Cutting data for automated turning tool selection in industry

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ABSTRACT

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This thesis is concerned with the determination of cutting parameters (cutting speed, feed rate and depth of cut) in turning operations within an industrial environment. The parameters are required for the purposes of tool selection, working with a variety of batches of different materials. Previous work of this nature, little of which has been transferred into industry, has concentrated primarily on deriving optimum cutting conditions, based on a variety of deterministic and non-deterministic approaches, with a general reliance on experimentally-derived input variables. However, this work is only suited to tool selection for a single material. Under industrial conditions tools will frequently need to be selected for more than one material, in tool/material combinations not recommended by tool makers.

Consequently, the objective of the research described in this thesis was to employ existing cutting data technology and to use it as the basis for a cutting data system, suitable for multi-batch tool selection. Two companies collaborated in this work, by making available suitable personnel and the provision of shop floor facilities on their premises.

The initial work concentrated on the development of an algorithmic model, based on established theory. This was then tested industrially, using the concept of shop floor approved data as a substitute for optimum cutting data. The model was found to work reasonably, but required further development to make it suitable for multi-batch tool selection. This development took three main forms:

a) a reduction of input data, particularly in the number of experimentally-derived variables,
b) the removal of the tool/material-specific constraints traditionally used in cutting data optimisation,
c) a method of data correction based on adjustment of the mean and standard deviation of the data.

Further industrial testing was carried out using the resulting system. It was demonstrated that it was possible for a relaxed system with reduced input variables and appropriate data correction to function within an industrial environment.

Cutting Data for Automated Turning Tool Selection in Industry

by

Paul Robert Lewis

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DECLARATION

The work contained in this thesis has not been submitted elsewhere for any other degree or qualification and unless otherwise referenced it is the author's own work.

ACKNOWLEDGEMENTS

I think there's a world market for about 5 computers
Thomas J. Watson, Chairman of the Board, IBM (around 1948)
Technology + Methodology = A Better Chance To Succeed
B. Wu, Manufacturing Systems Design and Analysis, (1992)
If you can't do it excellently, don't do it at all.
Because if it's not excellent it won't be profitable or fun, and if you're not in business for fun or profit, what the hell are you doing here?
Robert Townsend, Up The Organisation, (1971)

First and foremost, I am extremely grateful to my supervisor, Professor John Simmons (Heriot-Watt University), not only for his ability to listen, discuss and criticise constructively both during the project and whilst writing up, but also for providing me with the inspiration and motivation to finish this thesis.

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NOTATION

α	exponent in the extended Taylor equation
α	general exponent
α	constant
β	exponent in the extended Taylor equation
β	general exponent
δ	constant
ε	insert included angle (°)
γ	exponent in the extended Taylor equation
γ	general exponent
κ	insert approach angle (°)
μ	population mean
μ	tool flank wear land width (mm)
μ_a	longitudinal coefficient of friction between workpiece and chuck/collet
μ_c	tangential coefficient of friction between workpiece and chuck/collet
σ	population standard deviation
σ^2	population variance
A	the actual area of cut (mm^2)
a	depth of cut (mm)
$a_{(max)}$	maximum depth of cut for a tool (mm)
$a_{(total)}$	total amount of stock to be removed (mm)
C	general term for C_V, C_S or C_a
C	constant in the Taylor equation
C	general constant
C_1	constant in the extended Taylor equation
C_1	general term for C_{V1}, C_{S1} or C_{a1}
C_2	general term for C_{V2}, C_{S2} or C_{a2}
C_a	constant for radial cutting force calculations
C_{a1}	constant for radial cutting force calculations
C_{a2}	constant for radial cutting force calculations
C_f	material-dependent constant
C_{le}	insert shape-dependent constant
C_S	constant for longitudinal cutting force calculations
C_{S1}	constant for longitudinal cutting force calculations
C_{S2}	constant for longitudinal cutting force calculations

C_V	constant for tangential cutting force calculations
C_{V1}	constant for tangential cutting force calculations
C_{V2}	constant for tangential cutting force calculations
c_1	workpiece set-up cost (£)
c_2	effective cutting cost (£)
c_3	tool change cost (£)
c_4	tool cost (£)
c_i	cost of insert (£)
c_h	cost of tool holder (£)
DOF	degrees of freedom
d_i	general/maximum workpiece inside diameter (mm)
$d_{(cut)}$	diameter of cut (mm)
$d_{(held)}$	diameter of workpiece held in chuck/collet (mm)
$d_{(final)}$	workpiece final diameter (mm)
$d_{(initial)}$	workpiece initial diameter (mm)
d_o	general/minimum workpiece outside diameter (mm)
E	Youngs modulus (N/mm^2)
EI_x	workpiece flexural rigidity ($N\ mm^2$)
$e.u.c.$	effective unit cost (£)
F	the sampling distribution of the ratio of two sample variances
$F_{(CL, DOF1, DOF2)}$	F-distribution at CL confidence limit and $DOF1$, $DOF2$ degrees of freedom
$F_{(con)}$	general term for $F_{V(con)}$, $F_{S(con)}$ or $F_{a(con)}$
F_a	radial force (N)
$F_{a(calc)}$	calculated radial force (N)
$F_{a(con)}$	maximum permissible, or constraining radial force (N)
F_e	clamping force (N)
F_S	longitudinal force (N)
$F_{S(calc)}$	calculated longitudinal force (N)
$F_{S(con)}$	maximum permissible, or constraining longitudinal force (N)
F_V	tangential force (N)
F_{V1}	maximum tangential force before rotational slipping occurs (N)
F_{V2}	maximum tangential force before component throw-out occurs (N)
F_{V3}	maximum tangential force for the available power (N)
$F_{V(calc)}$	calculated tangential force (N)
$F_{V(con)}$	maximum permissible, or constraining tangential force (N)
h_e	chip-equivalent (1/mm) (see q)
K	'straightening' constant for the Taylor equation

K_s	specific cutting force (N/mm^2)
L	length of insert cutting edge (mm)
L_c	length of cut (mm)
L_e	engaged length of cutting edge (mm)
L_{wc}	length of workpiece held in chuck/collet (mm)
L_t	maximum distance from chuck/collet to tool (mm)
l_1	approved standard deviation, $s_{(n-1)app}$
l_2	mean corrected standard deviation, $s_{(n)mean\ corrected}$
l_3	difference between the corrected parameter and the mean corrected mean
l_4	difference between the mean corrected parameter and the mean corrected mean
MMR	metal removal rate (mm^3/sec)
m	exponent in the Taylor equation
m_c	machining cost per component (£)
$m_{c(min)}$	minimum machining cost per component (£)
N	machine tool rotational speed (rpm)
n	sample size
n	exponent in the Taylor equation
n	current job number
nce	number of cutting edges on an insert
nop	number of passes
nT	number of tools used
$nT_{(max)}$	maximum specified number of tools
P	power of the machine tool (kW)
$P_{(n)}$	parameter for current job
$P_{(n)corrected}$	corrected parameter
$P_{(n)mean\ corrected}$	mean corrected parameter
$P_{(equivalent)}$	equivalent ISO P insert grade, for an ISO K or M insert grade
q	chip-equivalent (1/mm) (see h_c)
R_a	surface finish (µm)
r_e	insert nose radius (mm)
$r_{(CL,\ DOF)}$	the linear regression correlation coefficient, with *CL* confidence limits and *DOF* degrees of freedom
S	feed rate (mm/rev)
s	a sample estimate of the population standard deviation, σ
s^2	a sample estimate of the population variance, σ^2
$s_{(n-1)app}$	approved standard deviation up to and including the previous job

$s_{(n)corrected}$	corrected standard deviation
$s_{(n)mean\ corrected}$	mean corrected standard deviation
$s_{(n-1)sys}$	system standard deviation up to and including the previous job
T	tool life (mins)
$T_{(min)}$	minimum specified tool life (mins)
$T_{(opt)}$	optimum tool life (mins)
t	the number of standard errors away from the mean which a given point in a t-distribution lies
t_1	workpiece set-up time (mins)
t_2	effective cutting time per pass (mins)
t_3	tool change time (mins)
$t_{(CL,DOF)}$	t-distribution at CL confidence limit and DOF degrees of freedom
tol	plus/minus dimensional tolerance (mm)
V	cutting speed (m/min)
$V_{(average)}$	average cutting speed (m/min)
$V_{(mean\ mod\ LIFE.DAT)}$	average cutting speed in the file LIFE.DAT after modification (m/min)
$V_{(cost)}$	cutting speed for minimm machining cost (m/min)
$V_{(life)}$	cutting speed for maximum tool life (m/min)
$V_{(max)}$	maximum cutting speed (m/min)
$V_{(min)}$	minimum cutting speed (m/min)
$V_{(nT)}$	constraining cutting speed (m/min)
$V_{(number)}$	cutting speed for minimum number of tools (m/min)
$V_{(P20)}$	average cutting speed for an ISO P20 grade insert when used to machine mild steel (210 m/min)
$V_{(T)}$	cutting speed for specified minimum tool life (m/min)
$V_{(time)}$	cutting speed for manimum machining time (m/min)
W	relief wear of the tool, represented by μ
x	hourly machine cost (£/hour)
$\bar{x}$	a sample estimate of the population mean, μ
$\bar{x}_{(n-1)app}$	approved mean up to and including the previous job
$\bar{x}_{(n)corrected}$	corrected mean
$\bar{x}_{(n)mean\ corrected}$	mean corrected mean
$\bar{x}_{(n-1)sys}$	system mean up to and including the previous job
Y	generalised machining response

GLOSSARY OF TERMS

Approved data	Cutting parameterswhich have been found to be satisfactory on the shop floor
Company(ies)	Harkers and/or Reyrolle.
Corrected data	The system data after being corrected in accordance with the approved mean and approved standard deviation
Corrected mean	The system mean after it had been corrected in accordance with the approved mean and after the standard deviation had been corrected
Corrected parameter	A cutting parameter after it had been adjusted to take into account both the difference between the approved and system means and the approved and system standard deviations
Corrected standard deviation	The system standard deviation after it had been corrected in accordance with the approved mean and the approved standard deviation
Cutting data	Cutting speed V (m/min) and/or feed rate S (mm/rev) and/or depth of cut a (mm) An alternative to cutting parameter.
Cutting parameter(s)	Cutting speed V (m/min) and/or feed rate S (mm/rev) and/or depth of cut a (mm) An alternative to cutting data.
Engineering data	The cutting parameters encoded in the NC program by the part programmers
FORC.DAT	An ASCII data file containing values of the forces parameters C_V, C_{V1}, C_{V2}, C_S, C_{S1}, C_{S2}, C_a, C_{a1} and C_{a2} used to calculate actual cutting forces
Forces parameters	The constants and exponents C_V, C_{V1}, C_{V2}, C_S, C_{S1}, C_{S2}, C_a, C_{a1} and C_{a2} used to calculate cutting forces.
Harkers	A collaborating company: Harkers Engineering Ltd Stockton on Tees, Cleveland.
Job	A single test with the system and therefore the machining of a single feature or element

Job group	A collection of jobs with certain similar attributes, but not necessarily from the same component.
LIFE.DAT	An ASCII data file containing information (*V*, *S*, *a* and *T*) for calculating values for α, β, γ and C_1 from the extended Taylor equation
Mean corrected data	The system data after being corrected in accordance with the approved mean
Mean corrected mean	The system mean after being corrected in accordance with the approved mean
Mean corrected parameter	A parameter after it had been adjusted to take into account the difference between the approved and system means
Mean corrected standard deviation	The system standard deviation after the mean had been corrected
Multiple batch (or multi-batch) tool selection problem	The tool selection problem where a tools are selected for a number of batches at the same time
Recommended insert/material (or tool/material) combination	A combination of material and tool (particularly the insert ISO grade) which is recommended by a tool manufacturer
Reyrolle	A collaborating company: Rolls Royce Industrial Power Group Reyrolle Switchgear Hebburn, Tyne and Wear
System	A generic term for Systems 1, 2 and 3
System 1, 2 or 3	The software produced by the work, each system being a further development of the previous system
System data	The cutting parameters calculated by the system
Tool	The assembly consisting of both the ISO tool holder and the ISO insert
Tool life data	Data consisting of approved values of *V*, *S*, *a* and *T*, sufficient to enable α, β, γ and C_1 (from the extended Taylor equation) to be calculated by multiple regression analysis.

PREFACE

"UK manufacturing is under intense and increasing pressure from many parts of the world. In many cases, particularly those majority of instances when actual market size is not increasing, low inventory manufacturing techniques pioneered by Japanese firms are being implemented as a means of achieving more efficient, cost effective production. As overall inventories are reduced, problems concerning the efficient selection and management of manufacturing consumables become increasingly important.

In the manufacture by machining of discrete components the principal consumables are cutting tools. There is now a huge selection of these tools and inserts available to machinists. Frequent additions are made to the portfolio of choices as suppliers vie to produce the best equipment for this or that set of cutting conditions. Many manufacturers' tool inventories have grown enormously in recent years and carrying costs are considerable. The most widely shared problem, common to all sectors, is that of establishing and retaining control of tools and tooling at a time of fast increasing choice."

(Simmons and Maropoulos (1989))

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Tool selection is concerned with choosing the appropriate cutting tool or set of tools to perform one or more machining operations. One approach to the problem is to first determine those tools which can achieve the necessary cut or cuts geometrically. The geometrically acceptable set of tools are then compared in terms of their cutting performance, in accordance with one or more pre-determined criteria. For this comparison to be carried out, the technical performance of the tools has to be known, where the technical performance is based on cutting data (cutting parameters), in terms of cutting speed, feed rate and depth of cut.

This thesis is concerned with the provision of cutting data for turning tool selection purposes. Although there are many methods currently available for calculating cutting data, the majority "...are based on a large amount of experimentally or theoretically derived data...their implementation in real production environments can be difficult since some of the required data may not be readily available." (Maropoulos (1992)). The work in this thesis addresses this problem of lack of derived data and extends this to include the specific difficulty encountered by tool selection systems.

Conventionally, for a given tool there is a limited range of materials for which the tool is recommended, this recommendation being made by the tool manufacturer concerned. However, it is perfectly reasonable for a tool selection method to consider tool types to cut materials, for which the tool types are not recommended. If, as Maropoulos says, there is difficulty in obtaining suitable derived data, the problem is made worse if the derived data has never existed in the first place, as is likely for the non-recommended tool/material situation.

The cutting data system described in this thesis is aimed primarily at the situation where tools are to be selected for a number of different materials simultaneously and thus non-recommended tool/material combinations may well be involved. This differs from the simpler tool selection situations where only one material is involved. For industrial applications, the only practical tool selection system is one that can deal with a range of materials. These two factors (more than one material and industrial applications) pose real problems in determining the appropriate derived data for the cutting data calculations. Not only may the data be difficult to obtain, it may not even exist unless generated experimentally. However, the production of experimental data is neither realistic nor practical in an industrial environment.

The aim of this work is to develop and test a cutting data algorithm suitable for use in a multiple batch production environment. It must have the following features:

1) input data that is readily available,
2) the ability to handle any combination of materials and tools,
3) acceptability to companies,
4) applicability to jobbing and make-to-order operations.

The system described in this thesis addresses the problem of obtaining cutting data for a practical tool selection system. Particular problems are encountered in respect of tool life and cutting forces calculations, which rely very much on experimentally-derived constants and exponents. Taking as its starting point an algorithm for generating cutting data, the algorithm is extensively modified to allow it to work with existing available data for a single material, irrespective of the tool/material combination under consideration, rather than requiring additional data for every new combination that is encountered.

Methods are also developed to deal with the problem of other data which is difficult to define numerically under industrial conditions, either because it is subject to change or not readily available. Solutions include the use of default values, as well as correction factors applied to the calculated results. In this way, the cutting data system described in this thesis provides an important contribution to the further development of a realistic industrially-based tool selection system, particularly with respect to the range of materials which will be encountered.

Section 1.2 starts with a discussion concerning the need for improved tool selection and then explains the background to the work. Since the work is centred around the needs of tool selection, section 1.3 describes the different levels of the tool selection problem. Section 1.4 explains what the work is about and where it fits into current work in the field. The objectives are also stated here. Finally section 1.5 describe the main parts and the contents of each chapter of the thesis .

1.2 BACKGROUND TO THE WORK

A common problem in many industrial sectors in recent years is a proliferation of tooling (Simmons and Maropoulos (1989)). One approach to the problem is improved tool selection, which can be used to reduce the number of tools required for either a component with a number of features or, alternatively, a number of batches. This in turn can be made to lead to a smaller tool inventory and hence simpler tool management.

Improved tool selection can reduce the overall cycle time for producing a batch. The cycle time for machined components is made up of two main components:

a) set-up time,

b) machining time.

One way of reducing overall cycle time is to reduce the overall machining time for the component or batch. This is often achieved by changing to more efficient tooling, which reduces the machining cycle time. However, the saving in time may well be offset by the tooling being more expensive. In addition, this tends to add to, rather than reduce, the number of tools held in stock, leading to more complex tool management as well as representing spent capital.

Another approach to reducing the overall cycle time is to reduce the overall set-up time. This is made up of two main components:

a) job setting-up,

b) tool setting-up.

As batch sizes reduce, the set-up time becomes more significant as a proportion of the overall cost of the product. If the same tool can be used for a number of batches, rather than using new tooling for each batch, the tool set-up time can be reduced. It may be that the selected tool might have sub-optimum performance for most, if not all, of the batches concerned. However, the saving in tool set-up time may more than compensate for the increased machining cycle times, provided batch sizes are sufficiently small.

Consequently, it was proposed that efforts should be made to find improved methods for selecting tools (Simmons and Maropoulos (1989) and Maropoulos et al (1993)). A project was carried out in collaboration with two local manufacturing companies, which were considered to be examples of their respective industrial sectors i.e. sub-contract (jobbing) machining and make-to-order. Compared to some high volume production organisations such as batch manufacturers, neither company had invested to any great extent in new technology. It was considered that if the resulting system was workable within both of these companies, then it would be likely to work in other, similar organisations as well.

Both companies had identified tooling in general as a problem area, including such topics as the level of tool inventories and tooling costs. The companies' involvement in the project was such that all trials of the resulting system were carried out on their premises, under production conditions and often by their own personnel, which differentiated the work from previous, similar research by other workers in the field.

Originally, the project had intended to include the selection of both milling and turning tools. However, further thought indicated that, geometrically, tool selection for prismatic components was sufficiently different to tool selection for cylindrical components to justify treating them as two separate problems. In addition, the 3-D geometry of prismatic components suggested that milling tool selection was more complex, compared to turning tool selection for 2-D cylindrical components. In the circumstances, the decision was made to concentrate on turning tool selection initially, with milling tool selection forming the basis of subsequent work. Thus this thesis also only considers turning tools.

1.3 SELECTION OF CUTTING TOOLS

Maropoulos (1992) has recognised five levels of an intelligent tool selection system (ITS):

a) ITS level 1 - Machining operation

   This is concerned with selecting tools at the process planning stage that are geometrically and technically capable of performing the cut, whilst satisfying all the manufacturing constraints e.g. quality.

b) ITS level 2 - Component and machine tool

   The main considerations are the number of tools required for fully machining a component (based on the number of features to be machined) and the tool replacement strategy.

c) ITS level 3 - Multi-batch/single machine tool

   Where a variety of batches of different components are to be machined using one set of tools, the size of the set of selected tools cannot be larger than the number of tool positions on the machine tool.

d) ITS level 4 - Multi-machine

This level performs the final tool rationalisation with respect to shop floor resources.

e) ITS level 5 - Shop floor/tool stores

The main objectives here are to reduce tool inventory, define the overall tool requirements and manage the efficient allocation and distribution of tools to machines.

These levels show quite clearly the interface between tool selection and tool management. The first three levels are concerned with determining the appropriate tool or tools. The last two levels are concerned with making sure that the required tooling is available and at the right place at the right time. This point was previously made by Lewis et al (1991), who defined the five 'rights' of tool management as "...the right tool, in the right place, at the right time, in the right condition, at the right cost". This is aided by such factors as a smaller tool inventory.

Generally, the process of selecting a cutting tool for ITS level 1 consists of starting with a set of tools and reducing the size of the set until the 'best' tool is found. 'Best' can defined in terms of one of a number of production criteria e.g. minimum cost, minimum time or maximum profit.

In the general case of one element to be machined, the starting set of tools contains all the tools in the tool store. To reduce this starting set, the steps are:

1) select the set of a particular tool type appropriate for the planned operation e.g. single point turning, milling,

2) select the set of tools that are capable of performing the cut geometrically, in terms of e.g. approach angle, trailing angle,

3) select the set of tools that are capable of carrying out the cut technically, in

terms of cutting speed, feed rate, depth of cut,

4) select the best tool according to a chosen criteria, e.g. minimum machining cost, minimum machining time.

At each step the new set of tools is drawn from the previous set, but is reduced in size until a single tool, or a number of tools with identical performance, is found.

ITS levels 1 - 3 can be divided into five discrete problems, which are illustrated in figure 1.1. The five problems are:

1) Single feature or element problem (ITS level 1)

This is a single geometric feature on a single component. For the purposes of this discussion, a geometric feature is defined as an element of a workpiece where the machining is carried out by a single tool i.e. one operation. For example, a roughing cut and a finish cut of the same component element are counted as two geometric features. It is the simplest tool selection problem and, for a given set of tools in a tool store, has only one solution (which may be one or more tools of identical performance).

2a) Single component or multiple feature problem (ITS level 2)

The solutions range from a unique tool for every feature to be machined to a single tool which will machine all the required elements. The performance of this single tool may be sub-optimum for most or all of the machining operations. However, it may have the fastest set-up time. Generally, with the exception of very large components, a tool or set of tools will complete the machining of the component with very few, if any, changes of tools, providing that new tools are used.

2b) Single batch or multiple component problem (ITS level 2)

This is the same as the component problem, except that there is more than one component. As the number of components within the batch increases, tool life and tool wear assume greater importance. Consequently the rate at which tools have to be replaced due to tool wear becomes a consideration in the selection of tools. For any feature, the best tool may not be the fastest, since tool life becomes an important criteria and hence the number of tool set-ups will be a parameter to consider.

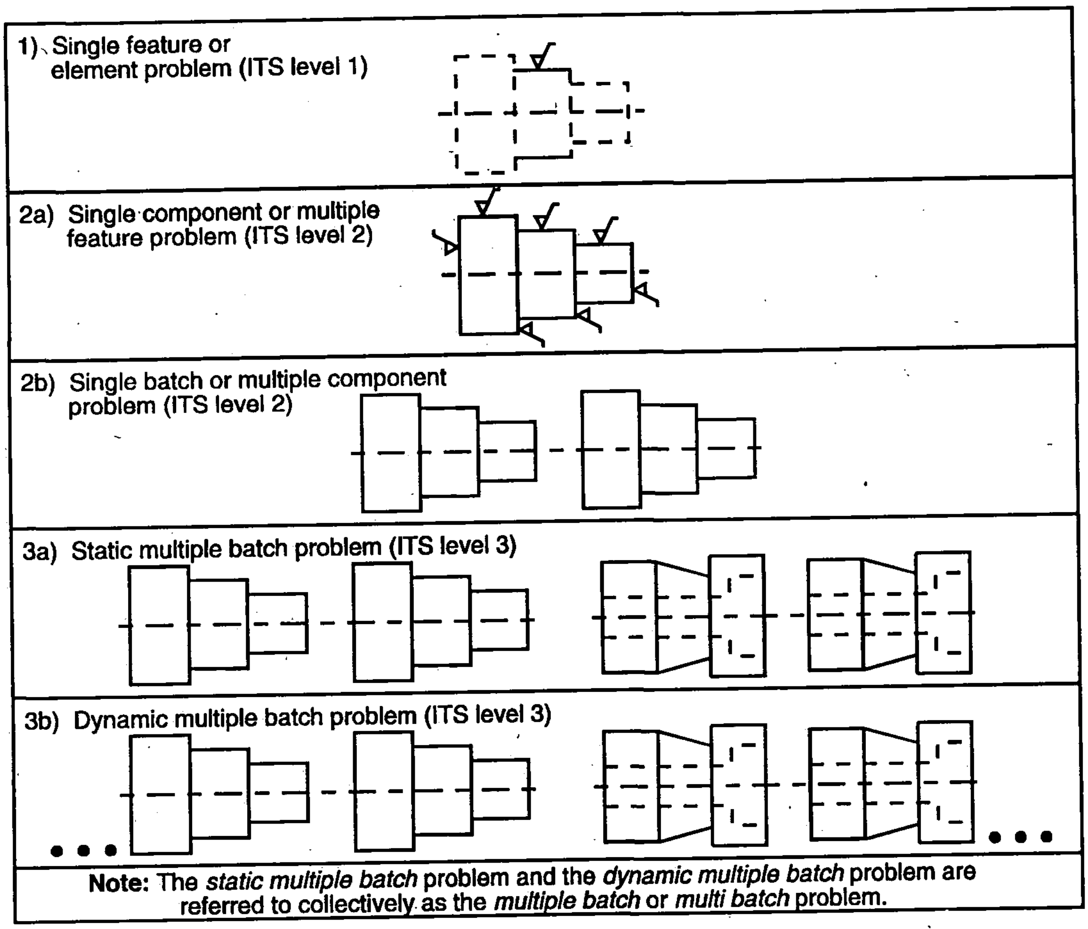

Figure 1.1

The five tool selection problems

3a) Static multiple batch problem (ITS level 3)

In this case, tools have to be selected for a number of batches, although the number of batches is fixed. Any further batches will form the basis of a new set of selected tools. A complication is that the batches can be made from different materials. To reduce the number of tools required, it may be necessary to machine materials with tools not recommended by tool makers.

3b) Dynamic multiple batch problem (ITS level 3)

This is the most extreme of the tool selection problems. It is similar to the previous case, except that the number of batches is not fixed. Extra batches can be considered at any time, as items are added to the production schedule, and the selected tools may therefore be subject to change.

Generally, the divisions between the tool selection problems are well-defined, with the exception of the boundary between problems 2a and 2b, which depends on the definition of a large component and the quantity of metal to be removed. There is, however, another way in which the tool selection problems can be categorised:

a) Single material (Tool selection problems 1, 2a and 2b)

These problems are based around a single material. All the tools selected, whether for a single feature or for a complete batch, will be suitable for cutting the same material.

b) Multiple material (Tool selection problems 3a and 3b)

In this category, usually more than one material will be considered, since the different batches will almost certainly be made from a range of materials. It becomes necessary to consider materials being machined by tools that are not recommended by the tool manufacturers.

Table 1.1 summarises some of the factors to consider in tool selection.

ITS level	Tool selection problem	Number of geometric features	Number of tool setups	Number of materials	Nature of problem	Number of batches
1	1	1	1	1	Static	<1
2	2a	>1	1	1	Static	<1
2	2b	>1	>1	1	Static	1
3	3a	>1	>1	>1	Static	>1
3	3b	>1	>1	>1	Dynamic	>1

Table 1.1

Factors of the tool selection problems

Realistically, only the solutions to the multiple batch problem[1] s have any application in an industrial environment. In practice, a further constraint on the multiple batch problem is imposed by the machine tool. This is the need to ensure that if a tool is selected for more than one batch, then it remains in the same pocket on the machine tool carousel or magazine. If there is a need to move a tool in the magazine, this reduces or negates the set-up advantages of careful tool selection. However, the problem can be simplified if the order of the batches can be changed, although this must be kept within the requirements of the production schedule.

A second constraint on the multiple batch problem concerns the number of selected tools, compared to the number of pockets on the machine tool turret (Maropoulos and Hinduja (1989)). Where the number of pockets is greater than the number of tools, the free turret positions can be used to accommodate extra tools, which are duplicates of tools already selected but have high wear rates. Should the opposite occur i.e. the number of tools is greater than the number of pockets, substitution of tools takes place to reduce the number of tools. The substitution tools should be able to perform multiple operations.

1.4 OBJECTIVES OF THE WORK

It is shown in chapter 2 that tool selection systems frequently rely on algorithms for the provision of cutting data and that algorithms for this purpose already exist. However, these are only suitable for the first three tool selection problems (section 1.3). The work in this thesis is intended to extend this work to include the fourth and fifth tool selection problems (static and dynamic multiple batches). This situation is summarised in figure 1.2.

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[1] The phrases *multi* and *multiple batch tool selection problem* (and similar phrases) refer to the static and dynamic problems collectively.

TOOL SELECTION PROBLEMS	ITS LEVEL	CUTTING DATA ALGORITHMS	
1) Single feature or element problem	1	Existing algorithms contribute to solutions for these problems	New algorithm (this thesis) contributes to solutions for these problems
2) Single component or multiple feature problem	2		
3) Single batch or multiple component problem	2		
4) Static multiple batch problem	3		
5) Dynamic multiple batch problem	3		

Figure 1.2

The applications to the tool selection problems for the work in this thesis

The requirements of the multi-batch tool selection problem dictate that the cutting data algorithm requires a number of features not currently available in such work:

1) **The input variables should be readily available**

Existing algorithms require input data of various types to be entered. Some of this data is standard and determining it presents no problem. However, other information is difficult to obtain. This type of data includes:

a) experimentally derived data, which can only reasonably be derived under laboratory conditions, rather than from a shop floor,

b) data for which there is no single value and may only be decided once machining has commenced,

c) data for which only approximate values can be obtained.

2) **The system should have the ability to accept any material and to consider any material with any tool**

Some of the input data relates to specific materials and specific combinations of material and tool, as recommended by tool manufacturers. For the multiple batch tool selection problem, the algorithm has to be able to accept not only new materials but also consider non-approved material/tool combinations, without any cutting tests. In other words, the material cannot be allowed to be a constraint, either for the system or for the tool under consideration.

3) **Cutting data similar to accepted company practice should be produced**

It is explained in section 3.1 that it is not normal practice for companies of this type to attempt to optimise cutting data, even though existing algorithms are normally based on the concept of optimisation. They are much more concerned with the time that a machine tool is occupied whilst machining a batch, during which time it is not available for an alternative batch.

4) **The system should be industrially applicable**

As explained in section 1.3, the multiple batch problem is the only tool selection problem with industrial applications. Consequently, any solution has to be suitable for industrial implementation. Ideally, this would mean *any* industrial environment. However, in the context of this thesis, the industrial environments concerned are restricted to jobbing and make-to-order manufacturing, as explained in section 1.2.

In practice the first three points (available input data, ability to consider machining any material with any tool and the production of cutting data similar to accepted company practice) are also concerned with making the algorithm more industrially acceptable. Nevertheless, to confirm whether this has been achieved, testing within these environments is necessary.

1.5 DESCRIPTION OF THE THESIS

The thesis is in four main parts, which are summarised in figure 1.3. This is followed by a description of the thesis, chapter by chapter.

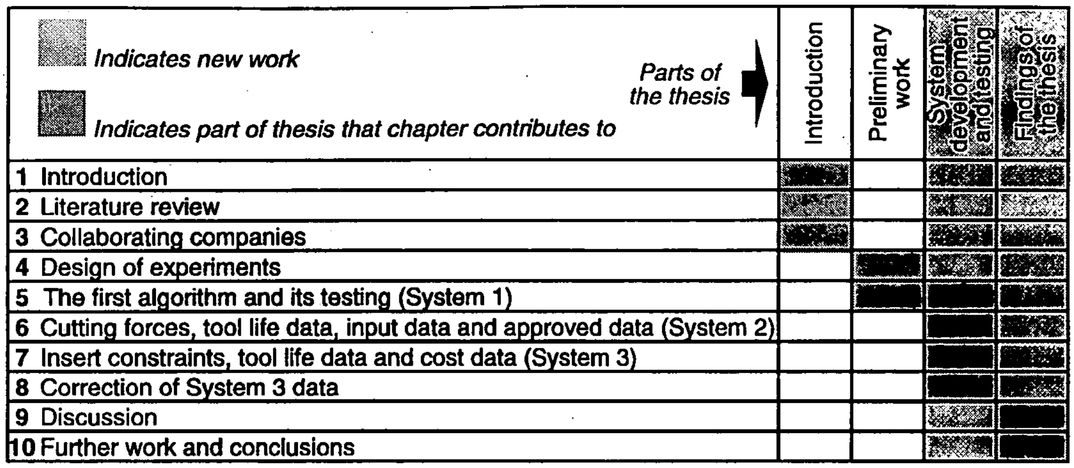


Figure 1.3
Parts of the thesis

Chapter 2 Literature Review

The original work in determining cutting parameters was carried out by Taylor (1907) who concentrated on tool life and tool wear. This review traces the development of this early work through to more modern methods for establishing cutting parameters, particularly those used for tool selection systems. These modern methods include both deterministic and non-deterministic methods, the use of machinability databases and the concept of multi-pass machining.

Chapter 3 Collaborating Companies

Since the companies were instrumental in the successful completion of the work, included in this chapter is a description and comparison of both companies. As well as qualitative descriptions covering such items as products and manufacturing facilities, included here is suitable quantitative data, such as tool purchase costs, tool inventory levels and details of tool management. There is also information, based on a questionnaire, of the background of the part programmers.

Chapter 4 Design of Experiments

When tests are carried out by industrial personnel under industrial conditions, certain experimental principles have to be modified to suit the conditions. This chapter discusses the methods of experimentation used and highlights where the tests differed from normal laboratory practice, with respect to the industrial environments concerned.

Chapter 5 The first algorithm and its testing (System 1)

The starting point for the work was the development of a program based upon a cutting data algorithm. This was subjected to testing within one of the companies. The intention was to compare the results from the algorithm with company practice and to determine what changes were required to make it suitable for the multiple batch selection problem. This chapter contains details of the tests and the results and analysis.

Chapter 6 Cutting forces, tool life data, input data and approved data (System 2)

Work was carried out on the algorithm to remove the need for material-specific input data. This also contributed to the reduction of input data generally. Testing was carried out on a range of materials. This chapter contains a description of the changes to the algorithm, resulting in System 2, and details of the tests, results and analysis.

Chapter 7 Insert constraints, tool life data and cost data (System 3)

Further work was carried in on the reduction of material-specific and other input data and testing was carried out in both companies. This chapter contains a description of the changes to the algorithm, resulting in System 3, and details of the tests, results and analysis. In this case, the testing was much more extensive than for Systems 1 and 2.

Chapter 8 Correction of System 3 data

From the results in chapter 7, it was evident that some form of constant error was occurring between company shop floor data (approved data) and the data generated by System 3. As a means of correcting the error, the mean and standard deviation of the System 3 data was adjusted. Included in this chapter are the details of the corrections, with the results and analysis of the corrected data.

Chapter 9 Discussion

The opportunity is taken to discuss some of the other lessons learnt during the course of the work. At one time an attempt was made to record tool life on the shop floor and the outcome of this is explained. The opportunity was also taken to observe at first hand the role of the part programmers.

The concepts of cost in manufacturing and the differences between databases and data files is examined. Some areas where the work would benefit from further development are suggested, as well as the advantages of the introduction of intelligence. Finally, the possibility of commercial exploitation is suggested.

Chapter 10 Further work and conclusions

The final chapter is concerned with a summary of further work, based on the discussions in chapter 9, and the conclusions which can be drawn from the work. As a primary conclusion, it was found that the work met the original objectives. In addition, a number of secondary conclusions were also formed. The thesis concludes with a short discussion as to where work of this type may lead in the future.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Arguably the first person to apply scientific principles to the cutting of metal was Taylor (1907). In a famous paper, he established for the first time an empirical relationship between tool life and cutting speed, in the form of the Taylor equation for tool life. This equation is still in common use today, either in its original form or as a modified version.

Whilst some writers have tackled the problem of multi-cut operations, whereby several tool are used simultaneously, e.g. Bartalucci et al (1970), Mayer (1974), the work in this thesis is concerned with single cutting tool operations. The view is taken that multi-cut operations may form the basis for further work, but are not considered here.

Although work in cutting data selection has been carried out since the time of Taylor, the introduction of computers allowed further methods to be developed. The use of computers in the selection of machining parameters dates back to the early 1960's (Balakrishnan and DeVries (1982)). This presumably referred to digital computers, since Weller and Reitz (1966) noted that an analogue computer was successfully used in the mid 1950's for simplifying the solution of machinability problems.

Much of the work reviewed here is based on expert systems. Expert systems are characterised by three features (Niwa (1990)). Firstly, they use a knowledge base that consists of knowledge obtained from specialists in the field. Secondly, they have an inference engine that is capable of deducing new conclusions from the available facts. Finally, they attempt to solve real problems as effectively as human specialists. In the context of this work, expert systems have a number of benefits (Turban (1988)):

a) a frequently used expert system is cheaper than human expertise,

b) an expert system can improve quality by providing consistent advice,

c) expert systems are more reliable than people,

d) an expert system will often respond much quicker than a human, particularly when large quantities of data are involved,

e) unlike conventional computer systems, an expert system can work with incomplete and uncertain information.

Many cutting data selection systems rely on predictions of tool life, hence section 2.2 looks at the question of tool life and tool wear. Closely associated with cutting conditions and tool life are tool replacement policies, which form the subject of section 2.3. Sections 2.4 and 2.5 discuss deterministic and non-deterministic methods for cutting data selection respectively, whilst section 2.6 considers the use of machining data banks.

When more than one pass is required (multi-pass machining), optimisation of cutting data becomes more complex. Current thinking is this area is reviewed in section 2.7. Since the whole purpose of this thesis is to find a method for cutting data which is suitable for a tool selection system, section 2.8 looks at tool selection and the methods used with these systems for finding cutting parameters. Finally, the situation is discussed in section 2.9 and conclusions are drawn.

2.2 TOOL WEAR AND TOOL LIFE

The mechanisms of tool wear can be divided into six categories (Smith (1989b)):

1) Diffusion wear

This is due to actual atomic transfer across the tool/chip interface. It is highly temperature-dependent. The wear rate depends heavily on the metallurgical relationship between the workpiece and tool materials.

2) Attrition wear

This is found mainly on the face of the tool and is the result of an unstable built-up edge. When the built-up edge breaks away, it takes fragments of the tool with it.

3) Fatigue wear

If the tool surface is repeatedly subjected to a loading and unloading cycle (fatigue action), small portions of the tool material may become detached from the tool surface.

4) Abrasion wear

This is the most common form of wear. The tool is abraded by high surface concentrations of hard particles in the workpiece, such as sand in a casting or oxide on a hot-rolled bar. Even soft materials may contain precipitates or hard inclusions, as a result of previous processes.

5) Electrochemical wear

It may be that an electrolytic reaction is set up between the tool and the workpiece, which may cause small amounts of tool material to be removed.

6) Other factors that increase tool wear

Other factors, which can include plastic deformation, brittle fracture and edge chipping, are not necessarily true tool wear, but they do contribute to tool wear.

Tool life calculations are an integral part of most, if not all, mathematical cutting data models which include optimisation of the cutting data, since tool life is the most important factor in machining economics (Yellowley and Barrow (1971)). The traditional approach to tool life is based on the use of either Taylor's equation for tool life (Taylor[1] (1907)):

$$VT^n = C$$

or a modified version such as the extended Taylor equation e.g. Hoffman (1984):

$$T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}}$$

The established approach for determining values for the constant and exponents is to linearise the appropriate equation by taking logarithms and then applying regression analysis, e.g. Leslie and Lorenz (1964), Levi and Rossetto (1975), BS 5623 (1973).

Since Taylor first developed his equation, many researchers have carried out further work on the equation, particularly with respect to the value of n. An example of this was Leslie and Lorenz (1964), who established that variations in the value of the tool life exponent n in Taylor's original equation were chance effects due to random discrepancies in the steel and tool material. According to Pilafidis (1971), values of n much larger than those normally quoted can often be encountered. Friedman and Zlatin (1974) started with the assumption that the variance of log(T) was homogeneous. However, they found that under certain circumstances this was not the case.

Other work concentrated on modifying Taylor's equation. Woxén (1932) formulated an expression for tool life which depended on Taylor's equation, as well as including a second term which indicated the dependence of the cutting speed on the chip-equivalent q, where:

$$q = \frac{\text{the engaged length of the cutting edge}}{\text{the actual area of cut}} = \frac{L_e}{A} \text{ (1/mm)}$$

---

[1] Although this is the form of the equation which is traditionally used, Taylor did not actually express the equation in quite this particular form. In his original work (paragraph 718), the general form of the equation had n equal to 1/8.

The quantity A was a measure of the quantity of heat generated at a certain cutting speed, whilst L_e was a measure of the quantity of heat carried off by the chip. Based on the work of Woxén, Colding (1959) developed a three-dimensional tool life equation of hyperboloid form. In the discussion of the paper, Brewer commented that the "...analysis was too far ahead of the knowledge about the justifications for the assumptions made."

Further instances of attempts to modify the equation included Wu et al (1966), who used power transformations to linearise the equation, and Mukherjee and Basu (1967) who assumed the relationship:

$$W = f(V, S, a, T)$$

where W was the relief wear of the tool, measured by the width of the flank wear land µ(mm).

For certain materials, Kronenberg (1970) pointed out that a plot of V against T on log-log graph paper did not give the straight line expected from the Taylor equation. He introduced a 'straightening' constant K into the equation, such that the form of the equation became either:

$$(V \pm K) \times T^n = C \text{ or } (T \pm K) \times V^m = C$$

This had the effect of converting the curved line into an equivalent straight line.

Various methods of tool life testing have been developed. These can broadly be categorised as conventional and accelerated (e.g. taper turning and facing). This work included Heginbotham and Pandey (1966) and (1967), who used taper turning and variable rate machining tests to evaluate n and C in the Taylor equation. Yellowley and Barrow (1971) preferred conventional tests as the basis for providing data which could be extrapolated to other tools and workpieces, although they commented that the accuracy of both methods was limited.

By contrast, Thomas and Lambert (1974), who compared accelerated methods of tool life testing with conventional methods, concluded that accelerated tests were a suitable substitute for conventional methods. Even so, Levi and Rossetto (1975) found that "...a large amount of testing was found to be required to obtain data on tool life even with a moderate precision." Taking a pragmatic view, they realised that what industry was looking for was a reliable estimate, rather than a new equation. This was summarised by their opinion that "prevention of sudden failure is far more valuable...than is an unreliable guarantee of long average lives."

Some work has been aimed at gaining a better understanding of the concept of the underlying mathematics of tool life. One such example was Ramalingam et al (1977), who concluded that the most probable distributions for tool failure mechanisms were Weibull, Gaussian and log-normal. Another alternative approach was that of Colding and König (1971), who carried out work on economic tool life, based on a non-linear tool-life relationship.

All the work mentioned so far has been concentrated at finding improved methods for predicting tool life. With the increasing popularity of CNC machine tools, the emphasis of the work has shifted from prediction to real-time monitoring, e.g. Yao et al (1990). Whilst such work is suitable for obtaining satisfactory machining conditions, it is of no value in assisting in the prediction of cutting data.

2.3 TOOL REPLACEMENT

Calculation of tool life can indicate to the machinist when the tool may be likely to require changing. However, in a production environment, there are other factors to consider. These factors should also be taken into account in a realistic tool selection system. For example, La Commare et al (1983) investigated a number of tool replacement policies:

a) scheduled tool replacement policy (the tool is replaced either if it has cut for a fixed time or upon failure),

b) preventative planned tool replacement policy (when it may be convenient to replaced the tool at the end of a scheduled period),

c) failure tool replacement policy (the tool is replaced only when it fails).

Included in their analysis was the economic cost of tool failure whilst cutting and the resulting rejection of the workpiece.

Doyle (1973) considered that the effect of tool life variation was strongly influenced by the policy followed for changing tools. He considered the cases where tools were changed either on failure, after a predetermined time or upon completion of a predetermined quantity of work. The preferred policy depended on the particular situation. Two tool renewal schemes were suggested by Vil'son and Samkharadze (1987). The first was serial renewal, whereby only the failed tool was replaced when failure occurred. This was in contrast to parallel renewal. Under this scheme, if any single tool failed, all the tools in the set-up were replaced. However, these schemes relied on a diagnostic system which detected specified levels of wear or complete tool failure.

Another approach to tool replacement relied on economic analysis (Koulamas (1991)). Their model simultaneously determined both the optimal machining conditions and the optimal tool replacement policy, whilst minimising the cost of the machining operation. The concept of quality loss was examined by Jeang and Yang (1992) in the context of optimal tool replacement. In this case, quality was defined in terms of the change in part dimension over a period of time. This was considered to be due to tool wear. Both linear and non-linear tool wear was included in the model.

2.4 DETERMINISTIC SELECTION OF CUTTING DATA

The general principle of determining cutting data, based on complete information, is to decide on one or more criteria to be applied. Typically, these may include minimum cost, minimum production time, maximum production rate or maximum profit. These are then expressed mathematically as the objective functions. Before a solution can be found, one or more constraints may have to be defined, such as the cutting speed must lie between the limits for the machine tool or the power required must not be greater than the maximum power available. A solution is then sought which satisfies the objective function or functions, without violating the constraints. The solution is generally concerned with the cutting speed.

Since the early days, the use of computers in this field has been widespread. Gardiner (1965) reported the use of a computer to produce cutting data tables, based on Taylor's tool life equation. Ham and Faria-Gonzalez (1970) employed a computer to iterate a solution for the extended Taylor equation, as an aid to optimising cutting data. Field et al (1968) used a computer to print out a detailed cost breakdown for analysis of the significance of the variables. In a similar vein, Ramaswami (1968) used a computer to calculate constraints for a range of cutting speeds and feed rates before choosing the optimal conditions, whilst Weill (1962) produced several possible solutions. As part of a process and operations planning system, van Houten and Kals (1984) displayed the cutting data combinations on a computer in the form of graphs, as well as numerically.

The use of computers allowed the development of more complex models, e.g. Weill (1962) and Peters and Pinte (1980), as well as simulation methods, e.g. Mayer et al (1974), and an increase in the number of factors to be considered, such as original surface condition and type of coolant, e.g. Weller and Reitz (1966).

The ease of computation also allowed the output from different systems to be readily compared, such as French and Quinn (1974). Ham and McClenahan (1974) used a feedback loop of shop floor data and arrived at optimum conditions iteratively by means of regression analysis, carried out on a computer. A similar iterative approach was developed by Groover and Velnich (1981), using an index of performance to drive the search for optimum cutting data.

There have been many different deterministic methods devised to ascertain cutting parameters. These have included graphical methods (Akers and Smith (1960), Brewer and Reuda (1963) and Ravignani (1976)), complex mathematical approaches such as Langrangian algorithm (Saxena and Khare (1976)), geometric programming (Petropoulos (1973) and Gopalakrishnan and Al-Khayyal (1991)), and linear programming and sensitivity analysis (Ermer and Patel (1974)).

Various optimising techniques have been tried, such as the optimisation with constraints work of Rasch and Rolstadås (1971) and non-linear constrained optimisation by Taraman and Taraman (1983). Brown (1980) discussed the process of experimentation, whilst Zdeblick and De Vor (1981) based their work on the unusual approach of scrap and rework penalties. Other work included a rule-based approach (Kegg (1971)), response surface technology (Lambert and Taraman (1973)) and simulation and a Fibonacci sequence (Wysk et al (1978)). Chua et al (1993) used design of experiments techniques to develop a series of equations of the general form:

$$Y = C \times V^{\alpha} \times S^{\beta} \times a^{\gamma}$$

where Y was the machining response, α, β and γ were exponents and C a constant.

Many attempts have been made to analyse the cutting process in economic terms. One of the first workers to carry this out quantitatively was Brewer (1958). Brown (1962) deliberated on the economics of the machining operation and formed the opinion that for any given depth of cut, the lowest cost was achieved with the maximum feed rate. Okushima and Hitomi (1964) considered maximum profit in a constant time interval, whilst Wu and Ermer (1966) looked at demand curves.

The concept of minimum loss was introduced by Armarego and Russell (1966), whilst Bartalucci et al (1969) took into account the economics of the machine tool, as well as the tool. Ermer (1971) applied geometric programming, a technique he considered "...especially effective in machining economics problems, where the constraints may be non-linear and the objective function of more than second degree".

Ermer and Faria-Gonzalez (1967) considered that sensitivity analysis could be applied to defining an optimum range, which could form the basis of a realistic optimum, provided it was maintained within a specified variation of the actual economic optimum. Ramaswamy and Lambert (1974) added to the variables in the equations by including the effects of "...due date violation and in-process inventory costs".

Boothroyd and Rusek (1976) concluded that the maximum rate of profit lay between the conditions of minimum cost and minimum production time, and Ravignani (1980) allowed for the probabilistic nature of tool life. Primrose and Leonard (1986) took an accountant's viewpoint and considered that the use of variable costing produced better machining parameters than absorption costing, whilst Boucher (1987) questioned some of the assumptions underlying conventional economic analyses in terms of fixed costs and concluded that "...there has been a general tendency to specify cutting speeds higher than the cost minimum speed". Cowton and Wirth (1993) expressed the view that the contributions from both Primrose and Leonard and Boucher were special cases. They (Cowton and Wirth) modified some of the economic constraints and non-linearised the revenue function.

Various researchers have concentrated on one or more specific aspects of cutting data algorithms. For example, Arsecularatne et al (1993) looked at the prediction of the radial force when the longitudinal force was already known, based on the chip flow angle. Jeng et al (1995) investigated the minimum clamping force for a variety of different situations e.g. clamping on a circular area and an elliptical area. They concluded that once the cutting conditions have been given, the minimum clamping force could then be estimated. However, some cutting data algorithms required the clamping force as part of the input data e.g. Hinduja et al (1985) and Hinduja and Maropoulos (1991). Hinduja and Huang (1989) carried out work on the determination of workholding parameters, based on the premise that factors such as concentricity and runout should be considered when optimising cutting parameters.

2.5 NON-DETERMINISTIC SELECTION OF CUTTING DATA

Iwata et al (1972) defined two objective functions used to define optimum cutting data:

a) volume of material machined per unit of tool wear,

b) production cost per component,

which they assumed to be deterministic although recognising that they could be probabilistic. They assigned probabilities to certain constraints, where the constraints contained probabilistic coefficients. (Other constraints were considered deterministic.) The overall solution to the problem was found by the chance-constrained programming technique, which converted the probabilistic constraints into deterministic form. In later work Iwata et al (1977) assumed that the objective functions were probabilistic.

Hati and Rao (1976) adopted a similar methodology when comparing deterministic and probabilistic approaches. The probability element was based on the fact that some of the objective function parameters and constraints varied about their means. For the example chosen, for both the optimum cost of production per piece and the optimum production rate, the cutting speed was higher and the feed rate lower for the probabilistic case.

Another non-deterministic approach to selecting cutting data was taken by Wang and Wysk (1986), who developed an expert system (ESMDS) for this purpose. Although it was difficult to asses the effectiveness of their approach, nevertheless in the example quoted, a tungsten carbide insert was used to machine free machining alloy steel of hardness 250 BHN, with a minimum tool life of 30 minutes. The resulting cutting speed of 85.87 m/min seemed low. For example, Seco (1988) suggests that a cutting speed of approximately 150 m/min would be suitable, using an ISO P20 grade insert. In this case the material was either alloy steel (220 - 270 BHN) or alloy steel casting (200 - 250 BHN).

A comparison of three different non-deterministic methods (multiple regression analysis, group method of data handling (GMDH) and neural networks) was carried out by Chryssolouris and Guillot (1990). The process parameter that was controlled was feed rate. The state variables were spindle power, surface roughness, noise level and chip merit mark, which was "...an indicator of how easily the chips can be evacuated and how inoffensive they can be to the surface finish". All the state variables were constrained. Accuracy of the models was characterised by measuring the state variables against feed rate. However, this gave no indication as to whether the system was capable of optimising cutting conditions. They concluded that the best overall results were given by GMDH and neural nets. These models were felt to be superior to multiple regression models.

Yeo et al (1991a) preferred the use of the term 'knowledge-based system' to 'expert system' to describe their work. This was to focus attention on the knowledge carried by the system, rather than whether such knowledge constituted expertise. The system provided cutting data taken from tool manufacturers' handbooks, which was modified by heuristic rules to take into account data fed back from the shop floor.

2.6 CUTTING DATA FROM MACHINING DATABASES

In contrast to the use of algorithms or other methods for determining data, an alternative approach centres around the use of standard data. Prior to the development of computerised systems, this data was only available in printed form, such as that commonly known as Metcut (1972), which is still available today. This gave typical machining conditions for a wide range of materials and tools for different depths of cut. An alternative to tables were graphical representations e.g. Fisher and Hargreaves (1974).

More recent developments concern the use of computers and what are often referred to as machinability or machining data banks or databases. Balakrishnan and DeVries (1982) carried out a survey of data banks and identified the main developers of the systems:

a) research institutes and universities,

b) cutting tool and machine tool manufacturers,

c) numerical control programming language processor suppliers,

d) individual companies,

e) consulting firms.

They also categorised the data bank systems as follows:

Classification:	stand-alone, integrated
Integrated to:	process planning, machine, CAD
Type:	data storage/retrieval, empirical equation, mathematical model
Cutting conditions:	recommended, optimum

Whilst most of these terms are self-explanatory, it is worthwhile clarifying 'type':

a) Data storage and retrieval systems

These are effectively cutting data manuals with data, taken from the shop floor, laboratory experiments or handbooks, stored in a computer for speed of access to the data.

b) Generalised empirical equation systems

The data for a particular operation is reduced to a suitable empirical form and expressed as generalised empirical equations or machinability charts, relating cutting speed, feed rate and tool life. The reliability of the systems depends on various factors, constants and exponents, which are determined empirically from extensive tests.

c) Mathematical model systems

These depend on mathematical models fitted to experimental data which are again empirical in nature. They differ from the generalised empirical equation systems in that the equations are obtained from experimental data which closely matches the machining situation, rather than much more general empirical equations. Coefficients for the models are obtained by regression analysis and are normally stored in a data storage and retrieval system.

