
X	209852	Y	209852	N	22
X	231065	Y	231065	N	23
X	18935			N	24
X	40145	Y	209852	N	25
X	61361	Y	188639	N	26
X	82574	Y	167462	N	27
X	103787	Y	146213	N	28
X	146213	Y	103787	N	29
X	167426	Y	82574	N	30
X	188639	Y	61361	N	31
X	209852	Y	40148	N	32
X	231065	Y	18935	N	33
X	86732	Y	32612	N	34
X	163268			N	35
X	217388	Y	86732	N	36
		Y	163268	N	37
X	163268	Y	217388	N	38
X	86732			N	39
X	32612	Y	163268	N	40
		Y	86732	N	41
X	35000	Y	125000	N	42
X	65000	Y	125000	N	43
X	95000			N	44
X	155000			N	45
X	185000			N	46
X	215000			N	47
X	125000	Y	215000	N	48
		Y	185000	N	49
		Y	155000	N	50
		Y	95000	N	51
		Y	65000	N	52
		Y	35000	N	53
X	18935	Y	18935	N	54
X	40148	Y	40148	N	55
X	61361	Y	61361	N	56
X	82574	Y	82574	N	57
X	103787	Y	103787	N	58
X	125000	Y	125000	N	59
X	146213	Y	146213	N	60
X	167426	Y	167426	N	61
X	188639	Y	188639	N	62
X	209852	Y	209852	N	63
X	231065	Y	231065	N	64
X	18935			N	65

```
X    40145   Y 209852                    N    66
X    61361   Y 188639                    N    67
X    82574   Y 167462                    N    68
X 103787     Y 146213                    N    69
X 146213     Y 103787                    N    70
X 167426     Y  82574                    N    71
X 188639     Y  61361                    N    72
X 209852     Y  40148                    N    73
X 231065     Y  18935                    N    74
X  86732     Y  32612                    N    75
X 163268                                 N    76
X 217388     Y  86732                    N    77
             Y 163268                    N    78
X 163268     Y 217388                    N    79
X  86732                                 N    80
X  32612     Y 163268                    N    81
             Y  86732                    N    82
X  18935     Y  18935                    N    83
X  40148     Y  40148                    N    84
X  61361     Y  61361                    N    85
X  82574     Y  82574                    N    86
X 103787     Y 103787                    N    87
X 146213     Y 146213                    N    88
X 167426     Y 167426                    N    89
X 188639     Y 188639                    N    90
X 209852     Y 209852                    N    91
X 231065     Y 231065                    N    92
X  18935                                 N    93
X  40145     Y 209852                    N    94
X  61361     Y 188639                    N    95
X  82574     Y 167462                    N    96
X 103787     Y 146213                    N    97
X 125000     Y 125000                    N    98
X 146213     Y 103787                    N    99
X 167426     Y  82574                    N   100
X 188639     Y  61361                    N   101
X 209852     Y  40148                    N   102
X 231065     Y  18935                    N   103
X  35000     Y 125000                    N   104
X 215000                                 N   105
X 125000     Y 215000                    N   106
             Y  35000                    N   107
```

1

```
        INPUT10=CR0
        INPUT20=TR0
        OUTPUT30=LP0
        OUTPUT40=TP0
        TRACE2
        END
        MASTER TESP
```

END OF SEGMENT, LENGTH   611, NAME   TESP

    SUBROUTINE NUMBERS

END OF SEGMENT, LENGTH   87, NAME   NUMBERS

    SUBROUTINE TESTX

END OF SEGMENT, LENGTH   174, NAME   TESTX

    SUBROUTINE TESTY

END OF SEGMENT, LENGTH   179, NAME   TESTY

    SUBROUTINE TESTT

END OF SEGMENT, LENGTH   181, NAME   TESTT

    SUBROUTINE TESTN

END OF SEGMENT, LENGTH   194, NAME   TESTN

    SUBROUTINE ERROR

END OF SEGMENT, LENGTH   33, NAME   ERROR

    FINISH

END OF COMPILATION -   NO ERRORS

S/C SUBFILE: 38 BUCKETS USED

PROGRAM BJEL
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE   6144

X	35000	Y	125000	N	1
X	65000	Y	125000	N	2
X	95000			N	3
X	125000			N	4
X	155000			N	5
X	185000			N	6
X	215000			N	7
X	125000	Y	215000	N	8
		Y	185000	N	9
		Y	95000	N	11	ERROR	VY000000N000
		Y	65000	N	12
						ERROR	W000000N000
X	18935	Y	19935	N	14
X	40148	Y	40148	N	15
						ERROR	X000'61Y061361N016
X	82574	Y	82574	N	17
X	103787	Y	103787	N	18
X	146213	Y	146213	N	19
X	67426	Y	167426	N	20
X	188639	Y	188639	N	21
X	209852					ERROR	X000000Y000000N000
X	231065	Y	231065	N	23
X	18935			N	24
X	40145	Y	209852	N	25
X	61361	Y	188639	N	26
X	82574	Y	167462	N	27
X	103787				
X	146213	Y	103787	N	29
X	167426	Y	82574	N	30
X	188639	Y	61361	N	31
X	209852	Y	40148	N	32
		Y	18935	N	33
X	86732	Y	32612	N	34
X	163268			N	35
X	217388	Y	86732	N	36
						ERROR	0Y000000N000
X	163268	Y	217388	N	38
X	86732			N	39
X	32612	Y	163268	N	40
		Y	86732	N	41
X	35000	Y	125000	N	42
X	65000	Y	125000	N	43
X	95000			N	44
X	155000			N	45
X	185000			N	46
X	215000			N	47
X	125000	Y	215000	N	48
		Y	185000	N	49
		Y	155000	N	50
		Y	95000	N	51