König et al (1973) used a data bank, known as the INFOS database, to store data (cutting parameters and cutting conditions) from industry and research institutions. This was used as the basis for an advisory or information service. Despite this wealth of information, they still resorted to algorithmic methods for the determination of new cutting data (Eversheim and König (1979), Eversheim et al (1981)).

A later development concerned a company-independent data bank (Eversheim et al (1987)). The data bank was independent in that the independence of tool makers and users was protected. Access to the data (both inputting and updating) was strictly controlled. The data may be supplemented by company-specific information.

Friedman and Field (1974) were of the opinion that a mathematical model for a numerical machinability data bank depended on a reliable mathematical tool life model in order to provide reliable predictions of cutting data. Kals et al (1978) used a data bank to provide input data, e.g. constraints and machine specifications, to an algorithmic cutting data program. An algorithmic method for deciding which data should be taken from a data bank, and was designed to work with incomplete data, was described by Cook (1980). In the case of incomplete data, default data from the data bank was used.

Lindberg et al (1982) were of the opinion that "...mathematical models...often reveal machining costs to be sensitive to relatively small variations in cutting speed and/or feed rate". Their data selection system included a number of data modules, including cutting tools, cutting fluids, process constraints and machine tools, as well as cutting data. Each module presented and selected the appropriate data from the data files, either based on algorithms or as a result of user input.

An example of a mathematical model database system was provided by Balakrishnan and DeVries (1985). The machinability database was updated with data from actual machining processes, fed back via suitable sensors. In this case, instead of the use of regression analysis to determine the machining data, a sequential Maximum A Posteriori (MAP) estimation technique was used. They claimed that this had a number of advantages, including:

a) data storage requirements were small,

b) the computation was efficient,

c) use could be made of subjective prior information,

d) it allowed adaptive estimation of changing machinability parameters.

It is questionable nowadays whether the first two points are as important as they were when the work was carried out.

'WHAT-IF' questions were possible with the application packages developed by Ravichandran and Sudheendra (1988), which interrogated a machining data bank. The output was in the form of a tables of recommendations, rather than optimised data.

As part of their work into a knowledge-based integrated machining system, Yeo et al (1991b) produced a system that included the selection of cutting data. There was more than one level of search. One level calculated the cutting speed, although if no data was available, cutting data was obtained which was based on the tool manufacturer's handbook. Another level made use of empirical models obtained from extensive shop floor machinability tests.

Balakrishnan and DeVries (1985) had commented that shop floor data should be fed back automatically to a data bank, so that it can be updated and improved for future use. This would also help the data bank reflect new technology. Ten years later, in work concerned with data optimisation for multi-pass turning, Yeo et al (1995) suggested that this still was not done. Yeo et al used an empirical model so that shop floor feedback data could be included in the shop floor machining database, although there was no mention of how this should be achieved.

2.7 CUTTING DATA FOR MULTI-PASS MACHINING

When considering a cut, the tool size and amount of stock to remove will often determine whether is possible to treat the operation as a single cut or a multi-pass cut. On other occasions it may be considered that two or more passes are more economic or efficient than a single pass. According to Kee (1996), "...the multi-pass turning problem is clearly more complicated than single pass turning, since the optimum number of passes as well as the cutting conditions for each pass have to be determined while satisfying various practical constraints at each pass."

In an early work on the subject, Brown (1962) took the view, based on a mathematical analysis, that "...two passes were not cheaper than one if the single pass did not use maximum power", although this was based on the two passes consisting of a roughing and finishing cut.

The topic of multi-pass operations was discussed by Crookall and Venkataramani (1971). With one pass, there were three parameters to control (cutting speed, feed rate and depth of cut). This increased to six parameters for a two-pass operation, but only one combination was optimal. However, this may result in different cutting parameters for each pass. Constraints included surface finish (finish cuts), power and workpiece deflection.

Their work suggested that "...the true best operating point cannot be deduced intuitively, or by simple calculation from the Taylor Law. It could only be determined by rigorous consideration of the many factors involved." They also made the unsubstantiated but interesting observation that the optimal solution, whether of one or more passes, was often near the point of maximum power.

One of the first people to apply geometric programming to the problem were Lambert and Walvekar (1978). Their optimal solution utilised unequal depths of cut. An alternative approach was that of goal programming (Philipson and Ravindran (1978)). Interestingly, they were one of the few people to consider maximising metal removal rate. However, although their example showed an optimum cutting speed and feed rate, there was no mention of the depth of cut nor the number of passes.

Ermer and Kromodihardjo (1981) set out to show, with a number of examples based on geometric programming combined with linear programming, that in many cases two or three passes may be more economical than a single pass. Their solution, like that of Lambert and Walvekar, also had different depths of cut for each pass. Yellowley (1983) confirmed this view, with the finding that two even passes was the worst possible choice.

Hinduja et al (1985) paid great attention to the question of the depth of cut for multi-pass operations. They took the view that passes of equal depth were "...a serious disadvantage if a considerable amount of material has to be removed...". They discussed four alternative methods, but in each case the depth of cut for each pass was optimised, rather than equal for each pass.

However, in later work from the same group, (Chen et al (1989) and Maropoulos and Hinduja (1991)), instead of roughing passes of changing depth for multi-pass operations, there was a change to passes of equal depth. Chen at al considered that "...the cutting conditions calculated will not be as precise as those in Hinduja et al (1985), but they will be good enough to provide an estimate for the cost of performing an operation with a given tool", whilst Maropoulos and Hinduja took the view that this provided an "...approximate but still realistic process model."

Armareggo et al (1988) studied the optimisation trends for the number of passes and the depth of cut numerically, making full use of single pass trends. With regard to the whether the passes were of equal depth, "...using equal cutting conditions for all passes are...useful approximations but the final solution results in unequal conditions for each pass". Yellowley and Gunn (1989) disagreed with that, having shown that numerically all the passes but the last one should be at the maximum depth of cut.

Chua et al (1991) tried optimising for different numbers of passes. They compared the results of what they defined as the "...classical optimisation method together with feed-speed diagram" (unequal depths) with sequential quadratic programming (equal depth except last pass) and found a marginal improvement in production time using the latter method. In a later work Chua et al (1993), using design for experiments techniques to generate an optimum result, produced an example that had both passes of equal depth.

Agapiou (1992a) presented a solution for the optimisation of multi-pass machining by means of dynamic programming, which produced the optimum number of passes, not necessarily of equal depth. Shin and Joo (1992) considered the case of a combined roughing and finishing cut numerically. The solution resulting from their mathematical model was passes of equal depth for the roughing cut. Implicit in the solution was a finish pass of minimum depth.

Gupta et al (1994) examined the effect of profit rate maximisation for single, two and three pass models, using geometric programming. They concluded that the least number of passes would maximise profit or production rate, although they did not comment on the depth of cut for each pass. This question of depth of cut was covered in a later publication (Gupta et al (1995)), where they disagreed with Shin and Joo (after applying both techniques to the same example) on the subject of both equal depths for roughing and the minimum depth for finishing.

Another team who compared their method with that of previous published work was Tan and Creese (1995), who used an example by Ermer and Kromodihardjo (1981). Like Ermer and Kromodihardjo, Tan and Creese arrived at a solution with unequal depths, but their depths for each pass were different to the earlier work. In calculating the total production time for a multi-pass operation, Yeo et al (1995) assumed equal depths of cut. Finally, it was noted by Kee (1996) that a "...single pass could sometimes give an optimum solution...even in a multi-pass optimisation strategy.".

2.8 TOOL SELECTION SYSTEMS AND CUTTING DATA

In an early example of the single component/single batch problem, Etin et al (1973) concentrated on finding the optimum set of tools for each operation. Each tool and element was described by a word, or code, where each letter, or descriptor, defined an attribute of the element or tool. Tool selection was made by matching the relevant parts of the tool and element descriptors. The cutting performance of each tool was assigned a characteristic quality, which in this case was the mean thickness of the undeformed chip thickness, allied to the cutting speed. However, no indication was given as to how the characteristic quality was derived.

Barkocy and Zdeblick (1985) used a knowledge-based system (CUTTECH) for selecting tools. Once a set of tools had been selected for their ability to carry out the cut, they were ranked by means of rules and numerical heuristics. Factors such as cost, machining time, metal removal rate and rigidity were considered, as well as quantitative estimates which included machining time and machining cost. The rules are designed to reflect the "...overall judgement of planners who frequently select tools under complex input conditions" and to assist them in their decisions.

Once a final tool had been selected, a further set of rules were used to divide the cut into entry, roughing and finishing passes. This determined the depth of cut. Finally, the cutting speed and feed rate were selected, by means of data tables. There was a facility for updating the tables in the light of shop floor experience. The system applied rules to the data from the tables, so that the data could be modified in the event of severe machining conditions, e.g. excessive tool overhang or thin wall sections. It would appear that the system was only suitable for selecting a tool for a particular element or feature and could not consider either the previous feature or component, nor the next.

A later system for tool selection, developed by Hinduja and Kroeze (1985), selected tools for a component according to rules designed to minimise the number of tool interruptions. The system contained a cutting technology module described in two other sources. The first of these was van Houten (1981), who introduced an interesting concept by which he used the same equation for optimising both the minimum cost and maximum production rate criteria. The machining cost function was made up of two functions:

a) production cost function,

b) production time function.

van Houten multiplied the cost function by a variable, C_0. When $C_0 = 1$, the objective was minimum production cost. Alternatively, for $C_0 = 0$, the cost function was reduced to zero and the objective became maximum production rate. If $0 < C_0 < 1$ then a compromise solution was reached, from which it was possible to obtain the maximum profit rate. (Agapiou (1992b) also combined both production criteria into a single objective function, with the difference that he applied separate weighting factors to both parts of the function.)

The constraints defined by van Houten (e.g. feed and speed range of the tool and machine tool, tool maximum depth) were not untypical for a system of this type, with the addition of the maximum area of the chip and the maximum slenderness ratio of the cut. Both the objective machining cost function and the constraints could be represented in terms of the cutting speed, feed rate and depth of cut. The economic cutting conditions were found from "...calculating the intersection of the spatial representation of the objective (machining) cost function with the limited area of solutions for the cutting conditions which can be reached technically".

van Houten claimed that the method gave reliable results for machining times and machining costs. There was no comment on the reliability of the calculated cutting parameters *V*, *S* and *a*. The overall system itself, a process planning system known as ROUND which incorporated the cutting module, was described in a later paper (van Houten and Kals (1984)) although very few details of the tool selection process were given.

The second work upon which Hinduja and Kroeze (1985) based their cutting technology module was Hinduja et al (1985). For roughing, Hinduja et al maintained the tool within the *a-S* (or chipbreaking) diagram. After the diagram had been divided into a grid, the cutting speed for each node on the grid was calculated according to the equation:

$$V^{1/\alpha} = \frac{C}{T \times h_c^{1/\delta}}$$

where C, α and δ were constants and h_c was the chip area divided by the active contact length between the tool and the workpiece (the chip-equivalent). The value of T was based on either minimum cost or maximum production rate criteria. This equation took the tool geometry into account.

The point at which V was a minimum gave the feed rate and depth of cut. Rather than use passes of equal depths, Hinduja et al recalculated the cutting parameters for each pass, giving unequal depths of cut. Other constraints considered included vibration, torque and power of the machine and workholding limitations.

For finishing, a similar method was adopted, although the point on the *a-S* diagram was chosen the maximise the feed rate. Additional constraints included surface finish and workpiece accuracy. Although the roughing and finishing methodologies were tested and yielded reasonable results, no numerical comparison was given with other methods for determining cutting parameters. Some preliminary tests were also carried out in industry. It was claimed that the results were comparable to those provided by experienced part programmers. A disadvantage of the system was the need to derive certain values experimentally.

Chen et al (1989) used six levels to select a tool for an operation:

1) tool function,

2) insert clamping method,

3) holder dimensions i.e. shank height and width, and tool length,

4) holder type i.e. approach angle, insert shape, size and thickness,

5) insert type i.e. chipbreaker type and carbide grade,

6) tool nose radius and insert tolerance.

Cutting performance was considered at level 5. To reduce the number of tool combinations possible, a heuristic method was employed to eliminate tools prior to consideration. Hence the selected tool may be sub-optimum.

Jang and Bagchi (1989) set up a number of databases and both tool and cutting data selection from the databases was governed by heuristics rules, based on the experience of tool engineers. The expert tool selection system developed by Gopalakrishnan (1989), which also selected other parameters such as the machine tool and coolant, had an algorithmic cutting parameter module based on geometric programming. He considered that it was "...necessary to use expert systems along with traditional algorithms for the best selection of machining parameters." A later publication (Gopalakrishnan (1990)), which was concerned with the intelligent selection of cutting parameters, reinforced this view:

> "The selection of machining parameters is best done using algorithms, as substantial computation is involved in determining the costs associated with optimal machine parameters".

Maropoulos and Hinduja (1991) selected tools for rough turning based primarily on geometrical considerations and cutting performance, where the cutting performance was obtained algorithmically. Maropoulos and Hinduja (1990) defined seven conditions for a tool selection system for finish turning:

1) the cheapest tool should be selected,

2) the combination of tools selected (the tool unit) should be able to machine the profile completely,

3) the number of tools in the unit should be the minimum possible,

4) tools from one unit should be available for other units,

5) the user should be able to override the decision made by the system,

6) the system should provide visual verification that a selected tool can complete the cut,

7) the system should calculate and display the total cost, time and the percentage of tool life used for every tool in the unit.

The performance of each tool was defined in terms of its effective unit cost (e.u.c.):

$$e.u.c. = t_2\left(\frac{x}{60} + \frac{\frac{x}{60}t_3 + y}{T_{(opt)}}\right) \ (£)$$

where t_2 was the effective cutting time (mins), x was the machine hourly rate (£/hr), t_3 was the tool change time (mins), y was the cost per cutting edge (£) and $T_{(opt)}$ was the optimum tool life (mins). Tool selection was based on the total e.u.c. for each tool unit.

In all three of these cases (Chen et al (1989) - rough turning, Maropoulos and Hinduja (1991) - rough turning, Maropoulos and Hinduja (1990) - finish turning), a similar algorithmic method to Hinduja et al (1985) was used. However, there was an important change. There was a bias in favour of the minimum cost criterion, in preference to the minimum machining time criterion. This was reinforced in later publications from this research group, such as Arsecularatne et al (1992) and Hinduja and Barrow (1993), who used an "...algorithmic/deterministic approach" to select tools for components.

A number of authors, starting from the mid-1980's, considered the application of expert systems to the problem of tool selection. An early example was PICAP (Santochi and Giusti (1987)), an expert system designed to test the automatic link between the CAD design stage and the machining stage on an NC lathe, known as a CAPP system (Giusti et al (1986)). The cutting data selection module of PICAP was "...a simple economic optimisation for each single operation taking into account the technological limits of the machine tool-tool-workpiece system". Necessary data was provided by a data file.

Another module of PICAP was a self-learning monitoring system (Giusti et al (1986)). The monitoring system was attached to various sensors on the machine, which measured such factors as tool wear, diameter, vibration, chip form and power. These were compared with required values. Once the first workpiece had been machined, a diagnostic program indicated the tool parameters to be modified. The program then searched for a new tool to meet the new parameters.

This type of adaptive control system was only suitable for selecting tools for one component a time, since the final selection of tool was made after the machining process has been started. To select tools for a range of batches requires not only all possible tool types, but also their performance to be known prior to machining, so that the appropriate selection can be made. For this reason, PICAP did not appear to be appropriate for selecting tools across a range of batches.

The use of expert systems in tool selection was put forward in two similar papers by Arezoo and Ridgway (1989) and (1990). However, the determination of cutting conditions was algorithmic. The constraints were similar to those discussed previously, as were the production criteria i.e. minimum cost or minimum machining time, but the constants for some of the constraints were not available and had to be obtained experimentally. The user either specified the tool life or it was optimised within a stated range. In an example test case, although the stability of the machine tool and clamping were classified as 'fair', there was no positive indication as to how this information was used. (In the example, the 'fair' stability of the operation caused round nose tools to be rejected, but no reason was given for this.)

The use of the production rules matrix method for tool selection was put forward by Domazet (1990). In this method, instead of the logical 'IF-THEN' statements of a traditional knowledge based system, the production rules were in a tabular form. Amongst the benefits that he noted were:

1) search and interpretation of the knowledge base was much faster,
2) generally all the rules were analysed, resulting in the best solution,
3) the rules were simple to modify, even without programming knowledge,
4) the advantages of both algorithmic and non-algorithmic approaches were obtained,
5) the results contained the rule number, making future modification easier.

Domazet used very simple rules to determine the depth of cut. The cutting speed was based on the recommendations of the tool makers and read from a file, as was the feed rate.

Another expert system for tool selection was developed by Zhou and Wysk (1992). Their work was guided by three observations as to why the application of cutting data models in industry had been limited:

a) "...parameters for the tool life equation are not readily available since tests must be conducted to find these parameters which pertain to the machining process to be performed",
b) "...tremendous effort is required for implementation. It may not be worth the effort to obtain and enter all the necessary data required for optimisation",
c) "...unexpected tool failure due to the random nature of tool life is not

normally accounted for in deterministic models. Discrepancies between expected values and the actual performance have been experienced on the shop floor".

To minimise the entry of data into the system, a database was implemented which collected data pertinent to the processes. Again, though, the optimisation of cutting speed was deterministic, based on a constrained objective function. A penalty cost was included, which covered such costs as bringing the system back to normal after an in-process tool failure.

Dhage and Usher (1993) recognised two problems with the work of some of the other researchers in the field of tool selection:

1) the systems were constrained in either the parameters considered or the type of cut permitted (either roughing or finishing),
2) the assumptions made in the selection process weakened the selection.

The methodology of selection that they adopted was similar to that of Domazet (1990), in that it was a combination of both algorithmic and non-algorithmic methods. It was possible to consider all tools in the database for the cut, including roughing tools for finishing and vice versa. In this system, cutting data was taken from an insert database. There was also a reasonable amount of user involvement as the software progressed through the various stages of tool selection at the operation level.

The concept of a knowledge-based module for tool selection cutting data was used by Maropoulos and Gill (1995) and Maropoulos and Alamin (1995) in two papers which jointly describe the work carried out. As usual, the system had two main functions:

1) an expert system for selection of tools for operations,
2) specification of efficient cutting conditions.

The cutting data could be taken from two sources. A tools database contained details or attributes of previous jobs and the associated cutting data as records, where the cutting data had been approved as satisfactory by the appropriate personnel.

Initially, database records were selected for identical jobs, in terms of material type and type of cut. The cutting conditions were then calculated, based on the algorithms contained in Maropoulos and Hinduja (1990) and (1991). If various constraints were violated, data from the database was used instead of the calculated data. Interestingly for these types of equations, there was no explicit tool life consideration. Refinements included vibration analysis. Maropoulos and Gill noted that "...algorithmic modelling is an efficient and reliable method for generating initial data for new component materials, machine tools, cutting tools and carbide inserts".

The work was tested under laboratory conditions. In the majority of cases, the systems predictions were found to work at the first attempt. It was noted that the system required an identical material type for the approved and new operations. It was not tested with a new material for a new job. However, a new material would:

1) require the alteration of cutting data,

2) probably result in the reduced accuracy of data,

This inability to change materials easily was not perceived to be a disadvantage, since the system was aimed at industries where components are made from similar materials e.g. the automotive industry.

Fuzzy logic was used by Chen et al (1995) for the selection of both tools and cutting data. Fuzzy logic is useful where there is partial and imprecise information. The basic optimising model used for determining cutting data was conventional. However, they noted that some of the coefficients used in the model were of a "fuzzy" nature. One example was the machining cost with overhead, which is normally considered to be constant, but "...it is hard to judge whether...$1.5 or ...$1.6 is more reasonable". The system also had a learning capability for self-improvement.

One criteria for effective tool selection is that there must be sufficient spaces in the tool changer for all the selected tools, which was an issue raised by Maropoulos and Hinduja (1989). Their solution was to substitute one tool for another, which is a procedure that a tool selection system should be able to handle. If necessary, the wear rate of the selected tool was altered so that an integer number of components were machined before the tool failed, whilst minimising the increase in the machining cost. A similar approach was advocated by Arsecularatne and Mathew (1992), except that they always increased the cutting speed.

The multi-batch tool selection problem raises another issue related to tool selection. For example, Bard (1988) described a typical tool selection dilemma. Each batch to be machined has its own set of tools, which must be in place in a limited-capacity tool magazine prior to machining taking place for that batch. Each time one or more tools are switched for new tooling, a cost is incurred which is proportional to the number of switches that have taken place. The solution that Bard adopted to minimise the number of switches was to re-schedule the batches. An alternative solution would have been to select different tooling.

2.9 DISCUSSION AND CONCLUSIONS

During the review of this literature, a number of observations were made. Whilst general in nature and not applicable in every case, nevertheless they do summarise the situation:

1) Many researchers have attempted to optimise cutting conditions. There was no doubt that the mathematical procedures used did determine theoretical optimum conditions. However, in practise this would depend on the quality

of input data. Implicit in the methods was the assumption that the input data was always correct. Under shop floor conditions, this was unlikely to be the case.

2) In some cases, optimum cutting conditions were determined. However other researchers, using the same example but a different methodology, would arrive at a different set of cutting conditions. This posed the question as to which set of conditions were truly optimum.

3) In many cases, only one or two examples were produced. Whilst laboratory conditions provide assurance in this regard, it is more difficult to have similar confidence industrially, given typical shop floor conditions. It is perhaps revealing that very little industrial application or even testing appears to have taken place of any of the proposed methods. If machining was carried out, this simply proved that the conditions worked, rather than that they were optimal.

4) In a number of cases, the proposed methodologies were reliant on fed back shop floor data. How this was to be carried out was never made clear.

5) In many cases, there was a reliance on experimentally derived data. Whilst in theory such data could be stored in a data bank, this was provided that it existed for the particular situation in the first place.

6) In the case of multi-pass turning, there was no clear consensus as the preferred approach i.e. equal depths passes, unequal depth passes or equal depth passes with the last pass if an unequal depth.

7) In tool life work, there was a high dependency on either the Taylor equation,

the extended Taylor equation, or variations of these.

8) In tool selection work, even when expert systems were used, invariably cutting data selection was algorithmic.

9) Algorithmic methods for determining cutting data and machining data banks relied very much on each other. The classification of the method was defined by which method was primary. If an algorithm used stored data then the method was algorithmic. However, if data was taken from the data bank prior to any calculations, then the method was defined as a data bank.

10) There was no evidence that anyone had attempted to solve the multi-batch tool selection problem. Efforts were concentrated on a specific feature of a component. It was not possible to determine whether this was due to a lack of a reliable cutting data selection method for the multi-batch problem. However, it was likely that this was because it was considered that the single feature/component/batch problems had still not been satisfactorily solved.

11) Irrespective of the method chosen, there was very little difference in either the objective functions or the constraints.

In summary, if the multi-batch problem was to be tackled, there was a need for a reliable method for selecting cutting data. The preferred method for cutting data selection was algorithmic, based on a variation of Taylor's equation for tool life. Since there was apparently nothing to choose between the different multi-pass methods, at this stage the simplest was chosen i.e. equal depth passes. At a later stage, one of the other methods could be substituted, if required. Whilst optimisation of the data was obviously desirable, the whole concept of optimisation on the shop floor needed to be examined.

CHAPTER 3

COLLABORATING COMPANIES

3.1 INTRODUCTION

The work in this thesis was carried out in collaboration with two companies:

a) Rolls Royce Industrial Power Group, Reyrolle Switchgear,
Hebburn, Tyne and Wear,

b) Harkers Engineering,
Stockton on Tees, Cleveland.

They are referred to as Reyrolle and Harkers respectively and their involvement in the project was the provision of resources. These resources consisted of both personnel and equipment. As a result, all the trials and tests described in this thesis were carried out on either one or both companies' premises, using their production machine tools and their personnel.

Both companies were "...representative of two important sectors of manufacturing industry: the sub-contract machining of large high value, high integrity components on a unit basis and the batch manufacture of relatively simple components for use in electro-mechanical systems." (Simmons and Maropoulos (1989)). Alternative descriptions would be those of a jobbing shop (Harkers) and a make-to-order company (Reyrolle).

Jobbing manufacture is concerned with the manufacture of one-off jobs, often on a sub-contract basis. It is characterised by small batch sizes, often as little as one. Frequently items are not repeated and if they are repeated, there is likely to be a long time period between repeating items. This variety of work does not allow for shop floor trials to try and obtain optimum tooling selections and cutting conditions. Furthermore, sub-contractors can be asked to machine a wide range of materials, including those materials where their experience is limited. In these circumstances they can be content to arrive at a set of cutting conditions that will perform the machining operation, irrespective of efficiency. In addition, there may be other considerations e.g. heat input into the material, that give the efficiency of the operation a very low priority.

Where sub-contract machining is involved, the design is carried out by the customer, with no regard to the tooling held in stock at the sub-contractor's premises. Given the wide choice of tools made available by the various tool manufacturers, it is inevitable that tool inventories tend to be large.

Make-to-order companies make complex items in small numbers. Although the product is generic, each order is generally unique and it is rare for an order to be repeated exactly. There can even be differences between supposedly identical items built for the same order. Even small changes in an overall specification may have a significant influence on the design and manufacture of the items which make up a complete assembly or product. These items are often made by batch manufacture. However, these batches frequently tend to be small and the batch variety is high. Again, there can be long periods between repeat or similar batches. As batches reduce in size, so set-up time becomes more important.

In addition, as with jobbing manufacture, there comes a point with make-to-order batch sizes where insufficient machining is carried out on a batch to permit the optimisation of either tools or cutting data. This is also a function of component size, with smaller components being more prone to lack of optimisation during cutting, due to the reduced machining time. A further complication is that with the shortened machining time for a batch, brought about by the reduction in batch size, a tool may not reach the end of its life at the end of the batch. It is then available to machine further batches of different components.

This chapter focuses on the two companies, concentrating on the salient similarities and differences between them, in an effort to give a better understanding of the way in which they work. This understanding is important in the context of the testing carried out on their premises and in particular chapter 4, which covers the design of experiments.

The purpose of this chapter is not to give an in-depth analysis of the two companies. It is intended simply to describe them in such a way that the work in this thesis can be better appreciated. Therefore sections 3.2 and 3.3 describe the companies in qualitative terms, looking at each one individually. This is followed by a quantitative comparison in section 3.4. The next sections examine various aspects of the tooling systems, with section 3.5 looking at tool ordering and costs, section 3.6 examining tool inventories levels on the shop floors and section 3.7 covering tool store records within Harkers. The role and experience of the part programmers is discussed in section 3.8. The findings of this chapter are summarised in section 3.9 and includes an explanation of some of the findings, in terms of company culture.

3.2 DESCRIPTION OF HARKERS ENGINEERING

Harkers is a family-owned company which started out approximately 100 years ago by manufacturing marine diesel engines. Nowadays it is a sub-contract machine shop, specialising in precision work such as aerospace components and gas turbine casings. The components that they machine are often of a complex nature, such that other sub-contract machine shops may be reluctant to consider the contract. Harkers pride themselves on taking on jobs that no other company is able to, or prepared to, consider. Their reputation is such that they obtain considerable work from America.

Until comparatively recently they would have been considered a jobbing shop. However, for commercial reasons they now actively seek work which would be classified as batches, although they still carry out jobbing work as well. Nevertheless, the batches are normally small in size. A typical job for Harkers will weigh several tonnes, be larger than one cubic metre and require several hours machining time for each operation.

3.3 DESCRIPTION OF REYROLLE SWITCHGEAR

Reyrolle was a constituent company of the Northern Engineering Industries (NEI) group, and thus became a member of the Rolls-Royce group of companies when the two groups merged. Its product range is the manufacture of switchgear, typically for power generation and transmission applications. Thus its activities fit in with the main business of Rolls Royce Industrial Power Group.

In common with the rest of the industrial switchgear sector, Reyrolle is a make-to-order organisation. They generally manufacture components in medium size batches, although they are actively trying to reduce the size of their batches, and contend with a wide variety of component designs. Typical components are small (they can generally be manhandled) and consequently machining operation times are short.

3.4 COMPARISON OF THE TWO COMPANIES

The similarities and differences between the two companies are summarised in table 3.1:

	Harkers	Reyrolle
Total machining turnover*	£4m	£6m
No of CNC machines	21 (approx)	20 (approx)
Total tool inventory replacement cost*	£0.5m - £0.75m	£1m
Batch size range*	1 - 6	1 - 1,500 (typically 100 - 200)
Typical component size	> 1 tonne, > 1 m^3	< 1 kg, < 0.1 m^3
Typical machining time per part*	210 hrs	6 minutes (80% parts lower) (20% parts higher)
Typical set up time per part*	90 hrs	1.5 mins
Typical number of set ups per part*	4 - 8	1 - 3
Industrial classification	Jobbing	Batch/Make to order
Typical work materials	Cast iron, 'exotic' materials such as inconel and titanium	Mild steel, brass, copper, aluminium
*Simmons and Maropoulos (1989)		

Table 3.1

Comparison between the two companies

3.5 TOOL ORDERING AND TOOL COSTS

Harkers used a conventional ordering system whereby orders were placed, as and when necessary, with the appropriate suppliers. Although they had a preference for certain tool suppliers, in essence tools were ordered from any supplier who could meet the order requirements. A number of personnel within the company were authorised to order tooling. At the beginning of the project this number of personnel was seventeen, although this number was subsequently reduced. Part of the reason for the reduction was that they often received tools and were unsure who had ordered them, or why. At the completion of the project, this problem had not been fully eliminated.

The orders were coded to reflect the type of items concerned. These cost codes covered such categories as tooling, tooling consumables, raw materials, bought-in services and other machine shop consumables. This information was collated into the nominal summary, which was available as a computer printout, broken down by the relevant cost codes. It was from the nominal summary that the tool cost information could be taken.

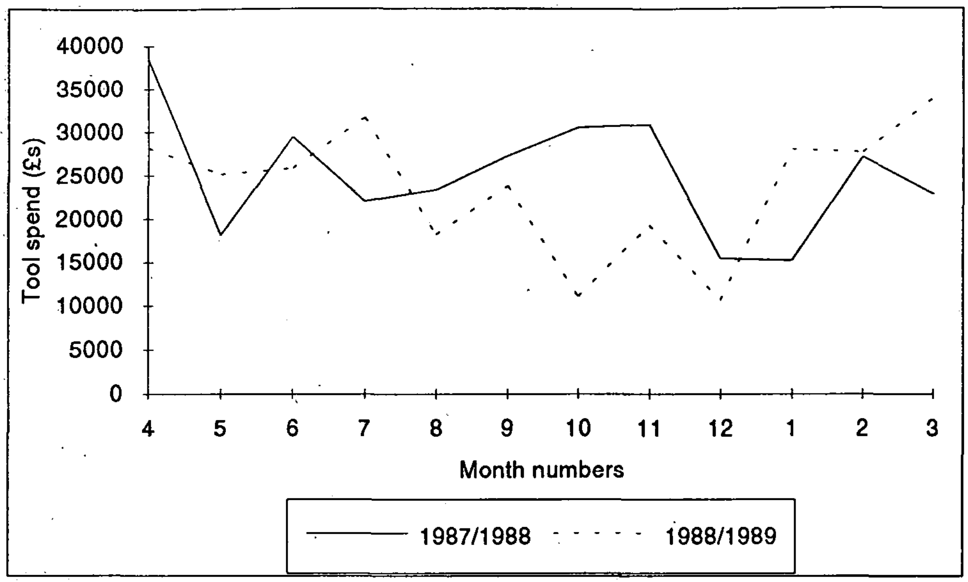
Reyrolle had put all their tooling information into two spreadsheets on a stand-alone PC computer. They had rationalised their tool suppliers and only used two, with one spreadsheet per supplier. These spreadsheets were used as databases and included in the information for each item were the minimum, maximum and current stock levels. Once a week, using suitable macros, a list was generated from each spreadsheet for all the items requiring re-ordering, based on the information held in the computer. These lists were given to the relevant suppliers as orders. The tool cost information could be extracted from these weekly lists, provided it was accurately maintained.

Data on the expenditure on tooling for both companies was collected for the project (from the nominal summary in the case of Harkers and for Reyrolle, from the weekly lists). Example tool purchase costs are shown in table 3.2 and are shown in more detail in graphs 3.1 - 3.4. Two graphs are shown for each company, these being monthly or weekly spending, as appropriate, and cumulative spending.

Reyrolle		
	1989	**1990**
Total	£98203	£50595
Weekly mean	£ 2046	£ 2300
Standard deviation	£ 355	£ 348
Standard deviation as percentage of mean	17.33%	15.13%
Note 1: 1990 consists of weeks 1-24 only *Note 2: Means exclude holiday shutdown weeks with zero expenditure*		
Harkers		
	1987-1988	**1988-1989**
Total	£ 300814	£ 283489
Monthly mean	£ 25068	£ 23624
Standard deviation	£ 6635	£ 7131
Standard deviation as percentage of mean	26.47%	30.19%
Note: The year runs from April to March		

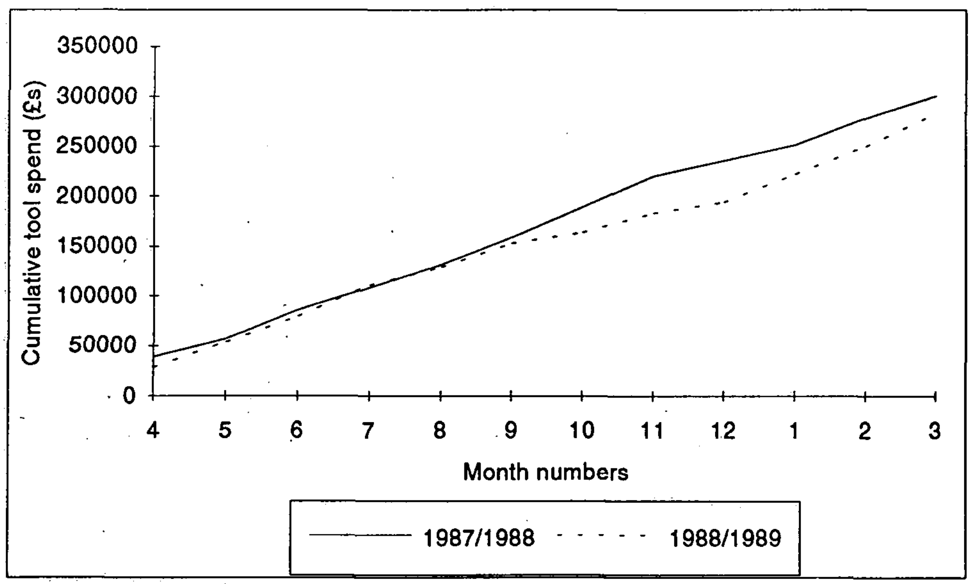
Table 3.2

Tool spending for collaborating companies



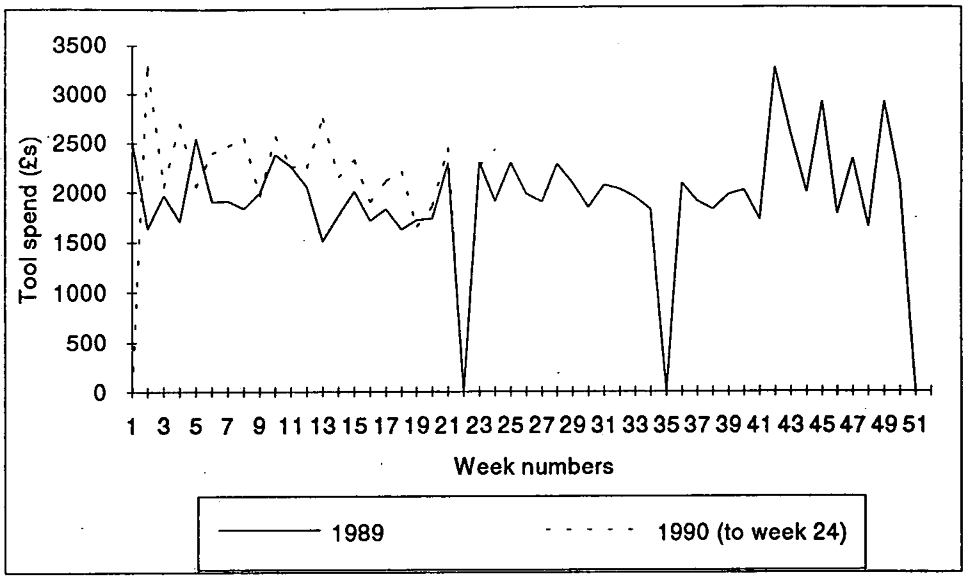
Graph 3.1

Harkers monthly tool spending - 1987/1988 and 1988/1989



Graph 3.2

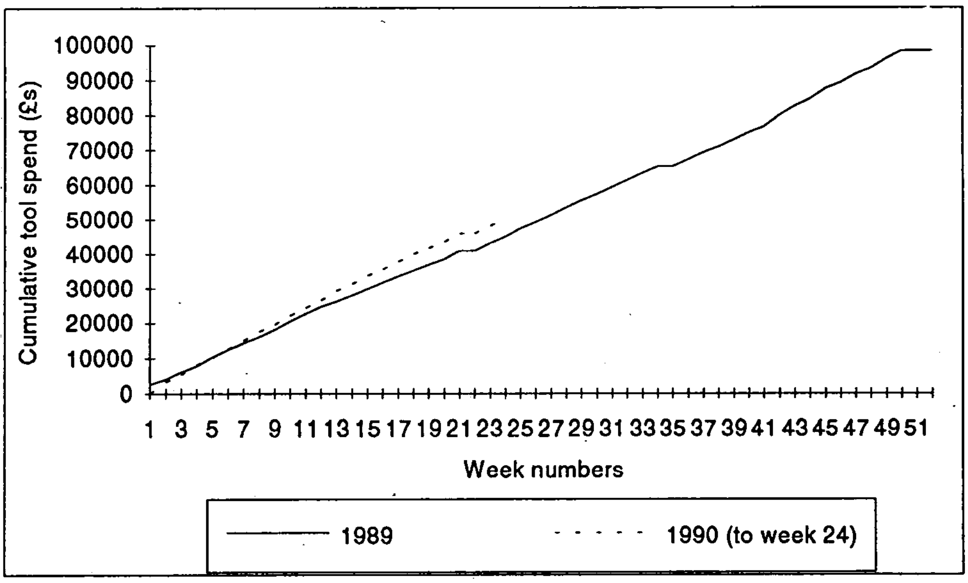
Harkers cumulative tool spending - 1987/1988 and 1988/1989



Graph 3.3

Reyrolle monthly tool spending - 1989 and 1990 (to week 24)

Note: 1989 weeks 22, 35, 51 and 52 and 1990 weeks 1 and 22 are holiday shutdown weeks with zero expenditure



Graph 3.4

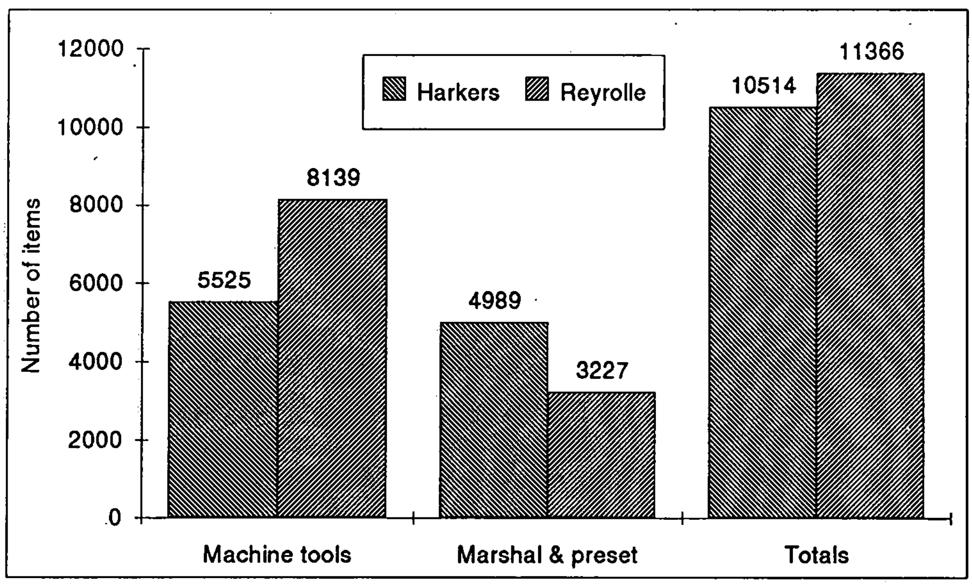
Reyrolle cumulative tool spending - 1989 and 1990 (to week 24)

3.6 TOOL INVENTORIES

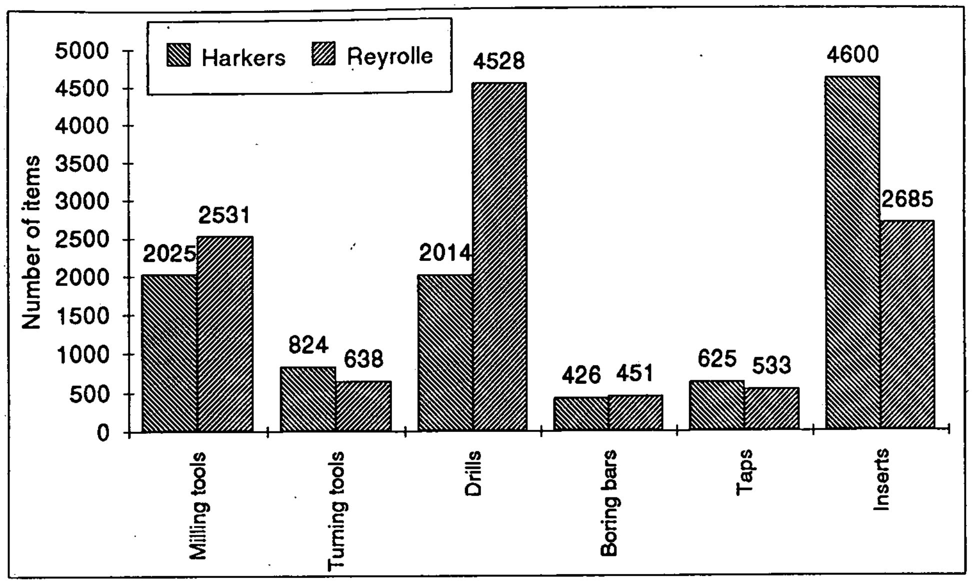
According to the systems operated by both companies, tools were meant to be returned to the tool stores at the end of a job. Observation of both companies showed this was not the case, with an apparently large number of tools of all types outside the tool stores. These were concentrated in a number of areas:

1) CNC machine tools
2) Tool pre-set area(s)
3) Tool marshalling area(s)

To determine the numbers of items concerned, a tool inventory of high speed steel tools, cutter bodies and inserts, was carried out in both companies outside the tool stores. (The tool stores was not included in the inventory). A description of the procedure used and a breakdown of the results are given in appendix A, whilst a summary of the results is shown in graphs 3.5 and 3.6.



Graph 3.5
Summary of tool inventories totals

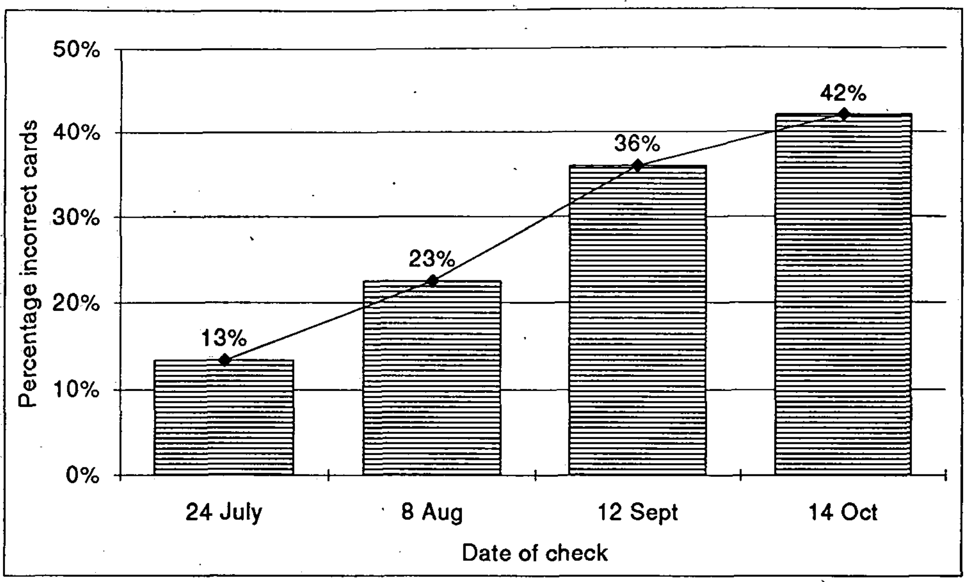


Graph 3.6
Summary of tool inventories by tool categories

3.7 TOOL STORE RECORDS

At one stage during the project, Harkers set up a tool store record system. This was a manual card index system and was designed to record the stores location and stock quantity of tools. The system was designed to be operated by the tool storeman. This provided an opportunity to observe whether a system of this nature was viable in an environment such as Harkers, or whether the information held in the system would degrade.

At the time when the checks were carried out, cards were only made up for inserts, with the intention of adding cards for other tooling later. The method of checking was to select a number of record cards at random. (The population size was 127 record cards, with sample sizes ranging from 30 to 50.) The total contents shown was then checked against the actual contents at the specified stores location, both for number and type of items. The number of incorrect cards (expressed as a percentage of the total number of cards checked), is shown in graph 3.7. From graph 3.7, it can be seen that the number of incorrect cards increased every month.



Graph 3.7

Percentage of incorrect cards in tool stores card index system

3.8 PART PROGRAMMERS

A number of writers have commented on the role of the parts programmer. For instance, according to Balakrishnan and Devries (1982):

> "The introduction of numerical control gave management the opportunity to shift the responsibility of feed and speed selection from the operator to the parts programmer. However, in many instances, the programmer was not well versed in metal cutting technology."

Lindberg et al (1982) agree with this:

> "...critical machining decisions...are now made by NC programmers and process planners away from the production environment. These programmers and process planners often do not have the necessary experience to completely understand the effects of their decisions."

Wang and Wysk (1986) are as critical:

> "However, due to the introduction of numerical control...the responsibility of assigning machining data has shifted to parts programmers and process planners. Today's planners may not have the same experience as operators do to accomplish this task effectively. Furthermore, these planners usually

perform their functions in an office, receiving little feedback from the shop concerning the adequacy of their plans."

These statements suggest a shared view that parts programmers have little experience for the job that they are doing and that they are unaware of the results of their decisions. In other words, there is no learning associated with the job. Since it was their knowledge and experience that it was intended to duplicate and improve on, it became important to determine the true state of affairs.

Discussions with the part programmers and observation of them within both companies revealed a different situation to that described by the writers cited above. When a new job was machined for the first time, provided the part programmer responsible was working the shift, he would normally be present at the machine. Often he would be responsible for recommending changes in the program as a means of achieving satisfactory machining conditions. Furthermore, both companies had procedures, such that any changes made to the program by the operator were reported back to the part programmer, so that the program concerned could be updated for future use.

However, their role went further and they were often called to a machine where problems had occurred after the initial setting up period. For example, Keating (1991) reported an incident at Reyrolle (GS is a part programmer):

> "Went on the shop floor with GS to view a problem one of the machinist(s had) encountered. It focused around a component that was not meeting the required tolerances. The same machining operations on this type of component on a previous occasion caused no problems. The component could be classified as a thin wall cylinder. GS believed that the machinist was over tightening the fixtures and it was then suggested that after a particular pass the bolts on the fixture should be loosened for a length of

time and then re-tightened. This seemed to have solved the problem. GS also suggested that a torque wrench should be used in such cases to achieve the proper set up of fixtures."

This was a prime example of the part programmer using his experience and possessing more knowledge than the apparent 'expert' - in this case the machinist.

To determine their level of experience, each part programmer and process planner within both companies was asked to complete a simple questionnaire anonymously. The questions asked are shown in box 3.1 and the results of the survey are shown in table 3.3 and graph 3.8.

1)	Time served apprenticeship - YES / NO
2)	Highest qualification
3)	Age
4)	Total number of years industrial experience
5)	Total number of years as machinist
6)	Total number of years as part programmer/process planner
7)	Other work experience - Please specify, including total number of years:

Box 3.1

Questions on the part programmers survey

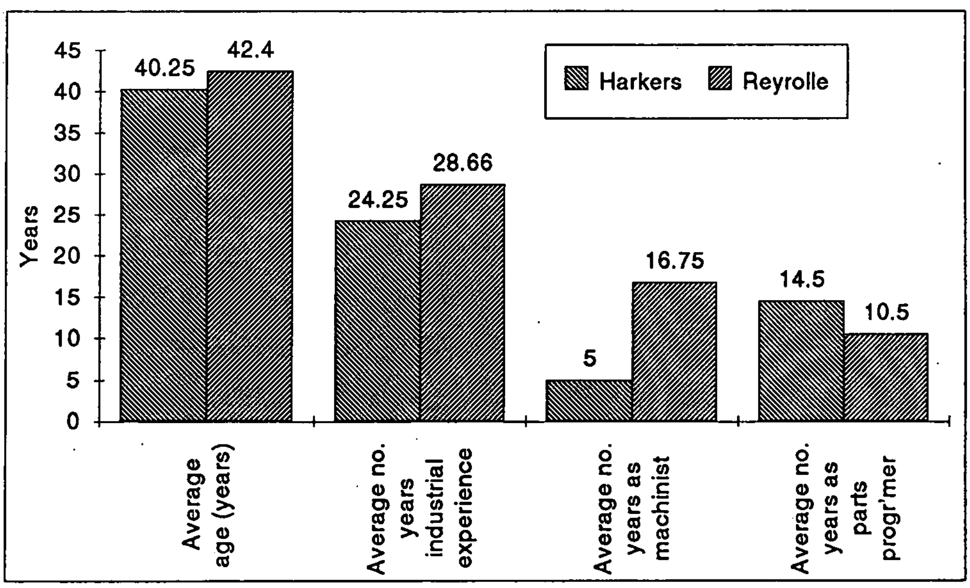
Most respondents made no comment concerning other work experience. However, the comments received included:

Reyrolle (sample size 6)	**Harkers (sample size 4):**
jig and tool designer and draughtsman - 30 years	production drawing office - 4 years
jig and tool drawing office - 3.5 years	inspection and metrology - 1 year
instrument mechanic - 2 years	process and plant engineering - 1 year
	industrial engineering - 5 years
	estimator - 4 years
	tool-making - 2 years

	Harkers	Reyrolle
Sample size	**4**	**6**
Time served apprenticeship (Numbers in brackets are the number of respondents)	YES (4) NO (0)	YES (5) NO (1)
Highest qualification (Numbers in brackets are the number of respondents)	HNC (3) FTC (1)	HND (1) HNC (1) ONC (1) Final C&G (2) O levels (1)
Age (years)	Average: 40.25 Range: 32 - 49	Average: 42.4 Range: 26 - 56 (1 respondent declined to answer)
Total number of years industrial experience	Average: 24.25 Range: 16 - 33	Average: 28.66 Range: 10 - 41
Total number of years as parts programmer/process planner	Average: 14.5 Range: 6 - 22	Average: 10.5 Range: 2 - 29
Total number of years as machinist	Average: 5 Range: 4 - 6	Average: 16.75 Range: 7 - 24 (2 respondents declined to answer - possibly having no machining experience)

Table 3.3

Summary of part programmers/process planners experience survey



Graph 3.8

Partial summary of part programmers/process planners experience survey

3.9 DISCUSSION

Table 3.1 showed that the operations of the two companies were of a completely different nature, in aspects ranging from set up time to batch size and work materials. This was not unexpected, since the two companies produced completely different products.

On the subject of tool expenditure, table 3.2 showed that, on average, there would seem to have been very little overall difference between the two years for each company. The smaller standard deviation, when expressed as a percentage of the mean, for Reyrolle was presumably a reflection of the more standard workload of the company.

It was apparent from the cumulative graphs (graphs 3.2 and 3.4) that in both cases expenditure rose reasonably smoothly throughout the year. This was despite the apparent weekly or monthly variation in graphs 3.1 and 3.3. Furthermore, overall there was little difference between the two periods on the cumulative graphs.

The exception to this was Harkers, where there was a reduction in tool spending between the summer and Christmas for 1988/1989, compared to 1987/1988. This may have been due to a reduced workload. However, there was an almost complete recovery to the previous years' expenditure before the end of the financial year, indicating a possible upturn in workload.

Graph 3.2 showed a reduction in tool spending during the Christmas period for both years at Harkers, whilst graphs 3.3 and 3.4 clearly showed the Reyrolle holiday shutdown weeks. Other than this, there was no marked seasonality. It might have been expected that there would be a tendency to re-equip with new tools at, for example, the beginning of the financial year[1]. However, tools were evidently bought as required throughout the year, which was surprising given the size of the tool inventories described in section 3.6.

It had been expected that the two companies would show quite a difference in the totals of the tool inventories (graph 3.5). In the event, the difference between them was quite small. Even when the machine tools and marshalling and preset areas were compared, the differences were not as pronounced as might be expected. When examined by categories the inventory levels were, with few exceptions, also comparable. The main exception was in the number of drills. However, the Reyrolle value was somewhat distorted by the discovery of a steel cabinet on the shop floor, containing over 3000 high speed steel drills. The higher number of inserts at Harkers was probably a result of the 'exotic' materials that they machined, where tool lives could be unpredictably short.

Although the size of the tool inventories were comparable, section 3.5 has shown that annual tool costs differed greatly, with Harkers spending appreciably more. The reason for this was that tooling purchased by Harkers tooling was, on average, physically much larger than at Reyrolle. This was a direct consequence of the typical size of jobs handled by each company, and hence the size of the machine tools. Further confirmation of this was demonstrated by the fact that, as a percentage of turnover, Reyrolle spent less on tooling than Harkers, yet the tool

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[1] In a subsequent year to the periods used for this data, during one mid-financial year period Harkers management issued an instruction to restrict tool spending for a specified period. Had that year been examined for tool costs, it is quite possible that this instruction would have been apparent in the data. It may also have been followed by a period of increased spending. That such an instruction was issued tends to indicate that, even if tool spending is not excessive, it is still greater than necessary. It does pose the question as to whether the steady rise in cumulative tool expenditure during the year is necessary. It is not known if a similar instruction was issued during the period covered by the data here.

inventories were similar.

Among the reasons for the large number of tools on the shop floor were:

1) operators retaining favourite tools for future use,
2) tools 'stolen' from another machine, for a variety of reasons,
3) tools not returned at the end of a job because a different operator (on a different shift) took the tool out in their name,
4) broken tooling that the operator did not want to admit to,
5) tooling retained because there was a known shortage,
6) tooling retained because it was known to be needed again soon.

The check on the stores record cards (graph 3.7) showed a very interesting situation. Although degradation of data was expected, the rate of degradation was higher than expected. In less than three months, about a third of the cards had incorrect data entered onto them. There were a number of possible reasons for this:

1) the tool storeman was issuing tools without entering them on the cards,
2) errors were being made when entering data onto the cards,
3) tools were being taken without the tool storeman's knowledge, and hence not being entered on the cards[1],
4) the shop floor worked a three shift system, whilst the tool storeman only worked a normal day shift, yet tools had to be issued when he was not present[2].

---

[1] The writer witnessed such an event, when an operator walked into the stores. The storeman was at the back of the stores, out of sight. The operator helped himself to tooling, in this case a packet of hacksaw blades, and then left. The storeman was unaware of what had happened.

[2] Locking the tool stores when the tool store man was not on shift e.g at nights, did not eliminate the problem. The key was held by a supervisor or supervisors, who were meant to issue tools. However, it was admitted that the key would often be handed over to the operator seeking tools.

These situations demonstrated that the companies operated in an environment that could best be described as 'informal' or 'flexible'. Despite procedures and instructions being in place, they were regularly ignored. However, there was no bad intent in this method of working. The underlying philosophy was to finish jobs as soon as possible and to the best possible standard.

Of particular interest in both table 3.3 and graph 3.8 were the similarities in the experience of part programmers and process planners in the two companies. Where graph 3.8 showed a major difference between the two companies was the average number of years as a machinist. Perhaps this was not surprising given the different backgrounds of each company and the distinct industries within which each company operated, which may well have led to different training schemes and promotion principles.

At Reyrolle it took longer for a machinist to be promoted off the shop floor, whilst Harkers was more flexible in this respect. As a generalisation, both companies seemed typical of certain types of companies i.e. a strategic business unit of a multi-national corporation (Reyrolle) and a long-established family-owned concern (Harkers). However, conclusions drawn from the survey should be tempered by the small sample sizes.

Although the intention of this chapter was to describe the companies, it has served to highlight another issue. From some of the data presented in this chapter, there would seem to be a lack of managerial control with regard to tooling. Tool inventories outside the tool stores might be considered excessive and the situation with regard to the tool stores record cards suggests that control can be improved. Furthermore, informal observation of other functions within both companies has shown that this situation is not restricted to tooling.

However, since both companies have survived for many years, this suggests that this apparent lack of managerial control is more than just that. In fact, it was closely related to the flexibility of the companies, which was essential for survival in their particular markets.

Modern manufacturing systems can be categorised in five ways (Rembold et al (1993)). As figure 3.1 shows, at one extreme is the transfer line, followed by the batch flow line, the flexible manufacturing system (FMS), the manufacturing cell and the NC machine at the other extreme. The transfer line has the capacity for high production rates, but it can only handle a limited range of workpiece types. Hence flexibility is low. The NC machine, on the other hand, has much lower production rates and can produce a wide range of workpiece types, since it is a much more flexible system. It is into this latter category that both Harkers and Reyrolle fell.

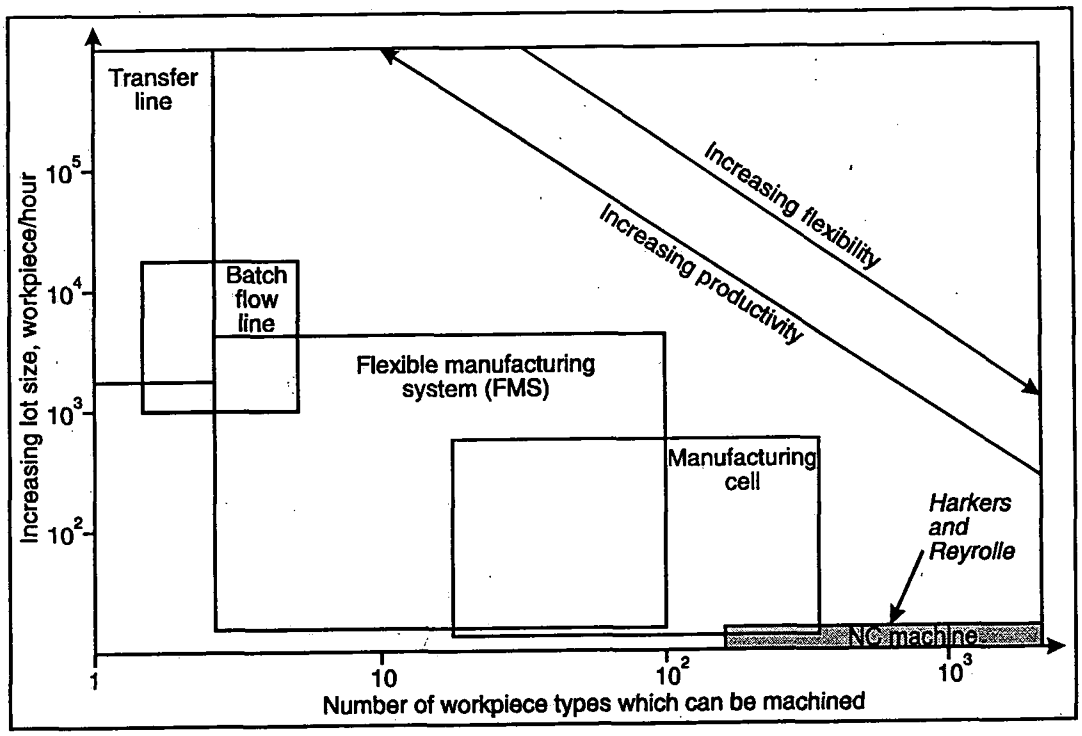

Figure 3.1

Modern manufacturing concepts (Rembold et al (1993))

Wild (1984a) has summarised work by Woodward (1965), which examined the relationship between technology and the nature of an organisation, which also describes figure 3.1. The general conclusions, as summarised by Wild, are:

> "Task uncertainty
>
> The greater the routineness or repetitiveness of tasks and the less the task variability, complexity and uncertainty, then the less the degree of participation in organisation decision-making and the greater the formalisation of roles, procedures and practices.
>
> Task interdependence
>
> The greater the interdependence of tasks, roles and activities and the less the rigidity of the work flows, then the greater the participation in decision-making and the less formalised the authority structures, procedures, etc.
>
> Work flow uncertainty
>
> The less the variability, complexity or uncertainty of work flow, the greater the standardisation of inputs and outputs, then the more formalised and centralised the management, the greater the vertical integration and departmentalisation, and the more sophisticated the control procedures.
>
> External uncertainty
>
> The less the rate of change in products/service specifications and ranges, the less the rate of programme/demand change, the less the market uncertainty and the greater its homogeneity, then the more mechanistic the management of the organisation, the greater the normalisation and centralisation of management, and the more structured the organisation."

Many companies have written procedures and other documentation, which details how various functions should be carried out. This is particularly so since the introduction of quality standards such as BS 5750. Both Harkers and Reyrolle were accredited to BS 5750 and had suitable documentation. However, one of the factors which differentiated the level of flexibility between the different types of manufacturing systems was the level of adherence to these procedures, which was a function of company culture.

The organisation ideology or culture of a company performs a number of functions, including (Harrison (1972)):

- "♦ Prescribes the appropriate relationships between individuals and the organisation (i.e. the 'social contract' that legislates what the organisation should be able to expect from its people, and vice versa).
- ♦ Indicates how behaviour should be controlled in the organisation and what kinds of control are legitimate and illegitimate.
- ♦ Depicts which qualities and characteristics of organisation members should be valued or vilified, as well as how these should be rewarded or punished.
- ♦ Shows members how they should treat one another - competitively or collaboratively, honestly or dishonestly, closely or distantly."

In other words, the culture governs the behaviour of individuals, irrespective of any written instructions or procedures. The culture is the set of unwritten rules which enable the organisation to function.

In a company which requires flexibility, it is not feasible to provide written instructions to cover every eventuality. Should this be attempted, the company would become too inflexible and it would be unlikely that the procedures would cover all the required circumstances. As a result, many activities carried out are not in accordance with the specified company practice. To an outside observer, this may appear to be lack of management control. However, the management may be aware of the situation and allow it to continue since the resulting work is of the appropriate quality. They are aware, either explicitly or implicitly, that the organisational culture will normally prevent a deterioration of the situation and in fact the culture will act as a control.

In those cases where there is a deterioration of working practices beyond that which is acceptable, the management will exercise greater control. However, even where they attempt to tighten the working practices to more closely match the rules and procedures, i.e. less flexibility than before, often the final situation will be very similar to the original situation i.e. the equilibrium between rules and working practice will have been restored. This may also be considered to be part of the culture, in that the shop floor will know that periodically the management will attempt to impose its will in certain ways, and that this new situation will only be temporary.

For example, in section 3.6, the number of tools outside the tool stores was discussed. Harkers and Reyrolle management would periodically give instructions for all tools on the shop floor to be returned to the tool stores and that this should continue to be normal practice. When this was carried out, it is doubtful whether all the tools were returned on these occasions but in any case, within a period of time the situation would revert back to normal i.e. a considerable number of tools would be retained on the shop floor.

The reason that the situation returned to normal was that culture is a very powerful force. Whilst culture changes are possible, to deliberately carry out such a change requires considerable time and effort. Very few organisations can afford to utilise the necessary resources for anything like the time necessary to effect a permanent change. Hence the equilibrium tends to be maintained.

To summarise the situation, with Harkers, and to a lesser extent Reyrolle, flexibility was the key to survival. This flexibility was inherent in the culture and allowed a greater degree of freedom of action than may be found in more formalised environments e.g. batch flow line or transfer line. The quality of the operators is higher in flexible environments, which helps compensate for the lack of managerial control. Provided all those concerned are part of the culture, the equilibrium should be maintained.

CHAPTER 4

DESIGN OF EXPERIMENTS

4.1 INTRODUCTION

The work was carried out in three stages, the first stage being the encoding into software of the initial algorithm. This software was then modified in two stages. These three versions of the software were designated Systems 1 - 3 (generically referred to as the system). At the end of each stage, the work was subjected to testing, as a means of checking the effect of the work up to that point. The final stage (System 3) incorporated much more extensive testing than the previous two stages (Systems 1 and 2), as a way of providing confirmation of the results. Testing of the first stage (System 1) acted as a control, or reference, for the subsequent work. At each stage testing consisted of comparing the output from the system for a range of jobs (where a job was defined as a single test with the system and was therefore the machining of a single feature or element) with actual data from the shop floor, in terms of the cutting parameters (cutting speed, feed rate and depth of cut).

Montgomery (1991) provided a number of guidelines for the design of experiments:

1) recognition of and statement of the problem,
2) choice of factors and levels,
3) selection of the response variable,
4) choice of experimental design,
5) performing the experiment,
6) data analysis,
7) conclusions and recommendations.

Section 4.2 provides a background to the tests, in terms of the industrial conditions and constraints. The subsequent sections (4.3 - 4.9) discuss the points made by Montgomery.

4.2 BACKGROUND TO THE TESTS

Chapter 3 has described the two companies involved in the testing of the work. All the tests were carried out on their premises, using their production machine tools and production components, with the assistance of their personnel. It was considered important to minimise any disruption to the normal course of the work in the companies, since the quality of the tests relied upon the goodwill of the personnel concerned. Consequently discretion had to be exercised when asking them to perform various tasks. In fact Harkers made some of their workforce redundant[1] during the project, hence the normal workload for the remaining personnel increased, making it harder for them to find the time to assist.

To minimise the disruption to the companies during the testing periods, wherever possible there was no attempt to influence the scheduling of jobs. This philosophy held good for the testing of Systems 1 and 2. The collection of data for System 3 was carried out in a different manner and this is explained in section 7.6.1.

There were a number of restrictions on which jobs could be used for the tests, although these restrictions varied depending on the purpose of the tests. A major restriction in all cases was the choice of machine tools used. In both companies different part programmers concentrated on different machines. For the testing periods both companies allocated one part programmer to assist. Therefore the range of machine tools available for testing purposes was limited to those which the part programmer was familiar with. Another restriction in most of the tests was in the choice of materials and/or tools to be used for the tests.

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[1] This was the first time during their 100 year history that such measures had been taken. There was an immediate change in the company culture in the production areas, from that of a family business with feelings of loyalty to a "them-and-us" approach. Not unnaturally, it also increased the feeling of insecurity amongst the workforce.

An additional restriction on testing was that the tester (i.e. researcher or part programmer) could not always be present. In some cases they were occupied elsewhere. Other than this, suitable jobs were often machined during the night shift[1], when the tester was not working. When this occurred, the opportunity to perform a test was lost. Similar problems were found with respect to weekend working.

As a consequence of these restrictions, the number of jobs that could be tested within an agreed testing period[2] was considerably less than the number of jobs passing through the workshop. It was decided to make the final testing period, which was for System 3, into the major test period to test the work fully, whilst limiting the earlier test periods to far fewer tests, acting more as a progress check.

4.3 RECOGNITION OF AND STATEMENT OF THE PROBLEM

The problem has already been described in section 1.4, which was to produce a method for determining cutting data for the multi-batch tool selection problems. The criteria which the methodology should have achieved, as specified in section 1.4, were:

1) the input variables should be readily available,
2) the system should have the ability to accept any material and to consider any material with any tool,
3) cutting data similar to accepted company practice should be produced,
4) the system should be industrially applicable.

---

[1] Reyrolle operated a two-shift system, whilst Harkers maintained a three shift system. Both companies also had certain production employees on a day shift system.

[2] An agreed testing period was that period of time which the company concerned had agreed to allow testing to be carried out. Such a period was a compromise between performing sufficient tests whilst causing the least disruption to the production operations.

Some of these criteria were difficult to assess experimentally, since they were subjective, whilst others were numerical. Examining these criteria individually:

1) **The input variables should be readily available**

One variable that was difficult to determine could cause more problems than several much simpler variables. As a general rule, the fewer the number of input variables, the better.

The ideal situation was no input variables. Whilst this may be have been a possibility in the future, when the system may be able to accept data from a CAD/CAM system, at the present stage of development this was not feasible. For the purposes of experimentation, this criteria was redefined as a reduction in the total number of input variables, provided values could be assigned to those variables that were left.

2) **The system should have the ability to accept any material and to consider any material with any tool**

This was a combinatorial problem, except that the number of combinations was unknown, since the full range of materials and tools were unknown. The alternative was to show that the system worked with a limited range of tools and materials. From this, it was reasonable to assume that other combinations would also work, although this assumption should always be borne in mind.

3) **Cutting data similar to accepted company practice should be produced**

This could be tested and analysed numerically. The details of the analyses are given in section 4.8 and the results of the tests included in chapters 5 - 8.

4) The system should be industrially applicable

It was not reasonable to expect a prototype system, developed for a research project, to be fully compatible with industrial requirements. Such acceptability would come later, when the commercial version was written, in terms of such considerations as user interfaces. In the context of this work, industrial applicability referred to whether the input data values could be determined in an industrial environment and the total number of input variables. In addition, subjective comments were solicited from those concerned with the tests as to the ease of use of the system undergoing testing.

During the Hawthorne studies (Handy (1985)) into the effect of output on working conditions, the productivity of the test group of females increased as the working conditions changed. This increase continued even when they were returned to the original, significantly worse, working conditions. It was concluded that their output had increased because they felt special at being singled out for a research role. In a later experiment, it was noted that a different group (this time males) were suspicious of a trained outsider, acting as an observer around the clock and who sat in a corner of the room. In this case, since nothing special happened as a result of his presence, in time the men relaxed and fell into normal working routines. Nevertheless, these two cases do illustrate the effects of research activities on production working.

It should be appreciated that to test industrial acceptability, particularly with respect to ease of use, the tests should be carried out by a company employee without any assistance from a researcher. As demonstrated above, to observe a test carried out by a company employee would invalidate the tests, since the act of observing may well influence the employee's actions. This would then only prove that the system was being used properly when being watched. There was no practical way to assess how an employee was using the system, without observing them and risking negating the tests. However, it was possible to form an assessment, based on the results and expert knowledge of the nature of the tests, as to whether the tests were being carried out correctly.

4.4 CHOICE OF FACTORS AND LEVELS

There were four factors concerned in the tests, which were the tool, the machine tool, the workpiece material and the workpiece geometry. Each of these factors was defined by one or more attributes. Wherever possible, the level of each factor was kept to a minimum. In some cases, the choice of one factor determined another factor. For example, for the testing of System 1, the machine tool was two levels i.e. two machines were used. The two machines used tools of different sizes, hence the tool factor level was also two. Ideally, only one machine would have been used, but this would not have generated enough data. Another exception was for some of the tests with System 2, where the intention of the test was to use a range of workpiece materials. In this case the material factor level was three.

The exception to this limitation of factor levels was the workpiece. Although there was a theoretical limit to the factor levels for the workpiece, since it only required one workpiece attribute to change to introduce another level, in practice the number of levels was considered to be without any limit. Where more than one test was carried out on the same workpiece (i.e. the same workpiece formed more than one job), each job had one or more different workpiece attributes.

4.5 SELECTION OF THE RESPONSE VARIABLE

The outputs from the system were the cutting parameters (cutting speed, feed rate and depth of cut). However, there was no useful way to compare the cutting parameters from a single test with the equivalent shop floor data. A more meaningful approach was to combine the results from several tests. This was done using the relevant means and standard deviations. Consequently these were the response variables.

4.6 CHOICE OF EXPERIMENTAL DESIGN

The choice of design involves three factors: replication, randomisation and blocking. These are discussed below:

1) **Replication**

This refers to the number of tests carried out during a single testing period. A single testing period refers to all the tests on a particular system within a particular company. It is usual practice to determine the sample size (i.e. the number of replicates or tests) before starting, to maintain the error within specified limits.

In section 4.2 it was explained that there were other constraints on the number of tests that could be carried out during a testing period. Therefore the philosophy of performing as many tests as possible was adopted. Nevertheless, this resulted in only a few tests for Systems 1 and 2: for reasons described above System 3 was tested more extensively (section 4.2).

Since the purpose of determining the sample size before testing is to contain the error, an alternative approach was to calculate the confidence limits (expressed as both a value and a percentage of the mean). This was done for each population mean at 95% confidence limits, using equation 4.1 (Cass (1973)):

$$\mu \text{ lies between} = \bar{x} \pm t_{(0.025,\, DOF)} \frac{s}{\sqrt{n}} \qquad \text{Equ 4.1}$$

where:

$\frac{\sqrt{s}}{n}$ = the standard error

and where:

μ - population mean

$\bar{x}$ - sample mean

$t_{(0.025, DOF)}$ - t-distribution at 95% confidence limit and DOF degrees of freedom $(DOF = n - 1)$

s - sample standard deviation

n - sample size

In other words, there was a 95% probability that $\bar{x}$ was not more than $t_{(0.025, DOF)}$ standard errors away from μ. The standard error is the standard deviation of a sampling distribution.

2) **Randomisation**

With randomisation, the order of the tests and the allocation of experimental material are randomly determined. This is to eliminate any extraneous effects, whereby a particular attribute of certain factors influences the results. However, in these tests, true randomisation was not possible. Jobs were selected for testing based on their position on the production schedule and no attempt was made to influence this order. If a job was available and suitable for testing, then the test was carried out.

Where randomisation may not have applied was when a component had more than one feature suitable for testing i.e. the same component was used for more than one job. Whilst not ideal, this was permitted, since it was necessary to perform sufficient tests. Where this occurred, it may have been the same operation on different elements e.g. external turning, or different operations on different elements e.g. external turning and boring.

3) **Blocking**

Blocking occurs when a number of the tests, which should be more homogeneous than the entire set of sets, are compared. It allows examination of the conditions of interest within each block. For the testing of Systems 1 and 2, there was not sufficient testing carried out to permit both blocking and also having large enough groups of data for analysis of the results. Nevertheless, limited blocking was possible by keeping the factor levels low.

With the increased number of tests for System 3, increased blocking was possible, in terms of the machine tool. Where blocking was used, this was not allowed to influence the order of the tests i.e. the order was determined by the production schedule, as explained above.

4.7 PERFORMING THE EXPERIMENT

The tests for Systems 1 and some of the System 2 tests were initially carried out by company personnel, in the presence of a researcher. Thus these tests were monitored. The later tests with System 2 and tests with System 3 were performed by company personnel only, without any monitoring of the tests. The justification for this has already been given in section 4.3.

As a result of this, it was not possible to know precisely how carefully the procedures were followed. Nevertheless, at the outset it was believed that examination of the results, allied to experience, would act as a good indicator. An example of this is given in section 9.2, in relation to tool life data.

4.8 DATA ANALYSIS

The tests were classified as simple comparative experiments, where the intention was to compare two conditions, or treatments. The analysis was designed to show whether the two sets of data were from the same population, where each set of data was sub-divided into cutting speed, feed rate and depth of cut. In other words, the analysis was:

the system cutting speed compared to approved cutting speed,

the system feed rate compared to approved feed rate,

the system depth of cut compared to approved depth of cut.

Both the means and the variances (or standard deviations squared) were compared, using the *t*-distribution and *F*-distribution respectively. It was assumed that the data was normal, or approximately normal, based on the Central Limit Theorem[1]. Details of the two analysis methods are given below (Cass (1973)).

Comparing Two Sample Variances (*F*-distribution):

1. Null hypothesis

   There is no difference in the variances of the populations from which the samples are taken:

   $$\sigma_1^2 = \sigma_2^2 \qquad \text{Equ 4.2}$$

   where σ_1^2, σ_2^2 are the variances of the populations.

2. Alternative hypothesis

   The variances of the populations are different:

   $$\sigma_1^2 \neq \sigma_2^2 \qquad \text{Equ 4.3}$$

3. Significance level

   The 0.05 significance level will be used.

---

[1] According to the Central Limit Theorem, if a number of independent random variables are drawn from a population, the variables will be approximately normally distributed. The approximation improves as the sample size increases, even when the population from which the samples are drawn is not normally distributed.

4. Identify the rejection area of the appropriate sampling distribution under the assumption that the null hypothesis is true.

Since a two-tailed test is required, the rejection area will be the extreme 2.5% of both tails. There are two critical values of F; one larger than 1 and the other smaller than 1. The smaller one is, however, the reciprocal of the larger. Therefore only one tail is tabulated.

The degrees of freedom (*DOF*1 and *DOF*2) are (n_1-1) and (n_2-1), where n_1, n_2 are the sample sizes. The upper critical value is therefore $F_{(0.025, DOF1, DOF2)}$ (where $F_{(0.025, DOF1, DOF2)}$ is the F-distribution at 95% confidence limit and *DOF*1, *DOF*2 are the degrees of freedom), which is obtained from tables.

5. Calculate the position of the sample result in the sampling distribution.

This is carried out by means of equation 4.4:

$$F = \frac{s_1^2}{s_2^2} \qquad \text{Equ 4.4}$$

where s_1^2, s_2^2 are the sample variances. If the variance s_1^2 is always the larger sample variance, this ensures that F>1 and hence the upper critical value can be used. The sample variances are used as approximations to the population variances, which are unknown.

6. Test the hypothesis

If:

$$F < F_{(0.025, DOF1, DOF2)} \qquad \text{Equ 4.5}$$

then accept the null hypothesis, otherwise reject the null hypothesis and accept the alternative hypothesis.

Comparing Two Sample Means With The Same Variance (*t*-distribution)

It is assumed that the variances of the two samples are from the same population. This is tested using the *F*-distribution (as above). If this is not the case, the following test cannot be used.

1. Null hypothesis

   There is no difference in the means of the populations from which the samples are taken:

   $$\mu_1 = \mu_2 \qquad \text{Equ 4.6}$$

   where μ_1, μ_2 are the population means.

2. Alternative hypothesis

   The means of the populations are different:

   $$\mu_1 \neq \mu_2 \qquad \text{Equ 4.7}$$

3. Significance level

   The 0.05 significance level will be used.

4. Identify the rejection area of the appropriate sampling distribution under the assumption that the null hypothesis is true.

   Since a two-tailed test is required, the rejection area will be the extreme 2.5% of both tails. The degrees of freedom, *DOF* are $n_1 + n_2 - 2$, where n_1, n_2 are the sample sizes. The critical value is therefore $t_{(0.025, DOF)}$ (where $t_{(0.025, DOF)}$ is the *t*-distribution at 95% confidence limit and *DOF* degrees of freedom), which is obtained from tables.

5. Calculate the position of the sample result in the sampling distribution.

   This is carried out by means of equation 4.8:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s\sqrt{\left(\frac{1}{n_1} - \frac{1}{n_2}\right)}}$$ Equ 4.8

where s is the combined standard deviation:

$$s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$ Equ 4.9

and where $\bar{x}_1$, $\bar{x}_2$ are the sample means.

6. Test the hypothesis

If:

$$|t| < t_{(0.025,\ DOF)}$$ Equ 4.10

then accept the null hypothesis, otherwise reject the null hypothesis and accept the alternative hypothesis.

Comparing Two Sample Means With Different Variances:

If the variances for the two samples are from different populations, testing with the *t*-distribution is not valid. The best that can be done in such circumstances is to calculate confidence limits for each of the sample means separately, in this case at 95% confidence limits (Cass (1973)).

μ_1 lies between $\bar{x}_1 \pm t_{(0.025,\ DOF)} \frac{s_1}{\sqrt{n_1}}$ Equ 4.11

μ_2 lies between $\bar{x}_2 \pm t_{(0.025,\ DOF)} \frac{s_2}{\sqrt{n_2}}$ Equ 4.12

where $DOF = n - 1$. If the two confidence bands do not overlap, then it is reasonable to assume that there is a difference between the means from which the samples come.

4.9 CONCLUSIONS AND RECOMMENDATIONS

After each analysis, conclusions were drawn concerning the results. These centred on whether the changes to the input data had affected the system to the extent that the results were worse than before the changes. Although the statistical analyses provided a good indication, they were not absolute. Conclusions were often aided by inspection of the raw data or by representing the data in graphical form. After the final series of tests (System 3), recommendations were also considered.

CHAPTER 5

THE FIRST ALGORITHM AND ITS TESTING (SYSTEM 1)

5.1 INTRODUCTION

This chapter is concerned with the testing of the original system, designated System 1, the algorithm of which is described in section 5.2, with a full description given in appendix B. The primary objective behind this set of trials was to establish the effectiveness of System 1 in predicting cutting parameters for turning operations, before any changes were made to the algorithm. In this way, reference or control data was established. In addition, since the opportunity presented itself, a secondary objective was also included. This was to determine the skill of the part programmers in predicting cutting conditions, as encoded into the NC program.

These tests were carried out in Reyrolle (Keating (1991)). All tests were conducted using mild steel. The reason for this was that the algorithm required a number of variables which were themselves only available from experimentation. The only suitable data available was for mild (medium carbon) steel being machined with an ISO P20 grade insert (Maropoulos (1990)). Therefore it was this combination of material and insert that was used.

Details of the tests are given in section 5.3. In both cases (System 1 results and part programmers' results), the reference against which they were compared are the best conditions attainable during actual machining. This concept of best conditions (approved data) is explained in section 5.3.1, as is the methodology.

A brief description of the jobs is given in section 5.3.2, where a job is an individual test and represents a feature or element of a component. The test results are included in section 5.3.3, whilst section 5.3.4 details the analysis carried out on them, as explained in section 4.8. Finally, section 5.4 discusses the results.

5.2 THE ALGORITHM

The algorithm which was used in System 1 (and is described in detail in appendix B), was designed to handle external turning, boring and facing, as appropriate, for both roughing and finishing cuts. It was based on the methods developed by Maropoulos and Hinduja (1990) and (1991). The principles of the logic are shown in figure 5.1, where the program is shown divided into two parts. The first part of the program was concerned with the entire cut. Once the necessary data had been entered, the feed rate and depth of cut were determined, consistent with any constraints such as the limits of the insert. The maximum allowable (constraining) forces were compared with the calculated forces, and adjustments made to the feed rate or depth of cut, if necessary, to ensure that the calculated forces were less than the constraining forces.

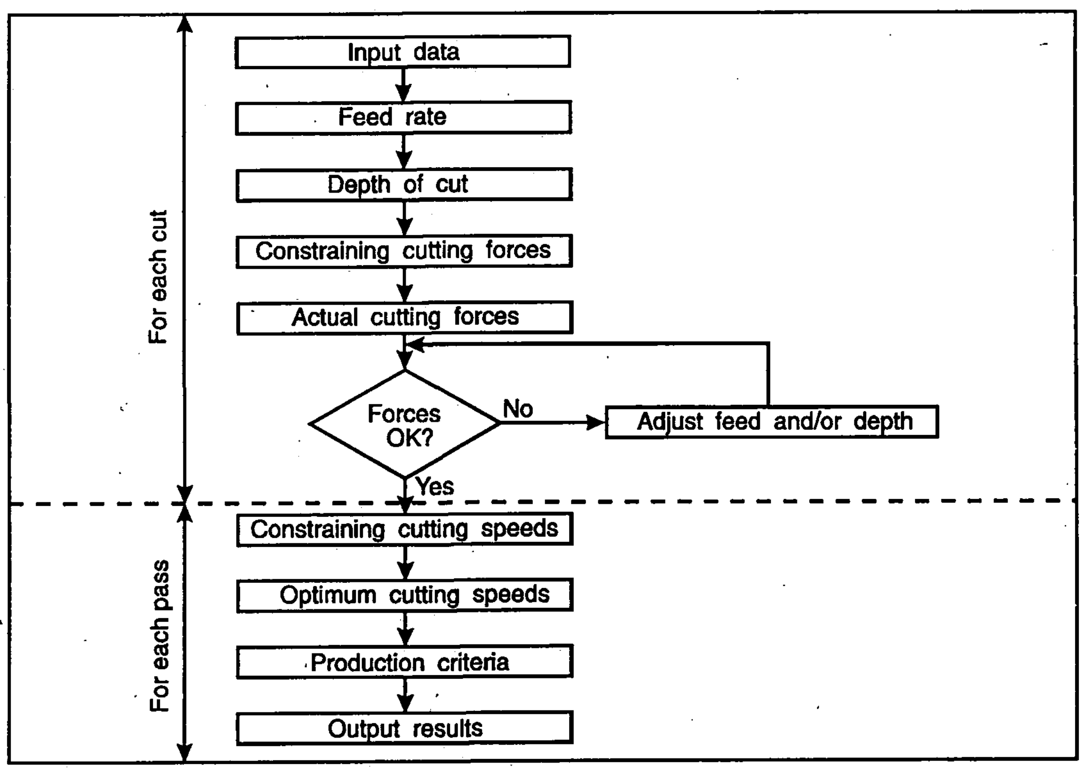


Figure 5.1
Flow diagram of System 1

The second part of the program carried out calculations for each pass of the tool. Any constraints on the cutting speed were determined e.g. tool life or maximum speed of the machine, and the optimum cutting speeds calculated, each speed based on a different production criterion. Finally, to permit comparisons of various tools, production criteria[1] were produced and the results sent to the screen. A tool that was technically unsuitable was able to be rejected at a number of different stages.

5.3 TESTS AND RESULTS FOR SYSTEM 1

5.3.1 METHODOLOGY

The general procedure was (Keating et al (1992)):

1) The tool holder and insert were selected.
2) The cutting conditions were calculated by System 1, based on the cutting speed for minimum cost.
3) The selected cutting conditions were tested on the machine in the presence of the machinist and, where possible, the supervisor, part programmer or the tooling engineer.
4) If the cutting conditions were judged not to be satisfactory, then they were adjusted until satisfactory cutting conditions were achieved.
5) For each job, three sets of results were recorded:
    a) the cutting parameters encoded in the NC program by the part programmers, referred to as 'engineering' (Eng),
    b) the cutting parameters calculated by System 1, referred to as 'System 1' (Sys 1),
    c) the approved cutting parameters, referred to as 'approved' (App).

In all cases, the minimum specified tool life was set at 30 minutes.

The subjective criteria that were used to judge the quality of the cut included

---

[1] The optimum cutting speeds, and hence the production criteria, were based on the minimum machining cost, the minimum machining time, the maximum tool life and the minimum number of tools.

vibration of the machine tool, vibration of the bar feeder (if fitted), fuming of the coolant, machine tool load or power meter and condition of the swarf. Also considered were the surface finish and dimensional tolerance. In all cases, the operator's judgement was used to determine whether a criterion was satisfactory.

Once preliminary machining had taken place with the System 1 data, if the cut was not satisfactory, the procedure that was followed was to adjust the cutting conditions involved, reducing the cutting speed, feed rate and depth of cut, in that order. This procedure is summarised in figure 5.2. This was based on the heuristic rules adopted by the part programmers when proving their own programs. Alternatively, if the cutting conditions were acceptable, one or more of the cutting parameters was increased until the operation was judged satisfactory. In every job more than one component was used to establish the satisfactory cutting conditions. It was these satisfactory cutting conditions which were designated 'approved' data.

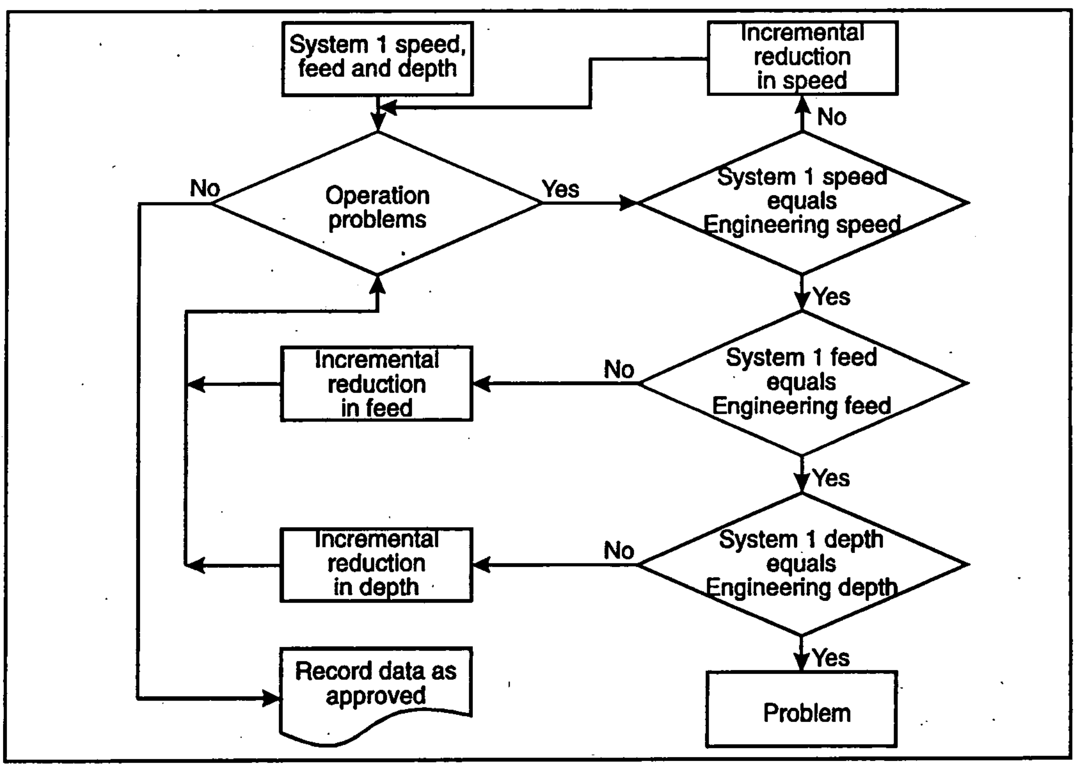


Figure 5.2

Procedure for achieving approved cutting conditions

5.3.2 DESCRIPTIONS OF JOBS

The jobs are described in table 5.1. It should be noted that despite the fact that some of the jobs on the FT20 machine used a collet, whilst others (FT20 and TS15) were held in a chuck, the same values were used for both μ_a and μ_c (coefficients of friction) throughout the tests. This was due to the lack of availability of any data for these variables. Therefore the different workholding was not significant.

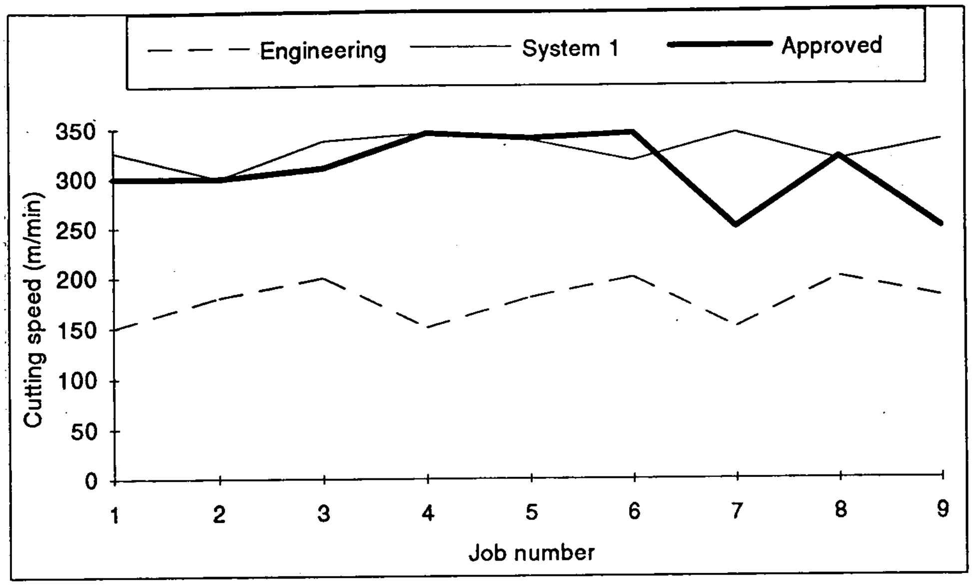
Machine	*Jobs 1 - 3 and 7 - 9* FT20 (lathe) *Jobs 4 - 6* TS15 (lathe)
Workholding	*Jobs 1 - 3* collet, *Jobs 4- 9* chuck
Roughing/Finish cut	*All jobs* roughing
External/Internal turning	*All jobs* external
Turning or facing	*All jobs* turning
Tool ISO code	*Jobs 1 - 3* PCLNR2525 *Jobs 4 - 6* PCLNR2020 *Jobs 7 - 9* PCLNR2525
Insert ISO code	*All jobs* CNMG120408 *except test 3* CNMG120404 *(Some jobs used inserts with different manufacturers chipbreaking designation)*
Insert ISO grade	*All jobs* P20
Material	*All jobs* MS rod AR20 BRT
Minimum specified tool life	*All jobs* 30 mins

Table 5.1

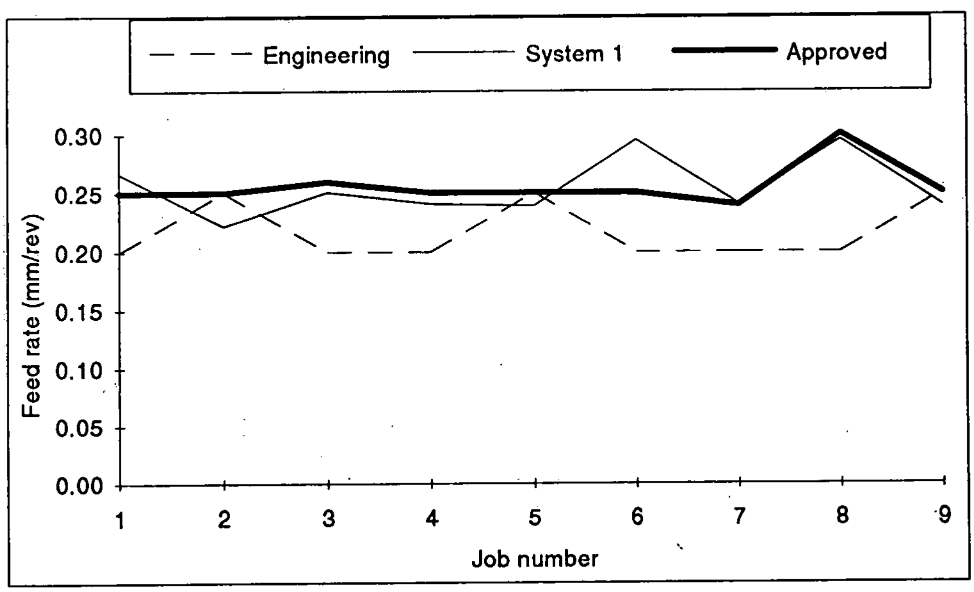
Descriptions of jobs for System 1

5.3.3 TEST RESULTS

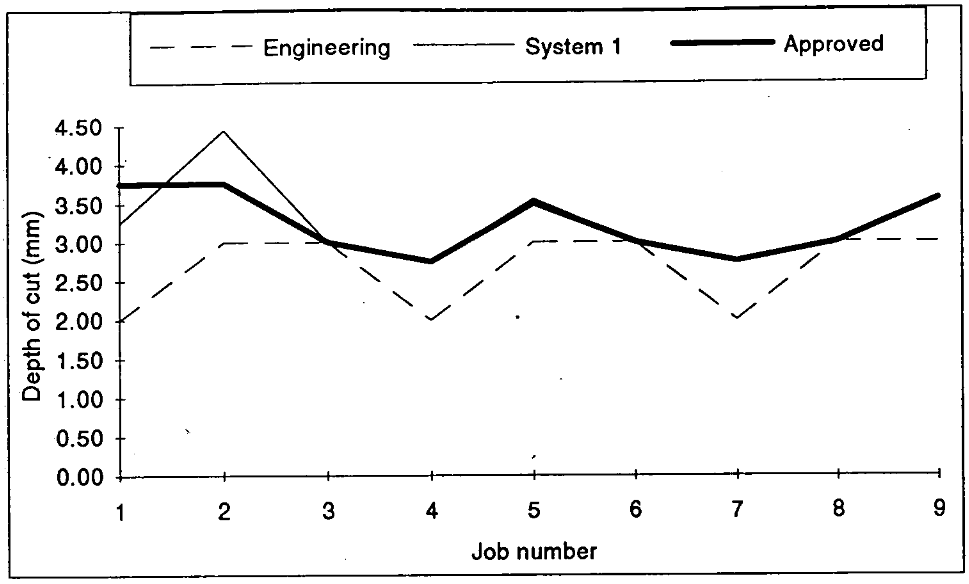
The results of the tests are shown in table 5.2 and summarised in graphs 5.1 - 5.3.



Graph 5.1
Test results for System 1 - cutting speed



Graph 5.2
Test results for System 1 - feed rate



Graph 5.3
Test results for System 1 - depth of cut

Job Number	Cutting speed (m/min)			Feed rate (mm/rev)			Depth of cut (mm)		
	Eng	**Sys 1**	**App**	**Eng**	**Sys 1**	**App**	**Eng**	**Sys 1**	**App**
1	150	326	300	0.20	0.27	0.25	2.00	3.25	3.75
2	180	300	300	0.25	0.22	0.25	3.00	4.44	3.75
3	200	337	310	0.20	0.25	0.26	3.00	3.00	3.00
4	150	345	345	0.20	0.24	0.25	2.00	2.75	2.75
5	180	338	340	0.25	0.24	0.25	3.00	3.55	3.50
6	200	317	345	0.20	0.30	0.25	3.00	3.00	3.00
7	150	345	250	0.20	0.24	0.24	2.00	2.75	2.75
8	200	317	320	0.20	0.30	0.30	3.00	3.00	3.00
9	180	337	250	0.25	0.24	0.25	3.00	3.55	3.55
Mean	177 ±17	329 ±12	307 ±28	0.22 ±0.02	0.25 ±0.02	0.26 ±0.01	2.67 ±0.38	3.25 ±0.41	3.23 ±0.31
Mean %	±9%	±4%	±9%	±9%	±8%	±5%	±14%	±13%	±10%
SD	22	15	37	0.02	0.03	0.02	0.50	0.52	0.41

Table 5.2
Results for System 1

5.3.4 ANALYSIS OF RESULTS

The results were analysed for each parameter to see whether the three sets (engineering, System 1 and approved) were from the same statistical population. Since the approved results were what was achievable on the machine in practice, these were taken as the reference results, and the other two sets compared with them. The analysis consisted of comparing both the variability and the means, using the *F*-distribution and the *t*-distribution respectively, as described in section 4.8.

The approved data was assumed to be a sample of all the cutting data for mild steel in the workshop being machined with an ISO P20 grade insert on the machines concerned, although this was divided into three populations, one for each cutting parameter. The outcome of the comparisons is summarised in table 5.3. Where the *t*-distribution test was not valid, the confidence band was calculated (table 5.4), as described in section 4.8.

Parameter	**Samples**	**Variances**	**Means**
Cutting speed	System 1 and Approved	Different	Non-valid*
Feed rate	System 1 and Approved	***Same***	***Same***
Depth of cut	System 1 and Approved	***Same***	***Same***
Cutting speed	Engineering and Approved	***Same***	Different
Feed rate	Engineering and Approved	***Same***	Different
Depth of cut	Engineering and Approved	***Same***	Different
**Note: The test for the comparison of means is not valid if the variances are not from the same population.*			

Table 5.3

Results of comparisons of variances and means - System 1

Parameter	**Sample**	**Confidence band**	**Lower limit**	**Upper limit**
Cutting speed (m/min)	System 1 & Approved	329±11 307±26	318 281	340 333

Table 5.4

Confidence bands for non-valid means - System 1

5.4 DISCUSSION OF RESULTS

Graphs 7.1 - 7.3 showed that System 1 was following the trends in the approved data reasonably well. In addition, the improvement over the engineering data was demonstrated. The analysis in section 5.3.4 highlighted a number of points, bearing in mind the confidence limits that were applied:

1) With the exception of the cutting speed, System 1 and approved data means were drawn from the same populations, with the same variability. In the case of the cutting speeds, the variability of data was different. However, the overlap between the confidence bands for the means suggested that the means may still have been drawn from the same, or similar, populations, although this was not conclusive.

2) With regard to the engineering and approved data, none of the samples were drawn from the same populations. The variability of all three sets of data were the same, but the means indicated that the data was drawn from different populations. This suggested some kind of constant error between the sets of data.

3) System 1 provided theoretical optimum data within the specified constraints, whilst the approved procedure provided maximised data within the specified constraints. The similarity between the sets of data suggested one of two possible scenarios:

   a) the maximum and optimum data was the same,

   b) the optimum data was larger than the maximum data and hence the maximum data became the apparent optimum data, within the constraints.

   The second scenario was more likely.

CHAPTER 6

CUTTING FORCES, TOOL LIFE DATA, INPUT DATA AND APPROVED DATA (SYSTEM 2)

6.1 INTRODUCTION

To be effective as an aid to tool selection, the system had to be able to work with any tool and material combination. With System 1, there had been a reliance on existing experimentally derived data. The only material for which any data was available was mild steel and this was for a limited range of ISO tools. Whilst this permitted tests to take place at Reyrolle, since mild steel was a common material for them, the same did not apply to Harkers. For Harkers, a much more common material was cast iron, with very little mild steel machining taking place.

One solution would have been to generate more data by means of cutting tests. Whilst suitable for laboratory tests, this was unrealistic in the industrial environments concerned with this project. In addition, this would have to be carried out not only for cast iron, but also for every combination of material and tool that would be used in the future. Therefore methods were developed to enable the system to be used with not only any material, but also any tool/material combination. This resulted in the development of System 2.

This work concentrated primarily on the tool life data and cutting forces data, required as input data (sections 6.2 and 6.3), with the intention of making it possible to consider any tool and material combination. Whilst the cutting forces work was completed with System 2, the tool life work was continued with System 3 (chapter 7).

System 1 had highlighted the fact that it was difficult to assign values to a number of input variables and these were given default values, based on the work with

System 1. Basic data files were also introduced for storing data that was used repeatedly. A further simplification of the input data was arranged by deriving a number of tool attributes from the relevant ISO codes (section 6.4).

The intention was that System 2 was to be tested by company personnel. To this end, a more systematic data approval procedure was drawn up (section 6.5). Following these changes, System 2 was tested by both research personnel and company employees and the results analysed (section 6.6). Finally, the results are discussed (section 6.7).

6.2 CUTTING FORCES DATA

6.2.1 PRINCIPLE OF CUTTING FORCE METHODOLOGY

The equations used to calculate the cutting forces, which are defined in figure B.2, appendix B, are shown in equations 6.1 - 6.3:

$$F_{V(calc)} = C_V \times S^{C_{V1}} \times a^{C_{V2}} \text{ (N)} \qquad \text{Equ 6.1}$$

$$F_{S(calc)} = C_S \times S^{C_{S1}} \times a^{C_{S2}} \text{ (N)} \qquad \text{Equ 6.2}$$

$$F_{a(calc)} = C_a \times S^{C_{a1}} \times a^{C_{a2}} \text{ (N)} \qquad \text{Equ 6.3}$$

(equations B.6 - B.8, appendix B)

These calculations are dependent on the values of C_V, C_{V1}, C_{V2}, C_S, C_{S1}, C_{S2}, C_a, C_{a1} and C_{a2}, which can be referred to collectively as the forces parameters. The values of these forces parameters rely primarily upon the tool in use and the material being machined. They are derived experimentally, provided the test machine is suitably equipped.

For the system to be able to work with any tool/material combination, it was necessary to have values of the forces parameters for every such tool/material combination. Furthermore, there had to be a method for determining the values for any combination that occurred in the future. The concept of performing cutting tests was rejected since, given the range of current and future combinations, such an approach was considered impractical. Consequently an alternative method was developed, using existing data.

It was hypothesised that the ratios between the three forces F_V, F_S and F_a would be approximately constant for a specific tool, irrespective of the material being cut i.e.:

$$\frac{F_{V(material\,1)}}{F_{S(material\,1)}} \cong \frac{F_{V(material\,2)}}{F_{S(material\,2)}} \qquad \text{Equ 6.4}$$

and

$$\frac{F_{V(material\,1)}}{F_{a(material\,1)}} \cong \frac{F_{V(material\,2)}}{F_{a(material\,2)}} \qquad \text{Equ 6.5}$$

The hypothesis was tested and shown to work (appendix K). To use this method, it was necessary to know F_V, F_S and F_a for one material, and one force for the second material, which would be the material under consideration. Some existing experimental data for the forces parameters, applicable to medium carbon steel, was made available (Maropoulos (1990)), which is included in appendix C. (The use of this data is discussed further in section 6.2.2). Thus medium carbon steel was taken as the first material.

An alternative method for calculating F_V was given by Lissaman and Martin (1982c):

$$F_V = K_s \times S \times a \text{ (N)} \qquad \text{Equ 6.6}$$

where K_s (N/mm^2) was the specific cutting force. When the system was used, the feed and depth were already calculated prior to the cutting forces calculations, hence equations 6.1 - 6.3 were used to calculate the forces for the first material (medium carbon steel). The specific cutting force K_s for the second material was usually obtainable either within a tool manufacturers' catalogue or from the material supplier. Therefore F_V could be determined for the second material, whilst F_S and F_a for the second material were found from the appropriate ratios (equations 6.4 and 6.5).

In this way the nine experimentally derived forces parameters were replaced by the specific cutting force for the material in question. The advantage of using this approach was that System 2 could not only calculate cutting forces for any material, but was also able to process any material with any tool, irrespective of whether or not the tool manufacturer recommended that particular combination of insert and material.

6.2.2 FORCES PARAMETERS FOR MEDIUM CARBON STEEL

Examination of the forces parameters for medium carbon steel in appendix C (from Maropoulos (1990)) highlighted a number of points:

a) only seven tools were represented, where the tools were defined in terms of the approach angle κ (°) and the included angle ε (°),

b) within each tool, the data was further categorised by the type of insert chipbreaker C_b and the insert nose radius r_e (mm),

c) not all the data was complete.