1

		Y	65000	N	52		
		Y	35000	N	53		
X	18935	Y	18935	N	54		
X	40148	Y	40148	N	55		
X	61361	Y	61361	N	56		
X	82574	Y	82574	N	57		
X	103787	Y	103787	N	58		
X	125000	Y	125000	N	59		
X	146213	Y	146213	N	60		
X	167426	Y	167426	N	61		
X	188639	Y	188639	N	62		
X	209852					ERROR	X000000YA00000N000
X	231065	Y	231065	N	64		
X	18935			N	65		
X	40145	Y	209852	N	66		
X	61361	Y	188639	N	67		
X	82574	Y	167462	N	68		
X	103787	Y	146213	N	69		
X	146213	Y	103787	N	70		
X	167426	Y	82574	N	71		
X	188639	Y	61361	N	72		
X	209852	Y	40148	N	73		
X	231065	Y	18935	N	74		
X	86732	Y	32612	N	75		
X	163268			N	76		
		Y	86732	N	77		
		Y	163268	N	78		
X	163268	Y	217388	N	79		
X	86732			N	80		
X	32612	Y	163268	N	81		
		Y	86732	N	82		
X	18935	Y	18935	N	83		
X	40148	Y	40148	N	84		
X	61361	Y	61361	N	85		
X	82574	Y	82574	N	86		
X	103787	Y	103787	N	87		
X	146213	Y	146213	N	88		
X	167426	Y	167426	N	89		
X	188639	Y	188639	N	90		
X	209852	Y	209852	N	91		
X	231065	Y	231065	N	92		
X	18935			N	93		
X	40145	Y	209852	N	94		
X	61361	Y	188639	N	95		
X	82574	Y	167462	N	96		
X	103787	Y	146213	N	97		
X	125000	Y	125000	N	98		
		Y	125000			ERROR	Y000000X0000000N000
X	167426	Y	82574	N	100		
X	188639	Y	61361	N	101		
X	209852	Y	40148	N	102		
X	231065	Y	18935	N	103		
X	35000	Y	125000	N	104		
X	215000			N	105		
X	125000	Y	215000	N	106		
		Y	35000	N	107		

1

APPENDIX B

        FINISH

END OF COMPILATION -- NO ERRORS

S/C SUBFILE: 12 BUCKETS USED

CONSOLIDATED BY XPCK 11C   DATE   16/06/71   TIME 09/33/08

PROGRAM BJEL
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE   2624

                        SEG   PLUGS
                        SEG   CONVERT
                        ENT   FTRAP
                        ENT   FRESET
            MODULE TABLE PLUG FIXTURE SIZES

    PLUG NO *1

    50MM DIA

    49.99721   49.99746   49.99746   49.99797   49.99752

    50.00063   50.00140   50.00025   50.00025   50.00063

    50.00330   50.00343   50.00343   50.00305   50.00330

    -0.00029
        25MM DIA TOP

    24.99111   24.99111   24.99111   24.99111   24.99111

    24.98984   24.98984   24.98984   24.98984   24.98984

    24.98984   24.98984   24.98984   24.98984   24.98984

        TAPER PER UNIT LENGTH

    0.00005
        25MM DIA BOTTOM

    24.99746   24.99746   24.99746   24.99809   24.99762

    24.99809   24.99619   24.99619   24.99619   24.99667

    24.99619   24.99619   24.99619   24.99683   24.99635

        TAPER PER UNIT LENGTH

    0.00005
        PLUG NO *2

50MM DIA

49.99848	49.99911	49.99898	49.99848	49.99876
50.00140	50.00241	50.00318	50.00254	50.00238
50.00483	50.00419	50.00381	50.00406	50.00422

-0.00028
25MM DIA TOP

24.99365	24.99301	24.99365	24.99365	24.99349
24.99365	24.99429	24.99365	24.99365	24.99381
24.99683	24.99619	24.99619	24.99619	24.99635

TAPER PER UNIT LENGTH

-0.00011
25MM DIA BOTTOM

24.99619	24.99619	24.99619	24.99619	24.99619
24.99619	24.99619	24.99619	24.99619	24.99619
24.99683	24.99683	24.99683	24.99683	24.99683