The arrangement of data is shown in figure 6.1, whilst table 6.1 provides details of the seven tools, in terms of the defining angles.

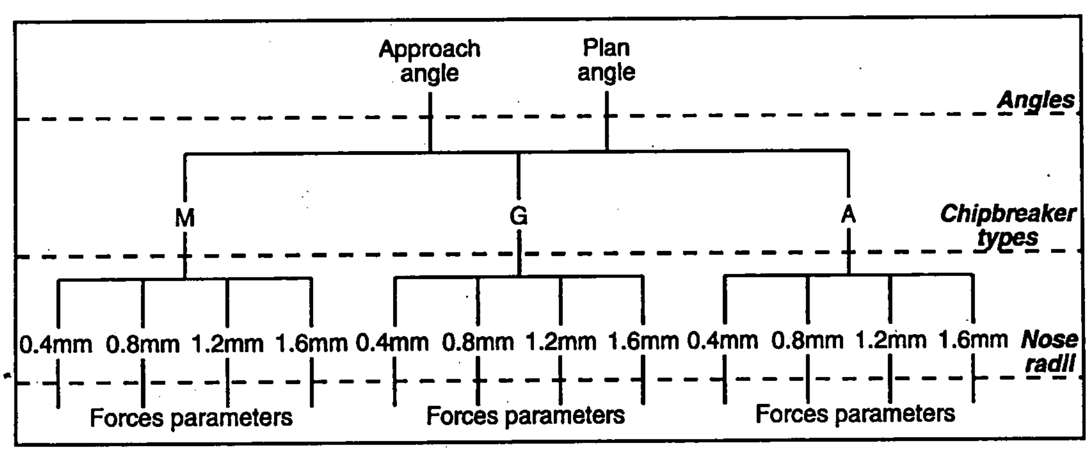


Figure 6.1

Arrangement of forces parameters data

For the ratios method described in section 6.2.1 to be fully effective, it was necessary for the limited range of tools in table 6.1 to provide the cutting forces for the full range of ISO tools, when cutting medium carbon steel. With only this limited range of data available, it was necessary to develop a method of using this data for any tool geometry, in terms of ascertaining the cutting forces.

Tool number	Approach angle, κ (°)	Included angle ε (°)
1	95	80
2	93	55
3	90	60
4	75	90
5	60	60
6	45	90
7	45	60

Table 6.1

Approach and included angles for tools in appendix C

For a tool with a combination of approach and included angles not shown in table 6.1, there was no immediate way in which one tool in the table could be considered a better approximation than another tool. For example:

ISO holder type	Approach angle κ (°)	Included angle ε (°)	Possible tools from table 6.1
PTJNR	93	60	2, 3
PDNNR	63	55	2, 5, 7
SVLBR	95	35	1, 2
SCGCR	90	80	1, 3

In some cases e.g. SVLBR, none of the alternatives appeared similar. It was therefore decided to eliminate one set of angles and select according to the remaining angle. To achieve this, the data was tested to determine whether one angle was less significant in terms of cutting forces.

To carry out the tests, two groups of tools were selected from table 6.1:

a) Group 1 - tools with the same included angle,

b) Group 2 - tools with the same approach angle.

The two groups are shown in table 6.2. Tool 5 should also belong in group 1, but was rejected since the available forces parameters data for this tool were limited.

	Approach angle κ(°)	Included angle ε(°)
Group 1 - variable approach angle, constant included angle		
Tool 3	90	60
Tool 7	45	60
Group 2 - constant approach angle, variable included angle		
Tool 6	45	90
Tool 7	45	60

Table 6.2

Tool groups for testing significance of angles

For each tool within each group, the values of F_V, F_S and F_a were calculated for the following combinations of feed rate and depth of cut:

	Feed rate	Depth of cut	Type of cut
Combination 1	0.1 mm/rev	1 mm	Finishing
Combination 2	0.4 mm/rev	4 mm	Medium roughing
Combination 3	0.8 mm/rev	8 mm	Roughing

All tools were missing certain data (chipbreaker type 'A', nose radius 0.4 mm). However, tool 6 was missing other data (chipbreaker type 'M', nose radii 1.6 mm and 0.4 mm). So that the results were comparable, this data was omitted from all the tools.

For each tool, all the values of F_V, F_S and F_a were added together and the mean and standard deviation of all the forces for each tool were calculated (table 6.3). Since tool 7 appeared in both groups, this was taken as the reference tool. Within each group, the differences between the results were found to be statistically not significant after hypothesis testing with the *t*- and *F*-distributions (section 4.8) i.e. the data from each group was produced by samples drawn from the same population. Nevertheless, the variable approach angle had made more of a difference to the results. Consequently it was decided to match tools based on the approach angle only, and ignore the included angle.

	Mean (N)	Standard deviation (N)
Group 1 - variable approach angle, constant included angle		
Tool 3	2651	3184
Tool 7	2731	3293
Group 2 - constant approach angle, variable included angle		
Tool 6	2738	3300
Tool 7	2731	3293

Table 6.3

Means and standard deviations of tool groups for testing significance of angles

Two tools were rejected at this stage:

a) There were two tools with an approach angle of 45° (tools 6 and 7 in table 6.1). It was therefore decided to retain the tool for which most data was available, in this case tool 7.

b) There was very little data available for tool 2. Its approach angle of 93° was considered to be adequately covered by tools 1 and 3, approach angles 90° and 95° respectively.

Examination of the data for the remaining five tools revealed that certain information was not available. Where this occurred, the information was obtained by using the data from the adjacent line i.e. the same approach angle and chipbreaker, but with a different nose radius. The alternative approach of linear interpolation was rejected since the data did not appear linear. The final selection of data was stored in the data file FORC.DAT, the contents of which are shown in appendix D. FORC.DAT was accessed by System 2, as appropriate.

The tool approach angle was matched to the data in FORC.DAT as follows:

Approach angle of tool under consideration	Approach angle of tool in FORC.DAT
$0° \leq \kappa \leq 52.5°$	45°
$52.5° < \kappa \leq 67.5°$	60°
$67.5° < \kappa \leq 82.5°$	75°
$82.5° < \kappa \leq 92.5°$	90°
$\kappa > 92.5°$	95°

The chipbreaker types included were 'A', 'G' and 'M', as defined by BS 4193 (1993). These were shown by BS 4193 to have a cylindrical fixing hole and thus the inserts could be double-sided. The relevant part of the standard is reproduced in figure 6.2. Examination of BS 4193 revealed that of the three specified chipbreakers, 'A' was without a chipbreaker, 'M' had a chipbreaker on one face only and 'G' had chipbreakers on both faces. All other chipbreaker designations could be categorised in a similar manner, the differences between them relating to the fixing hole.

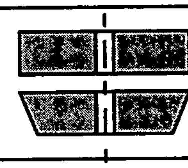
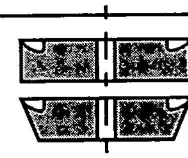
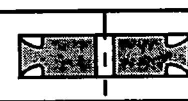
Letter symbol	Fixing	Chip breakers	Figure
A	With cylindrical fixing hole	Without chipbreakers	
M		Chip breakers on one face only	
G		Chip breakers on both faces	

Figure 6.2

Insert chipbreaker/fixing for ISO types 'A', 'G' and 'M'

(BS 4193 (1993))

Tool chipbreaker type was matched to the data in FORC.DAT as follows:

BS 4193 chipbreaker designation of tool under consideration	**Chipbreaker of tool in FORC.DAT**
A, N. W, Q, B or C	A
M, R, T or H	M
G, F, U or J	G

The tool nose radius was matched to the data in FORC.DAT as follows:

Nose radius of tool under consideration	**Nose radius of tool in FORC.DAT**
0 mm $\leq r_e \leq$ 0.6 mm	0.4 mm
0.6 mm $< r_e \leq$ 1.0 mm	0.8 mm
1.0 mm $< r_e \leq$ 1.4 mm	1.2 mm
$r_e >$ 1.4 mm	1.6 mm

6.2.3 ACCURACY OF CUTTING FORCES METHODOLOGY

As a test on the accuracy of the method described in section 6.2.1, equation 6.1:

$$F_V = C_V \times S^{C_{V1}} \times a^{C_{V2}} \text{ (N)}$$

was compared with equation 6.6:

$$F_V = K_s \times S \times a \text{ (N)}$$

The test was carried out by calculation. The tool was assumed to have the following attributes:

Approach angle κ	: 95°
Included angle ε	: 80°
Chipbreaker type C_b	: M
Nose radius r_e	: 0.8 mm

These attributes matched a ISO tool holder type PCLNR, with an ISO insert type CNMG120408. This tool was chosen for two reasons:

a) there was data available for calculating cutting forces (appendix C),

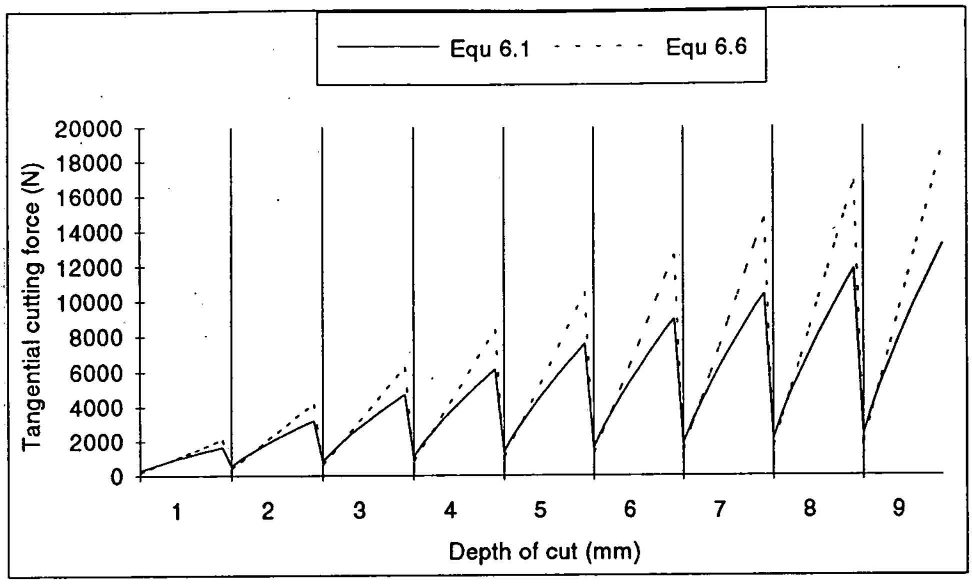
b) the tool was used in cutting tests on mild steel (section 6.6.2).

For this tool, the following data was used:

C_V	: 1665.6
C_{V1}	: 0.745
C_{V2}	: 0.941

The mild steel was assumed to contain 0.35% carbon and hence K_s was 2100 N/mm^2 (Sandvik (1988))

Nine different values of depth of cut were used, ranging from 1 mm to 9 mm, in increments of 1 mm. Within each depth of cut, ten feed rates were used, ranging from 0.1 mm/rev to 1 mm/rev, in increments of 0.1 mm/rev. The results are shown in graph 6.1.



Graph 6.1
Comparison of equations 6.1 and 6.6

With respect to graph 6.1, for different tools and materials i.e. specific values of K_s, C_V, C_{V1} and C_{V2}, each graph would be different. Nevertheless, it appeared that the two equations produce approximately similar data, although some combinations of feed rate and depth of cut produced better comparisons than other combinations.

The other part of the methodology used the concept of ratios to determine the longitudinal and radial forces. It was not possible to test this, since it required values of C_S, C_{S1}, C_{S2}, C_a, C_{a1} and C_{a2} for materials for which data was not available.

6.3 TOOL LIFE DATA

The formulae used to calculate the cutting speeds for minimum cost $V_{(cost)}$ and minimum time $V_{(time)}$ were :

$$V_{(cost)} = \left(\frac{\left(\frac{x}{60}\right) \times C_1}{S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1\right) \times \left(\left(\frac{x}{60} \times t_3\right) + y\right)} \right)^{\alpha} \text{ (m/min)} \qquad \text{Equ 6.7}$$

(equation B.24, appendix B)

and

$$V_{(time)} = \left(\frac{C_1}{t_3 \times S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1 \right)} \right)^{\alpha} \text{ (m/min)} \qquad \text{Equ 6.8}$$

(equation B.25, appendix B)

where x (£/hr) was the hourly rate of the machine, t_3 (mins) was the tool change time and y (£) was the cost per cutting edge. Both formulae relied on values of α, β, γ and C_1, which were the exponents and constant in the extended Taylor equation for tool life:

$$T = \left(\frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \right) \text{ (mins)} \qquad \text{Equ 6.9}$$

(equation B.21, appendix B)

Values of α, β, γ and C_1 were dependent on both the insert ISO grade and the workpiece material. For the system to be able to work with any tool/material combination, it was necessary to have values of α, β, γ and C_1 for every such combination used in testing. A permanent method is described in section 7.3 (System 3), but for System 2 a temporary method was used and is described below. A discussion on the industrial measurement of tool life is given in section 9.2.

Equation 6.9 can be re-written in a logarithmic form:

$$\ln[T] = \ln[C_1] - \frac{1}{\alpha}\ln[V] - \frac{1}{\beta}\ln[S] - \frac{1}{\gamma}\ln[a] \qquad \text{Equ 6.10}$$

which is the equation for a straight line. Provided suitable data is available, consisting of a number of sets of data for V, S, a and T, values for α, β, γ and C_1 can be determined using multiple regression. The method is not exact since α, β and γ are not constant (Barrow (1971)), but provided they are reasonably constant, the method is acceptable. This is an established technique for this kind of work e.g. Leslie and Lorenz (1964). BS 5623 (1979), which covers tool life testing, also recommends regression analysis as a suitable method for the evaluation of tool life data. Whilst Barrow recommended "...at least three sets of tests involving fifteen tool-life values", BS 5623 required at least four cutting speeds, with at least five points on each curve.

Some cutting data catalogues contain example cutting data (*V*, *S* and *a*), for a variety of insert grade/material combinations, for a number of different cutting conditions e.g. Seco (1988), Sandvik (1988). The purpose of this data is to provide a guide for what cutting parameters will give a reasonable tool life. Consequently, each set of machining parameters will give a standard tool life, typically fifteen minutes[1]. Factors are also available which, when the cutting speed is multiplied by them, will give estimated tool lives of thirty, forty five and sixty minutes (Seco (1988)).

A file (LIFE.DAT), containing data sets consisting of *V*, *S*, *a* and the associated tool life for a suitable variety of inset grade/material combinations, was created. This data was taken from Seco (1988) and Sandvik (1988). In use, the appropriate data in LIFE.DAT was accessed by System 2 and extracted. Values of α, β, γ and C_1 were then calculated, as outlined above.

However, the data in Seco (1988) and Sandvik (1988) was limited in the insert grade/material combinations included and System 2 was tested with combinations where there was no available data in these publications. Where the data was not available in either of these two publications, substitute data was used. This substitute data was for a material with similar attributes (hardness or specific cutting force), allied with what was considered to be the nearest approximate insert grade.

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[1] Mr Max Townson, Technical Sales Engineer for Seco Tools (UK) Ltd, explained how these figures are obtained by Seco, at a meeting at Reyrolle on 30 May 1991. Seco use as near perfect a setup as possible e.g. rigid workpiece, tool in perfect condition, machine tool with good bearings. Each set of figures quoted are an average of several tests. In a manufacturing situation it is unlikely that the results can be duplicated and they are produced only as a guide.

6.4 REDUCTION OF INPUT DATA

6.4.1 INTRODUCTION

It was intended that System 2 would be tested by company personnel. During testing of System 1 it became evident that there were a number of input variables, for which data was either not available or was difficult to obtain. During the earlier tests with System 1, to enable testing to continue, estimated values had been used. Judging by the results for System 1, it was apparent that these estimated values were not causing any problems. Consequently, it was decided to make the values used into default values (sections 6.4.2 and 6.4.3). Furthermore, it was possible for certain tool attributes were defined by the relevant ISO codes (section 6.4.4). Finally, certain input data was liable to be repeated each time the system was used and it was found to be worthwhile to introduce simple data files (section 6.4.5).

6.4.2 DEFAULT TOOL ATTRIBUTES

1) Constant C_f

The constant C_f was included in the calculation for the feed S for a finish cut:

$$S = \sqrt{(0.0312 \times R_a \times r_e)} \times C_f \text{ (mm/rev)} \qquad \text{Equ 6.11}$$

(equation B.2, appendix B)

where R_a (μm) was the surface finish and r_e (mm) was the insert nose radius. C_f was a material-dependent constant (Maropoulos and Hinduja (1990)). A value of 1 was used for C_f (Maropoulos (1990)).

2) Constant C_{le}

Another constant, C_{le}, was involved in the equation which determined the depth of cut a:

$$a_{(max)} = C_{le} \times L \times sin(\kappa) \text{ (mm)} \qquad \text{Equ 6.12}$$

(equation B.3, appendix B)

where L (mm) was the length of the insert cutting edge and κ (°) the approach angle. C_{le} was used to reduce the depth of cut, and hence the cutting forces, when the insert included angle ε was small, resulting in a relatively weak insert. It was assigned one of two values and the insert included angle ε at which the value changed was approximately 80°. The two values suggested by Maropoulos (1990) were:

Included angle	C_{le}
$\varepsilon \geq 80°$	0.75
$\varepsilon < 80°$	0.5

6.4.3 DEFAULT MACHINE TOOL ATTRIBUTES

1) Coefficients of friction μ_a and μ_c

The longitudinal and tangential coefficients of friction, μ_a and μ_c, referred to the rotating and sliding of the workpiece in the chuck or collet. This data was utilised in determining the constraining longitudinal and tangential cutting forces. The constraining longitudinal force was:

$$F_{S(con)} = F_g \times \mu_a \text{ (N)} \qquad \text{Equ 6.13}$$

where F_g (N) was the clamping force.

(equation B.9, appendix B)

The constraining tangential force before rotational slipping took place was:

a) for external turning and facing:

$$F_{V1(con)} = \frac{\mu_c \times F_g \times d_{(held)}}{d_{(initial)}} \text{ (N)} \qquad \text{Equ 6.14}$$

(equation B.14, appendix B)

or

b) for internal turning

$$F_{V1(con)} = \frac{\mu_c \times F_g \times d_{(held)}}{d_{(final)}} \text{ (N)} \qquad \text{Equ 6.15}$$

(equation B.15, appendix B)

where $d_{(held)}$ (mm) was the diameter of the workpiece that was being held and $d_{(final)}$ (mm) and $d_{(initial)}$ (mm) were the cut and uncut diameters respectively.

The maximum tangential force before component throw-out occurred was:

$$F_{V2(con)} = \frac{F_g \times \left((0.5 \times L_{wc}) + (\mu_a \times d_{(held)}) \right)}{\sqrt{3} \times L_t} \text{ (N)} \qquad \text{Equ 6.16}$$

(equation B.16, appendix B)

where L_{wc} (mm) was the length of the workpiece held in the chuck or collet and L_t (mm) was the maximum distance from the workholding to the tool.

There was a need for μ_a and μ_c to be available for every workpiece material, even assuming that the chuck or collet material remained unchanged. The following default values were used, as suggested by Maropoulos (1990):

a) chuck - μ_c and μ_a both equal to 0.9

b) collet - μ_c and μ_a both equal to 0.3

To distinguish between the values of μ_a and μ_c, the method of workholding was added (CHUCK or COLLET) as input data.

One unforeseen problem concerned Harkers, where vertical boring mills were used for the trials. On these the components were clamped vertically to the bed of the machine. For simplicity, this arrangement was considered to be a chuck.

2) Clamping force F_g

The clamping force F_g was used (in conjunction with one or other of the coefficients of friction μ_a and μ_c) in determining the constraining forces (equations 6.13 - 6.16). At Reyrolle, the clamping pressure could be obtained from a meter on the machine. If the contact area of the chuck jaws or collet was known, the clamping force could be ascertained. However, further investigation showed that the clamping force was not constant but was adjusted by the operator, to suit the particular machining conditions. For System 1, estimated values were:

Machine	Clamping force
FT20	16587 N
TS15	22462 N

Based on these figures, a value of F_g equal to approximately 20 kN was considered reasonable for typical Reyrolle machine/component set-ups and this value was adopted for tests on any new machines.

At Harkers, clamps were used to attach the jobs to the tables of the boring mills used for the tests. Due to the typical mass and dimensions of the components e.g. gas turbine casings, it was considered unlikely that cutting forces would present a problem with respect to the component. Therefore a value of F_g was determined (36 kN) which, it was estimated, would ensure that in all cases the constraining forces would be higher than the associated calculated forces.

3) **Hourly cost *x***

The hourly cost of the machines was needed for two purposes:

a) calculation of the cutting speed for minimum cost $V_{(cost)}$ (equation 6.7):

b) calculation of the total machining cost m_c, to allow various tools to be compared:

$$m_c = \left(\left(t_2 \times \frac{x}{60} \right) + \frac{t_2 \times t_3 \times \frac{x}{60}}{T} + \frac{t_2 \times y}{T} \right) \times B \text{ (£)} \qquad \text{Equ 6.17}$$

(equation B.29, appendix B)

where t_2 (mins) was the effective machining time (equation B.30, appendix B), t_3 (mins) was the tool change time, x (£/hr) was the hourly machine cost, y (£) was the cost per cutting edge (equation B.23, appendix B), T (mins) was the tool life and B was the batch size.

Accurate hourly cost figures for the individual machine tools in both companies were not available. Senior production management in each company suggested approximate figures for their machines, which were adopted. These figures were:

Reyrolle: £35/hour and **Harkers:** £60/hour

4) Tool change time t_3

The tool change time was used for:

a) the cutting speed for minimum cost $V_{(cost)}$ (equations 6.7)

b) the cutting speed for minimum time $V_{(time)}$ (equations 6.8)

c) total machining cost m_c (equation 6.17)

d) total machining time:

$$m_t = \left(t_2 + \frac{t_2 \times t_3}{T} \right) \times B \text{ (mins)} \qquad \text{Equ 6.18}$$

(equation B.31, appendix B)

where t_2 (mins) was the effective machining time (equation B.30, appendix B), t_3 (mins) was the tool change time, T (mins) was the tool life and B was the batch size.

It was not possible to predict how long it would take to change a tool, since it depended on a variety of factors e.g. position of the tool on the work bench and the motivation of the operator. In the event a single value was adopted for each company:

Reyrolle: 1 minute

Harkers: 5 minutes

The longer time for Harkers was a reflection of their much larger tooling.

6.4.4 TOOL ATTRIBUTES FROM THE ISO CODE

Another change was the use of the tool holder and insert ISO codes, which permitted the removal of certain tool attributes from the input data. The ISO codes for the tool defined it geometrically and dimensionally. The nose radius r_ε (mm) was obtained directly from the insert ISO code, whilst the holder style defined the approach angle κ (°). The number of cutting edges, *nce*, on the insert was characterised by the insert shape, clearance angle, chipbreaker and fixing designation, all of which were included in the ISO code. Clearly, a clearance angle other than 0° implied that the insert was only single-sided. Regarding the length of the cutting edge L (mm), according to BS 4193 (1986) , this was either taken direct from the ISO code or calculated from the inscribed circle diameter, depending upon the insert shape.

6.4.5 USE OF DATA FILES

Simple data files were introduced for certain repeat data e.g. machine tool attributes. This meant adding certain names e.g. machine tool name, to the input data to act as key fields for data file interrogation but, since these were then stored in the relevant data file, they only had to be entered once. Separate data files were used for external tool holders, boring bars, inserts, materials and machine tools. The concept of data files is discussed in more detail in section 9.5.

6.5 DATA APPROVAL PROCEDURE

The original data approval procedure used for System 1 (section 5.3.1) relied on the subjective judgement of the operator as to when the best cutting conditions were obtained. It was considered that a more systematic approach was preferable when testing was carried out by the companies, based on maximising a specific machining parameter. Both companies were consulted at a senior level and they both gave the same response. Since all the machines concerned were fitted with power meters, they wished to achieve 100% power. They took the view that anything less than 100% power indicated that a machine was being under-utilised.

It is arguable as to whether this was the best choice. Changes in power of an electric motor can be achieved by changing either the speed or torque of the motor:

$$P = t \times \omega = t \times \frac{V}{r} \times \frac{1000}{60} \text{ (W)} \qquad \text{Equ 6.19}$$

where P (W) was the power, t (Nm) was the torque, ω (rads/sec) was the angular velocity and r (mm) was the radius of the cut.

The torque curve for a typical electric motor shows that maximum torque occurs at less than maximum speed, whilst the torque required is a function of the chip cross-sectional area i.e. the area of metal being sheared, which is approximately $S \times a$ (mm^2). Cutting at maximum power implies that the torque is less than maximum, with a consequent reduction in the chip cross-sectional area. However, an increase in the torque, and thus the chip-cross-sectional area, requires a decrease in the cutting speed. It is likely that the maximum metal removal rate (*MMR*) occurs between maximum torque and maximum power, where the metal removal rate is defined as:

$$MMR = V \times S \times a \text{ (mm}^3\text{/sec)} \qquad \text{Equ 6.20}$$

where V has units of mm/sec rather than the more conventional m/min.

Since both companies were interested in removing metal as fast as possible, maximising the metal removal rate may have been a better option and this point was made to them. Nevertheless, both companies were adamant on achieving 100% power consumption. The distinct advantage of using this approach was that it was easy to identify when the condition was reached.

A new data approval procedure was drawn up, in consultation with the part programmers from both companies. The procedure was designed to match, as closely as possible, the method followed in practice. Since the procedure was designed for the companies to use, the view was taken that the more complex the procedure, the less likelihood there was of it being followed. Consequently the procedure was kept as simple as possible. The new procedure is shown in box 6.1, with the associated flow diagram in figure 6.3.

PROCEDURE FOR APPROVING CUTTING DATA

1) Set the machine tool up with the following conditions:
   Cutting speed (m/min), feed rate (mm/rev) and depth of cut (mm) as per system
2) Try the first cut
3) If the first cut is not satisfactory, reduce or increase *V* until it becomes satisfactory.

IF MACHINE POWER IS LESS THAN 100%

4) Increase *S* until one of the following occurs:
   a) The cut is no longer satisfactory
   b) The machine is using more than 100% power
5) Decrease *S* to the previous level and record the machining conditions.

STOP IF THE MACHINE POWER IS GREATER THAN 100%

6) Decrease *S* until the machine is using 100% power.
7) If the cut is satisfactory, record the machining conditions.

STOP

8) If the cut is not satisfactory, decrease *a*, set *V* to $V_{(System)}$, set *S* to $S_{(System)}$ and go to paragraph 2.

Box 6.1

Procedure for approving cutting data

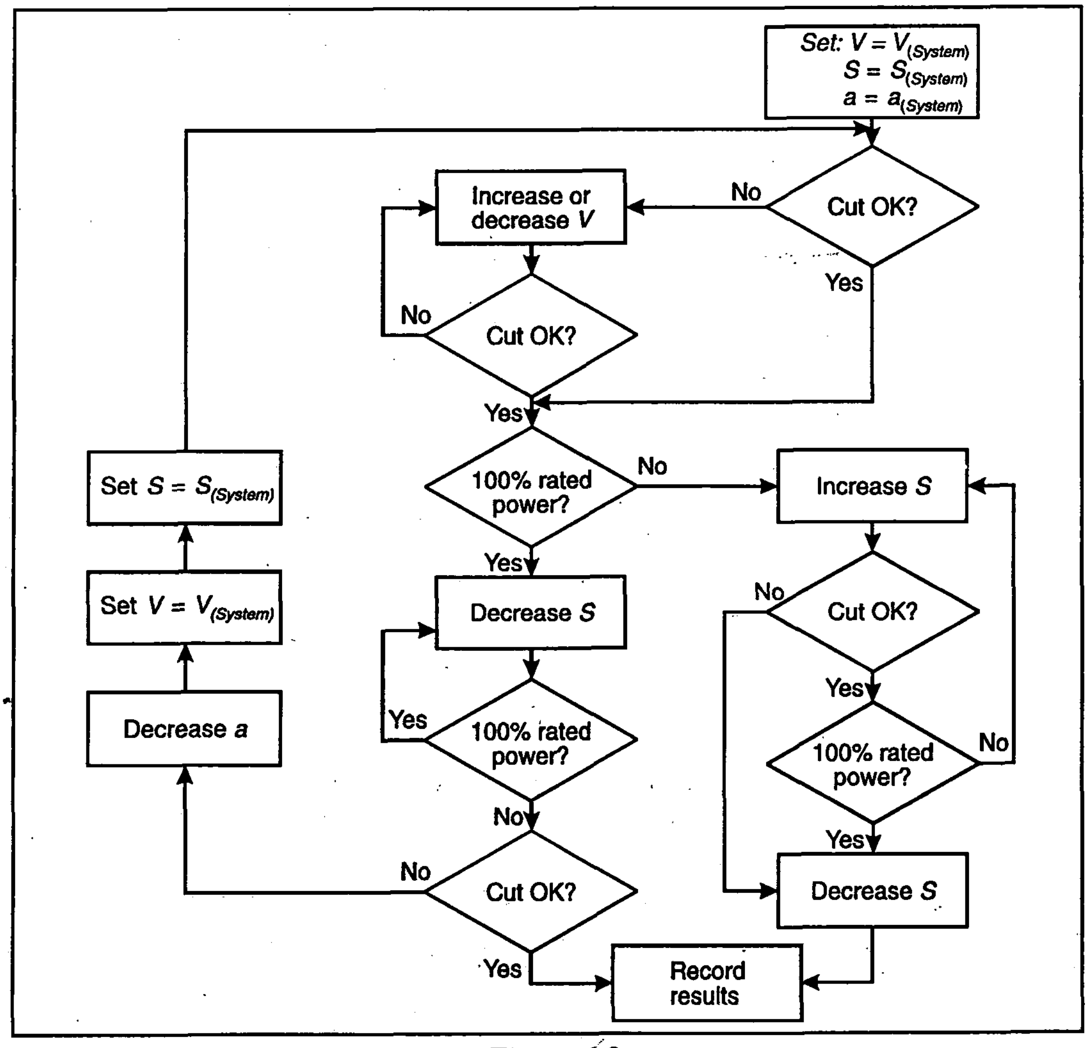


Figure 6.3

Method for approving cutting data

6.6 TESTS AND RESULTS FOR SYSTEM 2

6.6.1 METHODOLOGY

System 2 was tested within both companies, with a total of three separate sets of trials:

Trial 1 - Harkers

Trial 2 - Reyrolle

Trial 3 - Harkers

The major difference between the trials was that trial 1 was carried out under supervision (Keating (1992)), in a similar manner to that used for the testing of System 1 (chapter 5). In contrast, trials 2 and 3 were carried out by the companies, unassisted. Hence the new data approval procedure (section 6.5) was used with trials 2 and 3.

The primary objective of the trials were to test the system against a variety of materials, since System 1 had been limited to mild steel. Since Harkers worked within the aerospace industry, they were involved with some materials which may be termed exotic, such as titanium. This provided a good test for the changes that had been made to produce System 2 (trial 1). In addition, a range of materials was tested at Reyrolle (trial 2). An additional test not carried out on System 1 consisted of using System 2 for facing and boring operations, as well as external turning. Finally, since the eventual system would be used by the companies, trials 2 and 3 were carried out by the companies themselves, without supervision. A summary of the trials is shown in table 6.4.

	Company	**Materials**	**Level of supervision**
Trial 1	Harkers	Alloy steel, titanium, stainless steel	Supervised
Trial 2	Reyrolle	Mild steel, aluminium alloy, brass	Unsupervised
Trial 3	Harkers	Cast iron	Unsupervised

Table 6.4

Summary of System 2 trials

a) **Trial 1**

The methodology used, including data approval, was similar to that for System 1 (section 5.2).

b) **Trials 2 and 3**

Both companies had already had experience of the method of testing and they therefore only required training in the use of System 2 and the modified data approval procedure (section 6.6). Unfortunately there was no reasonable method by which they could be observed whilst carrying out the tests, without running the risk of influencing the results (section 4.3). Therefore the assessment of how well they used System 2 could only be made from the results.

6.6.2 DESCRIPTION OF JOBS

The jobs are described in table 6.5. As a general rule, the minimum tool life was set to 30 minutes. The exception to this was in trial 3, where for Harkers job 5 a minimum tool life of 90 minutes was used. Otherwise this was the same as Harkers job 4 (trial 3). This was because Harkers considered that 30 minutes tool life was too short for the size of their components. They wished to determine the effect of a longer minimum tool life.

	Trial 1	Trial 2	Trial 3
Company	Harkers	Reyrolle	Harkers
Machine	*Jobs 1 - 2* W & B 1.80S	*Jobs 1,2, 3 4* TS15	*Jobs 1, 2, 3* Schiess 5m
	Jobs 3 - 7 DS & G 4432	*Jobs 5, 6, 7, 8* FT20	*Jobs 4, 5* Schiess 4m
	Jobs 8 - 10 W & B 1.25S		
Machine type	*All machines* vertical boring mills	*All machines* lathes	*All machines* vertical boring mills
Workholding	*All jobs* chuck	*All jobs* chuck	*All jobs* chuck
Roughing/ Finish cut	*All jobs* roughing	*All jobs* roughing *except job 5* finishing	*All jobs* roughing
External/ Internal turning	*Jobs 1, 2, 4, 6, 7, 9* internal	*All jobs* external *except job 3* internal	*All jobs* internal *except job* 2 external
	Jobs 3, 5, 8, 10 external		
Turning or facing	*Jobs 1, 2, 3, 4, 6, 8, 9* turning	*Jobs 3, 6, 7, 8* turning	*All jobs* turning *except job* 2 facing
	Jobs 5, 7, 10 facing	*Jobs 1, 2, 4, 5* facing	
Tool ISO code	*Jobs 1 - 2* PCLNR3225A19-Q	*Jobs 1, 2, 4* PCLNR2020-A12	*All jobs* PCLNR4040-S19
	Jobs 3 - 7 PCLNR3225A12-Q	*Job 3* S16QSCLCR09	
	Jobs 8 - 10 PCLNR3225A19-Q	*Jobs 5, 6, 7, 8* PCLNR2525-A12	
Insert ISO code	*Jobs 1 - 2* CNMG190616-FR	*All jobs* CNMG120408 *except job 3* CNMM09T308 *(Some tests used inserts with different manufacturers chip-breaking designation)*	*All jobs* CNMG190616
	Jobs 3 - 7 CNMG120408-UP(SUM)		
	Jobs 8 - 10 CNMG190616-E48		
ISO Grade	*Jobs 1 - 2* P20	*Jobs 1, 2, 3, 4, 5, 6* P20	*All jobs* K15
	Jobs 3 - 7 K10		
	Jobs 8 - 10 P40	*Jobs 7, 8* K10	
Material	*Jobs 1 - 2* alloy steel	*Jobs 1,2, 3, 4, 5, 6* MS rod AR20 BRT	*All jobs* cast iron
	Jobs 3 - 7 titanium	*Job 7* aluminium alloy BS1474 6028 T6	
	Jobs 8 - 10 stainless steel	*Job 8* brass ERQ	
Min specified tool life	*All jobs* 30 mins *except job 1* none	*All jobs* 30 mins	*All jobs* 30 mins *except job 5* 90 mins

Table 6.5

Description of jobs for System 2

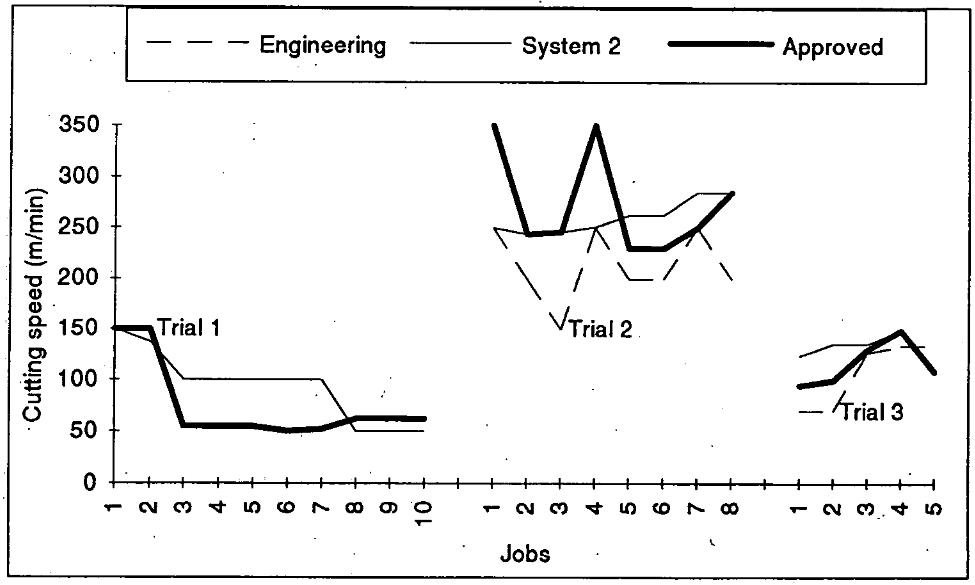
6.6.3 TEST RESULTS

The results of the tests are shown in table 6.6 - 6.8 and summarised in graphs 6.2 - 6.4.

Job Number	Trial 1			Trial 2			Trial 3		
	Eng	Sys 2	App	Eng	Sys 2	App	Eng	Sys 2	App
	Cutting speed (m/min)								
1	150	150	150	250	250	350	70	124	95
2	150	137	150	200	244	244	70	136	100
3	54	100	54	150	246	246	127	136	130
4	54	100	54	250	251	350	134	149	149
5	54	100	54	200	262	230	134	106	109
6	50	100	50	200	262	230			
7	52	100	52	250	285	250			
8	62	50	62	200	285	285			
9	62	50	62						
10	62	50	62						
Mean	75 ±28	94 ±25	75 ±28	213 ±30	261 ±14	273 ±42	107 ±42	130 ±20	117 ±28
Mean %	±38%	±27%	±38%	±14%	±5%	±15%	±39%	±15%	±24%
SD	40	35	40	35	16	50	34	16	23

Table 6.6

Test results for System 2 - cutting speed



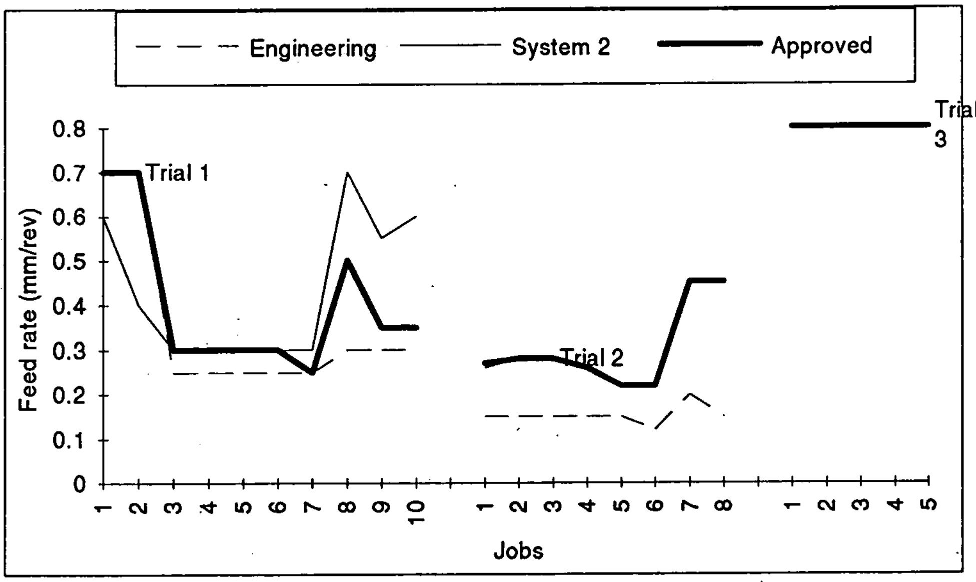
Graph 6.2

Test results for System 2 - cutting speed

	Trial 1			Trial 2			Trial 3		
Job Number	Eng	Sys 2	App	Eng	Sys 2	App	Eng	Sys 2	App
	Feed rate (mm/rev)								
1	0.70	0.60	0.70	0.15	0.26	0.27	0.80	0.80	0.80
2	0.70	0.40	0.70	0.15	0.28	0.28	0.80	0.80	0.80
3	0.25	0.30	0.30	0.15	0.28	0.28	0.80	0.80	0.80
4	0.25	0.30	0.30	0.15	0.26	0.26	0.80	0.80	0.80
5	0.25	0.30	0.30	0.15	0.22	0.22	0.80	0.80	0.80
6	0.25	0.30	0.30	0.12	0.22	0.22			
7	0.25	0.30	0.25	0.20	0.45	0.45			
8	0.30	0.70	0.50	0.15	0.45	0.45			
9	0.30	0.55	0.35						
10	0.30	0.60	0.35						
Mean	0.36 ±0.13	0.44 ±0.11	0.41 ±0.12	0.15 ±0.02	0.30 ±0.08	0.31 ±0.08	0.80 ±0.00	0.80 ±0.00	0.80 ±0.00
Mean %	±37%	±26%	±30%	±12%	±26%	±25%	±0%	±0%	±0%
SD	0.18	0.16	0.17	0.02	0.09	0.09	0.00	0.00	0.00

Table 6.7

Test results for System 2 - feed rate



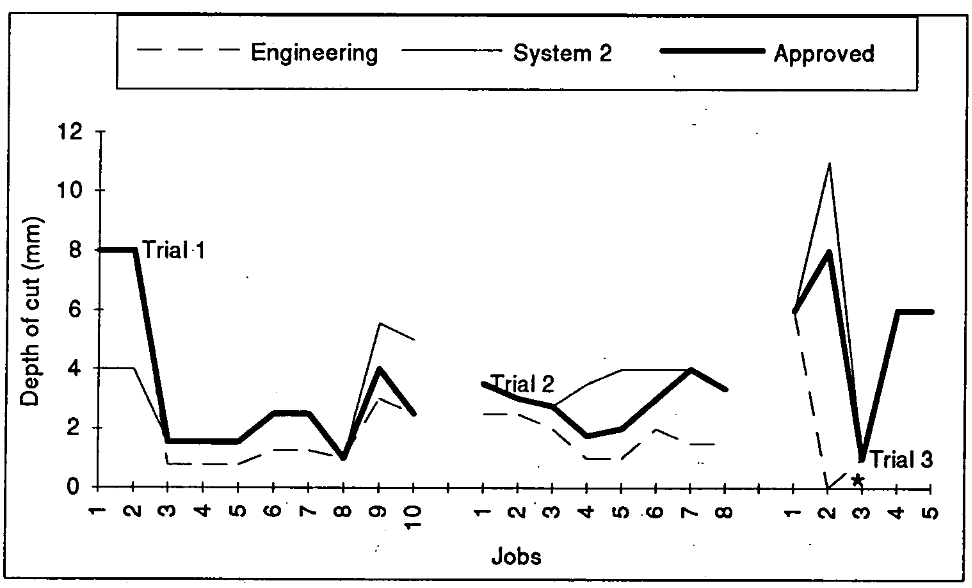
Graph 6.3

Test results for System 2 - feed rate

	Trial 1			Trial 2			Trial 3		
Job Number	**Eng**	**Sys 2**	**App**	**Eng**	**Sys 2**	**App**	**Eng**	**Sys 2**	**App**
	Depth of cut (mm)								
1	8.00	4.00	8.00	2.50	3.50	3.50	6.00	6.00	6.00
2	8.00	4.00	8.00	2.50	3.00	3.00	*	11.14	8.00
3	0.77	1.54	1.54	2.00	2.75	2.75	1.00	1.00	1.00
4	0.77	1.54	1.54	1.00	3.50	1.75	6.00	6.00	6.00
5	0.77	1.54	1.54	1.00	4.00	2.00	6.00	6.00	6.00
6	1.25	2.50	2.50	2.00	4.00	3.00			
7	1.25	2.50	2.50	1.50	4.00	4.00			
8	1.00	1.00	1.00	1.50	3.33	3.33			
9	3.00	5.56	4.00						
10	2.50	5.00	2.50						
Mean	2.73 ±2.06	2.92 ±1.15	3.31 ±1.87	1.75 ±0.50	3.51 ±0.40	2.92 ±0.63	4.75 ±3.98	6.03 ±4.45	5.40 ±3.24
Mean %	±75%	±40%	±56%	±29%	±11%	±21%	±84%	±74%	±60%
SD	2.88	1.61	2.61	0.60	0.48	0.75	2.50	3.59	2.61
** - Data not available*									

Table 6.8

Test results for System 2 - depth of cut



Graph 6.4

Test results for System 2 - depth of cut

*Note: At point marked * (Trial 3 Job 2), no value was recorded*

6.6.4 ANALYSIS OF RESULTS

The results were analysed for each parameter within each trial to see whether the three sets (engineering, System 2 and approved) were from the same statistical population for each trial. A population for a trial was the cutting data for that particular combination of tools, machines and materials. As before, the approved data was taken as the reference results, and the other two sets compared with them. The analysis consisted of comparing both the variability and the means, using the *F*-distribution and the *t*-distribution respectively, as described in section 4.8. The outcome of the comparisons is summarised in table 6.9. Where the *t*-distribution test was not valid, the confidence band was calculated (table 6.10).

Parameter	Samples	Variances	Means
	Trial 1 - Harkers		
Cutting speed	System 2 and Approved	*Same*	*Same*
Feed rate	System 2 and Approved	*Same*	*Same*
Depth of cut	System 2 and Approved	*Same*	*Same*
Cutting speed	Engineering and Approved	*Same*	*Same*
Feed rate	Engineering and Approved	*Same*	*Same*
Depth of cut	Engineering and Approved	*Same*	*Same*
	Trial 2 - Reyrolle		
Cutting speed	System 2 and Approved	Different	Non-valid*
Feed rate	System 2 and Approved	*Same*	*Same*
Depth of cut	System 2 and Approved	*Same*	*same*
Cutting speed	Engineering and Approved	*Same*	Different
Feed rate	Engineering and Approved	Different	Non-valid*
Depth of cut	Engineering and Approved	*Same*	Different
	Trial 3 - Harkers		
Cutting speed	System 2 and Approved	*Same*	*Same*
Feed rate	System 2 and Approved	*Same*	*Same*
Depth of cut	System 2 and Approved	*Same*	*Same*
Cutting speed	Engineering and Approved	*Same*	*Same*
Feed rate	Engineering and Approved	*Same*	*Same*
Depth of cut	Engineering and Approved	*Same*	*Same*
**Note: The test for the comparison of means is not valid if the variances are not from the same population.*			

Table 6.9

Results of comparisons of variances and means - System 2

Parameter	Sample	Confidence band	Lower limit	Upper limit
Trial 2 - Reyrolle				
Cutting speed (m/min)	System 2 & Approved	261±14 273±42	247 231	275 315
Trial 2 - Reyrolle				
Feed rate (mm/rev)	Engineering & Approved	0.15±0.02 0.31±0.08	0.13 0.23	0.17 0.39

Table 6.10

Confidence bands for non-valid means - System 2

6.7 DISCUSSION OF RESULTS

The results in section 6.7.5 highlighted a number of points, bearing in mind the confidence limits that were applied:

1) With respect to Harker's data, all the sets of data were drawn from the same respective populations. This suggested a number of interesting observations:
   a) the results were superior to the Reyrolle data for System 1, which suggested there was no apparent deterioration in the quality of the system data, irrespective of the changes in the method of calculation (sections 6.2 - 6.4),
   b) the change in data approval procedure (section 6.5) between trial 1 and trial 3 was not discernible,
   c) there was no apparent difference between the supervised and unsupervised tests (section 6.6.1),
   d) the quality of the part programmers was very good.

2) With respect to Reyrolle's data:
   a) compared to the analysis for System 1 between the system and approved data, there was no change for System 2, including an overlap of the confidence bands for the non-valid mean,
   b) there was a slight deterioration between the engineering and approved data.

3) There was a marked difference between the quality of the engineering data for Harkers and Reyrolle. Despite being a sub-contract machine shop, Harkers evidently made a serious attempt to maximise their cutting data. This was unusual for this type of company, since production runs were normally too short to either attempt this or to make the effort worthwhile (section 3.1). In the case of Harkers, there were two possible reasons for this:

   a) the components were often sufficiently large to justify maximising the cutting data,

   b) as a deliberate change in company policy, at about the time the project started, Harkers actively sought work with larger batch sizes, compared to their traditional batch sizes of one or two, which may have permitted them to maximise cutting data.

4) Subjectively, the graphs 6.2 - 6.4 did not show that System 2 was more effective for any one particular material i.e. the graphs did not show any particular patterns that could readily be defined as a particular material. This was gratifying, since one of the materials was titanium, which is a notoriously difficult material to machine, particularly with respect to maintaining a reasonable tool life. Again the graphs showed that, in most cases, System 2 was following the approved data trends reasonably well.

CHAPTER 7

INSERT CONSTRAINTS, TOOL LIFE DATA AND COST DATA (SYSTEM 3)

7.1 INTRODUCTION

With Systems 1 and 2, when entering the details of an insert, the maximum and minimum cutting speed, feed rate and depth of cut (known as the insert constraints) were also required. These constraints were related to a particular material when cut with that particular tool and, where possible, were obtained from the tool manufacturer's literature. This literature provided the information for certain recommended insert/material combinations.

However, in addition to recommended combinations, for tool selection purposes it was also necessary to consider non-recommended combinations, since to solve the multi-batch tool selection problem outlined in section 1.3 there was a need to consider any insert with any material. This raised the problem of the provision of insert constraints for non-recommended insert/material combinations, particularly where there was limited or no previous cutting experience. With System 3 these constraints were removed from the input and Section 7.2 explains the rationale behind this decision.

In section 6.3, a method for obtaining values for α, β, γ and C_t in the extended Taylor equation for tool life was described. This was based on manufacturer's catalogue data, contained in a data file LIFE.DAT. However, the limitation of this method was that when a new material/insert grade combination was to be machined, extra data was required and this was not always possible. This was particularly so with the requirement for non-recommended insert/material combinations. To overcome this problem, LIFE.DAT was limited to just one set of data and a method devised for this data to be universally usable i.e. any tool/material combination.

How this was achieved is described in section 7.3.

Another area where it was difficult to obtain and maintain accurate data related to cost, in particular the cost of the insert and the tool. This data was required to calculate the cutting speed for minimum cost $V_{(cost)}$. After discussions with the companies, an alternative criterion was adopted for the cutting speed and the cost data was no longer required. The consequences of this are discussed in section 7.4 (and further considered in section 9.4).

Section 7.5 is concerned with the mechanisms of data input and the recording of the results. The tests carried out with System 3 are detailed in section 7.6. This includes the methodology, description of jobs, the results obtained and an analysis of these results. In addition, since with System 3 the method of data collection assumed greater importance, the section also details how this was carried out. The chapter concludes with a discussion of the results in section 7.7.

7.2 INSERT CONSTRAINTS

7.2.1 FEED RATE AND DEPTH OF CUT

According to both Seco (date unknown) and Smith (1989a), there are three basic requirements for the formation of swarf:

> "The swarf must:
>
> 1) flow away smoothly from the cutting edge without impairing the efficiency of the cutting area,
> 2) be of convenient size and shape to facilitate handling, storage, transportation and disposal,
> 3) fall away into the swarf tray without snarling round workpiece or tool and without interfering with other functions of the machine..."

In terms of the machining process, the most important of these criteria is the first one. In addition, there are implications relating to operator safety and damage to equipment and the product (Shaw (1986)). Continuous chips represent a safety hazard and interfere with the proper running of the machine. However, discontinuous chips may cause problems by sticking to the moving parts of the machine or by clogging up the coolant pump (Smith (1989b)).

Traditionally, to meet the criteria specified above, chipping or discontinuous swarf has been considered to be desirable as an aid to swarf control since, apart from anything else, it provides a higher density of swarf, thus requiring removal from the machine bed less often. Discontinuous swarf is also generally more desirable (Smith (1989a)), irrespective of the possible risk of machine damage already mentioned.

To assist in effective chip-breaking, modern tooling often incorporates a chip-breaker. There are three methods for satisfactorily achieving this (Smith (1989a)):

a) a chip-breaker is ground directly onto the tip (brazed tool),

b) a separate mechanical chip-breaker is position on top of the insert (flat indexable insert),

c) the chip-breaking profile is pressed into the insert prior to sintering (chip-breaker insert).

Given the prevalence of carbide inserts nowadays, probably the most common type in use today is the chip-breaker insert.

The principle of the chip-breaker is to cause the swarf to curl and strike either the tool or the workpiece, causing it to break. However, the chip-breaker insert assists in chip-breaking in a second way (Shaw (1986)). The stresses due to the nose radius of the tool can cause the chip to fracture partially along this edge. The consequential release of stress in the chip allows it to strike the tool or workpiece without rupturing all the way across. With a chip-breaker insert, the chip is pressed into the chip-breaking groove which is parallel to the secondary cutting edge (figure 7.1i)). This thickens the side of the chip (figure 7.1ii)) and prevents premature fracturing. The chip is then more likely to break when it strikes the tool or workpiece.

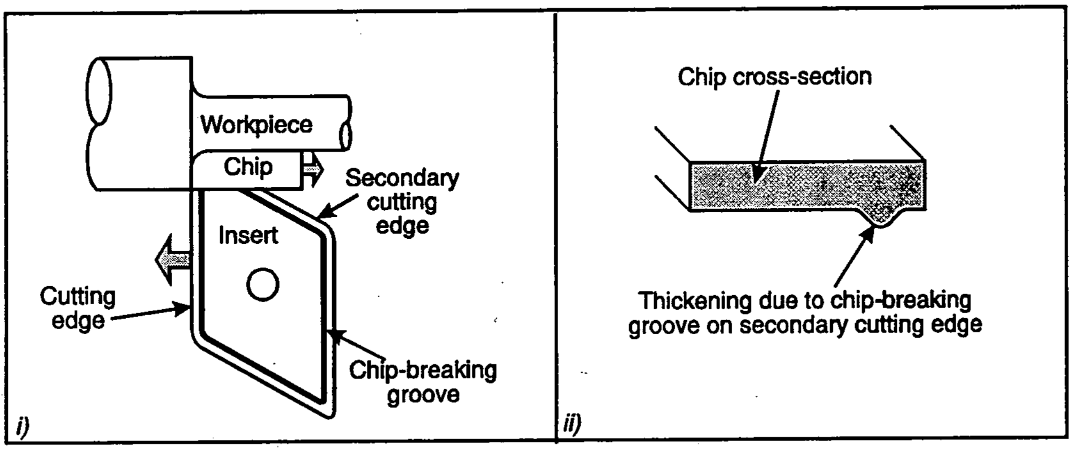


Figure 7.1
The chip-breaking insert and its effect on the chip

Chip-breakers work best over a limited range of feed rates and depths of cut. For example, as an aid to effective machining, Seco produced a Chipbreaker Manual, which provided the working range for various types of chipbreaker inserts for specific materials, such that they would produce acceptable chips. The working ranges were in terms of feed rate and depth of cut and the information was presented graphically (the so-called *a-S* diagram).

However, to keep the manual to a reasonable size, they were "...obliged to fix certain significant variables." (Seco (date unknown)). The variables that Seco fixed included the material (three steel grades), the setting or approach angle (four angles), one workpiece (160 mm - 180 mm diameter) and one cutting speed for each material. An alternative publication (Seco (1990)) again provided a number of *a-S* diagrams, but in this case only a dozen and they were all for medium carbon steel.

In practice, the type of swarf found to be acceptable depends very much on the operation in question. Occasional observation on the shop floor of both companies revealed some interesting situations. In one instance at Harkers, when a large casting was being externally turned on a vertical boring mill, discontinuous chips, either loose arc chips or elemental chips (BS 5623 (1979)), were being formed. However, these were coming off the tool at sufficient velocity to land in the adjacent aisle. Screens had to be erected around the machine to control the situation.

On another occasion at Harkers, again concerning a large casting although this time being bored, a 'ball' of snarled (BS 5623 (1979)) continuous swarf was positioned on the machine table in the centre of the bore. As the chip was formed, it continued to wrap itself around the ball. In this case a continuous chip was essential for swarf control.

Conversely, at Reyrolle a situation was observed on a lathe where again the swarf was continuous, of snarled tubular chip form (BS 5623 (1979)). This particular machine was fitted with a vertical turret. Whilst not interfering with the cutting process that was producing it, the swarf was dropping onto the next tool in the turret, which was below. As a result, when the machining cycle moved round to this tool, it was necessary to remove the swarf first.. Nevertheless, for reasons which were never ascertained, the operator evidently found this to be an acceptable situation, since machining continued on this basis.

These three examples have been included to illustrate that on the shop floor there are no definite rules governing chip formation. In practice, it is very much up to the operator to decide what situation is best for the job in hand. Indeed, it is likely that in the two examples concerning continuous chip formation, the cutting parameters were outside the envelope defined by the appropriate *a-S* diagram.

It was doubtful whether *a-S* diagrams were ever used by part programmers. At one stage during the project a request was made to a part programmer for a set of diagrams. The initial discussion was taken up by explaining what an *a-S* diagram was, since the part programmer seemed unaware of the existence of such diagrams. He then asked a colleague for the whereabouts of the information. The second programmer also did not know where to find the diagrams.

From the above discussion, it was questionable as to whether there was any advantage in applying the insert constraints for feed rate and depth of cut, given the difficulties in obtaining this information and the fact that the part programmers and operators apparently worked quite happily without knowledge of the constraints, although presumably experience played a significant role. Consequently, in System 3 the need for this input data was removed. This was carried out in the knowledge that this may have an adverse effect on the calculated data and that some type of data correction methodology may become necessary.

7.2.2 CUTTING SPEED

As far as the tool manufacturers' literature was concerned with cutting speed, a range or upper limit was normally indicated. However, this was in regard to the tool manufacturer's recommendations for tool life, rather than as absolute limits on the insert, since cutting speed has little, if any, influence on chip breaking or cutting forces. In appendix B, equation B.21 applied a minimum tool life constraint to the maximum cutting speed, based on a user-defined decision. Furthermore, another constraint was the 'power check' (equation B17, appendix B), which limited the cutting speed according to the available power. The cutting speed range, based on the tool maker's literature, was therefore considered redundant and was removed in System 3. Again, this was carried out in the knowledge that data correction may be required.

7.2.3 PRACTICAL CONSTRAINTS

Other than the constraints built into System 3, such as the cutting speed tool life and 'power check' constraints in section 7.2.2, the only limits for the cutting speed and feed rate were those applicable to the machine. In practice, these were normally far greater than the cut parameters. In consultation with the part programmers, general constraints was added for the depth of cut. The depth of cut was maintained between twice the nose radius r_e and three quarters of the effective length of the cutting edge L_e. This is shown in figure 7.2. Both r_e and L_e were readily available from the ISO code for the insert.

It was considered that if $a < (2 \times r_e)$, the tool may rub rather than 'dig in' and cut. It is interesting to note that this was also the minimum depth of cut specified in BS 5623 (1979) for tool life testing and may have been the basis for this empirical rule. Additionally, in both companies a typical finish cut had a depth of cut of 1 mm, for which a tool with a nose radius of 0.4 mm was in accordance with this rule. If $a > (0.75 \times L_e)$, there was an increased danger of tool failure during heavy cuts.

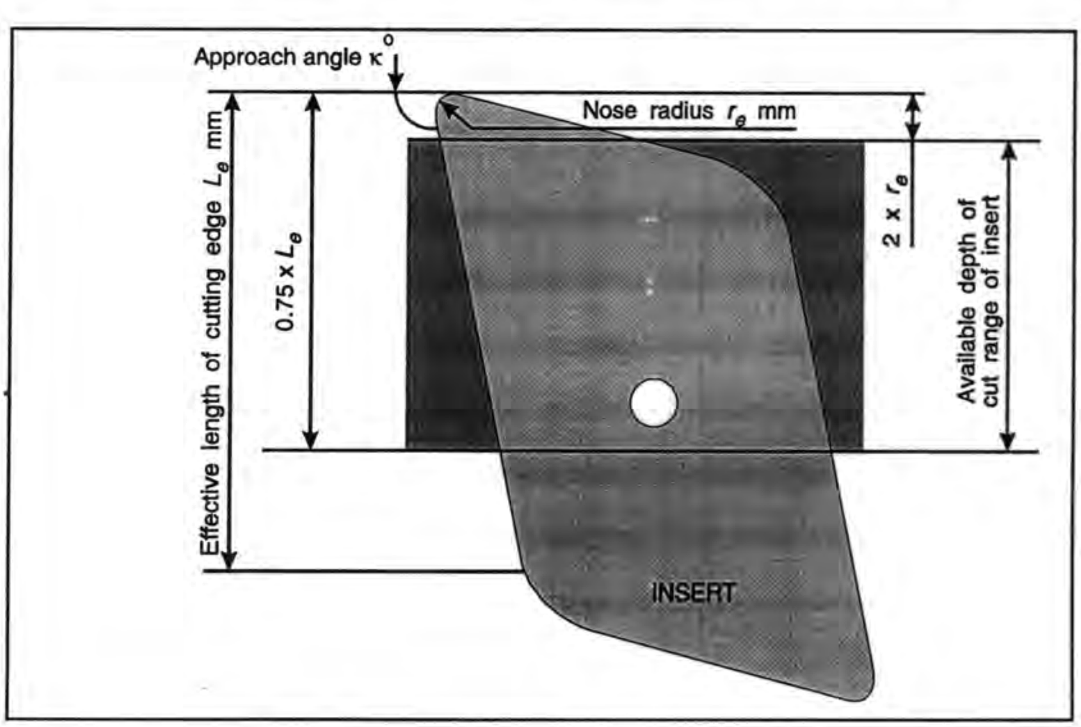


Figure 7.2
Available depth of cut range for insert

7.3 TOOL LIFE DATA

7.3.1 PRINCIPLES FOR OBTAINING TOOL LIFE DATA

In section 6.3 the problem of tool life data was discussed, whereby it was necessary to find values of α, β, γ and C_1 for every insert grade and material combination. As a short term measure, data for deriving these values was taken from tool manufacturers' catalogues (section 6.3). However, it was not considered reasonable to expect a user to determine the necessary information, either from existing data or by means of cutting tests, each time a new insert grade/material combination was considered by a tool selection system. Consequently a method was developed to determine the values for any combination that might occur in the future.

The method used was based on a data file, designated LIFE.DAT[1]. This file contained information (V, S, a and T) relating to mild steel being machined with a Seco insert of grade TP20, which was equivalent to an ISO grade P20. The information in the file, the contents of which are shown in appendix E, was extracted from literature supplied by a tool manufacturer (Seco (1988)). With the data in LIFE.DAT, α, β, γ and C_1 could be determined for the mild steel/P20 combination, using multiple regression techniques as explained in section 6.3.

For LIFE.DAT to be of use for any tool and material combinations, other than P20 and mild steel, it was necessary for the data within the file to be modified to suit the circumstances. Examination of cutting data in Seco (1988) and Sandvik (1988) showed that, irrespective of the grade or material, the main parameter to change for different tool lives was the cutting speed. Therefore a similar philosophy was adopted i.e. when data was taken from LIFE.DAT for materials and tools, only the cutting speed was altered.

---

[1] The file LIFE.DAT was the same file that was described in section 6.3, except that all data was removed, except for the data relating to the mild steel/P20 combination.

The steps required to convert the data in LIFE.DAT into the form for the current job and hence obtain values for α, β, γ and C_1 are summarised below and in figure 7.3. They are then described in greater detail in section 7.3.2. It should be noted that ISO insert grades are of the form of a letter (P, K or M), followed by a number, typically between 5 and 50 e.g. P10, K30, M25.

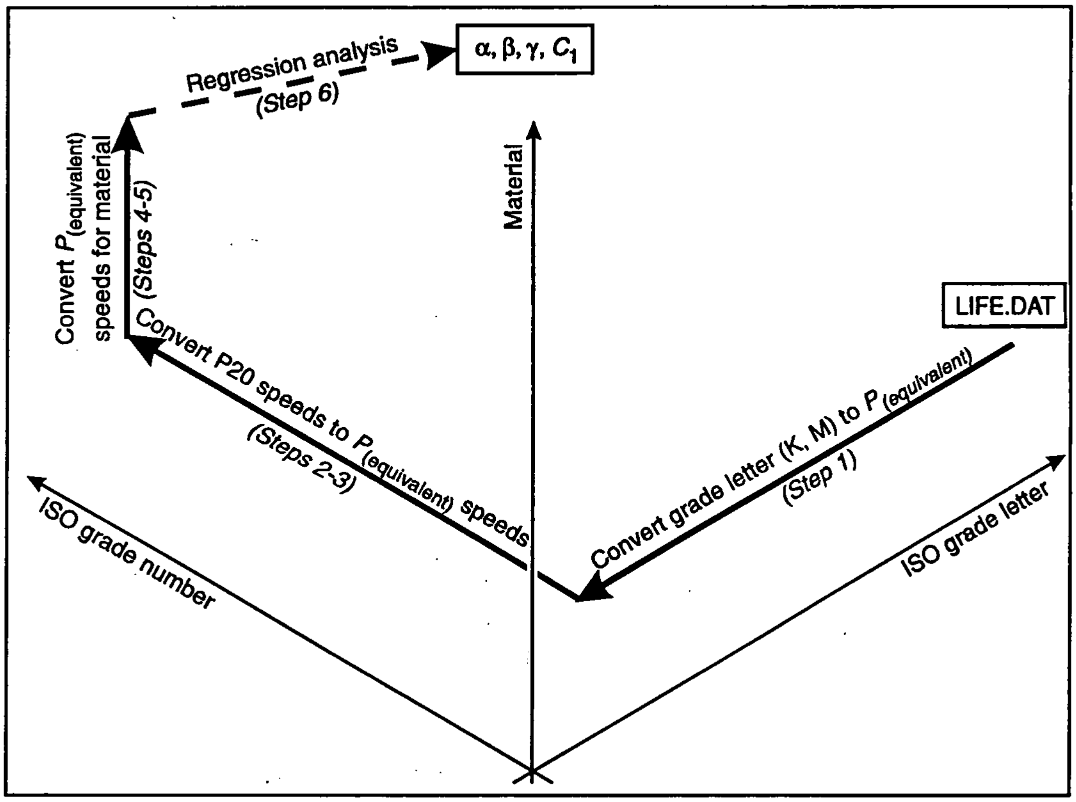


Figure 7.3

Conversion of data in file LIFE.DAT

The steps are:

Step 1

If the current job insert is an ISO K or M grade, then convert the current job insert ISO grade to an ISO P grade (designated $P_{(equivalent)}$).

Step 2

Calculate factor to convert P20 cutting speeds to P or $P_{(equivalent)}$ cutting speeds.

Step 3

Modify the cutting speed in LIFE.DAT to suit the appropriate P grade.

Step 4

Determine a factor to convert the cutting speed in LIFE.DAT to the equivalent speeds for the material for the current job (using specific cutting force K_s).

Step 5

Convert the cutting speeds in LIFE.DAT to the equivalent speeds for the material for the current job.

Step 6

Determine values for α, β, γ and C_1.

7.3.2 STEPS TO OBTAIN TOOL LIFE DATA

Step 1

If the current job insert is an ISO K or M grade, then convert the current job insert ISO grade to an ISO P grade (designated $P_{(equivalent)}$)

Should the ISO grade for the tool being used for the current job be either type K or M rather than type P, the first step was to convert it to the equivalent type P ($P_{(equivalent)}$). According to Sandvik (1988), certain Sandvik insert grades are the equivalent of more than one ISO grade. In addition, each of the Sandvik grades concerned covers a range of ISO grades. This suggested that there was an overlap within a particular grade range (P, K or M) as well as an overlap across the grade range. Of particular interest was the fact that these ranges included ISO type P. The ranges in question are shown in table 7.1.

Sandvik grade	ISO M grade range	ISO K grade range	ISO P grade range
GC415	10 - 25	5 - 20	5 - 30
GC425	15 - 25	-	10 - 35
GC235	25 - 40	-	30 - 50
GC435	-	5 - 25	15 - 40

Table 7.1

Equivalent insert grades (Sandvik (1988))

The relationships between P and M grades and P and K grades were examined using linear regression. Both cases were tested for either a straight line and an exponential line (by testing the natural logarithms of the data). The data sets were formed by matching the extreme ends of the ranges e.g. for the GC415 grade (M10, P5), (M25, P30), (K5, P5), (K20, P30). In both cases P was taken as the *y*-axis, since M and K were being used to predict P.

Consequently, the relationship between P and M grades was expressed as:

$$P_{(equivalent)} = 0.0876 \times M^{1.79} \qquad \text{Equ 7.1}$$

which resulted from regression analysis of the logarithms of the data sets in table 7.1 for P and M grades. The correlation coefficient r for this data was 0.9810, which compared favourably with $r_{(0.05,\,4)} = 0.8114$.

The corresponding expression relating P and K grades was:

$$P_{(equivalent)} = (1.45 \times K) + 2.55 \qquad \text{Equ 7.2}$$

based on regression analysis of the data sets for P and K grades in table 7.1. The correlation coefficient r for this data was 0.9621, which compared favourably with $r_{(0.05,\,2)} = 0.9500$.

It was appreciated that such a conversion might not be strictly applicable to inserts made by another tool manufacturer. Nevertheless, the assumption was made that the conversions would apply. Equations 7.1 and 7.2 allowed any ISO K or M grade to be converted to a $P_{(equivalent)}$ grade.

Example 7.1:

If the grade in question was an ISO grade M30, then from equation 7.1:

$$P_{(equivalent)} = 0.0876 \times 30^{1.79} = 38.6$$

i.e. ISO grade M30 was equivalent to ISO grade P38.6 (≈P39)

Step 2

Calculate factor to convert P20 cutting speeds to P or $P_{(equivalent)}$ cutting speeds

Having determined the equivalent P grade, the next step was to determine the factor by which the cutting speeds for the P20 grade in LIFE.DAT were to be adjusted, to allow for the P or $P_{(equivalent)}$ grade in question. To achieve this, the recommended cutting speeds for a Seco group 3 material were used. This information was found in Seco (1996) and reproduced in table 7.2. The construction of the table is described in appendix M.

ISO grade	Average cutting speed $V_{(average)}$ m/min for a feed rate of:					
	0.1 mm/rev	0.2 mm/rev	0.3 mm/rev	0.4 mm/rev	0.6 mm/rev	0.8 mm/rev
P10	442	351	293	258	211	-
P15	407	320	276	239	200	185
P20	387	305	260	228	193	178
P25	-	279	242	216	185	171
P30	359	277	234	208	178	160
P35	-	234	202	180	155	142
P40	292	220	182	161	139	128

Table 7.2

Average cutting speeds for ISO grade P inserts

Examination of LIFE.DAT showed that a number of different feed rates had been used; 0.1, 0.2, 0.3, 0.4, 0.6 and 0.8 mm/rev. Consequently these feed rates were used in table 7.2. For each of these feed rates, the correlation between the average speeds and the P grade was checked, using regression analysis. In each case the correlation was good at 95% confidence limits. The regression formulae relating the average cutting speeds to the P grades were:

0.1 mm/rev: $V_{(average)} = (-4.64 \times P) + 484.1$ Equ 7.3a

0.2 mm/rev: $V_{(average)} = (-4.23 \times P) + 389.4$ Equ 7.3b

0.3 mm/rev: $V_{(average)} = (-3.61 \times P) + 331.4$ Equ 7.3c

0.4 mm/rev: $V_{(average)} = (-3.06 \times P) + 289.4$ Equ 7.3d

0.6 mm/rev: $V_{(average)} = (-2.28 \times P) + 237.1$ Equ 7.3e

0.8 mm/rev: $V_{(average)} = (-2.30 \times P) + 223.8$ Equ 7.3f

The cutting speed in each line of the file LIFE.DAT was modified by multiplication by a factor. The factor represented the ratio of the average cutting speed for the P or $P_{(equivalent)}$ grade ($V_{(average,\ P(new))}$) over the average cutting speed for a P20 grade ($V_{(average,\ P20)}$), which was the insert ISO grade in LIFE.DAT i.e.:

$$Factor = \frac{V_{(average,\ P(new))}}{V_{(average,\ P20)}} \qquad \text{Equ 7.4}$$

Step 3

Modify the cutting speed in LIFE.DAT to suit the appropriate P grade.

The cutting speeds in LIFE.DAT were multiplied by the appropriate factor.

Example 7.2:

Using the $P_{(equivalent)}$ of P38.6 from example 7.1, with a feed rate of 0.1 mm/rev in LIFE.DAT, then from equations 7.3a and 7.4:

$$Factor = \frac{V_{(average,\ P(new))}}{V_{(average,\ P20)}} = \frac{(-4.64 \times 38.6) + 484.1}{(-4.64 \times 20) + 484.1} = 0.779$$

i.e. the cutting speeds with a feed rate of 0.1 mm/rev in LIFE.DAT have to be multiplied by 0.779 to make them suitable for the M30 grade insert in example 7.1.

Step 4

Determine a factor to convert the cutting speed in LIFE.DAT to the equivalent speeds for the material for the current job (using specific cutting force K_s).

To modify the file LIFE.DAT for different materials, the specific cutting force was utilised and a relationship between average cutting speed and specific cutting force defined. This information was found in Seco (1996) and reproduced in table 7.3 for a range of different steels. Although table 7.3 only included data for steel, it was assumed that K_s could be used to relate average cutting speed for any material. The construction of the table is described in appendix M.

	Average cutting speed $V_{(average)}$ m/min for a feed rate of:					
K_s N/mm²	0.1 mm/rev	0.2 mm/rev	0.3 mm/rev	0.4 mm/rev	0.6 mm/rev	0.8 mm/rev
1900	542	412	339	298	249	230
2100	380	288	232	205	169	156
2250	313	237	189	169	139	129
2300	305	233	186	166	136	-
2500	270	205	165	146	117	102
2550	242	183	148	130	107	99
2600	227	186	150	132	111	105
2700	130	98	79	70	58	54

Table 7.3

Average cutting speeds for specific cutting forces

The feed rates in table 7.3 were based on a similar philosophy to those in table 7.2. For each of these feed rates, the correlation between the average cutting speeds and K_s was checked, using regression analysis. In each case the correlation was good at 95% confidence limits. The regression formulae relating the average cutting speeds to K_s were:

0.1 mm/rev: $V_{(average)} = (-0.43 \times K_s) + 1315$ Equ 7.5a

0.2 mm/rev: $V_{(average)} = (-0.32 \times K_s) + 986.4$ Equ 7.5b

0.3 mm/rev: $V_{(average)} = (-0.26 \times K_s) + 808.2$ Equ 7.5c

0.4 mm/rev: $V_{(average)} = (-0.23 \times K_s) + 713.1$ Equ 7.5d

0.6 mm/rev: $V_{(average)} = (-0.19 \times K_s) + 592.8$ Equ 7.5e

0.8 mm/rev: $V_{(average)} = (-0.18 \times K_s) + 553.2$ Equ 7.5f

The cutting speed (already modified for the ISO grade) in each line of the file LIFE.DAT was modified by multiplication by a factor. The factor represented the ratio of the average cutting speed for K_s for the current job ($V_{(average,\ Ks(new))}$) over the average cutting speed for K_s = 2100 N/mm² ($V_{(average,\ Ks(2100))}$), which was the material in LIFE.DAT i.e.:

$$Factor = \frac{V_{(average,\ Ks(new))}}{V_{(average,\ Ks(2100))}}$$ Equ 7.6

Step 5

Convert the cutting speeds in LIFE.DAT to the equivalent speeds for the material for the current job.

The cutting speeds in LIFE.DAT were multiplied by the appropriate factor.

Example 7.3:

If the material in question had a specific cutting force of 2650 N/mm², with a feed rate of 0.1 mm/rev in LIFE.DAT, then from equations 7.5a and 7.6:

$$Factor = \frac{V_{(average,\ Ks(new))}}{V_{(average,\ Ks(2100))}} = \frac{(-0.43\times 2650)+1315}{(-0.43\times 2100)+1315} = 0.426$$

Step 6

Determine values for α, β, γ and C_1

Using the data in the file LIFE.DAT, modified as appropriate, values for α, β, γ and C_1 were determined, using multiple regression. This is an established technique for tool life data e.g. Leslie and Lorenz (1964).

7.4 COST DATA

Systems 1 and 2 gave the user the choice of a number of cutting speeds, each one being considered to be an appropriate optimum cutting speed, based on a particular production criteria (appendix B):

a) cutting speed for minimum machining time per component $V_{(time)}$ (m/min),

b) cutting speed for minimum machining cost per component $V_{(cost)}$ (m/min),

c) cutting speed for maximum tool life $V_{(life)}$ (m/min),

d) cutting speed for the minimum number of tools $V_{(number)}$ (m/min).

In practice, only one cutting speed was required. In discussions with the users in both companies (part programmers carrying out testing at that time), it was agreed that the cutting speed which was most useful to them was the speed for minimum machining time, $V_{(time)}$, in preference to the cutting speed for minimum machining cost, $V_{(cost)}$. This was confirmed in later discussions with the higher management within the companies. A discussion of the strategic approach to cost and the companies' views of cost is given in section 9.4.

Removal of the cost function had advantages in terms of input data. There were three cost variables required for input purposes:

a) cost of the insert c_i(£)

b) cost of the holder c_h (£)

c) machine hourly cost x (£)

The variables c_h and c_i were used to find the cost per cutting edge y (£):

$$y = \frac{c_i}{0.75 \times nce} \times \frac{1.3 \times c_h}{400} \text{ (£)} \qquad \text{Equ 7.7}$$

(equation B.23, appendix B)

where nce was the number of cutting edges.

The variables y and x were then used to find $V_{(cost)}$ in equation 7.8 and the total machining cost m_c (£) in equation 7.9 .

$$V_{(cost)} = \left(\frac{\left(\frac{x}{60}\right) \times C_1}{S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1\right) \times \left(\left(\frac{x}{60} \times t_3\right) + y \right)} \right)^{\alpha} \text{ (m/min)} \qquad \text{Equ 7.8}$$

(equation B.24, appendix B)

$$m_c = \left(\left(t_2 \times \frac{x}{60}\right) + \frac{t_2 \times t_3 \times \frac{x}{60}}{T} + \frac{t_2 \times y}{T} \right) \times B \text{ (£)} \qquad \text{Equ 7.9}$$

(equation B.29, appendix B)

where where t_2 (mins) was the effective machining time (equation B.30, appendix B), t_3 (mins) was the tool change time, y (£) was the cost per cutting edge, x (£/hr) was the hourly machine cost, T (mins) was the tool life, B was the batch size and α, β, γ and C_1 were from the extended Taylor equation (equation B.21, appendix B).

These three variables c_i, c_h and x were not always easy to determine, a view also taken by Chen et al (1995), who understood that "...the cost factor itself often cannot be precisely determined". Variable x has already been discussed in section 6.4.3, where it was explained that approximate default values were adopted. For c_i and c_h to be of any use, current values had to be available. Ideally, this would have been from a tooling data file. However, considerable work would have been entailed in keeping the data file current, since every time a tool manufacturer introduced a revised price list, the relevant details would need to be entered into the data file. The removal of the two variables from the input data simplified the situation.

7.5 DATA INPUT AND RECORDING OF RESULTS

7.5.1 DATA INPUT

In section 6.4.5 the use of data files was described for repeat input data[1]. They were still used in System 3, although certain fields were no longer required e.g. fields relating to cost variables. Where this occurred, default values were inserted in the data file records and ignored by System 3.

Since System 1, the input data describing the job was stored in a job file, so that the job could be processed again if this was required for any reason. In this way, the job file also gave the job basic attributes. During the development of the system from System 1 to System 3 the job files were subject to refinement. Typical data file records for System 3 are shown in appendix F, boxes F.1 - F.5, as is a typical job file in box F.7.

7.5.2 RECORDING OF RESULTS

During the development of System 3, it was considered that some form of data correction would become necessary. This was particularly so after the insert

[1] The data files covered holders, boring bars, inserts, materials and machine tools.

constraints had been removed (section 7.2) and the revised method for determining tool life data was incorporated (section 7.3). As a result, a data correction method was included in System 3. This method was based on regression analysis and is described in appendix I. It was subsequently found not to be as effective as expected and was abandoned. A new method of data correction was developed in its place (chapter 8), once the data had been collected. However, the data from Reyrolle for System 3 was collected with the regression analysis method in place.

A record sheet (box 7.1) was used to record both the corrected system data and the approved data. The details on the record sheet were used to transfer cutting parameters from the system to the machine tool operator[1], whilst the system data and certain job attributes were also stored in a data file, known as the main data file. An example record for the main data file is shown in appendix F, box F.6. The attributes stored were those which defined the jobs groups in tables 7.4 - 7.7. Each record in the main data file contained the details of a job. Once the approved data was returned from the shop floor, this was also stored in the main data file against the appropriate job. The complete record was then available as historical data for the purposes of data correction.

Since the regression analysis correction method was in use during the Reyrolle tests, the data sent to the shop floor as system data was in fact corrected data. However, there was no reason to suspect that this unduly influenced the approved data resulting from the tests.

[1] The CNC part program was written using the engineering cutting parameters, rather than the system cutting parameters. Thus re-programming took place on the machine, so that the system data could be tested.

CUTTING TESTS FOR DATABASE - REYROLLE	
BEFORE MACHINING (FROM ITS)	
RECORD NUMBER	40
IDENTIFICATION NUMBER	975A10 F-TURN
SPECIFIED MINIMUM TOOL LIFE (mins)	30
CUTTING SPEED (m/min)	263
FEED RATE (mm/rev)	·2
DEPTH OF CUT (mm)	1·1
AFTER MACHINING	
CUTTING SPEED (m/min)	150
FEED RATE (mm/rev)	·3
DEPTH OF CUT (mm)	1·1
ACTUAL TOOL LIFE (complete one box only)	
TOOL LIFE (mins)	
NUMBER OF ITEMS BEFORE TOOL FAILURE	51
LENGTH OF CUT (mm) BEFORE TOOL FAILURE (LESS THAN ONE PASS ONLY)	
NUMBER OF PASSES BEFORE TOOL FAILURE	
TOOL NOT FAILED	

(CUTD VERSION 6.0)
apprey2.dch/4/92/prl Signed J. Budlam Date 8/7/92

Box 7.1

Record sheet used with System 3

The introduction of the main data file had a further use. For System 3, sufficient tests were carried out to enable the jobs to be categorised by job groups, where a job group was a collection of jobs with similar attributes. The groups are explained more fully in section 7.6.2, tables 7.4 - 7.7. When historical data was used to correct the system calculations, data from previous similar jobs was chosen from the data file i.e. jobs from the same job group. This use of the data file enabled other job attributes, not required in the calculation, to be stored and used to help define the job groups. In this way the attributes of continuous or intermittent cutting were introduced. This was considered to be an important feature, since intermittent cutting often requires a lower cutting speed than continuous cutting.

7.6 TESTS AND RESULTS FOR SYSTEM 3

7.6.1 METHODOLOGY

The data used in these results was collected from both of the collaborating companies. It was planned that the actual methodology of testing was to be as previously described (section 6.6.1). Data approval was to be carried out in accordance with the data approval procedure (section 6.5).

Since these were planned to be the final tests, a larger number of tests were planned than had previously been the case. However, collecting industrial data in real time (as opposed to using historical data from company records) proved to be time consuming. Appendix G contains a sequence of events over a period of seven weeks. As the appendix points out, only five jobs were completed during this period. Because of these difficulties, the necessary data was collected from each company in a different manner.

The original intention had been to install System 3 in both companies, train company personnel in its use and then let them collect the necessary data. Each company nominated an employee for this purpose. At Reyrolle this worked perfectly well, although it required modifying the production schedule to bring forward jobs considered suitable for testing. In this case these were mild steel jobs for the FT20 lathes. Mild steel was chosen since it was the most common material in the production schedule for the forthcoming period, thus yielding the maximum number of tests.

At Harkers, the less rigid production schedule and longer manufacturing cycles resulted in very few tests being carried out over the initial period. However, those jobs which were tested showed negligible difference between engineering data and approved data. Harkers claimed that they had been machining these jobs (and the material - cast iron) for a long time and had already been through a data approval cycle. This was confirmed during the testing of System 2 where, in every case, the approved and engineering data were from the same population (section 6.6.4). In an effort to reduce the length of the testing period, it was agreed to use Harkers existing engineering data as approved data.

7.6.2. DESCRIPTION OF JOBS

Because there was considerably more data collected for System 3, it was possible to break the jobs down into a number of groups. These groups are described in tables 7.4 - 7.7.

Machine type	Vertical boring mills
ISO holder	PCLNR4040S19
ISO insert	CNMG190616
ISO insert grade	K15
Material	Cast iron
Roughing/Finishing	Roughing

Table 7.4

General attributes for Harkers jobs

Job group	Machine (Schiess)	Inside/ Outside diameter	Facing/ Longitudinal	Total number of jobs in group
1	3 metre	Inside	Longitudinal	13
2	5 metre	Outside	Longitudinal	7
3	5 metre	Outside	Facing	7
4	5 metre	Inside	Longitudinal	19
5	4 metre	Inside	Longitudinal	11

Table 7.5

Specific attributes for Harkers jobs

Machine	AL20 (lathe)
ISO holder/boring bar	PCLNR2525A12
ISO insert	CNMG120404
ISO insert grade	P30
Material	Mild steel plate/rod/tube/bar
Inside/Outside diameter	Outside

Table 7.6

General attributes for Reyrolle jobs

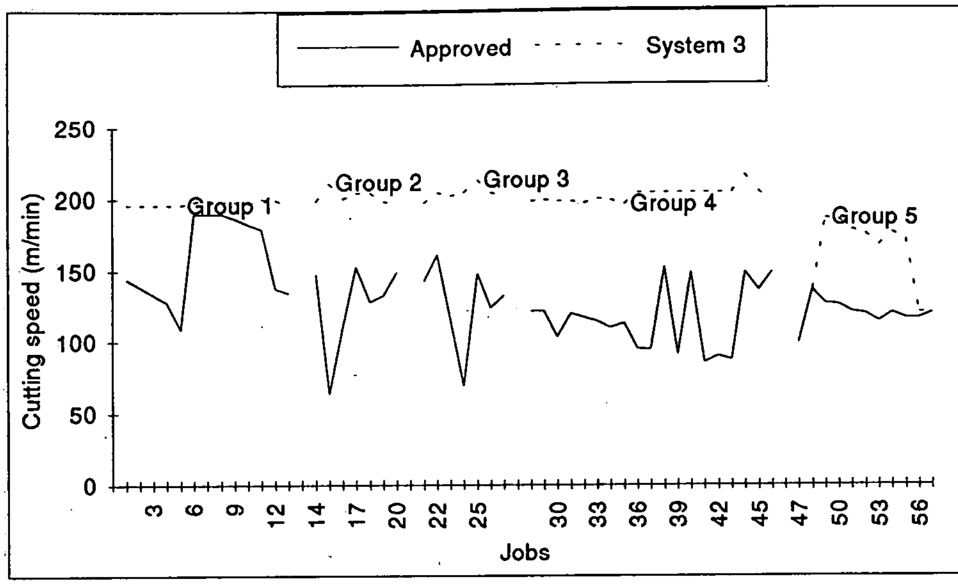
Job group	Roughing/ Finishing	Longitudinal/ Facing	Total number of jobs in group
A	Finishing	Longitudinal	8
B	Roughing	Longitudinal	8
C	Roughing	Facing	7

Table 7.7

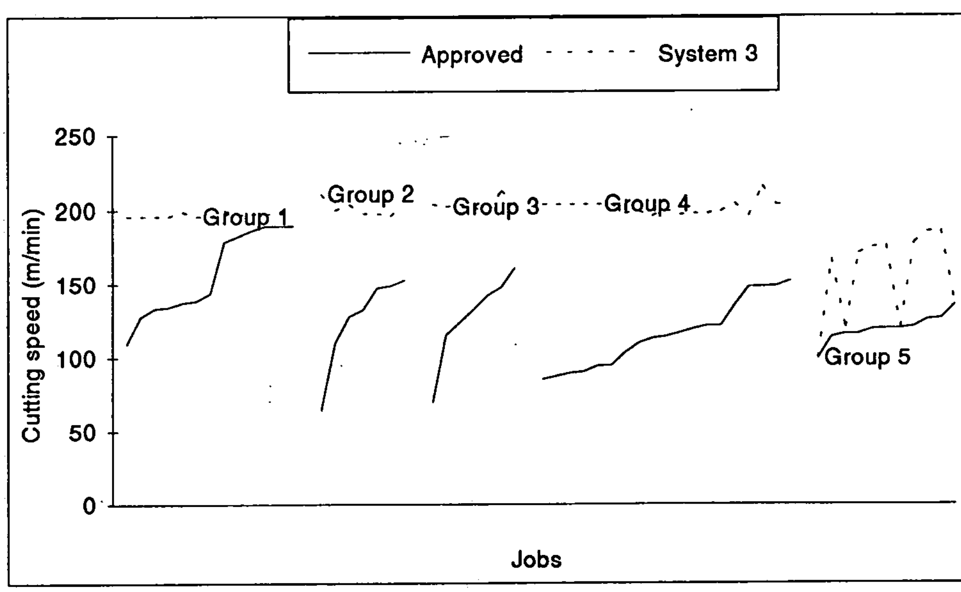
Specific attributes for Reyrolle jobs

7.6.3 TEST RESULTS

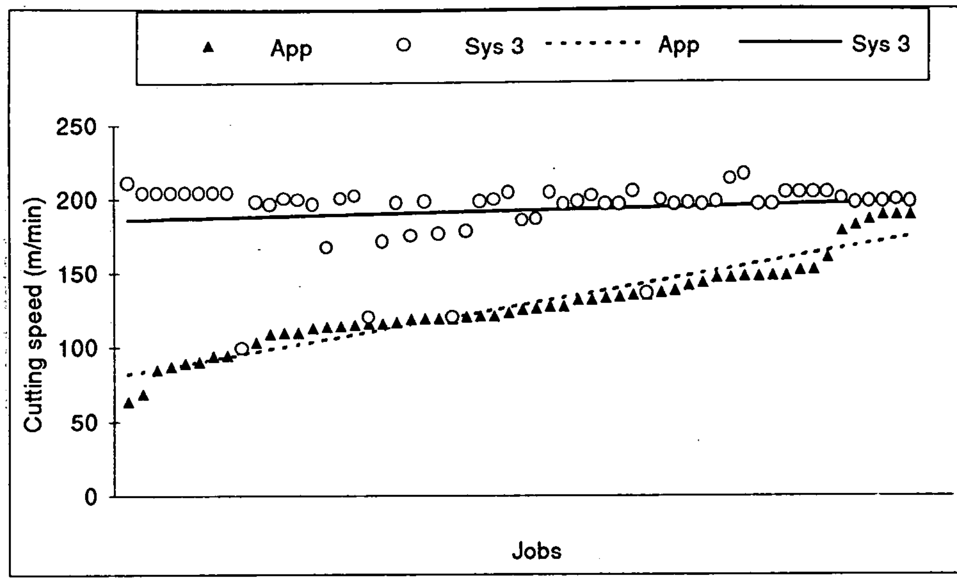
The results of the tests are shown in tables H.1 - H.8, (appendix H), and example graphs are shown in graphs 7.1 - 7.3. Graph 7.1 shows the results for Harkers cutting speed, in job order. Graph 7.2 shows the same data, but within each job the data has been ordered in approved data ascending order. Graph 7.3 is a scatter graph of all the data from the five groups combined, and again ordered in approved data ascending order. In addition, the best-fit line for each set of scatter points, determined by the least squares method, is also shown.



Graph 7.1
Example test results for System 3
Harkers cutting speed
(Groups 1 - 5 refer to Harkers job groups)



Graph 7.2
Example ordered test results for System 3
Harkers cutting speed
(Groups 1 - 5 refer to Harkers job groups)



Graph 7.3

Example combined ordered test results for System 3

Harkers cutting speed

7.6.4 ANALYSIS OF RESULTS

The results were analysed for each parameter within each job group to see whether the two sets (System 3 and approved) were from the same statistical population for each trial. A population for a trial was the cutting data for that particular job group. As before, the approved data was taken as the reference results, and the System 3 data was compared with the approved data. The analysis consisted of comparing both the variability and the means, using the *F*-distribution and the *t*-distribution respectively, as described in section 4.8. The outcome of the comparisons is summarised in table 7.8. Where the *t*-distribution test was not valid, the confidence band was calculated (table 7.9), as described in section 4.8.

Parameter	Samples	Variances	Means
Harkers job group 1			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*
Depth of cut	System 3 and Approved	***Same***	Different
Harkers job group 2			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*
Depth of cut	System 3 and Approved	***Same***	Different
Harkers job group 3			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	***Same***	Different
Depth of cut	System 3 and Approved	***Same***	Different
Harkers job group 4			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*
Depth of cut	System 3 and Approved	***Same***	Different
Harkers job group 5			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*
Depth of cut	System 3 and Approved	***Same***	Different
Reyrolle job group A			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*
Depth of cut	System 3 and Approved	***Same***	***Same***
Reyrolle job group B			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	***Same***	***Same***
Depth of cut	System 3 and Approved	***Same***	***Same***
Reyrolle job group C			
Cutting speed	System 3 and Approved	Different	Not valid*
Feed rate	System 3 and Approved	***Same***	***Same***
Depth of cut	System 3 and Approved	Different	Not valid*
**Note: The test for the comparison of means is not valid if the variances are not from the same population.*			

Table 7.8

Results of comparisons of variances and means - System 3

Parameter	Sample	Confidence band	Lower limit	Upper limit
Harkers job group 1				
Cutting speed (m/min)	System 3 & Approved	197±1 157±18	196 139	198 175
Feed rate (mm/rev)	System 3 & Approved	1.28±0.00 0.74±0.06	1.28 0.68	1.28 0.80
Harkers job group 2				
Cutting speed (m/min)	System 3 & Approved	202±5 126±29	197 97	206 155
Feed rate (mm/rev)	System 3 & Approved	1.25±0.07 0.71±0.18	1.19 0.53	1.32 0.89
Harkers job group 3				
Cutting speed (m/min)	System 3 & Approved	204±4 127±28	199 100	208 155
Harkers job group 4				
Cutting speed (m/min)	System 3 & Approved	202±2 115±11	200 105	204 126
Feed rate (mm/rev)	System 3 & Approved	1.26±0.03 0.58±0.15	1.23 0.43	1.29 0.74
Harkers job group 5				
Cutting speed (m/min)	System 3 & Approved	156±21 119±6	135 113	177 125
Feed rate (mm/rev)	System 3 & Approved	1.28±0.00 0.85±0.16	1.28 0.69	1.28 1.01
Reyrolle job group A				
Cutting speed (m/min)	System 3 & Approved	228±0 296±68	228 228	228 364
Feed rate (mm/rev)	System 3 & Approved	0.20±0.00 0.23±0.03	0.20 0.20	0.20 0.26
Reyrolle job group B				
Cutting speed (m/min)	System 3 & Approved	192±11 250±35	181 215	203 285
Reyrolle job group C				
Cutting speed (m/min)	System 3 & Approved	192±4 275±49	187 225	196 324
Depth of cut (mm)	System 3 & Approved	2.57±1.84 2.02±0.69	0.73 1.33	4.41 2.71

Table 7.9

Confidence bands for non-valid means - System 3

7.7 DISCUSSION OF RESULTS

The results for System 3 showed that there was a deterioration in the quality of the system data, compared to the results of Systems 1 and 2. However, graphs 7.1 - 7.3 and tables 7.8 - 7.9 indicated what had occurred. Examination of the data showed that in many cases. the approved and system data had both followed a similar trend, as with Systems 1 and 2. This suggested that the use of the forces parameters file FORC.DAT (section 6.2) and conversion of data in the tool life data file LIFE.DAT (section 7.3) were functioning as intended, to a greater or lesser extent. To judge the effectiveness of this, it is worthwhile comparing the insert grades and materials for the data within the files FORC.DAT and LIFE.DAT, compared to those for the job groups:

	Material	Insert grade
FORC.DAT	Mild steel	P20
LIFE.DAT	Mild steel	P20
Harkers job groups	Cast iron	K15
Reyrolle job groups	Mild steel	P30

In the case of Harkers, most of the jobs had larger system means and smaller standard deviations, compared to the approved data. Nevertheless, even in many cases, there were similarities in trends between the approved and system data, as demonstrated by the re-ordered data in graph 7.2. Again, the convergence of graph 7.3 was also a recurring feature. This suggested that in many cases, a relatively linear error was occurring. From the results, it was not obvious whether the change in the results was due to the tool life parameters or the removal of the insert constraints.

It was evident, from the results in this chapter, that whilst System 3 was tending to follow the approved trends, it was necessary to adjust or correct the data so that it would be from the same statistical populations as the approved data. This data correction is described in chapter 8.

CHAPTER 8

CORRECTION OF SYSTEM 3 DATA

8.1 INTRODUCTION

As shown in chapter 7, although System 3 produced similar data trends to the approved data, in many cases either the standard deviations and/or the means were incorrect i.e. the system data was not from the same statistical population as the approved data. Three different methods of correcting the data were assessed:

a) regression analysis,

b) rolling average,

c) mean and standard deviation correction.

Of the three, the last one (mean and standard deviation correction) was found to be the best and is discussed in this chapter. The other two methods are described briefly in appendix I, along with the reasons as to why they were rejected.

Once the method of correcting the data had been developed (section 8.2), the System 3 data was used to test the methodology and the usual analysis applied (section 8.3). As a further test of the correction method, it was applied to the results obtained with System 2 (chapter 6) and the results are shown in section 8.4. Finally, the corrected results are discussed (section 8.5).

8.2 METHODOLOGY OF CORRECTION OF DATA

8.2.1 PRINCIPLES OF DATA CORRECTION

For the job in question, each cutting parameter was independently corrected in turn. The process is shown in figure 8.1 in terms of a graph (similar to those used to show the results in chapters 5 - 7) and in figure 8.2 as distribution curves. The correction of each of the parameters was carried out in two stages:

1) Correction of the mean (figures 8.1 ii and 8.2 ii).

   The mean of the system data was adjusted to the same as the approved data.

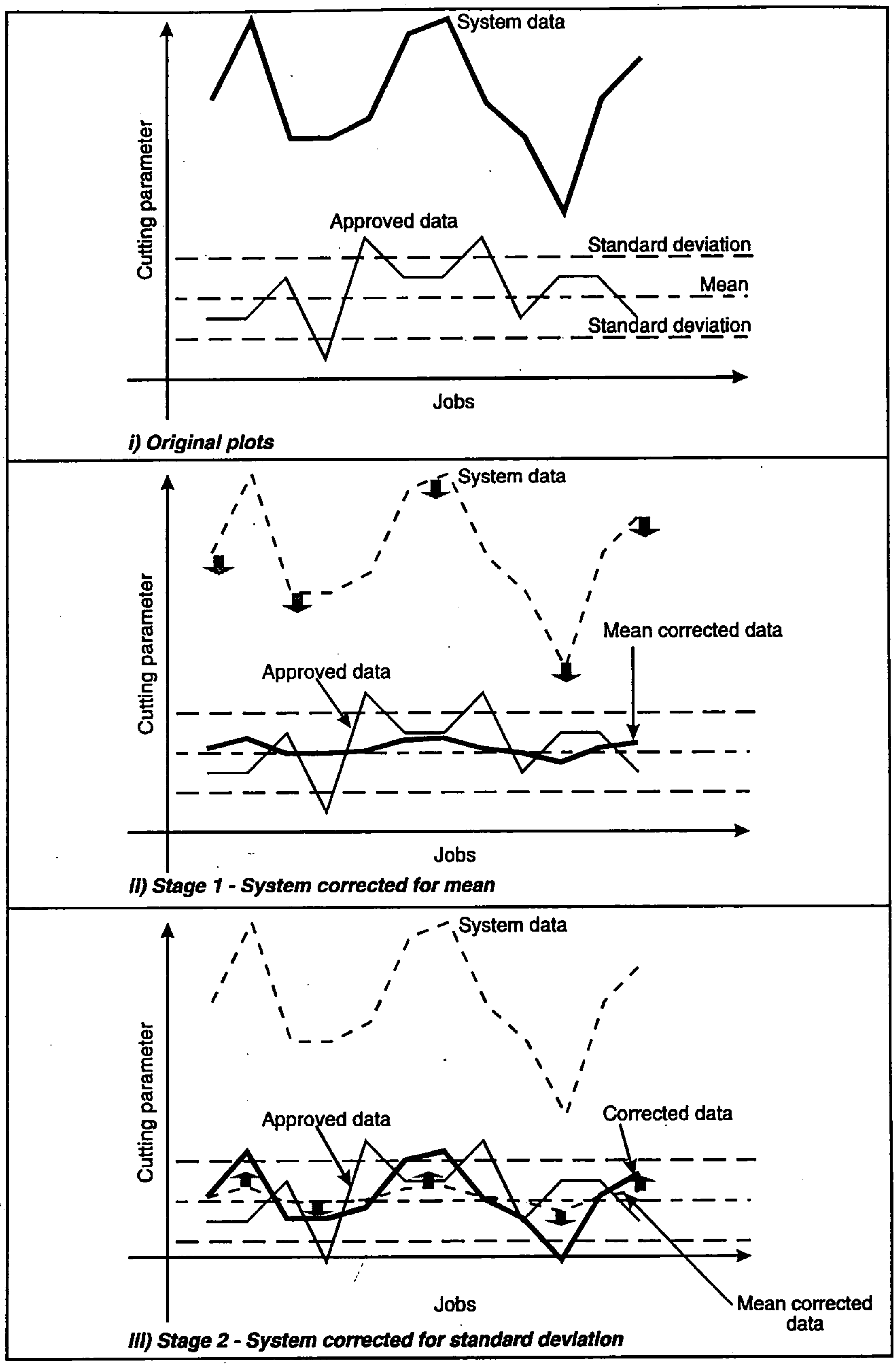


Figure 8.1

Correction of system mean and standard deviation (graphs)

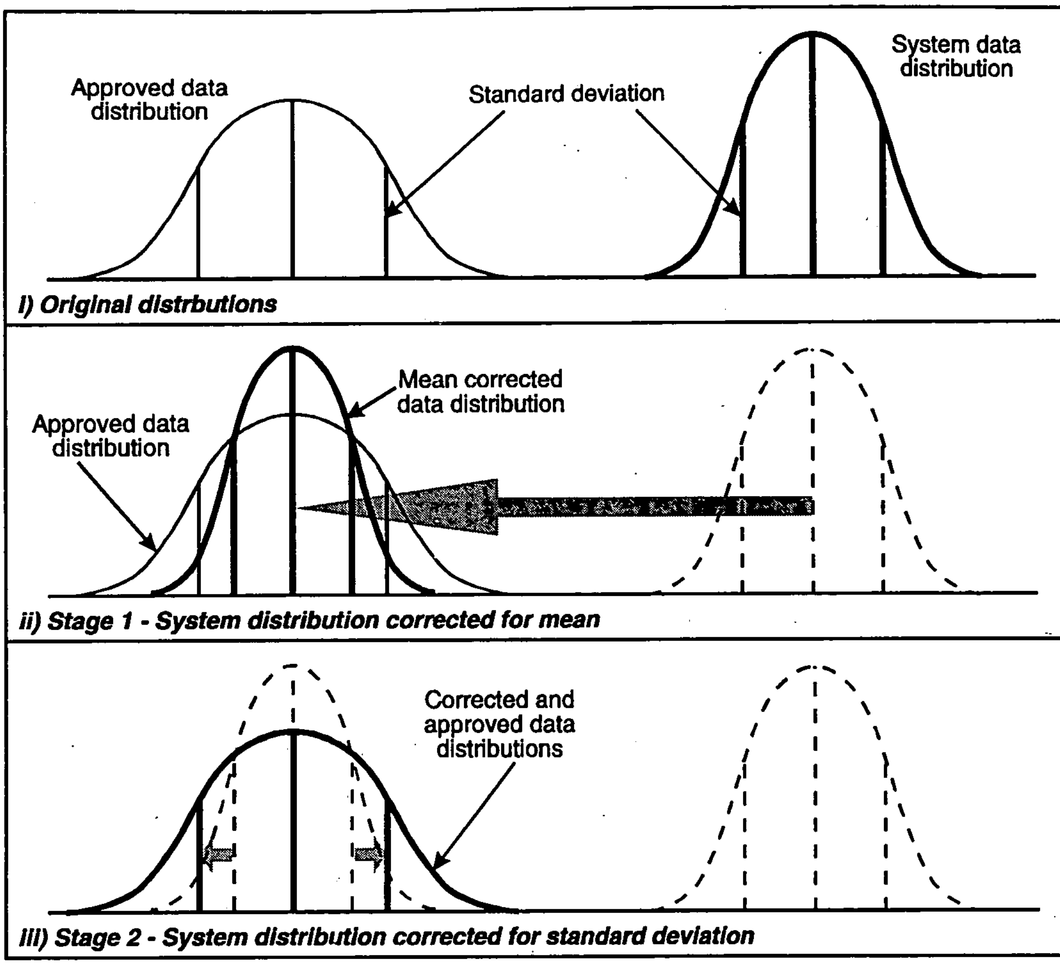


Figure 8.2

Correction of system mean and standard deviation (distribution curves)

2) Correction of standard deviation or variance (figures 8.1 iii and 8.2 iii). The standard deviation of the mean corrected data was modified to have the same standard deviation as the approved data.

At each stage the parameter to be corrected was corrected in a similar fashion.

The following nomenclature was adopted:

Mean corrected parameter $P_{(n)mean\ corrected}$	a parameter after it had been adjusted to take into account the difference between the approved and system means (stage 1)
Corrected parameter $P_{(n)corrected}$	a parameter after it had been adjusted to take into account both the difference between the approved and system means (stage 1) and the approved and system standard deviations (stage 2)

Mean corrected data	the system data after being corrected in accordance with the approved mean (stage 1)
Corrected data	the system data after being corrected in accordance with the approved mean (stage 1)and approved standard deviation (stage 2)
Mean corrected mean $\bar{x}_{(n)mean\ corrected}$	the system mean after being corrected in accordance with the approved mean (stage 1)
Mean corrected standard deviation $s_{(n)mean\ corrected}$	the system standard deviation after the mean had been corrected (stage 1)
Corrected mean $\bar{x}_{(n)corrected}$	the system mean after it had been corrected in accordance with the approved mean (stage 1) and after the standard deviation had been corrected (stage 2)
Corrected standard deviation $s_{(n)corrected}$	the system standard deviation after it had been corrected in accordance with the approved mean (stage 1) and the approved standard deviation (stage 2)

Strictly speaking, the second stage should have been referred to as 'standard deviation corrected mean corrected'. However, since it was the last stage of the process and produced the fully corrected parameter, the more basic designation 'corrected' was used for simplicity.