TAPER PER UNIT LENGTH

-0.00002
PLUG NO *3

50MM DIA

50.00711	50.00737	50.00686	50.00660	50.00699
50.00711	50.00737	50.00737	50.00660	50.00711
50.00483	50.00508	50.00457	50.00432	50.00470

0.00012
25MM DIA TOP

24.98730	24.98730	24.98730	24.98730	24.98730
24.98666	24.98666	24.98666	24.98666	24.98666
24.98540	24.98540	24.98603	24.98540	24.98555

TAPER PER UNIT LENGTH

0.00007
25MM DIA BOTTOM

24.99238	24.99238	24.99365	24.99365	24.99302
24.99365	24.99175	24.99175	24.99048	24.99190
24.98984	24.99048	24.99111	24.99048	24.99048

TAPER PER UNIT LENGTH

0.00010
PLUG NO *4

<u>Drill head position shown x</u>

<u>Deviation from straight-line indicates error</u>

Graph plotter output for test
piece shown fig. 22.   All drill
head positions correct.

Fig. 26

Graph plotter output for test
piece shown Fig. 22 indicating
dimensional errors evident in
appendix A.

Scale ½ : 1

Finish

Start
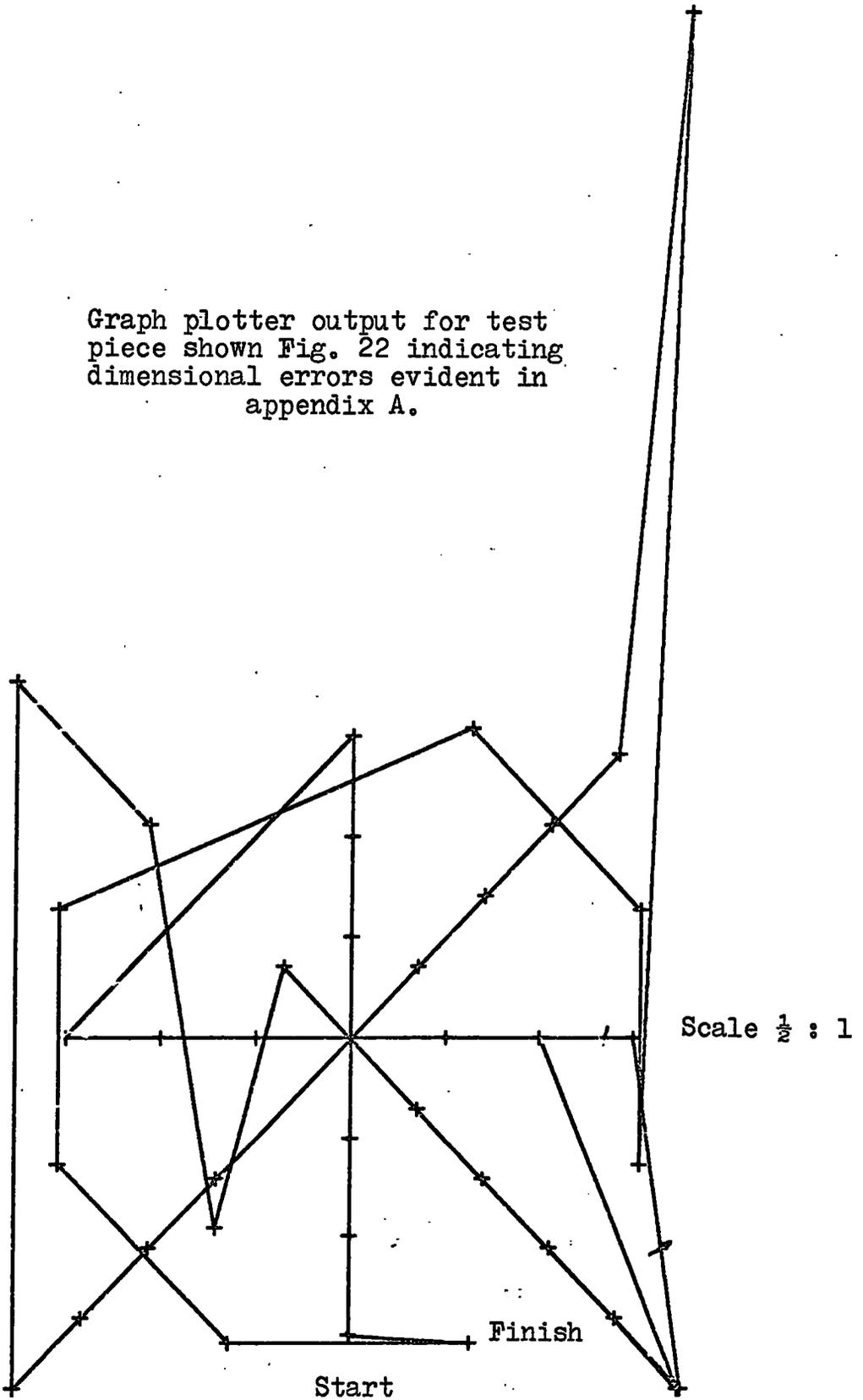
Fig. 27

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