8.2.2 CORRECTION OF THE MEAN

The situation is summarised in figure 8.3. The cutting parameter (V, S or a) which had been produced by System 3, and which required correcting, was designated $P_{(n)}$, where n was the job number. The mean of the associated approved data, up to and including the previous job (n–1), was calculated and designated $\bar{x}_{(n\text{-}1)app}$. Similarly, the mean for the system data, up to and including the previous job $(n-1)$, was designated $\bar{x}_{(n\text{-}1)sys}$.

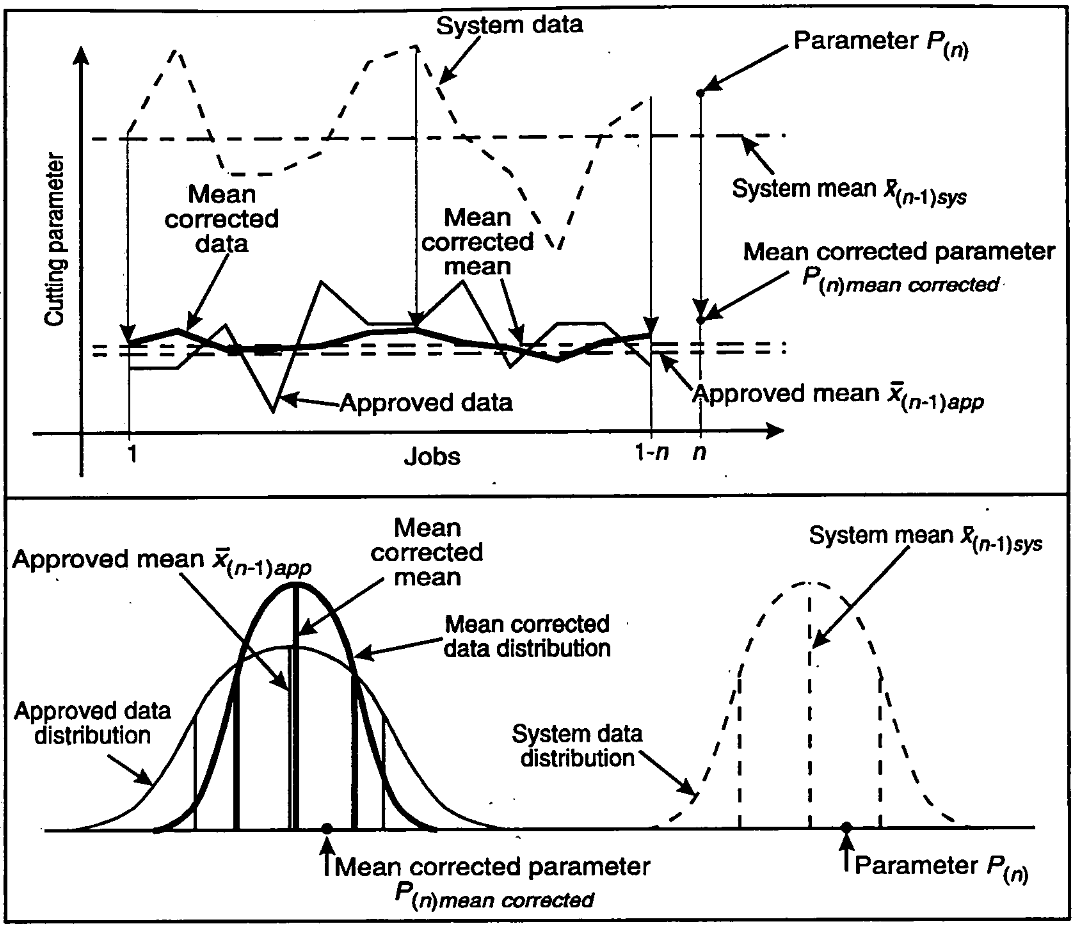


Figure 8.3

Correction of the mean

There were two method available for the correction of the mean:

$$P_{(n)mean\,corrected} = P_{(n)} \times \frac{\bar{x}_{(n-1)app}}{\bar{x}_{(n-1)sys}} \qquad \text{Equ 8.1}$$

and

$$P_{(n)mean\,corrected} = P_{(n)} - \left(\bar{x}_{(n-1)sys} - \bar{x}_{(n-1)app}\right) \qquad \text{Equ 8.2}$$

where $P_{(n)mean\ corrected}$ was known as the mean corrected parameter. This was the parameter which, having been calculated by the system, was corrected to take into account the difference between the system and approved means.

Equation 8.1 can be termed the ratio method, whilst equation 8.2 may be designated the subtraction method. To determine the differences between the use of the two equations, some tests were carried out using normally distributed random data

$(n = 20)$. Two sets of data were generated, one to represent the system data (pseudo-system) and the other the approved data (pseudo-approved). If correction was applied to the complete sample of pseudo-system data, using the complete means for both the pseudo-approved and pseudo-system data i.e. $n = 20$, then both equations corrected the mean of the pseudo-system data to be the same as that of the pseudo-approved data.

However, in reality each data point was corrected as it was calculated, as described above, based on the rolling averages. Under these circumstances, both methods produced means (and standard deviations) which were different from the pseudo-approved data. The reason for this is discussed in section 8.5. However, in each test case, the two corrected means were similar both to each other and to the mean of the pseudo-approved data. In conclusion, there seemed very little difference between the two methods. Hence the ratio method (equation 8.1) was adopted.

8.2.3 CORRECTION OF THE STANDARD DEVIATION

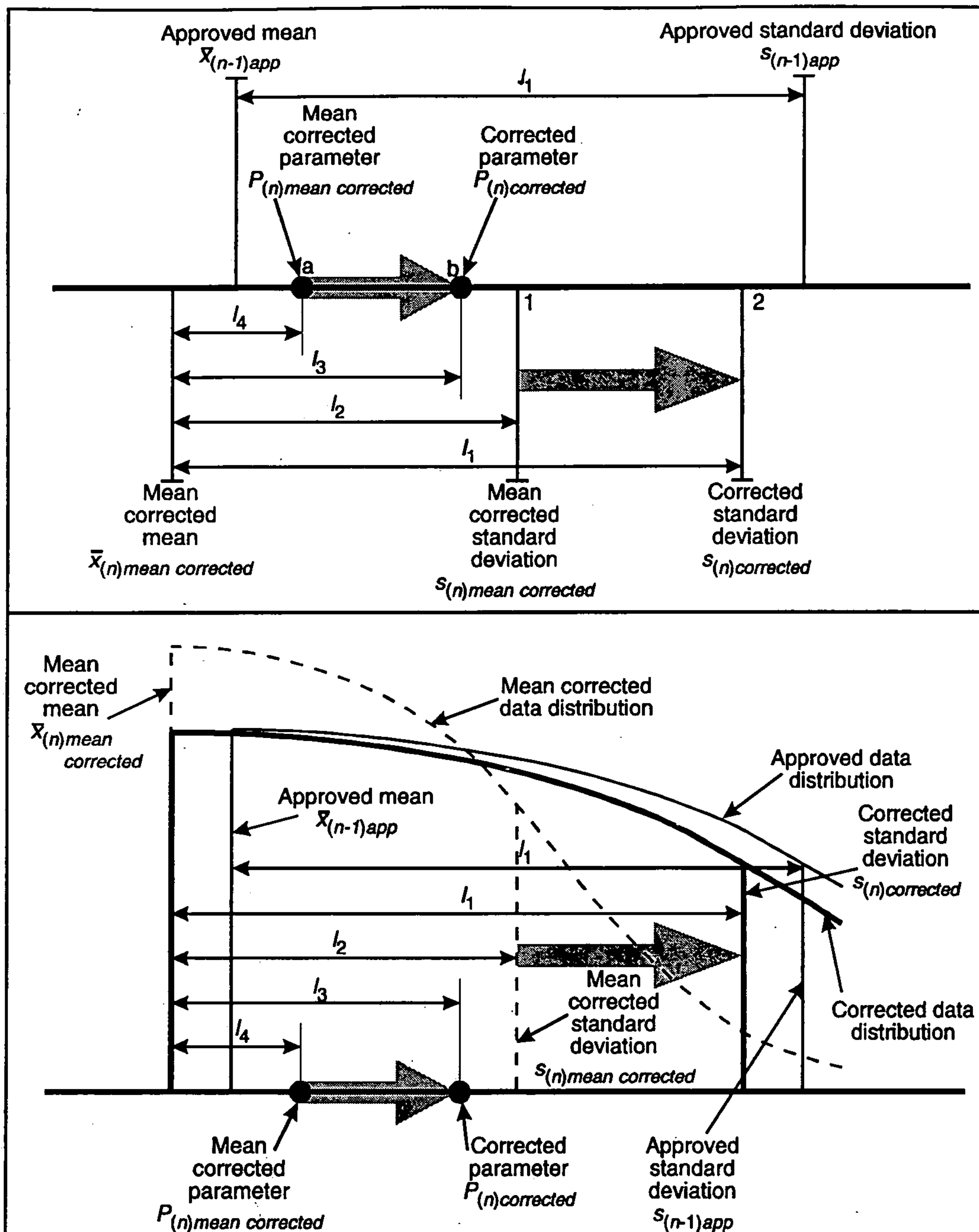
To correct the standard deviation, the standard deviation of the mean corrected data (up to and including job n) was increased or decreased, so that it became equal to the standard deviation of the approved data. The situation is shown in figure 8.4, where:

l_1 = approved standard deviation, $s_{(n-1)app}$

l_2 = mean corrected standard deviation, $s_{(n)mean\ corrected}$,

l_3 = difference between the corrected parameter $P_{(n)corrected}$ and the mean corrected mean $\bar{x}_{(n)\ mean\ corrected}$,

l_4 = difference between the mean corrected parameter $P_{(n)mean\ corrected}$ and the mean corrected mean $\bar{x}_{(n)\ mean\ corrected}$.



Note: The mean corrected mean *and the* approved mean *are similar, but not the same.*

Figure 8.4

Correction of the standard deviation

The mean corrected standard deviation $s_{(n)mean\ corrected}$ was increased from l_2 to the same value as the approved standard deviation $s_{(n-1)app}$ (l_1), i.e. from position 1 to position 2 in figure 8.4. This produced the corrected standard deviation $s_{(n)corrected}$ (distance l_1 from the mean corrected mean $\bar{x}_{(n)mean\ corrected}$). The mean corrected parameter $P_{(n)mean\ corrected}$ (distance l_4 from the mean corrected mean) was moved a similar proportional distance (l_1/l_2) relative to the mean corrected mean (distance l_3), giving the corrected parameter $P_{(n)corrected}$ i.e. from figure 8.4:

$$\frac{l_1}{l_2} = \frac{l_3}{l_4} \Rightarrow l_3 = \frac{l_1 \times l_4}{l_2} \qquad \text{Equ 8.3}$$

If the mean corrected parameter was greater than the mean corrected mean (as shown in figure 8.4) i.e.:

$$P_{(n)mean\ corrected} > \bar{x}_{(n)mean\ corrected}$$

then from equation 8.3 and figure 8.4:

$$l_3 = \frac{s_{(n-1)app} \times \left(P_{(n)mean\ corrected} - \bar{x}_{(n)mean\ corrected}\right)}{s_{(n)mean\ corrected}}$$

Since:

$$P_{(n)corrected} = \bar{x}_{(n)mean\ corrected} + l_3$$

then:

$$P_{(n)corrected} = \bar{x}_{(n)mean\ corrected} + \frac{s_{(n-1)app} \times \left(P_{(n)mean\ corrected} - \bar{x}_{(n)mean\ corrected}\right)}{s_{(n)mean\ corrected}} \qquad \text{Equ 8.4}$$

However, it may be that the mean corrected parameter was less than the mean corrected mean i.e.:

$$P_{(n)mean\ corrected} < \bar{x}_{(n)mean\ corrected}$$

then from equation 8.3 and figure 8.4:

$$l_3 = \frac{s_{(n-1)app} \times \left(\bar{x}_{(n)mean\ corrected} - P_{(n)mean\ corrected}\right)}{s_{(n)mean\ corrected}}$$

Since:

$$P_{(n)corrected} = \bar{x}_{(n)mean\ corrected} - l_3$$

then:

$$P_{(n)corrected} = \bar{x}_{(n)mean\ corrected} - \frac{s_{(n-1)app} \times \left(\bar{x}_{(n)mean\ corrected} - P_{(n)mean\ corrected}\right)}{s_{(n)mean\ corrected}} \qquad \text{Equ 8.5}$$

If the mean corrected data or the approved data had a standard deviation of zero i.e. all the points were the same, then:

$$P_{(n)corrected} = \bar{x}_{(n)mean\ corrected}$$

Two points should be noted:

1) Correcting the standard deviation in this way also had an influence on the value of the overall mean corrected mean,

2) As with the correction of the mean (section 8.2.2), the approved standard deviation and the corrected standard deviation were not exactly the same.

The reason for this is discussed in section 8.5.

8.2.4 NUMBER OF POINTS USED

There are two points worth noting about the correction process:

a) correction could not take place until the third job,

b) correction of the mean used (n-1) approved and systems jobs, whilst correction of the standard deviation used (n-1) approved jobs but n mean corrected jobs.

These two points are illustrated in figure 8.5, which shows the sources of data for both the mean correction and standard deviation correction.

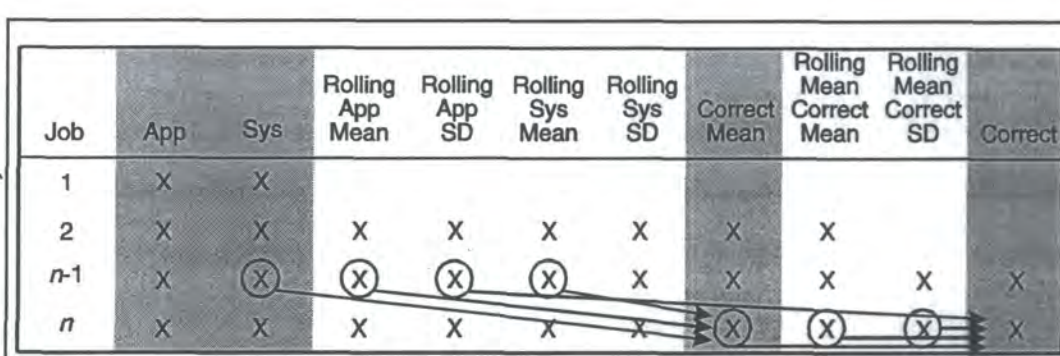


Figure 8.5

Sources of data for corrections

To carry out the correction required the calculation of the approved standard deviation for each cutting parameter. To calculate the standard deviation required a minimum sample size of two. Since the approved data for job *n* was only available after the system data (and corrected data) for job *n* had been calculated, two tests had to be completed before any data correction could take place i.e. correction could only start with the third test.

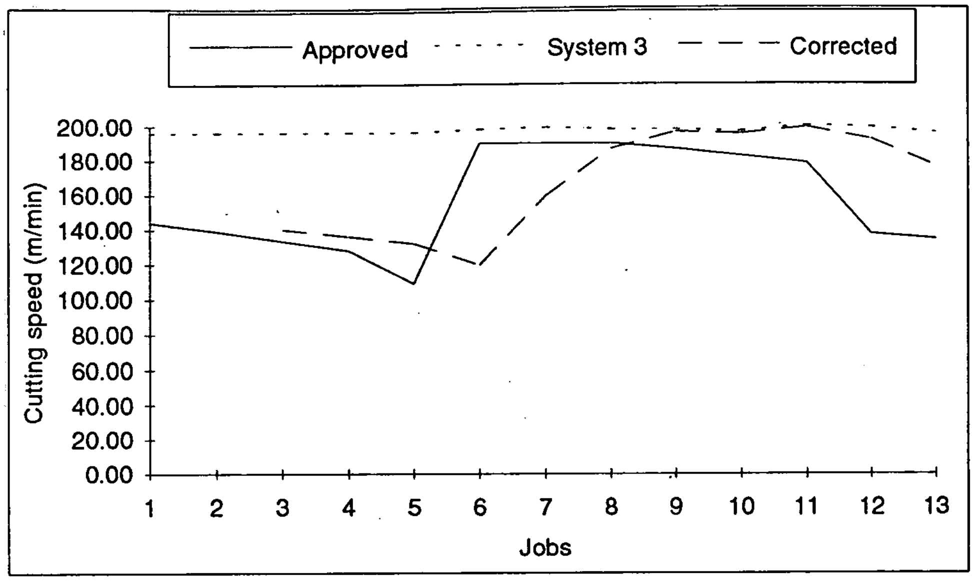
When the mean was corrected (section 8.2.2), to ensure that the means were comparable, identical sample sizes were used for both the approved and system data i.e. both samples were of size (n-1) jobs. If the system mean had been based on a sample of *n* jobs (since the system data for job *n* was available at that stage), the two means (approved and system) would not have been strictly comparable.

However, when correcting the standard deviation (section 8.2.3), the mean corrected mean for job *n* was important, since it provided the reference for the corrected point (figure 8.4). Therefore it seemed reasonable when calculating the standard deviation for the mean corrected data, to include the mean corrected parameter for job *n* in the sample. In practice, once the samples were of a reasonable size, it probably would not have made much difference whether the sample of mean corrected data included *n* or (n-1) jobs.

8.3 CORRECTED RESULTS

8.3.1 CORRECTED DATA

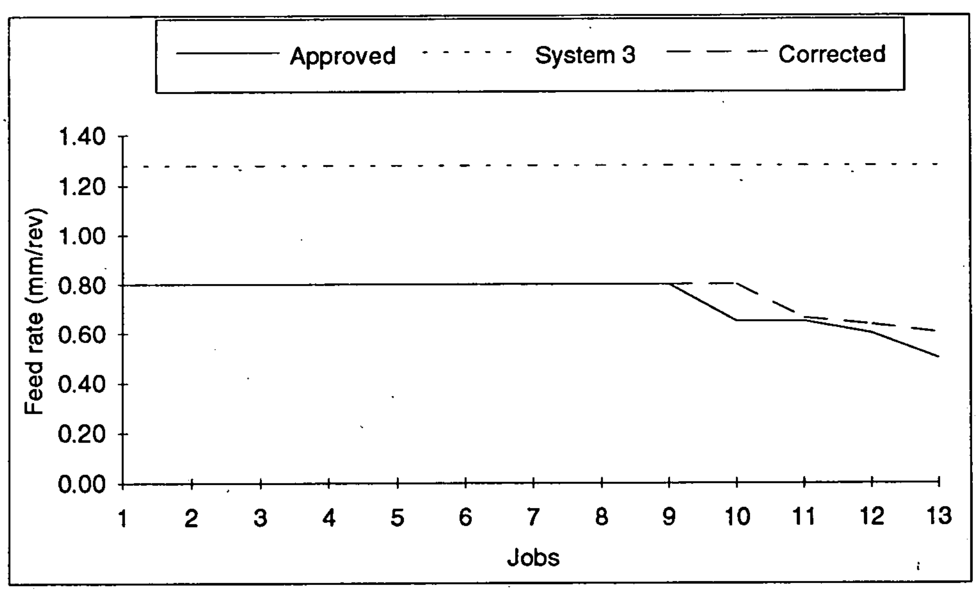
The corrected data is shown in tables J.1 - J.8, (appendix J), and example graphs are shown in graphs 8.1 - 8.3. System 3 data is included for comparison.



Graph 8.1

Example test results for System 3 and corrected data

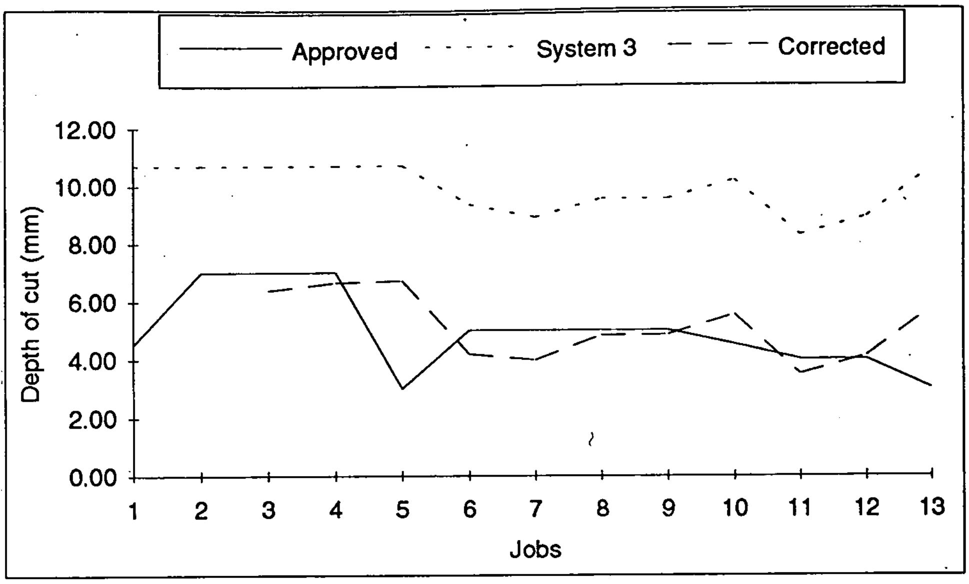
Harkers job group 1 cutting speed



Graph 8.2

Example test results for System 3 and corrected data

Harkers job group 1 feed rate



Graph 8.3
Example test results for System 3 and corrected data
Harkers job group 1 depth of cut

8.3.2 ANALYSIS OF CORRECTED DATA

The results were analysed as described in sections 4.8 and 7.5.4. Results for both System 3 and corrected data are included, so that comparisons may be drawn (table 8.1). As before, confidence bands are included for non-valid *t*-distribution tests (table 8.2).

		System 3		System 3 corrected	
Parameter	**Samples**	**Variances**	**Means**	**Variances**	**Means**
		Harkers job group 1			
Cutting speed	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Depth of cut	System 3 and Approved	*Same*	Different	*Same*	*Same*
		Harkers job group 2			
Cutting speed	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Depth of cut	System 3 and Approved	*Same*	Different	*Same*	*Same*
		Harkers job group 3			
Cutting speed	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 3 and Approved	*Same*	Different	Different	Not valid*
Depth of cut	System 3 and Approved	*Same*	Different	*Same*	*Same*
		Harkers job group 4			
Cutting speed	System 3 and Approved	Different	Not valid*	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Depth of cut	System 3 and Approved	*Same*	Different	*Same*	*Same*
		Harkers job group 5			
Cutting speed	System 3 and Approved	Different	Not valid*	Different	Not valid*
Feed rate	System 3 and Approved	Different	Not valid*	Different	Not valid*
Depth of cut	System 3 and Approved	*Same*	Different	*Same*	*Same*
		Reyrolle job group A			
Cutting speed	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Depth of cut	System 3 and Approved	*Same*	*Same*	*Same*	*Same*
		Reyrolle job group B			
Cutting speed	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 3 and Approved	*Same*	*Same*	*Same*	*Same*
Depth of cut	System 3 and Approved	*Same*	*Same*	*Same*	*Same*
		Reyrolle job group C			
Cutting speed	System 3 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 3 and Approved	*Same*	*Same*	*Same*	*Same*
Depth of cut	System 3 and Approved	Different	Not valid*	*Same*	*Same*
**Note: The test for the comparison of means is not valid if the variances are not from the same population.*					

Table 8.1

Result of comparisons of variances and means,

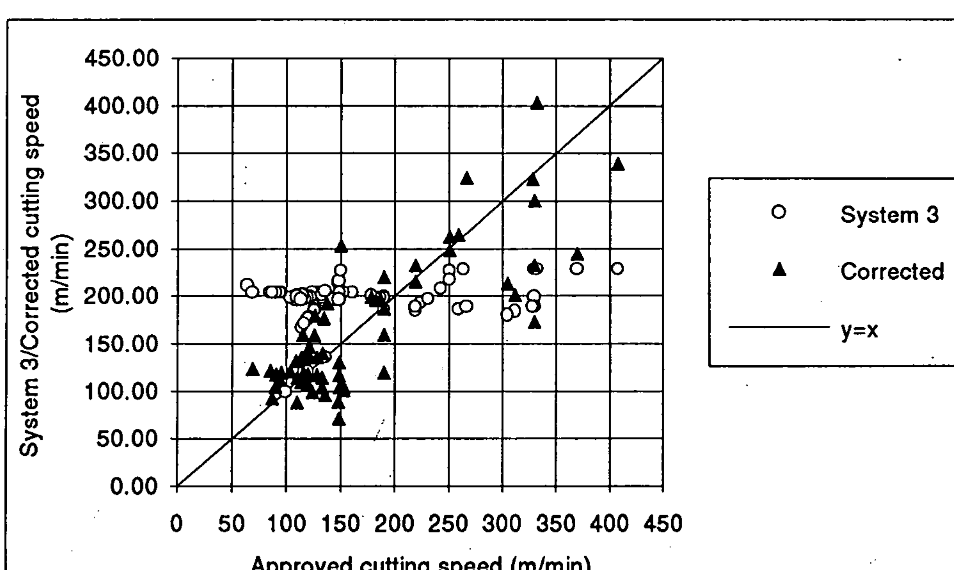
with System 3 data (from table 7.8) compared with corrected data

Parameter	Sample	Confidence band	Lower limit	Upper limit
Harkers job group 3				
Feed rate (mm/rev)	Corrected & Approved	115±35 127±28	81 100	150 155
Harkers job group 4				
Cutting speed (m/min)	Corrected & Approved	109±7 115±11	102 105	116 126
Harkers job group 5				
Cutting speed (m/min)	Corrected & Approved	141±15 119±6	126 113	156 125
Feed rate (mm/rev)	Corrected & Approved	0.95±0.07 0.85±0.16	0.88 0.69	1.01 1.01

Table 8.2

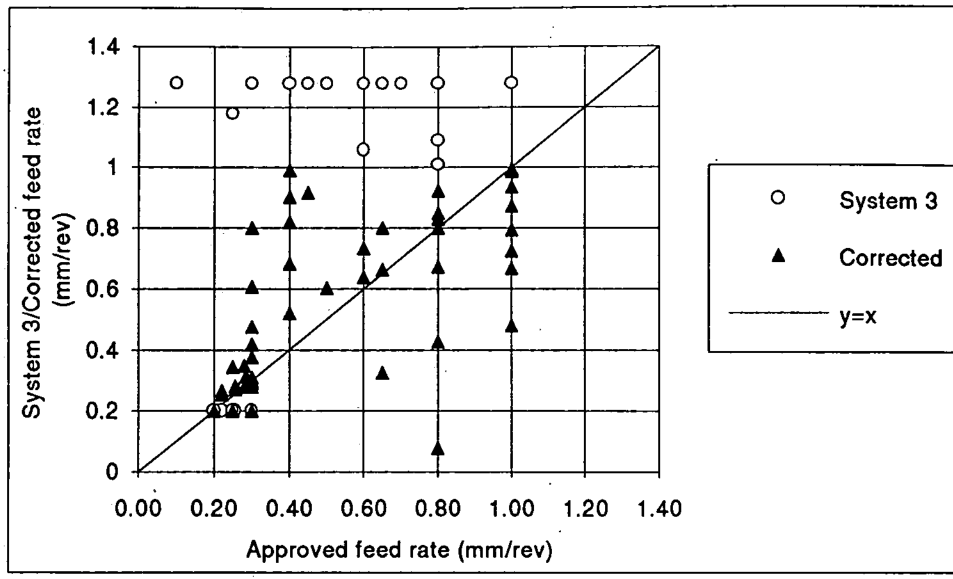
Confidence bands for non-valid means - corrected data

A more subjective method for viewing the change in the data was by means of a scatter graph, where both system and corrected data were shown on the same plot. If the corrected data was of superior quality to the system data, it should have shown an overall shift towards the line $y = x$. The scatter graphs are shown in graphs 8.4 - 8.6.



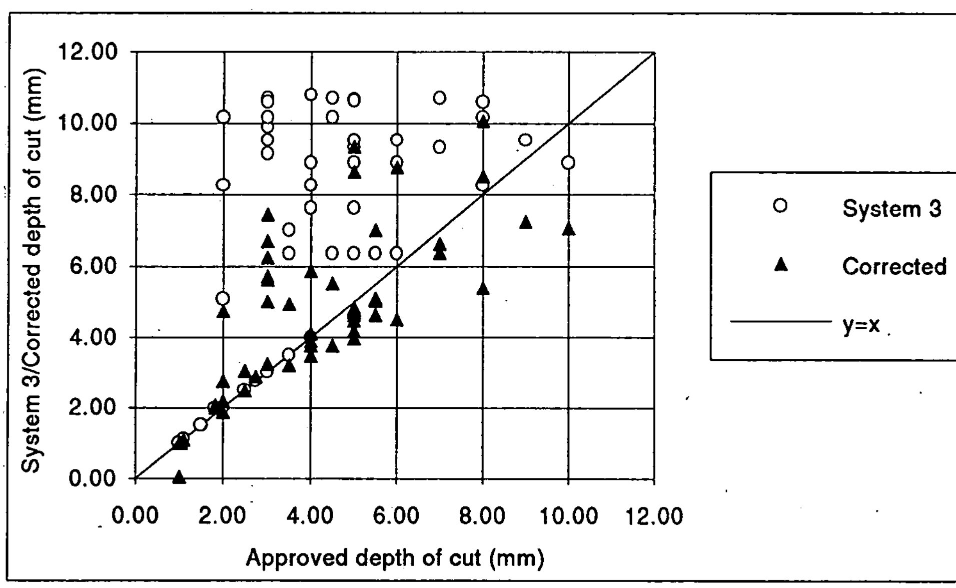
Graph 8.4

Scatter of System 3 and corrected points - cutting speed



Graph 8.5

Scatter of System 3 and corrected points - feed rate



Graph 8.6

Scatter of System 3 and corrected points - depth of cut

8.4 CORRECTION OF SYSTEM 2 DATA

Ideally, System 3 with data correction should also have been tested on a range of materials, with both recommended and non-recommended tools. However, there was no provision for testing of this nature. Nevertheless, System 2 (chapter 6) had been used on a variety of materials, albeit with recommended tools. Whilst there were insufficient jobs tested with System 2 to form job groups, it was considered that applying data correction to the jobs within each trial would indicate whether the data correction would be able to handle the extra requirement of different materials. The results were analysed as per section 4.8 and the engineering data was not considered in the analysis. The comparison is shown in table 8.3.

		System 2		System 2 corrected	
Parameter	**Samples**	**Variances**	**Means**	**Variances**	**Means**
Trial 1 - Harkers					
Cutting speed	System 2 and Approved	*Same*	*Same*	*Same*	*Same*
Feed rate	System 2 and Approved	*Same*	*Same*	*Same*	*Same*
Depth of cut	System 2 and Approved	*Same*	*Same*	*Same*	*Same*
Trial 2 - Reyrolle					
Cutting speed	System 2 and Approved	Different	Not valid*	*Same*	*Same*
Feed rate	System 2 and Approved	*Same*	*Same*	*Same*	*Same*
Depth of cut	System 2 and Approved	*Same*	*same*	*Same*	*Same*
Trial 3 - Harkers					
Cutting speed	System 2 and Approved	*Same*	*Same*	*Same*	*Same*
Feed rate	System 2 and Approved	*Same*	*Same*	*Same*	*Same*
Depth of cut	System 2 and Approved	*Same*	*Same*	Different	Not valid*
**Note: The test for the comparison of means is not valid if the variances are not from the same population.*					

Table 8.3

Result of comparisons of variances and means,

for System 2 data (from table 6.9) compared with corrected data

8.5 DISCUSSION

There was no doubt that the correction of the data improved its quality, as demonstrated by both the statistical analysis tables (tables 8.1 and 8.2) and the scatter graphs (graphs 8.4 - 8.6). This was also evident in the graphs of the test results (graphs 8.1 - 8.3). This improvement was particularly so in the case of Reyrolle, where for all parameters for all groups, the two sets of data were drawn from the same populations. In the case of Harkers, table 8.2 showed that, with one exception, in all the other cases where the standard deviations differed, nevertheless the confidence bands for the means were very similar, with large overlaps in the ranges.

The one exception was the cutting speed for Harkers job group 5. The explanation for this lay in the fact that the first two tests (tests 47 and 48) produced identical results for the approved and system cutting speed. This would have required no correction. The third test (test 49) produced different results for the approved and system data, a trend which continued for the rest of the job group. Because tests 47 and 48 produced identical results, test 49 would have remained uncorrected. Once correction started to take effect for the fourth test (test 50), the corrected data became an increasingly good match to the approved data with every test that took place. Had the group been larger, it was likely that the two samples would have became sufficiently similar so as to be from the same population.

A common trend with many of the groups where the data was drawn from different populations, was a sudden change in either the approved or system data. This had a more pronounced effect on the mean and/or standard deviation due to the small sample sizes, than if the groups had been larger. It therefore seems reasonable to state that with larger sample sizes, where applicable, better fits between the samples would have occurred.

For example, the feed rate for Harkers group 5 showed two low approved values for job 56 and 57, compared to the rest of the group. What caused the problem was the position of these two jobs in a small sample. If the data was re-ordered, for example sorting the approved data into ascending order prior to correction (the system data all had the same value), it was found that the two samples were then a good match, based on the tests described earlier.

There was one other source of error. It was noted in sections 8.2.2 and 8.2.3 that the corrections did not produce system data with the exact mean and standard deviation of the approved data. The reason for this was that each cutting parameter for each job was corrected using the data from the preceding jobs. Consequently the correction factors for each parameter varied with each job.

With regard to the correction of System 2 data, it can be seen from table 8.3 that there was very little difference between the uncorrected and corrected results. In the one case where the corrected and approved data were not from the same population, this may well have been due to the small sample size of the corrected data, which was three. Other than that, the correction method dealt with the mixture of materials without any obvious problems. Although such a test was not conclusive evidence that System 3 with corrected data would be able to deal with any tool/material combination (recommended or unrecommended), it nevertheless seemed to indicate that this would in fact be the case.

One further point was worth noting. Graph 8.2 shows that the system 3 data was a constant value for all the tests in that job group. However the corrected data shows a good fit to the approved data. This was considered a good demonstration of the ability of the correction method to improve the quality of the system data. The correction method relied on the starting point provided by the system. Without the system data, the correction method would need to resort to another technique such as rolling average, the drawbacks of which have been discussed in appendix I.

CHAPTER 9

DISCUSSION

9.1 INTRODUCTION

System 3, coupled with mean and standard deviation correction, has been shown to be successful as a means for providing a tool selection system with cutting data, prior to the selection of tools. (A comparison of Systems 2 and 3 is given in appendix L.) However, during the course of this project, a number of techniques were employed which were found not to be successful. These techniques included two methods of data correction, which have already been mentioned in section 8.1 and described in appendix I. Another unsuccessful technique concerned the collection of tool life data from the shop floor, which is discussed in section 9.3.

In addition, since the work was carried out so closely with personnel within the collaborating companies, other lessons were learnt which have not been recorded elsewhere. One of these concerns the work of a part programmer. Section 9.3 follows on from the discussion of the role of the part programmer in section 3.8 and describes the observed roles which they undertook within the companies. In section 7.4, it was explained that the cost variables had been removed from the data input. Sections 9.4 takes this discussion a stage further and examines the concept of cost in manufacturing. The final system relied on a number of data files and the differences between these and databases are described in section 9.5.

In principle, the work on System 3 has been completed, since it has been shown how reasonable cutting data can be achieved for tool selection purposes by means of an algorithm. Nevertheless, there is scope for further development (section 9.6). At the moment the system is algorithmic, although the introduction of intelligence may well be worthwhile (section 9.7). Finally, the possibilities for commercial exploitation are explored (section 9.8).

9.2 MEASUREMENT OF TOOL LIFE

One factor affecting tool selection is the number of tools required to complete the machining of a particular geometric feature on a batch. Tool life and tool requirements are closely related, in that tool life will enable a prediction to be made of tool requirements for a specific number of components.

Section 7.3 showed an approximate method for determining values of α, β, γ and C_1, using data from the file LIFE.DAT. An alternative method was to record the approved tool life along with the approved cutting parameters. Values for α, β, γ and C_1 could then be determined, based on the extended Taylor equation for tool life and using multiple regression analysis, as described in section 6.3.

The record sheet in box 7.1 showed a section concerned with the recording of actual tool life information for this purpose. On the record sheet it was possible to record the tool life in one of five ways:

1) tool life (mins),
2) number of items before tool failure,
3) length of cut (mm) before tool failure (less than one pass only),
4) number of passes before tool failure,
5) tool not failed.

Only one indication of tool life was to have been recorded. For items 2), 3) and 4) there was sufficient information to allow the tool life to be calculated. Item 2) was included primarily for Reyrolle, whilst items 3) and 4) were included mainly for Harkers. These differences were a reflection of the different sizes of components involved.

The standard covering tool life testing is BS 5623[1] (1979). According to this, prior to carrying out tool life testing, the failure criterion should be specified. For carbide tooling this relates either to the dimensions of the wear land on the tool flank or the depth of the crater on the top face (figure 9.1). At intervals during testing, measurements should be made of the size of the specified wear pattern. At least four cutting speeds should be used.

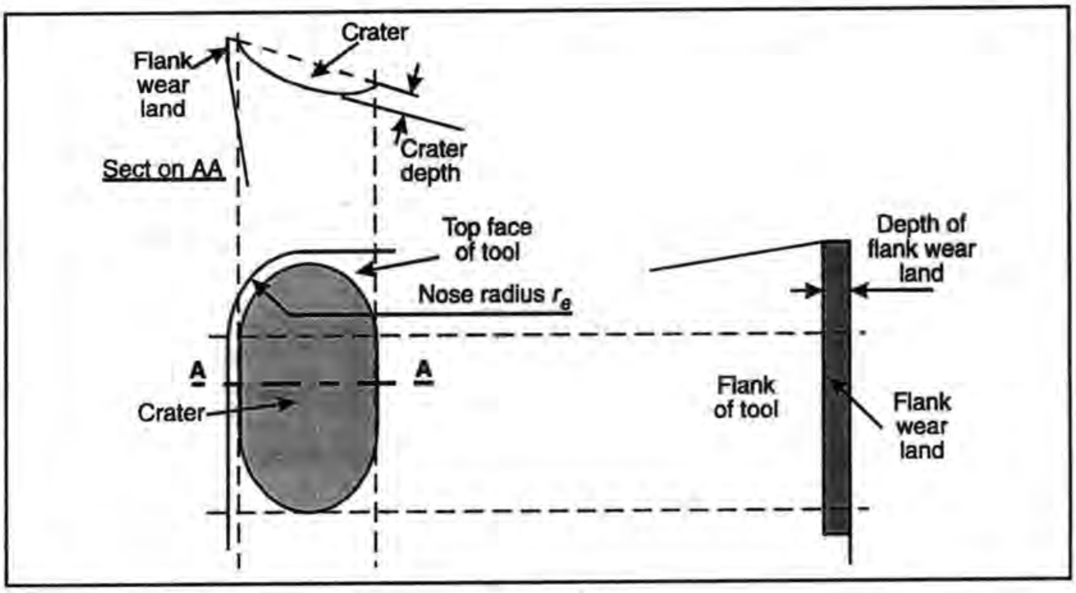


Figure 9.1

Simplified diagram of wear patterns during tool-life testing (from BS 5623 (1979))

Tool life can be determined after a minimum of five points have been obtained for each curve and plotted graphically, so that "...the time at which the value that is selected as the tool-life criterion is reached can be assessed with sufficient accuracy". Extrapolation of the graph is not permitted i.e. to determine the tool life, the wear pattern must at least reach the critical dimension. This number of tests required is greater than that recommended by Barrow (1971), who recommended "...at least three sets of tests involving fifteen tool-life values" (section 6.3)

[1] BS 5623 (1979) is equivalent to ISO 3685 (1977). At the time of writing, BS 5623 (1979) was currently withdrawn, although it was still applicable when the work took place. A discussion with BSI indicated that it was probably being updated to match ISO 3685 (1993). Nevertheless, at the present time there is no current British Standard covering tool life testing.

The equipment specified by BS 5623 for measurement of the tool wear pattern included:

"- a device for measuring tool geometry accurately,

- a profile projector for inspection of the tool corners,

- a toolmaker's microscope, or a microscope equipped with a filar eyepiece, for measuring flank wear,

- a dial indicator with a contact point approximately 0.2 mm in diameter for

- measuring crater depth."

The requirements of BS 5623 are not suitable for a production environment, unless the object of the exercise is specifically tool life testing. For instance, none of the above items are readily available on a typical shop floor. Nor is it feasible to stop production work, remove the tool and measure the wear.

For these tests the operators used their own criteria to decide when a tool had failed. This was to ensure that the tool life was consistent with the appropriate working practices. Depending on the circumstances, the failure criteria may have been any of the following:

a) catastrophic failure,

b) changing to a different batch,

c) the tool was unlikely to complete a further pass,

d) the tool had machined sufficient components,

e) the tool had significant wear patterns.

Zhou and Wysk (1992) have also observed that there can be a number of reasons why tools are replaced:

a) a time schedule,

b) a prescribed number of parts finished,

c) tool wear status,

d) quality of finished products.

They noted that the first two were the criteria commonly adopted for more advanced systems. The third criterion required a sophisticated detection system or close monitoring by the operator, whilst the fourth usually generated a defective product.

It was only possible to record approved tool lives with System 3 at Reyrolle, since the relevant tests were not performed at Harkers (section 7.6.1). Not all Reyrolle jobs had a tool life recorded, since in some cases the tool survived the batch. Furthermore, some of the jobs where a tool life was recorded were not included in the results in chapter 7, since they did not form part of any of the specified job groups. The actual approved tool lives recorded are shown in table 9.1.

	Shop floor record				
Job No	**Tool life (mins)**	**Number of items before tool failure**	**Length of cut before tool failure**	**Number of passes before tool failed**	**Calculated tool life (mins)**
a				2	**0.12**
b		10			**3.08**
c		4			**4.28**
d		50			**36.03**
e		25			**25.02**
f		30			**31.63**
g	50				**50.00**
h		150			**27.00**
i		120			**3.15**
j		120			**9.58**
k		120			**9.56**
l		51			**10.60**
m		37			**14.70**
n		92			**1.79**
o		32			**2.09**
p		106			**17.23**
q		106			**9.70**
r		106			**4.73**

Table 9.1

Shop floor recorded and calculated tool lives

As can be seen from table 9.1, the preferred method for recording tool life was in terms of the number of components. However, as noted previously this may well have been a function of the small component size at Reyrolle. Examination of table 9.1 showed a number of calculated tool lives which might be considered to be unreasonably short. There were a number of potential explanations for these:

a) several different cuts may be taken with the same tool on each component in the batch, under different cutting conditions (this may be what occurred with jobs i - k and p - r),

b) the tool may not be new at the start of the batch,

c) the tool may not fail during the batch in question, yet still be recorded as failed,

d) the difficulties of measuring tool life (in minutes) under industrial conditions,

e) recording may be inaccurate since the operator may not understand the significance of the data.

With respect to point a), Perera (1995) has suggested that if the issue of replacement tools are logged against specific jobs, then the consumption rate for a particular tool manufacturing a particular product can be calculated. By implication, in such circumstances the tool life for such a situation can be ascertained. However, methods such as this were unsuitable for incorporation into the system since:

a) in both companies product variety was high, with few repeat jobs,

b) this did not provide a method for calculating α, β, γ and C_1 in the extended Taylor equation for tool life, which were factors in deciding on the cutting speed (appendix B).

Whatever the reasons which applied, the data was not considered to be sufficiently accurate enough to be of any use. For this reason, the proposed method for determining α, β, γ and C_1 using this data was abandoned.

9.3 PART PROGRAMMERS

In chapter 3 the role of the part programmers was discussed. A number of writers had suggested that, in general, they would be people of little experience (section 3.8). As a means of determining the true situation, a survey was carried out within the two companies and the results reported in section 3.8. This suggested that the part programmers in fact had a high degree of expertise and experience.

The testing carried out with the system provided the opportunity to observe the part programmers in the course of their work. Despite being subjective and informal, this study served as a useful insight into the functions that they performed. Among the observations were:

a) they all spent a considerable amount of time on the shop floor, often up to half a working day or more,

b) when a machining problem occurred, it was standard practise to involve the part programmer concerned,

c) when unusual materials were being machined for the first time, their knowledge was sought after,

d) when a new job was being machined for the first time, the part programmer responsible would normally be in attendance,

e) when a demonstration was being performed e.g. a new type of tool by a tool manufacturer's representative, they would often be included as observers,

f) they were partially or totally responsible for determining what tooling was held in stock,

g) they could be asked to evaluate machine tools under consideration for future purchase.

In summary, the part programmers were not as remote from the shop floor as has previously been suggested. These observations indicated a high degree of involvement with day-to-day shop floor machining problems and operations. It is appreciated that this may not be the case for all organisations, but it was certainly true for Harkers and Reyrolle.

9.4 THE IMPLICATIONS OF COST

9.4.1 INTRODUCTION

In section 7.4 it was explained that the cost function was removed from the algorithm, on the basis that both companies preferred to concentrate on the time taken for the process. This may have seemed an unusual decision, especially so since many writers on the subject of manufacturing processes include at least one section on the cost of the process e.g. Lissaman and Martin (1982a), Haslehurst (1977). Included in these discussions may well be cost analyses similar to those shown in appendix B, as well as economic considerations.

Such discussions suggest that cost should be a primary consideration in a manufacturing process. For example, according to Haslehurst:

> "In order for a manufacturing organisation to remain competitive it must make its products at the minimum cost consistent with the required quality and function of the product."

Although quality is a word in common usage nowadays, to measure quality in absolute terms is rather difficult, particularly when at attempt is made to define whether the quality level is acceptable. An easier way of defining quality is in relative terms, by reference to the quality of products offered by the competition. A similar argument can also be applied to the function of a product. In the same way, the minimum cost referred to above can be defined as the cost level achieved by competitors producing the same product.

Lissaman and Martin (1982b) make a similar statement to Haslehurst. However, Haslehurst then goes on to say that:

> "The company will then make the maximum profit possible which will

ensure the continuing health of the organisation."

This statement is then qualified:

> "We will assume...that minimum costs will give maximum profits although an economist will assert that this is not always so."

A typical view of profit is that profit is the difference between revenue and total costs (Wild (1984b)). As volume production rises, so the unit cost decreases due to factors such as economies of scale and the effect of the learning curve. However, to sell the increased production, it is often necessary to reduce the selling price to stimulate demand, thus reducing the revenue per item sold. In other words, as volume output rises, both unit cost and unit revenue decrease and of course, vice versa. As volume output continues to rise and particularly as output approaches 100% capacity, the unit cost may start to rise again as factors such as inefficiencies and bottlenecks become more apparent. Nevertheless, unit revenue may still decrease.

From the above, it should be obvious that minimum costs do not necessarily yield maximum profit[1]. Other factors, such as selling price and volume production have to be taken into account. Irrespective of the effect on profits, at any level of production, it is uneconomical to try and reduce costs below a certain level, since cost reduction incurs a cost. This rather more complex situation suggests that cost analyses of the type described are very much simplifications of the real situation.

9.4.2 CORPORATE STRATEGY

It is interesting to note that neither collaborating company believed that it was in

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[1] Maximum profit occurs when marginal profit equals zero, provided the marginal profit is positive prior to becoming equal to zero (Pappas et al (1983)), where the marginal profit is the change in total profit associated with a one-unit change in output i.e. the maxima of the total profit graph. Marginal profit is represented by the first derivative of the total profit function.

business to machine metal as cheaply as possible. Rather, they tended to the view that they had to remove metal as quickly as possible, which was not necessarily the same thing. Porter (1985) recognised that cost is not always the main criteria. He described three generic strategies for achieving and sustaining competitive advantage in an industry. These are cost leadership, differentiation and focus. The focus strategy was further categorised into cost focus and differentiation focus. These generic strategies are shown in figure 9.2.

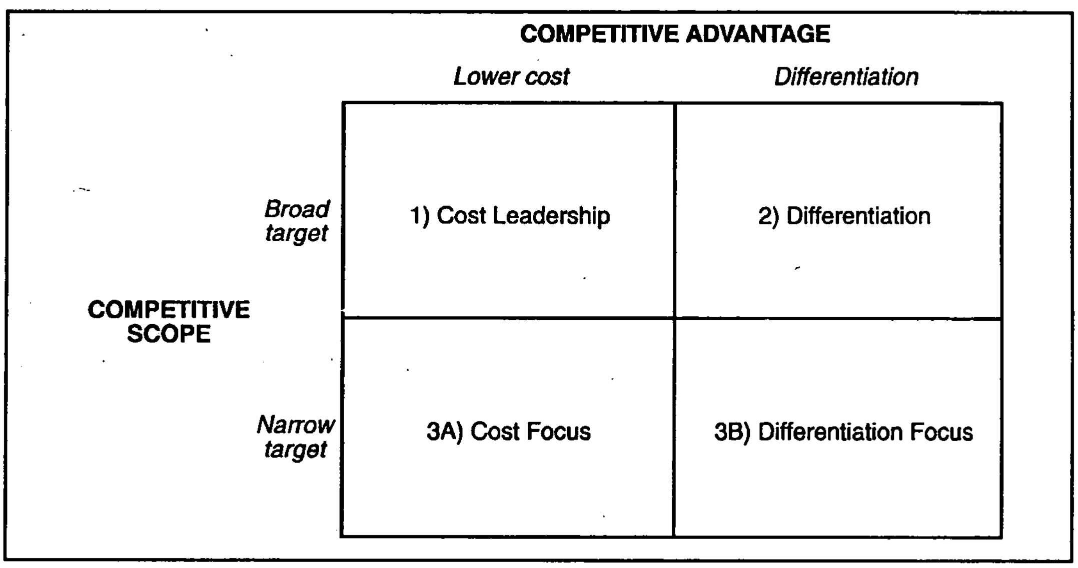

Figure 9.2

Three generic strategies (Porter (1985))

The three strategies can be described as:

1) Cost leadership

   The firm sets out to become the low cost producer in its industry.

2) Differentiation

   The firm seeks to be unique in its industry according to some attribute that is desired by the buyers.

3) Focus

   The firm selects a segment or group of segments in the industry and tailors its strategy to serving them to the exclusion of others. This can be sub-divided into:

3a) Cost Focus

The firm seeks a cost advantage in its target segment.

3b) Differentiation focus

The firm seeks differentiation in its target segment.

According to Porter, a firm that attempts to follow more than one strategy will become 'stuck in the middle' and will usually have below-average performance. For example, a company attempting to maintain minimum costs whilst producing maximum quality will be uncompetitive.

In a study of fifty top-performing companies, Peters and Waterman (1982) found that very few were cost-oriented. Nor was this confined to one market sector; they drew their sample from a variety categories, including high technology, consumer goods, service companies, miscellaneous manufacturers, project management and commodity businesses. Although admitting that their analysis was probably not statistically valid, they concluded that "...the overall sample is a sound one, and we do think the data are sufficient to establish that for most top-performing companies something besides cost usually comes first."

Harkers and Reyrolle both found themselves in markets governed by quality. In the case of Reyrolle, protection switchgear may not be required to work for many years after installation and commissioning, but when a fault condition does occur, the switchgear must trip out reliably first time. With a limited global marketplace in which to sell (there are not that many builders of power stations and associated equipment world-wide), any deficiencies in their equipment would soon become known to their current and potential customers.

Harkers prided themselves on their ability to carry out machining operations that no other company wanted to do, or was capable of doing. They often machined components that had been free-issued to them by their customers. A typical example were the landing gear legs for the European Airbus aircraft. These were high-integrity aluminium forgings, with an estimated value of approximately £50,000 before Harkers carried out any work on them. One of the more complex operations included drilling a 4" diameter hole along the central axis. Another example concerned the machining of cast iron gas turbine casings. The customer considered it worthwhile to ship these components over from America for Harkers to work on.

In terms of the strategies described by Porter, both companies differentiated on quality. Whilst neither company may have been an industry leader in their individual industry segments, no matter how much they reduced costs (and hence prices), if their quality fell below a certain level, they would have become uncompetitive. Conversely, Harkers in particular may, on occasions, have charged a premium for quality.

9.4.3 IMPLICIT COSTS

Irrespective of the above overall strategy, neither company could have afforded to ignore the question of cost control. However, such control tended to be implicit, based on experience of known shop practice. For instance, they were aware of what constituted reasonable machining conditions and provided they continued to use these, or similar, conditions, machining costs should have remained under control.

Unlike other industries, such as those manufacturing in high volume, where there may be many identical items sold at the same price, another implicit control is that both Harkers and Reyrolle estimated and priced each job separately. These estimates were again based on known shop practice. Provided the process was carried out in accordance with established shop practice, a profit should have been shown.

This project was concerned with improved tool selection. One advantage of this should have been reduced set-up times, which would then have reduced overall machining cycle times and hence cost (section 1.2). In this case the set-up time reduction was an explicit aim, whilst the cost reduction was an implicit or consequential aim.

Another benefit of improved tool selection is in a reduction in size of the tool inventory, leading to simpler tool management. However, the smaller tool inventory in itself may not reduce tool purchase costs, since tools will still be consumed at the same rate. Furthermore, with a reduced range of tools to choose from, selected tools may be sub-optimum. What it will achieve is a decrease in the amount of capital tied up in tooling. Improved tool management may also offer a further improvement in tool selection, saving further set-up time.

9.4.4 CONCLUSIONS

There is no doubt that both companies were concerned with costs. It makes good commercial sense to monitor costs, as a check as to whether there were any significant changes. It was highly likely that both companies performed this function, so that corrective action could be taken if costs started to rise. However, this would have tended to maintain costs at the current level, rather than drive them down.

After close association with both companies it was apparent that time occupied a more important role in their operations than did cost. This may well be have been due to the fact that the machining work carried out by the companies was frequently part of a larger contract. In contractual terms, as far as their customers were concerned, normally time was of the essence, rather than cost. A consequential effect of this was that where contractual dates were met, this reduced contract delays for the customer and thus assisted in controlling their costs. Therefore where cost did become a consideration, it was often as the result of other actions. Hence the decision to concentrate on $V_{(time)}$ appeared justifiable and in accordance with the working practices of both companies.

9.5 DATA FILES AND DATABASES

The data stored in a computer can be organised into a hierarchy of several levels (Fabbri and Schwab (1992)), which are shown in figure 9.3. These levels can be described as hierarchical since, at any level the data is made up of a number of items from the level below e.g. a character or byte contains a number of bits and a record is made up of a number of fields. Therefore a database comprises a number of files.

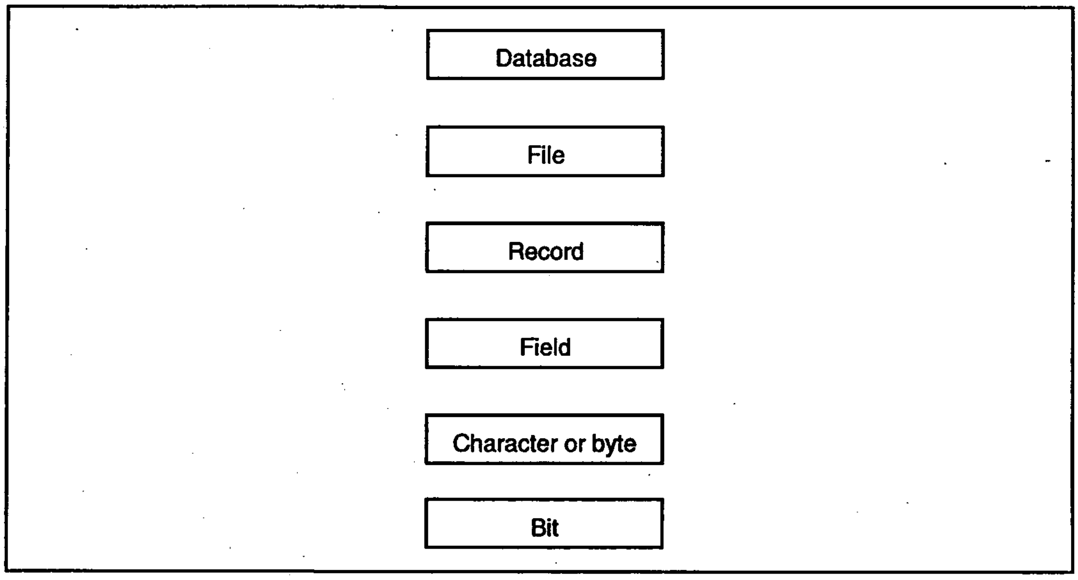

Figure 9.3
Data storage hierarchy (Fabbri and Schwab (1992))

Deen (1985) has defined a database as "...a generalised integrated collection of data together with its description, which is managed in such a way that it can fulfil the differing needs of its users". This is similar to a definition by Lars (1988): "A database can be defined as a set of master files, organised and administered in a flexible way, so that the files of the database can be easily adapted to new, unforeseen tasks".

This manipulation of a database is achieved by making the database part of a database system. A database system consists of a database, and software to create and maintain the database, known as a database management system (DBMS) (Elmasri and Navathe (1994)). The structure of a simplified database system is shown in figure 9.4.

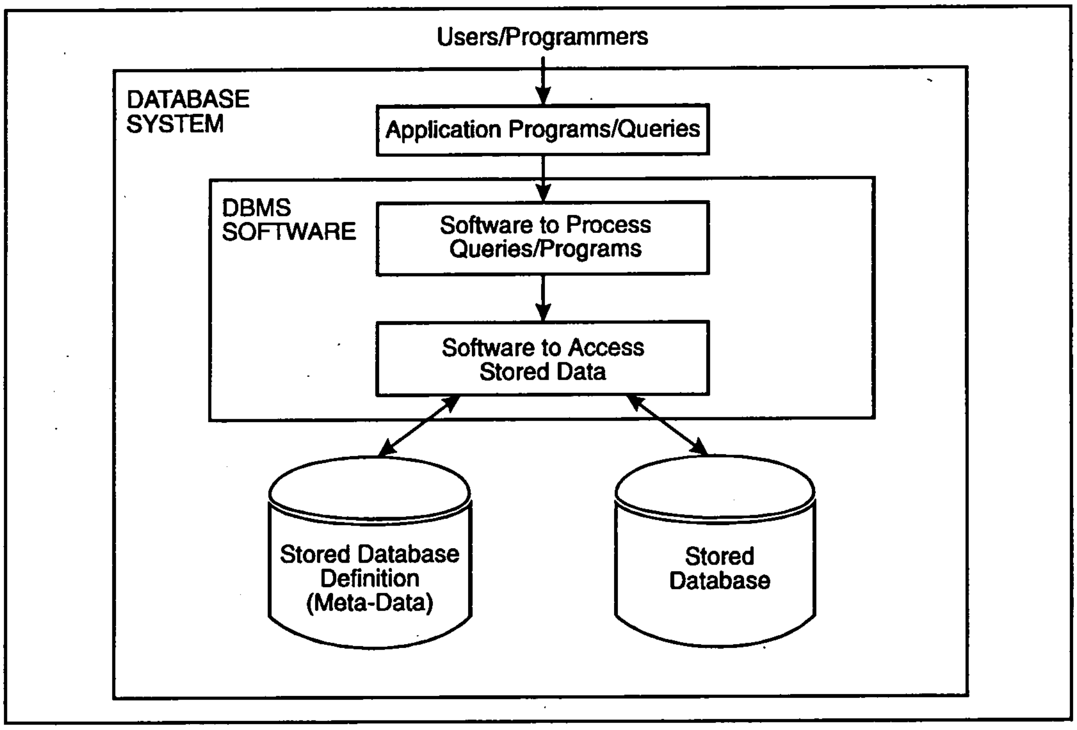

Figure 9.4

A simplified database system environment (Elmasri and Navathe (1994))

In figure 9.4, the DBMS software is a collection of programs that enables users to create and maintain a database. The stored database is the data which is to be manipulated by the database system, whilst the meta-data is the system catalogue and defines the structure of the files in the database, the type and storage format of each data item, and various constraints on the data. The DBMS software will work with any number of database applications, provided that each database definition is stored in the meta-data catalogue.

Data files were incorporated into System 3 (appendix F) for three purposes:

1) storage of commonly used input data (holders, boring bars, inserts, machine tools and materials data files),

2) storage of historical data for data correction purposes (main data file),

3) storage of input data for specific jobs (job files).

These data files differed from the database system described above in a number of aspects (Deen (1985)):

a) in a database system, the database and the application programs can be altered independently of each other, whilst the data files were only of use with System 3 and System 3 relied on the data files,

b) a database system reduces duplication of data, whereas for example in System 3 job attributes were held in both the job input files and the main data file,

c) in a database, privacy and the integrity of the data can be controlled, but the data files in System 3 were deliberately designed to be written in ASCII to permit editing with any suitable ASCII editor (this eliminated the need to write custom software to permit corrections to be made),

d) a database is expected to support high level query facilities, but in System 3 interrogation of the data files was rigid and did not allow the user to modify the interrogation.

In summary, the data files were developed exclusively for one application (System 3) and were unlikely to be of use in any other application. If they were to be required for another application, such as other modules of an intelligent tool selection system (appendix B), their structure would almost certainly have required modification and consequently so would System 3. This situation was deliberate in that System 3 was only a development program and the data files were the simplest way of testing the principles. In any form of commercial exploitation (section 9.8), a proper database system would need to be developed.

There is one other aspect of the data files to consider, which concerns the main data file. In time this will build up into a sizeable record of historical jobs. If a job with identical attributes to a record already stored in the main data file is to be processed, then it should be possible to obtain suitable approved data directly from the main data file, instead of using System 3 to calculate the cutting parameters. This use of data files has already been discussed in section 2.6.

9.6 FURTHER DEVELOPMENT OF THE SYSTEM

9.6.1 NON-RECOMMENDED INSERT GRADES AND MATERIALS

The original cutting data model upon which the system was based relied upon the use of insert ISO grades which were suitable for the material to be machined, since data of this type was required. Testing of a range of materials was carried out with System 2. This model was modified in System 3 to allow any insert grade to be matched to any material, irrespective of the recommendations of the tool manufacturer (chapter 7). Since the objective of the testing phases was primarily to determine the accuracy of the system, explicit testing of this aspect of the software was not carried out. Further testing should therefore be carried out on the system to determine the effectiveness of this part of the work.

9.6.2 NON-ISO TOOLS

System 3 was designed around ISO tooling, since this was likely to be the most common type of tooling in use at the present time. One advantage of using ISO tooling was that, with System 3, all the necessary tool attributes could be obtained from the relevant ISO codes for the holder/boring bar and insert (section 6.4.4). However, provision should be built into the system to allow it to consider non-ISO tools. These tools would fall into two categories:

a) carbide insert tools which do not conform to ISO standards,

b) tools with cutting edges made from other materials tools e.g. high speed steel, ceramics.

9.6.3 ADDITIONS TO LIFE.DAT

The data file LIFE.DAT consisted of records containing cutting speeds, feed rate, depths of cut and associated tool lives for an ISO P20 insert grade machining mild steel (section 7.3). For a different material and insert ISO grade, three conversions were necessary to convert the data in LIFE.DAT. Inevitably this would have resulted in an error build-up.

Ideally, this error should be minimised as much as possible for future materials. One way in which the error can be reduced would be to add extra data to LIFE.DAT. The data would be for alternative materials that are likely to be machined and the records would be of a similar type to that already in the file i.e. values of *V*, *S*, *a* and *T* being machined with a specific ISO insert grade. In this way, the data would only have to be converted for the tool type, but not for the material as well, which should result in a reduction of error.

9.6.4 REDUCTION OF INPUT DATA

Much of the work carried out has been concerned with reducing the input data to the system. This can be considered to be successful since, for example, the list of twenty seven tool attributes in appendix B was reduced to three attributes[1]: the tool and insert ISO codes and the insert ISO grade. Nevertheless, there are still a number of inputs required, which can be categorised as:

1) required every time e.g. cut attributes,
2) required first time only e.g. machine tool attributes.

To simplify the use of the system, the input data should be reduced to a minimum,

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[1] The final list of three attributes assumed that the cost attributes (insert and holder cost) were not required. In the discussions in sections 7.4 and 9.4, it was explained that these attributes were superfluous for companies such as Harkers and Reyrolle. However, this may not be true in all manufacturing environments. In other situations it may be necessary to retain these two attributes.

or even zero. Where this is not possible, an alternative would be to take data from other company computer files, by means of system integration. Apart from simplification, another advantage would be a reduction in the risk of errors in the input.

9.7 INTRODUCTION OF INTELLIGENCE

9.7.1 FLEXIBLE RULES

The mean and standard deviation data correction in chapter 8 made use of both the rolling average and the rolling standard deviations of the data sets. However, as the main data file increases in size, it becomes questionable as to whether all the historical data is needed for data correction or whether the more recent data alone is sufficient. It may be that a law of diminishing returns becomes apparent, whereby beyond a certain number of points the increase in accuracy becomes minimal, in which case the system would have to determine how many historical points to use. Such a system is likely to have a self-learning capability and thus may be termed intelligent.

Once the system has a self-learning intelligent element incorporated into it, it would be possible to incorporate other rule-based procedures, where the rules can be made flexible. One example may be the attributes which define the job groups, which could be made variable, so that the job group is a better match for the job in question.

9.7.2 ZERO, NEGATIVE AND STRAY POINTS

Using the method of correction in chapter 8, it was possible for a cutting parameter to be assigned a negative or zero value after correction. Should this situation have occurred, although statistically correct, such a result would have been considered meaningless. In its present form the system has no means for detecting or correcting for such situations, although it would be simple enough for these points to be detected algorithmically. To allow data of this type to be produced in a commercial system would lower the credibility of the system.

Not so easy to detect are stray points, which have either extremely high or extremely low values, either compared to the general trend of the data or outside the normal range for the cutting parameter. A good example was the depth of cut for Reyrolle job group C job number 20 (table J.8, appendix J). After correction this had an extremely low value (0.06 mm) and can clearly be identified in both graphs 8.3 and 8.6. Graph 8.3 also shows that this value was not part of the general trend, since subsequent corrected values were a much better fit to the approved data. Although detectable by a human observer, judgement is called for in deciding whether such points are reasonable or unreasonable. Hence an intelligent system would be better placed to do this.

In all these cases (negative, zero and stray points), having detected the anomaly, there needs to be some means of dealing with the situation. In the short term, a set of algorithmic rules may be used, but they cannot be guaranteed to foresee every eventuality. A better approach in the long term would be to include an intelligence self-learning component in the system to deal with these problems.

9.7.3 STARTING VALUES

It was pointed out in section 8.2.4 that mean and standard deviation correction of data could not take place until the third job within a job group. Furthermore, it was sometimes found that correction of the next few jobs of a job group was not necessarily entirely satisfactory. It was noted that correction of the data was likely to work best with large job groups (section 8.5).

An enhancement to the system would be improved starting values, until the full effects of data correction can take effect. Again, adding intelligence to the system would be one way of achieving this. The intelligent part of the system would learn from previous similar materials and apply a correction to the parameters, until there was sufficient data for normal mean and standard deviation correction to be applied.

9.7.4 OMISSION OF TOOL COMBINATIONS

In theory, each time a job is presented to ITS for tool selection purposes, all tools within the tool database which can machine the relevant features geometrically will be passed to the system for technical consideration, in terms of calculating the cutting parameters. This means that all the different ISO grades of tools with acceptable geometry will be available.

In practice it should quickly become apparent that a number of these combinations will not be worth considering technically for the particular job in question. The addition of an intelligent filter would permit these tools to be rejected at an early stage, thus reducing the number of tools processed technically by the system. This may reduce the run-time required for the system by a considerable amount. However, it may be that this function would be better handled by another module within ITS, rather than passing tools to System 3, only for them to be rejected without processing.

9.8 COMMERCIAL EXPLOITATION

It is considered that the software may be ready for commercial exploitation, after minor modifications. Whilst the tool selection system ITS is not yet available, software of the nature of System 3 is also appropriate for CAM and process planning systems, as well as tool selection systems. In both cases (CAM and process planning), cutting parameters for future jobs are required.

Although CAM systems produce tool paths complete with depths of cut, they are not so effective at giving other cutting parameters. For example the PEPS CAM system, which is produced by Camtek Ltd., will give a cutting speed in the final part program. However, examination shows that when a tool is entered into the PEPS tool library, part of the tool definition is a cutting speed. Therefore the cutting speed will be the same for the tool, irrespective of the job or material concerned. An enhancement to CAM systems of this type would be the inclusion of additional software based System 3.

Before exploitation can take place, however, the problems outlined in section 9.7.2 (zero, negative and stray points) would need to be investigated further. However, as already suggested, algorithmic rules may provide the answer to this. Whilst such a CAM system functioning in such a way would not be perfect, it would be an improvement over current CAM software. Similar arguments can be applied to process planning software although in time ITS in its entirety could be integrated into both CAM and process planning software.

CHAPTER 10

FURTHER WORK AND CONCLUSIONS

10.1 INTRODUCTION

There was no doubt, judging by the results in chapter 8, that in general the work was successful. This is borne out by the belief that the work is commercially exploitable, as discussed in section 9.8. Nevertheless, the discussion in chapter 9 highlighted a number of areas where further work on the system would be beneficial. These are summarised in section 10.2.

In chapter 1 a number of objectives were defined for the work. In section 10.3, the objectives of the work are re-stated and compared against what was achieved. Apart from the main conclusion in section 10.3, a number of other conclusions were drawn from the work in section 10.4. Finally, some closing remarks are made in section 10.5.

10.2 FURTHER WORK

There are two main areas where further work on the system would be warranted:

a) General system development

1) further testing (section 9.6.1),
2) provision for tooling other than ISO types (section 9.6.2),
3) the investigation and addition of further data in the file LIFE.DAT (section 9.6.3),
4) a further reduction of input data (section 9.6.4).

b) Intelligence

The addition of intelligence would be beneficial to the system in a number of ways:

1) self-learning capability (sections 9.7.1 - 9.7.3),

2) the introduction of flexible rules (section 9.7.1),

3) the ability to deal with unrealistic cutting data values (section 9.7.2),

4) the provision of more accurate initial cutting data for new material/tool combinations (section 9.7.3).

10.3 PRIMARY CONCLUSION

The aim of this work (section 1.4) was to develop and test a cutting data algorithm suitable for use in a multiple batch production environment. It required the following features:

1) the input variables should be readily available,
2) the system should have the ability to accept any material and to consider any material with any tool,
3) cutting data similar to accepted company practice should be produced,
4) the system should be industrially applicable.

As far as input data was concerned, the main areas of concern were with the constants and exponents concerning tool life and cutting forces, which were successfully dealt with. In other cases default values were shown to work as satisfactory substitute data and the quantity of input data was reduced, particularly where this caused problems in determining values for the data. Therefore this part of the objective has been met.

System 3 was designed to work with any tool/material combination, although this facility still needs to be fully tested (section 9.6.1). Nevertheless, System 3 worked for two materials (mild steel and cast iron), whilst System 2 was shown to be able to handle a variety of materials. It was therefore likely that this part of the objective was met.

It was shown that the data produced by System 3 was, in the main, from the same population as the approved data. Whilst a machinability database may be more accurate, in terms of using repeat or similar data, the advantage of an algorithm was that it could process any job, whether similar to a previous job or not. The disadvantage was that it was unlikely to produce data which was an exact match to the approved (or company) data. The reason for this was the number of variables not considered by the algorithm. In the circumstances, data from the same statistical population as the approved data was considered good enough and in this respect, this part of the objective was met.

System 3 was tested extensively in a manufacturing environment at Reyrolle, whilst System 2 was also tested industrially in both companies, to a lesser extent. Although the final data correction method was not tested within either company, nevertheless the concept of fed back data was implemented. Although further changes are desirable in terms of input data, nevertheless System 3 functioned as designed within Reyrolle. Therefore this part of the objective was met.

The final system showed how an algorithmic cutting data system might be designed to assist in the multiple batch tool selection problem. Since all the parts of the objective were met, it must be concluded that the work was successful. Furthermore, since there is no apparent reason to restrict any commercial exploitation (section 9.8) of the system to only jobbing and make-to-order environments, this objective may be considered to have been exceeded.

10.4 SECONDARY CONCLUSIONS

A number of secondary conclusions can be drawn from both the work on the system and other associated work:

1) the original algorithm was comparatively insensitive to changes in a number of input variables (chapters 5 and 6 - Systems 1 and 2),

2) industrially, maximisation of a process parameter can be preferable to

optimisation of a production criteria (section 6.5 - data approval procedure),

3) industrially, process parameters are not always maximised, since the criteria at the program proving stage is normally satisfactory machining performance (chapter 5 and 6 - Systems 1 and 2),

4) in certain manufacturing environments cost is not necessarily an explicit criteria for machining processes (sections 7.4 and 9.4),

5) where cutting data generated by an algorithm is not a good match to shop floor cutting data, statistical methods can be used for correction purposes (chapter 8),

6) the role of the part programmer can be more technical than is often considered to be (sections 3.8 and 9.3).

10.5 CLOSING REMARKS

This work has been concerned with finding a method for predicting cutting parameters in an industrial environment, in the context of tool selection. Rather than seeking optimum conditions, the criteria was approved conditions. Part of the reason for this was that there was no way of knowing whether cutting conditions were optimum or sub-optimum without further experimentation. Consequently it was found to be preferable to base the work on cutting conditions which were industrially acceptable.

As a result of the work in this thesis, it is believed that the concept of optimum data is not realistic in an industrial environment. As an example, a situation was observed at Reyrolle where a lathe was fitted with an automatic bar feeder mechanism. With a new length of bar stock, the cutting parameters had to be reduced, due to excessive vibration in the bar feeder mechanism caused by the length of the bar. Once the bar was nearly all used i.e. much shorter and hence more rigid, the parameters could be increased to values above those where vibration had been experienced.

Thus the cutting parameters depended on the amount of the bar in the feeder mechanism, resulting in every component in the batch having different optimum cutting conditions. To successfully model this situation mathematically would require data on, for example, the vibration characteristics of the bar, bar feeder mechanism and machine tool, the condition of the headstock bearings and the length of bar remaining for each component.

A further example took place at Harkers. The job was a gas turbine casing, made from two cast iron half castings. These were bolted together and the bore then machined as one unit on a vertical boring mill. Both halves of the casting had age-hardened, but by different amounts. Furthermore, the cast bore was not concentric, so that the initial cuts were intermittent. In this case the optimum conditions varied during each rotation of the workpiece.

Both of these examples demonstrate the difficulties in building algorithmic models for industrial applications. Whilst such models may work under carefully controlled laboratory conditions, industrially there are too many additional variables to consider which cannot easily be determined. Furthermore, these additional variables would have an adverse effect on the quantity and type of input data, such that any system would probably be unworkable.

The answer, for the moment, would seem to be to adopt the solution in thesis, which was to relax the model, rather than strengthen it. Undoubtedly the way forward for these types of models lies with the introduction of intelligence (section 9.7), as well as integration with other company systems. However, the future may bring a different type of solution.

It seems curious that a series of numbers are used to predict the effectiveness of the cutting process, given the quantity of sensory information given out by the process itself. A logical step must be the development of a more realistic simulation, perhaps using virtual reality (VR) techniques, so that the user can witness how the cut will take place, in a manner similar to the actual operation. Work by Bayliss et al (1995) has concentrated on visual simulations of machining processes, although they are more interested in watching a component take shape, rather than in the efficiency of the machining process.

It is suggested that a development of this work would involve VR simulations concerned with the effectiveness of the machining parameters e.g. swarf formation and chatter. However, this would require much more accurate models than are currently available. It has been suggested by Lewis and Meeran (1995) that imposing a neural net between sensors in the real world and a virtual world may allow this to be achieved.

For example, visual sensors could be used to see the type of swarf produced by real cuts, whilst other sensors would record different details about the cut e.g. vibration levels or temperature. The neural net would then learn from this and use this information to produce virtual swarf in the image. The virtual image could also take into account the wear in the real machine, by measuring such factors as real bearing wear. In this way, it may be possible to replace the current numerical approach with a visual approach.

APPENDIX A

TOOL INVENTORY

The proposed method was a manual count, using check sheets. However, it had to be borne in mind that during such an exercise, tools would move around the shop floors in the normal course of company operations. It was considered that there were two ways in which the inventory could be approached:

a) Minimum categories

This would be a quick method of performing this task, with the advantage that the tools moving during the count would be at a minimum. Hence less tools would be double-counted or missed and, as a result, the detail would be reduced but the accuracy increased.

b) Maximum categories

This would be a slower method and more tools would be missed or double-counted. However, this method would reveal greater detail but with reduced accuracy.

It was decided to opt for the 'minimum categories' method, since this lent itself to repeated checks in the future, by virtue of the quicker time involved. The intention was to include all tools, tool holders and inserts in the areas mentioned below, regardless of tool material or design. Items such as sleeves, chucks and tapping boxes were excluded.

The machine tools were checked for tools in four distinct locations:

a) Machine

Tools fitted on the machine tool fell into this category. This included the spindle and, where fitted, the automatic tool changer.

b) Bed/Table

This included tools on the machine tool, but not actually fitted. Generally, the tools were on the machine bed or table.

c) Exposed

This included tools not on the machine, but in the work area for that machine. Tools recorded were on, not in, benches and cupboards, or in open racks. In some cases, the tools were on the floor.

d) Hidden

This included tools kept in cupboards which would not be seen by a casual observer.

The preset and marshalling areas were checked for tools in the following locations:

a) Exposed

This included tools on view within the area. Tools recorded were on, not in, benches and cupboards, or in open racks. In some cases, the tools were on the floor.

b) Hidden

This included tools kept in cupboards which would not be seen by a casual observer.

In this way it was possible to establish how many tools would be observed by a passer-by and how many tools would never be seen until used.

The categories that the tools were divided into were:

a) milling tools (including slot and end mills)

- high speed steel and brazed tipped tools
- throwaway carbide insert tools

b) turning tools

- high speed steel and brazed tipped tools
- throwaway carbide insert tools

c) drills (including centre drills and reamers)

- high speed steel and brazed tipped tools

- throwaway carbide insert tools

d) boring bars

- high speed steel and brazed tipped tools
- throwaway carbide insert tools

e) taps

- all types

f) inserts

- loose
- fitted

Loose inserts were defined as those not fitted to a holder, whilst fitted inserts were attached to a holder. As a general rule used inserts, either loose or in some kind of container but not the original packet, were not included.

Recording was carried out by ticking the appropriate column of a record sheet (box A.1) to indicate every complete item, with damaged holders also included. Where a holder was fitted with one or more inserts, the inserts were recorded separately, with loose inserts counted individually, although it was not required that a distinction was made between different geometries and grades.

The only distinction for inserts was between milling and single point inserts. The area name or machine type/name was also recorded and in the machine tool areas, the machine tool type/name indicated the insert type. Separate record sheets were used for each individual machine or area. Machine tools and their associated areas, such as cupboards and benches, were counted as separate areas.

At Harkers the inventory took place during a shutdown period. Whilst this had initially appeared to be an advantage, due to the lack of movement of tools during the inventory, one disadvantage became apparent during the inventory. This

HARKERS ENGINEERING TOOL INVENTORY

Work area:

Sheet No: Date:

MILLING TOOLS (INC SLOT AND END MILLS)

High speed steel and brazed tipped tools

Throwaway carbide insert tools

TURNING TOOLS

High speed steel and brazed tipped tools

Throwaway carbide insert tools

DRILLS (INC CENTRE DRILLS AND REAMERS)

High speed steel and brazed tipped tools

Throwaway carbide insert tools

BORING BARS

High speed steel and brazed tipped tools

Throwaway carbide insert tools

TAPS

All types

INSERTS

Loose

Fitted

OTHER

COMMENTS:

invhar1.cht/5/90/prl Initials:

Box A.1

Sample tool inventory record sheet

disadvantage was that a number of machines were undergoing maintenance and thus had all the tools removed from them. In addition, although the period concerned was officially a shutdown, a number of machines were still machining on a single-shift basis. At Reyrolle the inventory took place during normal three-shift working and no problems were encountered. The results are shown in tables A.1 and A.2.

	Machine	Bed/Table	Exposed	Hidden
	Reyrolle			
Milling tools - HSS and brazed tip	26	14	48	1642
Milling tools - carbide insert	2	1	1	12
Turning tools - HSS and brazed tip	28	0	67	129
Turning tools - carbide insert	43	0	23	63
Drills - HSS and brazed tip	88	17	260	2948
Drills - carbide insert	1	0	3	8
Boring bars - HSS and brazed tip	11	0	4	210
Boring bars - carbide insert	0	0	1	63
Taps - all types	13	1	10	297
Inserts - loose	0	0	55	1671
Inserts - fitted	84	4	50	241
Total	**296**	**37**	**522**	**7284**
	Harkers			
Milling tools - HSS and brazed tip	65	32	97	288
Milling tools - carbide insert	19	14	23	17
Turning tools - HSS and brazed tip	2	21	57	278
Turning tools - carbide insert	22	21	24	350
Drills - HSS and brazed tip	32	55	111	192
Drills - carbide insert	3	2	2	5
Boring bars - HSS and brazed tip	1	5	11	23
Boring bars - carbide insert	0	12	67	74
Taps - all types	5	18	96	136
Inserts - loose	0	0	512	1845
Inserts - fitted	135	181	353	319
Total	**284**	**361**	**1353**	**3527**

Table A.1

Summary of machine tools inventories

	Exposed	Hidden	Exposed	Hidden
	Reyrolle		Harkers	
Milling tools - HSS and brazed tip	722	45	669	655
Milling tools - carbide insert	8	10	75	71
Turning tools - HSS and brazed tip	185	0	20	17
Turning tools - carbide insert	100	0	6	6
Drills - HSS and brazed tip	1131	71	870	673
Drills - carbide insert	1	0	40	29
Boring bars - HSS and brazed tip	58	0	172	18
Boring bars - carbide insert	88	16	2	41
Taps - all types	206	6	294	76
Inserts - loose	291	0	295	131
Inserts - fitted	186	103	217	612
Total	**2976**	**251**	**2660**	**2329**

Table A.2

Summary of marshal/preset inventories

APPENDIX B

DESCRIPTION OF THE ALGORITHM, CUTD

B.1 INTRODUCTION

The algorithm used as the starting point for the work in this thesis was a procedure known as CALC (CALCulations) within a Pascal program, which was designated CUTD (CUTting Data). Since CALC required the support of the rest of CUTD e.g. data input and output, the algorithm was generally referred to as CUTD. As the work progressed, other procedures and functions were added to CUTD, which were not strictly part of the algorithm, but which assisted in resolving the problems with the algorithm.

In its final form, CUTD was supported by written documentation and databases. CUTD, together with the documentation and databases, was designated System 1, 2 or 3, as appropriate. (Collectively, Systems 1, 2 and 3 are referred to as the system.) A brief history of the system, in the form of CUTD, is given in section B.2.

CUTD was written in version 5.5 of Borland's Turbo Pascal. It was designed to be used on a standard PC and was developed on a variety of computers with central processing units (CPU) ranging from an 8086 to an 80486. Within the companies, the CPU generally used was an 80286. The operating system that it was intended to run under was MS-DOS (version 3.2 onwards). It has also run successfully under an implementation of DR-DOS.

In its final executable form, CUTD consisted of a main program (filename extension .EXE) and a number of Pascal units (filename extension .TPU), some of which were overlaid. The overlaying of units became necessary to ensure that CUTD ran on a standard PC with the MS-DOS limitation of 640 kbytes of RAM[1]. The overlay operation of the program was controlled by the overlay manager file (filename extension .OVR). The overlay manager also utilised expanded memory (EMS), when sufficient memory was available, which enabled a faster run time. Reasons for the selection of Turbo Pascal are set out in section B.3.

Although major parts of the initial algorithm were novel, the algorithm also used previous work by other workers involved in tool selection (Maropoulos and Hinduja (1990, 1991)). Whilst suitable for the single batch or multiple component tool selection problem (section 1.3) i.e. a single material with recommended tools, it was not considered applicable for the multi-batch tool selection problem (section 1.3) i.e. a range of materials with non-recommended tools. However, until the algorithm was tested (chapter 5), it was not known what changes would be necessary.

Starting with an overview of CUTD, section B.4 explains the workings of the initial algorithm, complete with the ideas behind the logic. All the major equations used within CUTD are included in this section[2]. The derivations of some of the equations are explained in section B.5.

An essential part of CUTD was the entry of data into it. This was the only interactive part of the system i.e. where the user was actively involved. Other

---

[1] The total compiled code was nearly 500 kbytes. Whilst a program this size can be made to run within MS-DOS, when working within the Turbo Pascal programming environment there was insufficient memory left. The use of overlays also allowed CUTD to load faster, since initially less code had to be read from the disc.

[2] Some of the calculations of CALC are performed by other Pascal units within CUTD, such as FUNC (<u>FUNC</u>tions) and PROC (<u>PROC</u>edures), which are standard units for the use of the whole of CUTD. These calculations are included here and they are not identified separately, since they effectively form part of CALC.

interfaces, such as the output, were passive. In a system of this type, the needs of the user cannot be ignored, since they form an integral part of the system. As an aid to understanding the role of the user, all the necessary input data is listed in section B.6.

B.2 BACKGROUND HISTORY OF CUTD

CUTD was intended to form part of an Intelligent Tool Selection system (ITS), which was the name given to the system which will be responsible for the selection of cutting tools. ITS will consist of a number of modules, each of which will perform different functions. The module responsible for determining cutting data was designated the technology module, or ITS_T. Therefore ITS_T will consist of CUTD (the algorithm and associated software programming) and supporting documentation and databases.

Another component within ITS was the geometry module (ITS_G), described in Keating et al (1992). The function of this module was to select tools that were geometrically capable of machining the component element under consideration (Keating et al, (1992)). These tools would then be passed to ITS_T to be assessed technically. As envisaged, the input to ITS_T would, in the final form, be solely from ITS_G, with no user interface at that stage.

However, due to progress being made at a different rate from that of ITS generally, and ITS_G in particular, later development work on CUTD concentrated on treating it as a stand-alone package, rather than as a module of ITS. To enable CUTD to function as an independent piece of software, an interface to allow the user to input data directly into CUTD was developed. This replaced the ITS_G/ITS_T interface for information transfer.

Figure B.1 shows the overall layout of ITS, as it was envisaged at that time. The work in this thesis was intended to form the algorithmic module. Alongside the algorithmic module was shown the knowledge based module. The algorithmic module required complete information about the job but could be used for component, material, tool and machine tool combinations for which there was no previous experience. The knowledge based module, on the other hand, could function with complete data but required information from previous, similar jobs stored in the knowledge base.

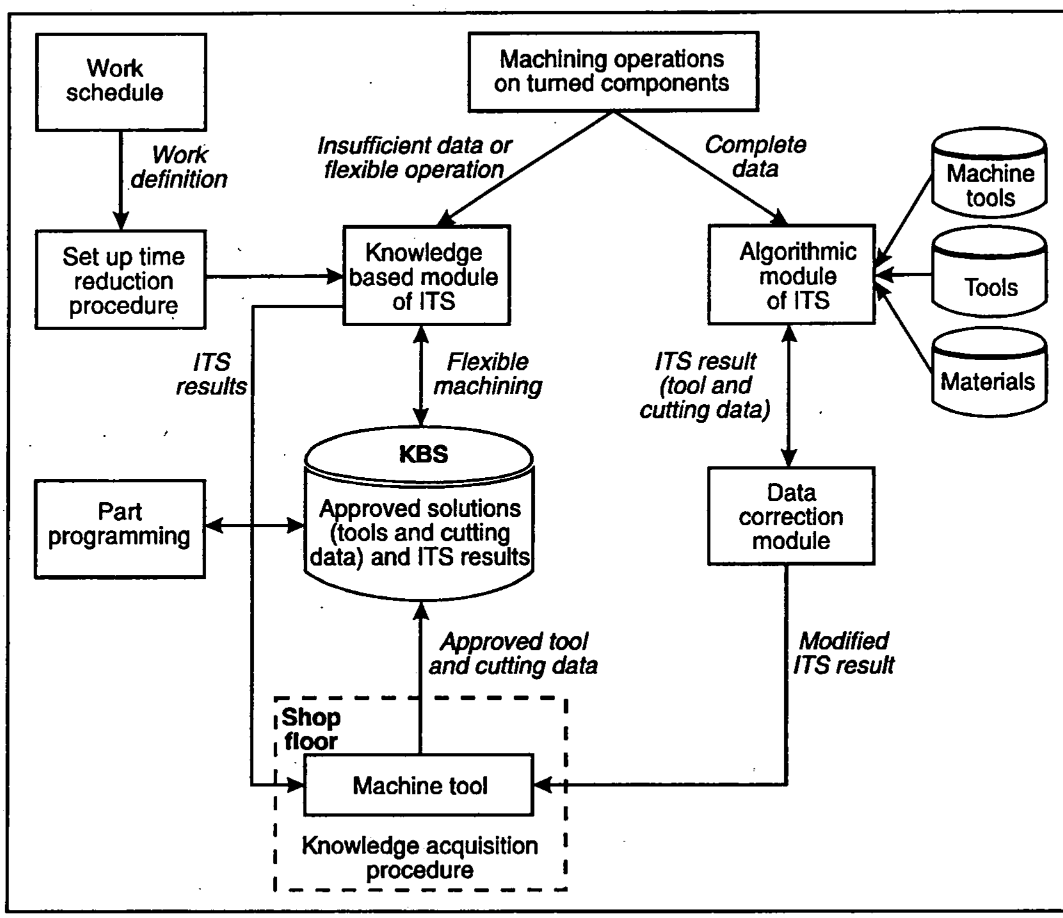


Figure B.1

Overall layout of the intelligent tool selection (ITS) system (based on Maropoulos et al (1993)

B.3 CHOICE OF LANGUAGE

There were several reasons for adopting Turbo Pascal as the programming language:

a) In its original form, CUTD was essentially a numerical processing program, for which Pascal is generally considered suitable. As a result, in the interests of portability between different computers, the original code was restricted to that available in any ANSI Pascal implementation[1].

b) Pascal is a modular language, in terms of its procedures and functions. Turbo Pascal takes this approach a stage further with its use of units, each of which can effectively be written as an independent program. In this way, parts of an overall program can be disabled and other parts added, without any effect on the part of the program that has been retained. This makes a program suitable for implementation and testing of a variety of approaches.

c) Pascal programs can be written in such a way that they are readable, even by someone not familiar with Pascal.

d) Pascal can read and write files in ASCII format. These files can be used to transfer information to and from other parts of ITS, provided that they are also written in languages which support ASCII files.

e) The original version of ITS_G was written in Borland's Turbo C++[2]. Where two Turbo-based programs have been written, one in C++ and the other in Pascal, there is provision within both languages to integrate the programs, such that they run together as a single program.

---

[1] As the program developed, string handling and screen displays became more important. Consequently, further use was made of the extra commands included in Turbo Pascal, which is suited to these applications, even though this is not true of ANSI Pascal. These extra commands were limited to string handling and certain basic graphics functions. The full graphics capability was not utilised. In this way, the task of converting CUTD to ANSI Pascal, should this ever be required, has been simplified.

[2] A subsequent implementation of ITS_G was written in AutoLisp, which is designed to integrate with the drawing software package, AutoCAD.

B.4 OPERATION OF CUTD UNIT

B.4.1 INITIAL FEED RATE AND DEPTH OF CUT

CUTD initially calculated the feed S (mm/rev) with respect to the nose radius of the tool r_e (mm). If the surface finish was not specified (Maropoulos and Hinduja (1991)):

$$S = 0.8 \times r_e \text{ (mm/rev)} \qquad \text{Equ B.1}$$

However, if the surface finish was specified, then the surface finish was taken into account (Hinduja et al (1985)):

$$S = \sqrt{(0.0312 \times R_a \times r_e)} \times C_f \text{ (mm/rev)} \qquad \text{Equ B.2}$$

where R_a (μm) was the surface finish, r_e was the nose radius of the insert and C_f was a material-dependent constant.

If the calculated feed was greater than the maximum feed for the machine or the insert, the feed was reduced to whichever was the lesser value. Conversely, if the calculated feed was less than the minimum available for the machine or the insert, the tool was rejected, since S was the maximum allowable feed rate and could not be increased.

The maximum depth of cut for the tool $a_{(max)}$ (mm) was determined, based on the length of the cutting edge L (mm) and the approach angle κ (°):

$$a_{(max)} = C_{le} \times L \times sin(\kappa) \text{ (mm)} \qquad \text{Equ B.3}$$

C_{le} was a constant that was dependent on the geometric shape of the insert (Maropoulos (1990)). If $a_{(max)}$ was greater than the maximum depth of cut for the insert, $a_{(max)}$ was reduced to this maximum value.

The user was given the option of deciding whether the cut will be completed with a specified number of passes. If the number of passes was unspecified, then the number of passes *nop* was calculated:

$$nop = \frac{a_{(total)}}{a_{(max)}} \qquad \text{Equ B.4}$$

where $a_{(total)}$ (mm) is the total depth of metal to be removed. If *nop* was not an integer, it was truncated and 1 was added. This ensured that two conditions are met:

a) the depth of cut was never greater than the calculated value,

b) each pass was of an equal depth[1].

If the user had specified the number of passes, a check was made to see whether the depth of cut was within the limits of the tool. If not, the tool was rejected. Having determined the number of passes, the final depth of cut a (mm) was determined:

$$a = \frac{a_{(total)}}{nop} \text{ (mm)} \qquad \text{Equ B.5}$$

If a was less than the minimum specified for the insert, the tool was rejected.

B.4.2 CUTTING FORCES

The direction of the three cutting forces are defined in figure B.2. The calculated cutting forces $F_{V(calc)}$ (N), $F_{S(calc)}$ (N) and $F_{a(calc)}$ (N) relating to the values of S (mm/rev) and a (mm) were found (Lissaman and Martin (1982c)):

$$F_{V(calc)} = C_V \times S^{C_{V1}} \times a^{C_{V2}} \text{ (N)} \qquad \text{Equ B.6}$$

$$F_{S(calc)} = C_S \times S^{C_{S1}} \times a^{C_{S2}} \text{ (N)} \qquad \text{Equ B.7}$$

$$F_{a(calc)} = C_a \times S^{C_{a1}} \times a^{C_{a2}} \text{ (N)} \qquad \text{Equ B.8}$$

where C_V, C_{V1}, C_{V2}, C_S, C_{S1}, C_{S2}, C_a, C_{a1} and C_{a2} were experimentally-derived constants.

---

[1] Some authorities prefer to maximise the depth of cut for all passes when roughing, and reduce the depth of the final pass to achieve the total depth of cut required. The final pass can be used as a semi-finish or finish cut, as appropriate. Compared to passes of equal depth for roughing, the final pass will be faster, since the reduced depth allows a faster cutting speed. However, the other passes will be cut at a lower speed, to compensate for the increased depth. For a more comprehensive discussion of this matter, see chapter 2.

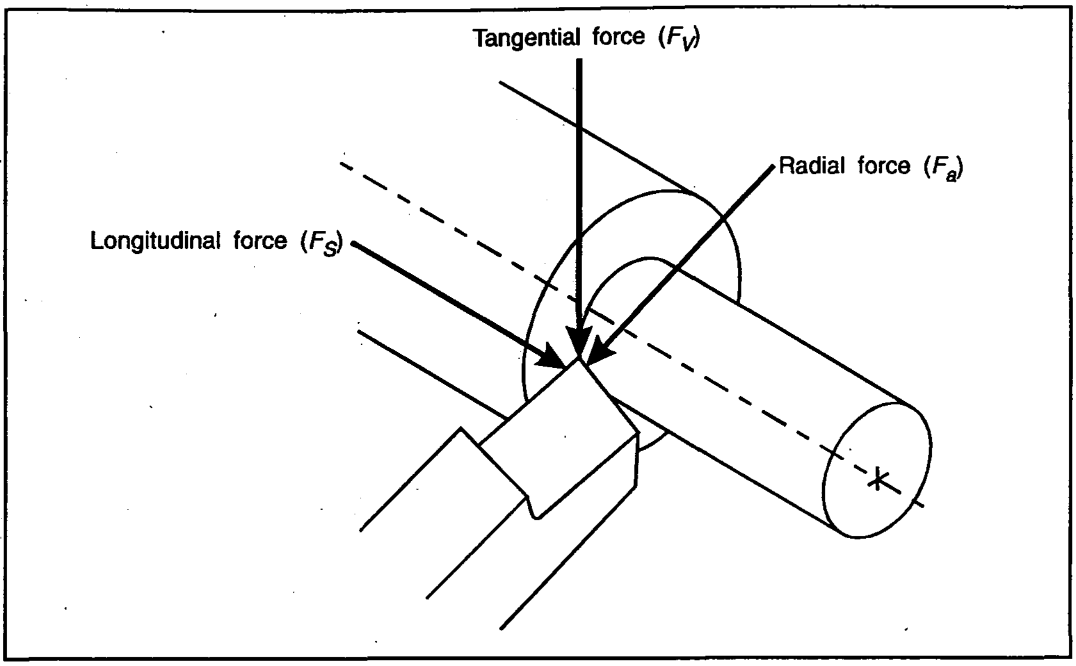


Figure B.2
Directions of cutting forces

The maximum permissible, or constraining, forces in the three principal directions (figure B.2) was ascertained. The first of these was the maximum longitudinal force before sliding in the chuck or collet took place (Hinduja et al (1985)):

$$F_{S(con)} = F_g \times \mu_a \text{ (N)} \qquad \text{Equ B.9}$$

where F_g (N) was the clamping force and μ_a was the longitudinal coefficient of friction between the workpiece and the chuck/collet.

The second constraining force was the tangential force. There were three possible effects due to the tangential force to consider:

a) rotational slipping F_{V1} (N),
b) workpiece throw-out (workpiece forced out of the workholding) F_{V2} (N),
c) insufficient machine tool power F_{V3} (N).

The minimum value of F_{V1}, F_{V2} and F_{V3} became $F_{V(con)}$ (N).

The starting point was the calculation of the flexural rigidity of the workpiece, using the standard formulae:

a) for a solid workpiece:

$$EI_x = \frac{E \times \pi \times d_o^{\ 4}}{64} \text{ (N mm}^2\text{)} \qquad \text{Equ B.10}$$

b) for a hollow workpiece:

$$EI_x = \frac{E \times \pi \times \left(d_o^{\ 4} - d_i^{\ 4}\right)}{64} \text{ (N mm}^2\text{)} \qquad \text{Equ B.11}$$

where E (N/mm^2) was Young's modulus for the material, and d_0 (mm) and d_i (mm) were the outside and inside diameters respectively.

The final diameter of the workpiece was calculated:

a) for external turning:

$$d_{(final)} = d_{(initial)} - \left(2 \times a_{(max)}\right) \text{ (mm)} \qquad \text{Equ B.12}$$

b) for internal turning:

$$d_{(final)} = d_{(initial)} + \left(2 \times a_{(max)}\right) \text{ (mm)} \qquad \text{Equ B.13}$$

where $d_{(final)}$ (mm) and $d_{(initial)}$ (mm) were the cut and uncut diameters respectively.

The maximum available cutting speed $V_{(max)}$ (m/min) was found, which was the lesser of the machine tool speed and the upper end of the insert range. The machine rotational speed was converted to a cutting speed, based on the initial or final diameter of the workpiece, as appropriate.

The maximum tangential force before rotational slipping takes place was calculated (Hinduja et al (1985)):

a) for external turning and facing:

$$F_{V1(con)} = \frac{\mu_c \times F_g \times d_{(held)}}{d_{(initial)}} \text{ (N)} \qquad \text{Equ B.14}$$

b) for internal turning:

$$F_{V1(con)} = \frac{\mu_c \times F_g \times d_{(held)}}{d_{(final)}} \text{ (N)} \qquad \text{Equ B.15}$$

where μ_c was the tangential coefficient of friction between the workpiece and the chuck or collet and $d_{(held)}$ (mm) was the diameter of the held part of the workpiece.

The maximum tangential force before component throw-out took place was calculated (Hinduja et al (1985)):

$$F_{V2(con)} = \frac{F_g \times \left((0.5 \times L_{wc}) + \left(\mu_a \times d_{(held)} \right) \right)}{\sqrt{3} \times L_t} \text{ (N)} \qquad \text{Equ B.16}$$

where L_{wc} (mm) was the length of the workpiece held in the chuck or collet and L_t (mm) was the maximum distance from the workholding to the tool.

The maximum tangential force for the power available was calculated (Lissaman and Martin (1982c)):

$$F_{V3(con)} = \left(\frac{6000 \times P}{V_{(max)}} \right) \text{ (N)} \qquad \text{Equ B.17}$$

where P (W) was the machine tool power and $V_{(max)}$ (m/min) was the maximum cutting speed available from the machine.

Whichever of the three forces $F_{V1(con)}$, $F_{V2(con)}$ or $F_{V3(con)}$ was the least became the tangential constraining force $F_{V(con)}$ (N).

The final constraining force was radial. If a tolerance had been specified, the maximum radial force was calculated which would limit the maximum deflection of the workpiece to 50% of the tolerance *tol* (mm), assuming the workpiece to be a cylindrical cantilever with a free end (all jobs tested were of this form of workholding):

$$F_{a(con)} = \frac{3 \times EI_x \times (0.5 \times tol)}{L_t^3} \text{ (N)} \qquad \text{Equ B.18}$$

The value of EI_x (N mm^2) had previously been determined (equation B.10 or B.11).

A check was then made as to whether all the calculated forces were less than the appropriate constraining forces:

a) for longitudinal turning (inside and outside turning):

$F_{V(calc)}$ was compared with $F_{V(con)}$

$F_{S(calc)}$ was compared with $F_{S(con)}$

$F_{a(calc)}$ was compared with $F_{a(con)}$, if a tolerance was specified

b) for facing:

$F_{V(calc)}$ was compared with $F_{V(con)}$

$F_{a(calc)}$ was compared with $F_{S(con)}$

$F_{S(calc)}$ was compared with $F_{a(con)}$, if a tolerance was specified

If all the calculated forces were lower than the constraining forces specified, no further action was taken with regard to the cutting forces.

If any calculated force was greater than the corresponding constraining force, the feed and the depth of cut were adjusted, as appropriate, until the forces were acceptable. This process is depicted in figure B.3. The original feed and depth are shown as point 1. If this was unacceptable, the feed was reduced in the direction of arrow 2, until either the cutting forces became acceptable or the minimum feed for the machine was reached. If the minimum feed was reached, the original feed at point 1 was resumed and the number of passes was increased by 1 in the direction of arrow 3, provided the number of passes had not been specified. The process was repeated until either the cutting forces became acceptable or the depth of cut became unacceptable for the tool, whereupon the tool was rejected.

In practice, for each pass the feed required to reduce the calculated force to equal the appropriate constraining force was determined by means of a general form of equations B.6, B.7 and B.8:

$$F_{(con)} = C \times S^{C_1} \times a^{C_2} \text{ (N)} \qquad \text{Equ B.19}$$

$$\Rightarrow S = \left(\frac{F_{(con)}}{C \times a^{C_2}} \right)^{\frac{1}{C_1}} \text{ (mm/rev)} \qquad \text{Equ B.20}$$

where $F_{(con)}$ represented $F_{V(con)}$, $F_{S(con)}$ or $F_{a(con)}$, as appropriate, C represented C_V, C_S

or C_a, as appropriate, C_1 represented C_{V1}, C_{S1} or C_{a1}, as appropriate, and C_2 represented C_{V2}, C_{S2} or C_{a2}, as appropriate.

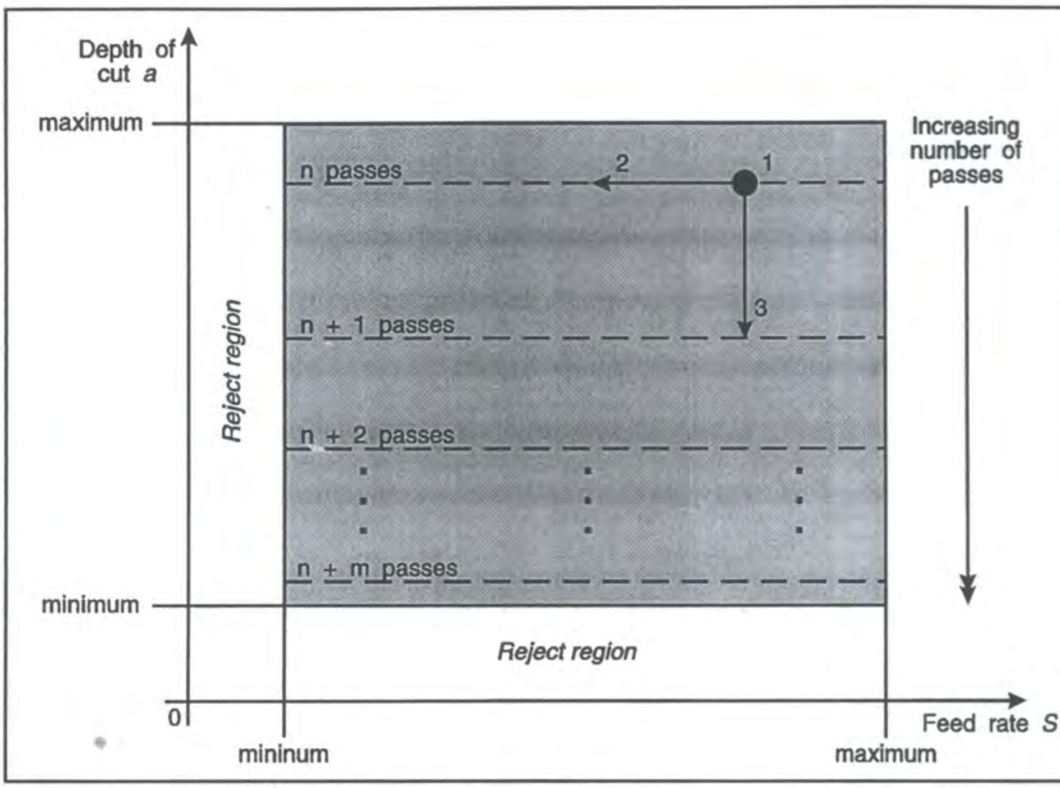


Figure B.3

Adjustment of feed and depth to obtain acceptable cutting forces

B.4.3 CUTTING SPEEDS

Cutting speeds were calculated for each pass of the tool. The starting point was to determine the overlap range between the machine and the tool, and to this end the machine tool maximum and minimum rotational speeds (in rpm) were converted to a cutting speed (in m/min), based on the diameter of the workpiece. The overlap range between the machine and the tool gave the maximum and minimum available cutting speeds for the pass ($V_{(max)}$ (m/min) and $V_{(min)}$ (m/min)).

Two constraints were then considered. The first of these constraints was user-defined and concerned the tool life, whereby the user could specify a minimum tool life $T_{(min)}$ (mins). The cutting speed for minimum tool life $V_{(T)}$ (m/min) was given by the extended Taylor equation for tool life e.g. Hoffman (1984):

$$V_{(T)} = \left(\frac{C_1}{T_{(min)} \times S^{1/\beta} \times a^{1/\gamma}} \right)^{\alpha} \quad \text{(m/min)} \qquad \text{Equ B.21}$$

If $V_{(T)}$ was greater than $V_{(max)}$, then $V_{(max)}$ became equal to $V_{(T)}$. If $V_{(T)}$ was less than $V_{(min)}$, the tool was rejected.

The second constraint was concerned with the maximum number of tools used. If the cut was a finish cut, then the maximum number of tools was automatically set to one. This constraint was included since most operators did not like to change the tool during a finish cut, since this could mark the work. The speed $V_{(nT)}$ (m/min) to ensure that not more than one tool was used for the pass was calculated:

$$V_{(nT)} = \left(\frac{C_1 \times nT_{(max)}}{0.001 \times \pi \times d_{(cut)} \times L_c \times S^{(1/\beta)-1} \times a^{1/\gamma}} \right)^{\alpha/(1-\alpha)} \quad \text{(m/min)} \qquad \text{Equ B.22}$$

The derivation of equation B.22 is shown in section B.5.1. If $V_{(nT)}$ was greater than $V_{(max)}$, then $V_{(max)}$ became equal to $V_{(nT)}$. If $V_{(nT)}$ was less than $V_{(min)}$, the tool was rejected.

The cost per cutting edge y (£) was calculated (Maropoulos and Hinduja (1990)):

$$y = \frac{c_i}{0.75 \times nce} \times \frac{1.3 \times c_h}{400} \quad \text{(£)} \qquad \text{Equ B.23}$$

where c_i (£) was the cost of the insert, c_h (£) was the cost of the holder and *nce* was the number of cutting edges on the insert.

Having determined the maximum permissible cutting speed, four cutting speeds were calculated, each one being considered to be an appropriate optimum cutting speed, based on a particular production criteria:

a) cutting speed for minimum machining time per component $V_{(time)}$ (m/min),

b) cutting speed for minimum machining cost per component $V_{(cost)}$ (m/min),

c) cutting speed for maximum tool life $V_{(life)}$ (m/min),

d) cutting speed for the minimum number of tools $V_{(number)}$ (m/min).

In the case of $V_{(time)}$ and $V_{(cost)}$, the graph of cutting speed against either machining time or machining cost per item had a single minimum (Kalpakjian (1989)). The origin of these graphs is shown in figure B.4.

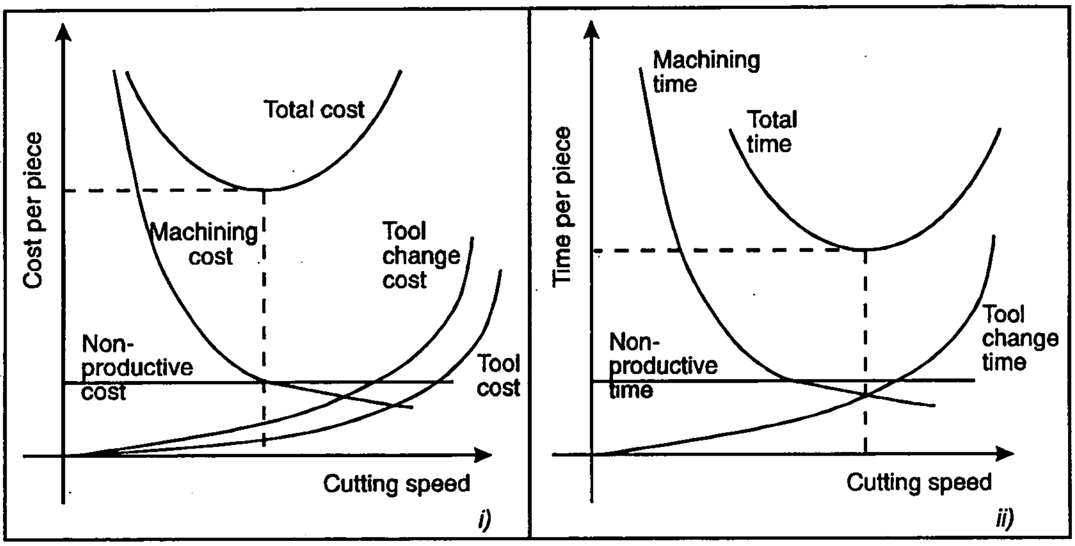


Figure B.4

Graphs of cost per item (i) and time per item (ii) in machining (Kalpakjian (1989))

The total cost per component was made up of:

a) non-productive cost,

b) effective machining or cutting cost,

c) tool change cost,

d) cost of the cutting tool.

The total machining time per component was made up of:

a) non-productive time,

b) effective machining or cutting time,

c) tool changing time.

The effective machining cost and time referred to that period of the machining cycle when the tool was actually cutting. As the cutting speed increased, so the effective machining time and cost per component decreased, since components were produced more quickly. However, tool life also decreased, necessitating more tool changes. Thus the graphs of machining cost and machining time per component both had a minimum, which represented the optimum cutting speeds. Since both these graphs were of the same form, a typical graph is shown in figure B.5, where it is evident that the optimum cutting speed occurs at the minimum. This is shown in the figure as the 'true optimum cutting speed'.

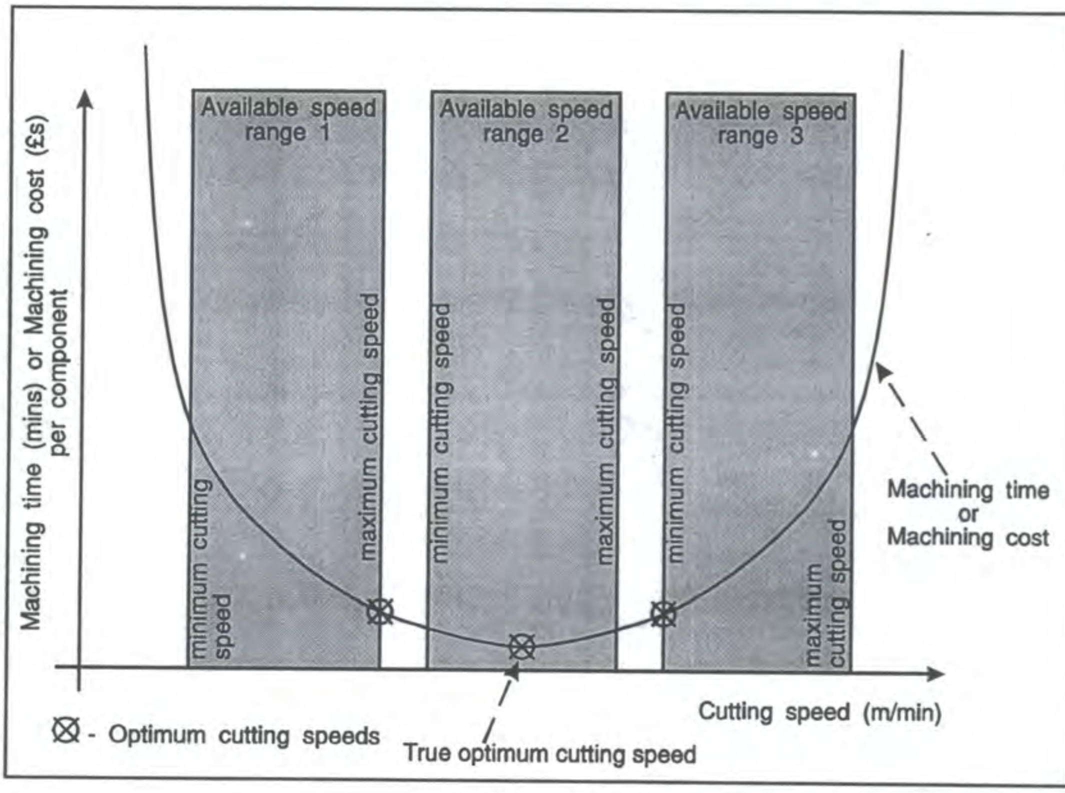


Figure B.5

General graph of cutting speed against machining time or machining cost

Note: Only one range is applicable at any one time

Also shown in figure B.5 are three typical speed ranges, although only one range was applicable at any one time. Each range was bounded by the maximum cutting speed, as described previously, and the minimum speed for the machine tool. The actual optimum was determined by the position of the minimum of the machining time or machining cost line, with respect to the speed range concerned, as shown in the figure. In effect, where the speed range did not include the minimum, the optimum speed was the speed range boundary closest to the minimum.

The cutting speed for minimum machining cost per component $V_{(cost)}$ was calculated (figure B.5):

$$V_{(cost)} = \left(\frac{\left(\frac{x}{60}\right) \times C_1}{S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1\right) \times \left(\left(\frac{x}{60} \times t_3 \right) + y \right)} \right)^{\alpha} \text{ (m/min)} \qquad \text{Equ B.24}$$

where x (£/hr) was the hourly machine cost and t_3 (mins) was the tool change time. If $V_{(cost)}$ was less than $V_{(min)}$, then $V_{(cost)}$ became equal to $V_{(min)}$. Conversely, if $V_{(cost)}$ was greater than $V_{(max)}$, then $V_{(cost)}$ became equal to $V_{(max)}$. The derivation of equation B.24 is shown in section B.5.2.

The cutting speed for minimum machining time per component $V_{(time)}$ was calculated (figure B.5):

$$V_{(time)} = \left(\frac{C_1}{t_3 \times S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1\right)} \right)^{\alpha} \text{ (m/min)} \qquad \text{Equ B.25}$$

If $V_{(time)}$ was less than $V_{(min)}$, then $V_{(time)}$ became equal to $V_{(min)}$. Conversely, if $V_{(time)}$ was greater than $V_{(max)}$, then $V_{(time)}$ became equal to $V_{(max)}$. The derivation of equation B.25 is shown in section B.5.3.

The situation for $V_{(time)}$ and $V_{(number)}$ was somewhat different. The graph of tool life against cutting speed is shown in figure B.5, based on the work of Taylor (1907). Since the number of tools used was the machining time divided by the tool life, the number of tools used is of the form T^{-1}. This graph is also shown in figure B.5. Superimposed on the graphs in figure B.6 is the available cutting speed range. This range was determined in accordance with the principles already outlined. It was evident from the graph that in both cases the optimum cutting speed was the minimum speed of the available range.

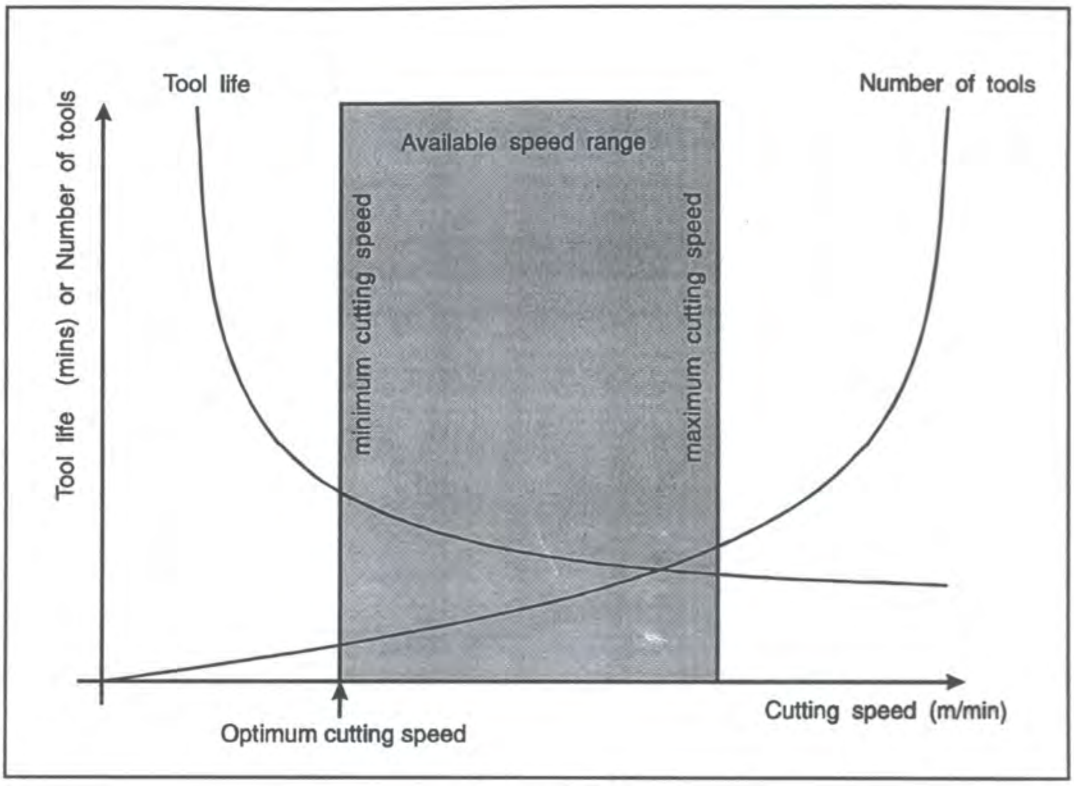


Figure B.6

General graphs of cutting speed against tool life or number of tools

The cutting speed for maximum tool life $V_{(life)}$ was calculated (figure B.6):

$$V_{(life)} = V_{(min)} \text{ (m/min)} \qquad \text{Equ B.26}$$

The cutting speed for the minimum number of tools $V_{(number)}$ was calculated (figure B.6):

$$V_{(number)} = V_{(min)} \text{ (m/min)} \qquad \text{Equ B.27}$$

The derivations of equations B.26 and B.27 are shown in sections B.5.4 and B.5.5.

B.4.4 PRODUCTION CRITERIA

For each of the four optimum speeds $V_{(life)}$, $V_{(cost)}$, $V_{(time)}$ and $V_{(number)}$, production criteria were calculated, where B was the batch size. These were:

a) tool life:

$$T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \text{ (mins)} \qquad \text{Equ B.28}$$

b) machining cost:

$$m_c = \left(\left(t_2 \times \frac{x}{60} \right) + \frac{t_2 \times t_3 \times \frac{x}{60}}{T} + \frac{t_2 \times y}{T} \right) \times B \text{ (£)} \qquad \text{Equ B.29}$$

where $$t_2 = \frac{0.001 \times \pi \times d_{(cut)} \times L_c}{V \times S} \text{ (mins)} \qquad \text{Equ B.30}$$

c) machining time:

$$m_t = \left(t_2 + \frac{t_2 \times t_3}{T} \right) \times B \text{ (mins)} \qquad \text{Equ B.31}$$

where t_2 (mins) was calculated as shown in equation B.30.

d) number of tools:

$$nT = \frac{t_2}{T} \times B \qquad \text{Equ B.32}$$

The workpiece set-up time t_1 was not included in the above equations. The purpose of CUTD was to enable different tools to be compared when cutting the same batch. Whichever tool was used, the workpiece set-up time remained unchanged and was thus not relevant to the calculations.

The batch size B was included, since it could influence the number of tools used (section 1.3). If a batch size of 1 used m tools, a batch size of n (where n>1), may well use less than $m \times n$ tools. For example, if:

$B = 1$ and $nT = 2.5$ tools

where nT was the number of tools, this would be counted as 3 tools, in terms of such factors as tool changes. However, if the batch size was doubled, the number of tools used does not also double i.e.:

$B = 2$ and $nT = 5$ tools

B.5 DERIVATIONS OF EQUATIONS

B.5.1 TO FIND THE SPEED FOR THE MAXIMUM NUMBER OF TOOLS PER PASS $V_{(nT)}$

$$\text{Number of tools used } nT = \frac{\text{Effective cutting time } t_2}{\text{Tool life } T} \qquad \text{Equ B.33}$$

where:

$$\text{Tool life } T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \text{ (mins)}$$

$$\text{Effective cutting time per pass } t_2 = \frac{\text{Length of cut } L_c}{\text{Rotational speed } N \times \text{Feed rate } S} \text{ (mins)}$$

and

$$N = \frac{V}{\pi \times d_{(cut)} \times 0.001} \text{ (rpm)}$$

$$\Rightarrow nT = \frac{0.001 \times \pi \times d_{(cut)} \times L_c \times V^{(1/\alpha)-1} \times S^{(1/\beta)-1} \times a^{1/\gamma}}{C_1} \qquad \text{Equ B.34}$$

If nT was assigned a maximum value $nT_{(max)}$, then V became $V_{(nT)}$ i.e.

$$V_{(nT)} = \left(\frac{C_1 \times nT_{(max)}}{0.001 \times \pi \times d_{(cut)} \times L_c \times S^{(1/\beta)-1} \times a^{1/\gamma}} \right)^{\alpha/(1-\alpha)} \text{ (m/min)} \qquad \text{Equ B.35}$$

B.5.2 TO FIND THE CUTTING SPEED FOR THE MINIMUM MACHINING COST PER COMPONENT $V_{(cost)}$

The cost could be considered as four components:

1) Workpiece set-up cost $c_1 = \frac{x}{60} \times t_1$ (£)

2) Effective cutting cost $c_2 = \frac{x}{60} \times t_2$ (£)

3) Tool change cost $c_3 = \frac{t_2}{T} \times t_3 \times \frac{x}{60}$ (£)

4) Tool cost $c_4 = y \times \left(\frac{t_2}{T}\right)$ (£)

where:

x - machine rate (£/hour)

t_1 - workpiece set-up time (mins)

t_2 - effective cutting time (mins)

t_3 - tool change time (mins)

y - tool cost (£) (equation 5.29)

T - tool life (mins)

Machining cost per component $m_c = c_1 + c_2 + c_3 + c_4$ (£) Equ B.36

$$\Rightarrow m_c = \left(\frac{x}{60} \times t_1\right) + \left(t_2 \times \frac{x}{60}\right) + \left(\frac{t_2}{T} \times t_3 \times \frac{x}{60}\right) + \left(\frac{t_2 \times y}{T}\right) \text{ (£)} \quad \text{Equ B.37}$$

where:

$$t_2 = \frac{0.001 \times \pi \times d_{(cut)} \times L_c}{V \times S} \text{ (mins)} \quad \text{Equ B.38}$$

and

$$T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \text{ (mins)} \quad \text{Equ B.39}$$

To find the cutting speed $V_{(cost)}$ for the minimum machining cost per component, $m_{c(min)}$, equations B.38 and B.39 were substituted into equation B.37. Equation B.37 was then differentiated with respect to V and equated to zero i.e.

$$\frac{\partial m_c}{\partial V} = 0 \quad \text{Equ B.40}$$

Therefore:

$$V_{(cost)} = \left(\frac{\frac{x}{60} \times C_1}{S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1\right) \times \left(\left(\frac{x}{60} \times t_3\right) + y\right)} \right)^{\alpha} \text{ (m/min)} \quad \text{Equ B.41}$$

Note: Valid for $\frac{1}{\alpha} > 1$ only.

B.5.3 TO FIND THE CUTTING SPEED FOR THE MINIMUM MACHINING TIME PER COMPONENT $V_{(time)}$

This could be considered as three components:

1) Workpiece set-up time t_1 (mins)
2) Effective cutting time t_2 (mins)
3) Total tool change time $= \frac{t_2}{T} \times t_3$ (mins)

where:

t_1 - workpiece set-up time (mins)

t_2 - effective cutting time (mins)

t_3 - tool change time (mins)

T - tool life (mins)

$$\text{Machining time per component } m_t = t_1 + t_2 + \left(\frac{t_2}{T} \times t_3\right) \text{ (mins)} \qquad \text{Equ B.42}$$

where:

$$t_2 = \frac{0.001 \times \pi \times d_{(cut)} \times L_c}{V \times S} \text{ (mins)} \qquad \text{Equ B.43}$$

and

$$T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \text{ (mins)} \qquad \text{Equ B.44}$$

To find the cutting speed $V_{(time)}$ for the minimum machining time per component $m_{t(min)}$, equations B.43 and B.44 were substituted into equation B.42. Equation B.42 was then differentiated with respect to V and equated to zero i.e.

$$\frac{\partial m_t}{\partial V} = 0 \qquad \text{Equ B.45}$$

Therefore:

$$V_{(time)} = \left(\frac{C_1}{t_3 \times S^{1/\beta} \times a^{1/\gamma} \times \left(\frac{1}{\alpha} - 1\right)}\right)^{\alpha} \text{ (m/min)} \qquad \text{Equ B.46}$$

Note: Valid for $\frac{1}{\alpha} > 1$ only.

B.5.4 TO FIND THE CUTTING SPEED FOR MAXIMUM TOOL LIFE $V_{(life)}$

$$\text{Tool life } T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \text{ (mins)} \qquad \text{Equ B.47}$$

To find the cutting speed $V_{(life)}$ for the maximum tool life $T_{(max)}$, equation B.47 was differentiated with respect to V and equated to zero i.e.

$$\frac{\partial T}{\partial V} = 0 \qquad \text{Equ B.48}$$

There was only one solution:

$$V_{(life)} = 0 \qquad \text{Equ B.49}$$

This was unrealistic in practical terms and therefore for $T_{(max)}$, $V_{(life)}$ had to be the minimum value available.

B.5.5 TO FIND THE CUTTING SPEED FOR THE MINIMUM NUMBER OF TOOLS USED $V_{(number)}$

Number of tools used $nT = \frac{t_2}{T}$ Equ B.50

where:

t_2 - effective cutting time (mins)

T - tool life (mins)

where:

$$t_2 = \frac{0.001 \times \pi \times d_{(cut)} \times L_c}{V \times S} \text{ (mins)} \qquad \text{Equ B.51}$$

and

$$T = \frac{C_1}{V^{1/\alpha} \times S^{1/\beta} \times a^{1/\gamma}} \text{ (mins)} \qquad \text{Equ B.52}$$

To find the cutting speed $V_{(number)}$ for the minimum number of tool used $nT_{(min)}$, substitute equations B.51 and B.52 were substituted into equation B.50. Equation B.50 was differentiated with respect to V and equated to zero i.e.

$$\frac{\partial nT}{\partial V} = 0 \qquad \text{Equ B.53}$$

There was only one solution:

$$V_{(number)} = 0 \qquad \text{Equ B.54}$$

This was unrealistic in practical terms and therefore for $nT_{(min)}$, $V_{(number)}$ had be the minimum value available.

B.6 INPUT DATA

B.6.1 CATEGORIES OF INPUT DATA

The input data required for CUTD to carry out a set of calculations could be divided into a number of categories:

Tool attributes	section B.6.2
Cut attributes	section B.6.3
Machine attributes	section B.6.4
Material attributes	section B.6.5
Control data	section B.6.6
Constraint data	section B.6.7

In all, a total of 56 different pieces of information were necessary. The remainder of this section lists all the necessary inputs, along with an indication of where they could be found or how they could be obtained.

B.6.2 TOOL ATTRIBUTES

The tool attributes could be divided into five categories:

tool geometry

tool constants

tool life data

force data

performance data

		Source of data
	Tool geometry	
1	nose radius r_e (mm)	tool specification
2	cost of insert c_i (£)	tool makers literature
3	cost of holder c_h (£)	tool makers literature
4	number of cutting edges *nce*	tool specification
5	length of cutting edge L (mm)	tool specification
6	approach angle κ (°)	tool specification
	Tool constants	
7	material-dependent constant C_f	experimentation
8	insert shape-dependent constant C_{le}	experimentation

	Tool life data	
9	constant in the extended Taylor equation C_1	experimentation
10	exponent in the extended Taylor equation α	experimentation
11	exponent in the extended Taylor equation β	experimentation
12	exponent in the extended Taylor equation γ	experimentation
	Force data	
13	constant for tangential cutting force calculations C_V	experimentation
14	exponent for tangential cutting force calculations C_{V1}	experimentation
15	exponent for tangential cutting force calculations C_{V2}	experimentation
16	constant for longitudinal cutting force calculations C_S	experimentation
17	exponent for longitudinal cutting force calculations C_{S1}	experimentation
18	exponent for longitudinal cutting force calculations C_{S2}	experimentation
19	constant for radial cutting force calculations C_a	experimentation
20	exponent for radial cutting force calculations C_{a1}	experimentation
21	exponent for radial cutting force calculations C_{a2}	experimentation
	Performance data	
22	maximum cutting speed $V_{(max)}$ (m/min)	tool makers literature
23	minimum cutting speed $V_{(min)}$ (m/min)	tool makers literature
24	maximum feed rate $S_{(max)}$ (mm/rev)	tool makers literature
25	minimum feed rate $S_{(min)}$ (mm/rev)	tool makers literature
26	maximum depth of cut $a_{(max)}$ (mm)	tool makers literature
27	minimum depth of cut $a_{(min)}$ (mm)	tool makers literature

B.6.3 CUT ATTRIBUTES

		Source of data
1	workpiece diameter in chuck/collet $d_{(held)}$ (mm)	process plan/drawing
2	workpiece initial diameter $d_{(initial)}$ (mm)	process plan/drawing
3	length of workpiece in chuck/collet L_{wc} (mm)	process plan/drawing
4	maximum distance from chuck/collet to tool L_t (mm)	process plan/drawing

5	length of cut L_c (mm)	drawing
6	total depth of cut $a_{(total)}$ (mm)	drawing
7	surface finish R_a (μm)	drawing
8	tolerance *tol* (mm)	drawing
9	required number of passes *nop*	process plan
10	batch size *B*	process plan
11	workpiece set-up time t_1 (mins)	machinist
12	general/minimum workpiece outside diameter d_o (mm)	drawing
13	general/maximum workpiece inside diameter d_i (mm)	drawing

Cut dimensions 1 - 6 are shown in figure B.7 for turning, boring and facing. Attributes 7 - 9 should have a value equal to, or greater than, zero. Zero was used to indicate that the attribute was not applicable for the job in question e.g. $tol = 0$ implied that a tolerance had not been specified. The required number of passes was used when it was required that the cut be completed within a pre-determined number of passes.

Attributes 12 and 13 were required for the calculation of deflection. Any part of the component further away from the workholding than the tool at its furthermost position was ignored. Essentially, the dimensions should have been chosen to reflect the part of the workpiece where maximum bending would take place. This position of maximum bending was judged subjectively by the user, based on their experience, and was not calculated. Typical examples are shown in figure B.8.

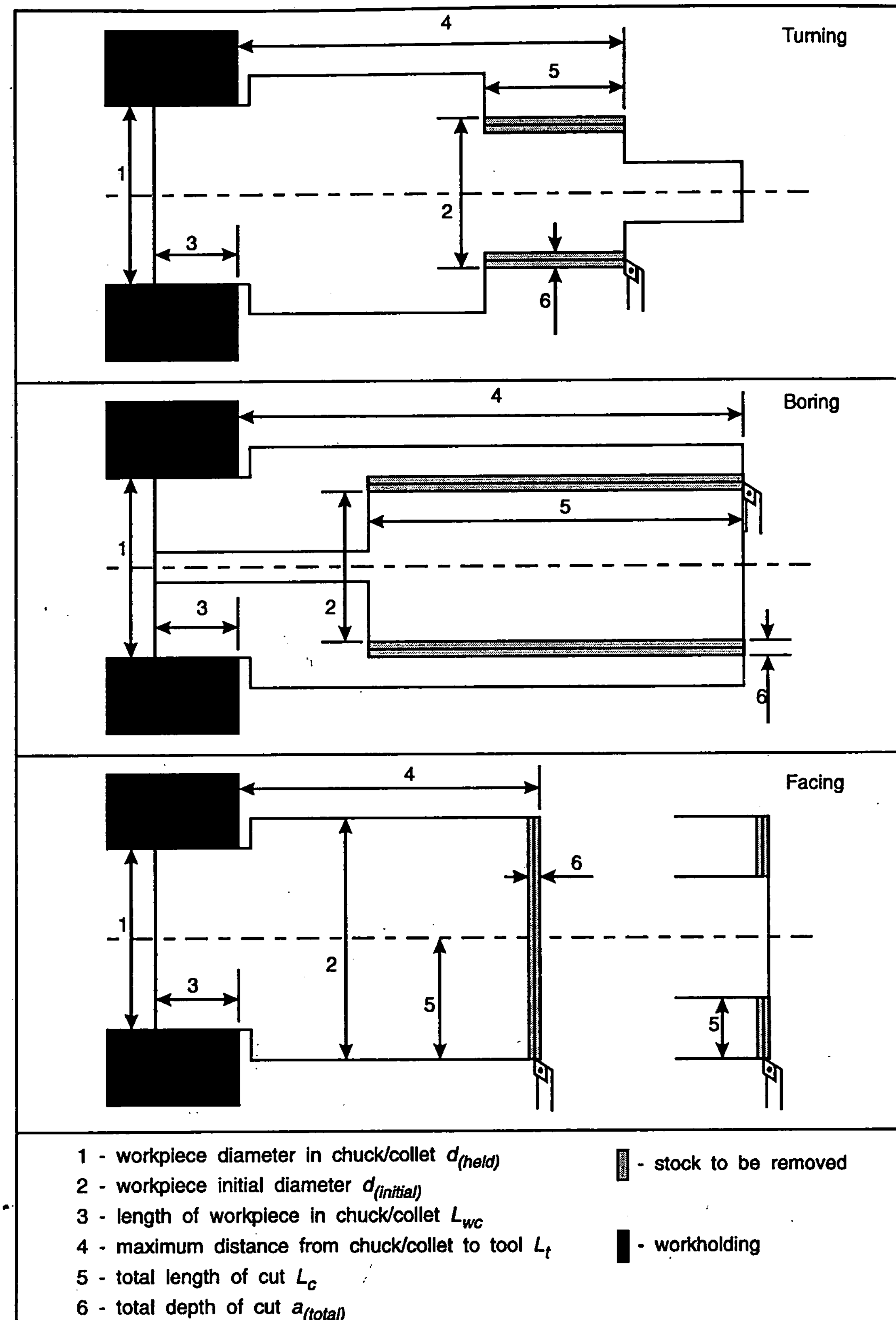


Figure B.7

Cut dimensions for turning, boring and facing

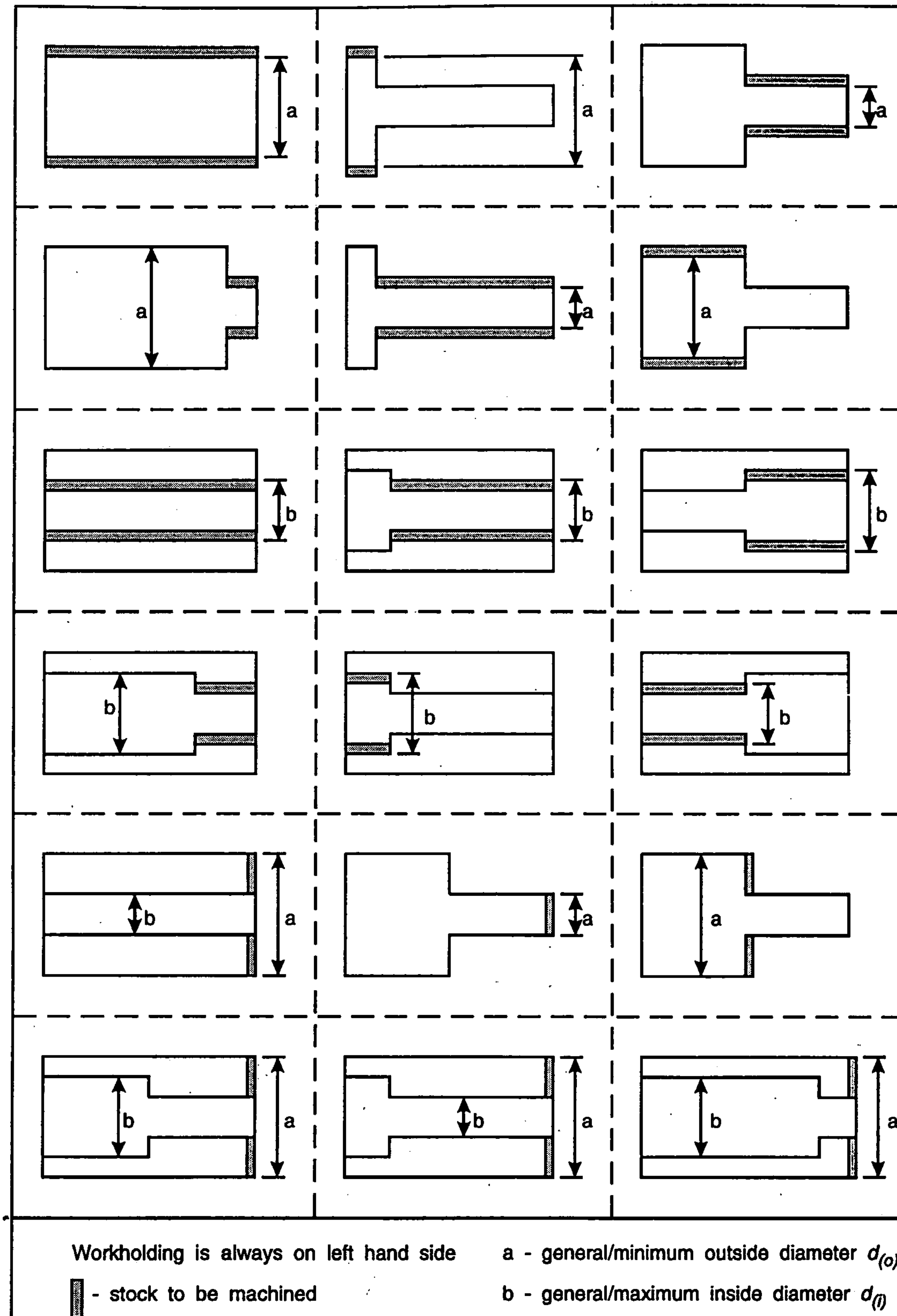


Figure B.8

Examples of general minimum/outside and maximum/inside diameters

B.6.4 MACHINE ATTRIBUTES

		Source of data
1	maximum rotational speed $N_{(max)}$ (rpm)	machine handbook
2	minimum rotational speed $N_{(min)}$ (rpm)	machine handbook
3	hourly cost x (£)	accounts dept
4	tool change time t_3 (mins)	machinist
5	clamping force F_e (N)	machinist
6	power P (kW)	machine handbook
7	maximum feed rate $S_{(max)}$ (mm/rev)	machine handbook
8	minimum feed rate $S_{(min)}$ (mm/rev)	machine handbook
9	longitudinal coefficient of friction in chuck/collet μ_a	experimentation
10	tangential coefficient of friction in chuck/collet μ_c	experimentation

B.6.5 MATERIAL ATTRIBUTES

		Source of data
1	Young's modulus E (N/mm^2)	material specification

B.6.6 CONTROL DATA

		Source of data
1	outside/inside diameter	drawing
2	roughing/finish cut	drawing
3	longitudinal turning/facing	drawing
4	solid/hollow component	drawing

B.6.7 CONSTRAINT DATA

		Source of data
1	minimum tool life T (mins)	part programmer

APPENDIX C

FORCES PARAMETERS FOR MEDIUM CARBON STEEL

Note: Units are κ (°), ε (°), C_b (mm), r_e (mm)

κ	ε	C_b	r_e	C_V	C_{V1}	C_{V2}	C_S	C_{S1}	C_{S2}	C_a	C_{a1}	C_{a2}
Tool 1												
95	80	M	1.6	1759.4	0.745	0.944	635.9	0.260	0.992	328.9	0.359	0.869
95	80	M	1.2	1763.3	0.746	0.943	636.7	0.259	0.992	315.6	0.357	0.880
95	80	M	0.8	1765.6	0.747	0.943	641.4	0.260	0.991	289.8	0.342	0.907
95	80	M	0.4	1765.6	0.747	0.943	637.5	0.255	0.995	259.4	0.328	0.941
95	80	G	1.6	1671.9	0.748	0.940	567.2	0.260	0.987	292.2	0.353	0.873
95	80	G	1.2	1670.3	0.748	0.941	573.4	0.264	0.984	282.0	0.355	0.884
95	80	G	0.8	1665.6	0.745	0.941	571.1	0.261	0.987	261.7	0.346	0.909
95	80	G	0.4	1675.0	0.749	0.941	570.3	0.259	0.991	233.6	0.329	0.941
95	80	A	1.6									
95	80	A	1.2	1878.1	0.748	0.941	710.9	0.257	0.994	355.5	0.348	0.888
95	80	A	0.8	1881.3	0.748	0.941	718.0	0.260	0.992	334.4	0.343	0.906
95	80	A	0.4	1878.1	0.748	0.942	721.9	0.259	0.991	303.1	0.335	0.936
Tool 2												
90	60	M	1.6	1771.9	0.747	0.942	635.2	0.259	0.992	321.9	0.356	0.872
90	60	M	1.2	1775.0	0.748	0.942	636.7	0.259	0.992	313.3	0.359	0.877
90	60	M	0.8	1773.4	0.748	0.942	639.8	0.260	0.993	286.7	0.342	0.903
90	60	M	0.4	1762.5	0.744	0.944	643.0	0.260	0.993	257.8	0.332	0.937
90	60	G	1.6	1675.0	0.747	0.940	568.0	0.262	0.988	289.8	0.356	0.871
90	60	G	1.2	1671.9	0.746	0.941	573.4	0.264	0.984	275.8	0.351	0.886
90	60	G	0.8	1675.0	0.748	0.941	571.9	0.264	0.989	257.8	0.342	0.904
90	60	G	0.4	1678.1	0.748	0.940	569.5	0.258	0.991	232.0	0.331	0.936
90	60	A	1.6	1884.4	0.748	0.941	709.4	0.257	0.994	368.8	0.353	0.872
90	60	A	1.2	1892.2	0.750	0.940	714.8	0.260	0.993	353.1	0.349	0.884
90	60	A	0.8	1890.6	0.749	0.940	717.2	0.259	0.992	333.6	0.348	0.902
90	60	A	0.4									
Tool 3												
60	60	M	1.6	1815.6	0.748	0.941	635.9	0.260	0.991	322.7	0.359	0.867
60	60	M	1.2	1815.6	0.748	0.941	632.8	0.257	0.995	311.7	0.360	0.887
60	60	M	0.8	1815.6	0.748	0.941	639.8	0.260	0.992	285.2	0.343	0.902
60	60	M	0.4	1823.4	0.750	0.940	646.1	0.260	0.991	257.0	0.333	0.934
60	60	G	1.6	1712.5	0.748	0.941	565.6	0.260	0.989	290.6	0.359	0.866
60	60	G	1.2	1712.5	0.748	0.941	573.4	0.264	0.984	275.8	0.352	0.880
60	60	G	0.8	1712.5	0.748	0.941	568.0	0.259	0.990	258.6	0.349	0.902
60	60	G	0.4	1712.5	0.748	0.941	572.7	0.260	0.990	228.9	0.330	0.939
60	60	A	1.6	1917.2	0.746	0.943	712.5	0.259	0.992	365.6	0.352	0.873
60	60	A	1.2	1917.2	0.746	0.943	710.9	0.257	0.994	346.9	0.346	0.889
60	60	A	0.8	1917.2	0.746	0.943	718.8	0.260	0.991	334.4	0.349	0.895
60	60	A	0.4									

κ	ε	C_b	r_e	C_V	C_{V1}	C_{V2}	C_S	C_{S1}	C_{S2}	C_a	C_{a1}	C_{a2}
Tool 4												
45	60	M	1.6	1837.5	0.747	0.943	641.4	0.263	0.988	334.4	0.354	0.884
45	60	M	1.2	1834.4	0.746	0.944	638.3	0.260	0.991	321.9	0.352	0.894
45	60	M	0.8	1834.4	0.747	0.945	640.6	0.260	0.992	301.6	0.345	0.914
45	60	M	0.4	1835.9	0.747	0.944	644.5	0.259	0.991	268.8	0.328	0.949
45	60	G	1.6	1737.5	0.748	0.942	567.2	0.262	0.988	300.0	0.352	0.884
45	60	G	1.2	1737.5	0.748	0.941	569.5	0.262	0.988	284.4	0.345	0.902
45	60	G	0.8	1739.1	0.748	0.941	568.8	0.260	0.990	268.0	0.339	0.917
45	60	G	0.4	1740.6	0.748	0.941	575.8	0.262	0.988	241.4	0.327	0.949
45	60	A	1.6	1948.2	0.746	0.943	707.8	0.256	0.994	384.4	0.352	0.884
45	60	A	1.2	1950.0	0.746	0.942	709.4	0.256	0.995	364.1	0.345	0.900
45	60	A	0.8	1950.0	0.746	0.942	710.9	0.254	0.995	339.1	0.337	0.924
45	60	A	0.4									
Tool 5												
93	55	M	1.6									
93	55	M	1.2									
93	55	M	0.8									
93	55	M	0.4									
93	55	G	1.6	1667.2	0.748	0.942	546.9	0.263	0.986	303.9	0.363	0.866
93	55	G	1.2	1678.1	0.751	0.940	546.9	0.262	0.987	283.6	0.349	0.887
93	55	G	0.8	1675.0	0.749	0.940	546.9	0.260	0.987	267.2	0.345	0.905
93	55	G	0.4	1668.8	0.746	0.940	551.6	0.263	0.989	238.3	0.331	0.940
93	55	A	1.6	1732.8	0.748	0.942	543.0	0.261	0.987	276.6	0.355	0.872
93	55	A	1.2									
93	55	A	0.8									
93	55	A	0.4									
Tool 6												
45	90	M	1.6									
45	90	M	1.2	1839.1	0.746	0.943	637.5	0.258	0.994	321.1	0.349	0.893
45	90	M	0.8	1837.5	0.746	0.944	642.2	0.259	0.992	300.8	0.342	0.914
45	90	M	0.4									
45	90	G	1.6	1740.6	0.746	0.941	569.5	0.260	0.988	299.2	0.349	0.886
45	90	G	1.2	1740.6	0.748	0.942	571.9	0.261	0.988	286.7	0.347	0.898
45	90	G	0.8	1742.2	0.748	0.942	570.3	0.259	0.991	268.8	0.339	0.917
45	90	G	0.4	1742.2	0.748	0.942	579.7	0.262	0.987	243.8	0.331	0.948
45	90	A	1.6	1953.1	0.746	0.943	710.9	0.257	0.995	388.3	0.355	0.880
45	90	A	1.2	1954.7	0.746	0.942	718.0	0.259	0.991	364.8	0.344	0.899
45	90	A	0.8	1953.1	0.746	0.942	721.1	0.259	0.991	341.4	0.337	0.920
45	90	A	0.4									

κ	ε	C_b	r_ε	C_V	C_{V1}	C_{V2}	C_S	C_{S1}	C_{S2}	C_a	C_{a1}	C_{a2}
Tool 7												
75	90	M	1.6									
75	90	M	1.2	1787.5	0.746	0.944	639.1	0.259	0.993	308.6	0.359	0.872
75	90	M	0.8	1789.1	0.746	0.943	641.4	0.259	0.993	284.4	0.347	0.898
75	90	M	0.4									
75	90	G	1.6	1694.5	0.748	0.941	569.5	0.260	0.988	288.3	0.360	0.865
75	90	G	1.2	1690.6	0.745	0.941	572.7	0.262	0.987	276.6	0.359	0.877
75	90	G	0.8	1689.8	0.745	0.941	568.8	0.257	0.991	256.3	0.346	0.897
75	90	G	0.4	1685.9	0.745	0.941	577.3	0.261	0.988	228.1	0.333	0.934
75	90	A	1.6	1909.4	0.748	0.941	717.2	0.260	0.991	364.1	0.354	0.869
75	90	A	1.2	1907.8	0.748	0.941	712.5	0.255	0.994	349.2	0.352	0.879
75	90	A	0.8	1907.8	0.748	0.941	720.3	0.259	0.992	332.0	0.352	0.892
75	90	A	0.4									

APPENDIX D

CONTENTS OF FILE FORC.DAT

Each line of the file contains the following information:

$$\# \ \kappa \ C_b \ r_e \ \# \ C_V \ C_{V1} \ C_{V2} \ C_S \ C_{S1} \ C_{S2} \ C_a \ C_{a1} \ C_{a2} \ *$$

Data in *italics* is assumed data, which was originally missing.

#	95	M	1.2	#	1763.3	0.746	0.943	636.7	0.259	0.992	315.6	0.357	0.880	*
#	95	M	0.8	#	1765.6	0.747	0.943	641.4	0.260	0.991	289.8	0.342	0.907	*
#	95	M	0.4	#	1765.6	0.747	0.943	637.5	0.255	0.995	259.4	0.328	0.941	*
#	95	G	1.6	#	1671.9	0.748	0.940	567.2	0.260	0.987	292.2	0.353	0.873	*
#	95	G	1.2	#	1670.3	0.748	0.941	573.4	0.264	0.984	282.0	0.355	0.884	*
#	95	G	0.8	#	1665.6	0.745	0.941	571.1	0.261	0.987	261.7	0.346	0.909	*
#	95	G	0.4	#	1675.0	0.749	0.941	570.3	0.259	0.991	233.6	0.329	0.941	*
#	*95*	*A*	*1.6*	*#*	*1878.1*	*0.748*	*0.941*	*710.9*	*0.257*	*0.994*	*355.5*	*0.348*	*0.888*	*
#	95	A	1.2	#	1878.1	0.748	0.941	710.9	0.257	0.994	355.5	0.348	0.888	*
#	95	A	0.8	#	1881.3	0.748	0.941	718.0	0.260	0.992	334.4	0.343	0.906	*
#	95	A	0.4	#	1878.1	0.748	0.942	721.9	0.259	0.991	303.1	0.335	0.936	*
#	90	M	1.6	#	1771.9	0.747	0.942	635.2	0.259	0.992	321.9	0.356	0.872	*
#	90	M	1.2	#	1775.0	0.748	0.942	636.7	0.259	0.992	313.3	0.359	0.877	*
#	90	M	0.8	#	1773.4	0.748	0.942	639.8	0.260	0.993	286.7	0.342	0.903	*
#	90	M	0.4	#	1762.5	0.744	0.944	643.0	0.260	0.993	257.8	0.332	0.937	*
#	90	G	1.6	#	1675.0	0.747	0.940	568.0	0.262	0.988	289.8	0.356	0.871	*
#	90	G	1.2	#	1671.9	0.746	0.941	573.4	0.264	0.984	275.8	0.351	0.886	*
#	90	G	0.8	#	1675.0	0.748	0.941	571.9	0.264	0.989	257.8	0.342	0.904	*
#	90	G	0.4	#	1678.1	0.748	0.940	569.5	0.258	0.991	232.0	0.331	0.936	*
#	90	A	1.6	#	1884.4	0.748	0.941	709.4	0.257	0.994	368.8	0.353	0.872	*
#	90	A	1.2	#	1892.2	0.750	0.940	714.8	0.260	0.993	353.1	0.349	0.884	*
#	90	A	0.8	#	1890.6	0.749	0.940	717.2	0.259	0.992	333.6	0.348	0.902	*
#	*90*	*A*	*0.4*	*#*	*1890.6*	*0.749*	*0.940*	*717.2*	*0.259*	*0.992*	*333.6*	*0.348*	*0.902*	*
#	*75*	*M*	*1.6*	*#*	*1787.5*	*0.746*	*0.944*	*639.1*	*0.259*	*0.993*	*308.6*	*0.359*	*0.872*	*
#	75	M	1.2	#	1787.5	0.746	0.944	639.1	0.259	0.993	308.6	0.359	0.872	*
#	75	M	0.8	#	1789.1	0.746	0.943	641.4	0.259	0.993	284.4	0.347	0.898	*
#	*75*	*M*	*0.4*	*#*	*1789.1*	*0.746*	*0.943*	*641.4*	*0.259*	*0.993*	*284.4*	*0.347*	*0.898*	*
#	75	G	1.6	#	1694.5	0.748	0.941	569.5	0.260	0.988	288.3	0.360	0.865	*
#	75	G	1.2	#	1690.6	0.745	0.941	572.7	0.262	0.987	276.6	0.359	0.877	*
#	75	G	0.8	#	1689.8	0.745	0.941	568.8	0.257	0.991	256.3	0.346	0.897	*
#	75	G	0.4	#	1685.9	0.745	0.941	577.3	0.261	0.988	228.1	0.333	0.934	*
#	75	A	1.6	#	1909.4	0.748	0.941	717.2	0.260	0.991	364.1	0.354	0.869	*
#	75	A	1.2	#	1907.8	0.748	0.941	712.5	0.255	0.994	349.2	0.352	0.879	*
#	75	A	0.8	#	1907.8	0.748	0.941	720.3	0.259	0.992	332.0	0.352	0.892	*
#	*75*	*A*	*0.4*	*#*	*1907.8*	*0.748*	*0.941*	*720.3*	*0.259*	*0.992*	*332.0*	*0.352*	*0.892*	*

#	60	M	1.6	#	1815.6	0.748	0.941	635.9	0.260	0.991	322.7	0.359	0.867	*
#	60	M	1.2	#	1815.6	0.748	0.941	632.8	0.257	0.995	311.7	0.360	0.887	*
#	60	M	0.8	#	1815.6	0.748	0.941	639.8	0.260	0.992	285.2	0.343	0.902	*
#	60	M	0.4	#	1823.4	0.750	0.940	646.1	0.260	0.991	257.0	0.333	0.934	*
#	60	G	1.6	#	1712.5	0.748	0.941	565.6	0.260	0.989	290.6	0.359	0.866	*
#	60	G	1.2	#	1712.5	0.748	0.941	573.4	0.264	0.984	275.8	0.352	0.880	*
#	60	G	0.8	#	1712.5	0.748	0.941	568.0	0.259	0.990	258.6	0.349	0.902	*
#	60	G	0.4	#	1712.5	0.748	0.941	572.7	0.260	0.990	228.9	0.330	0.939	*
#	60	A	1.6	#	1917.2	0.746	0.943	712.5	0.259	0.992	365.6	0.352	0.873	*
#	60	A	1.2	#	1917.2	0.746	0.943	710.9	0.257	0.994	346.9	0.346	0.889	*
#	60	A	0.8	#	1917.2	0.746	0.943	718.8	0.260	0.991	334.4	0.349	0.895	*
#	60	A	0.4	#	1917.2	0.746	0.943	718.8	0.260	0.991	334.4	0.349	0.895	*
#	45	M	1.6	#	1837.5	0.747	0.943	641.4	0.263	0.988	334.4	0.354	0.884	*
#	45	M	1.2	#	1834.4	0.746	0.944	638.3	0.260	0.991	321.9	0.352	0.894	*
#	45	M	0.8	#	1834.4	0.747	0.945	640.6	0.260	0.992	301.6	0.345	0.914	*
#	45	M	0.4	#	1835.9	0.747	0.944	644.5	0.259	0.991	268.8	0.328	0.949	*
#	45	G	1.6	#	1737.5	0.748	0.942	567.2	0.262	0.988	300.0	0.352	0.884	*
#	45	G	1.2	#	1737.5	0.748	0.941	569.5	0.262	0.988	284.4	0.345	0.902	*
#	45	G	0.8	#	1739.1	0.748	0.941	568.8	0.260	0.990	268.0	0.339	0.917	*
#	45	G	0.4	#	1740.6	0.748	0.941	575.8	0.262	0.988	241.4	0.327	0.949	*
#	45	A	1.6	#	1948.2	0.746	0.943	707.8	0.256	0.994	384.4	0.352	0.884	*
#	45	A	1.2	#	1950.0	0.746	0.942	709.4	0.256	0.995	364.1	0.345	0.900	*
#	45	A	0.8	#	1950.0	0.746	0.942	710.9	0.254	0.995	339.1	0.337	0.924	*
#	45	A	0.4	#	1950.0	0.746	0.942	710.9	0.254	0.995	339.1	0.337	0.924	*

APPENDIX E

CONTENTS OF FILE LIFE.DAT

NON-ALLOY CARBON STEEL C < 0.5%
Seco - Guide Turning, ST884564E, 1988, p 80, TP20, Group 3
K_s = 2186 N/mm^2, Grade P 20
Data order: *V S a T*

305	0.1	1.5	15	*
295	0.2	1.5	15	*
280	0.3	1.5	15	*
265	0.3	3	15	*
235	0.4	3	15	*
180	0.6	3	15	*
150	0.8	3	15	*
240	0.3	6	15	*
210	0.4	6	15	*
165	0.6	6	15	*
135	0.8	6	15	*
230	0.3	8	15	*
205	0.4	8	15	*
160	0.6	8	15	*
130	0.8	8	15	*
262	0.1	1.5	30	*
254	0.2	1.5	30	*
241	0.3	1.5	30	*
228	0.3	3	30	*
202	0.4	3	30	*
155	0.6	3	30	*
129	0.8	3	30	*
206	0.3	6	30	*
181	0.4	6	30	*
142	0.6	6	30	*
116	0.8	6	30	*
198	0.3	8	30	*
176	0.4	8	30	*
138	0.6	8	30	*
112	0.8	8	30	*
241	0.1	1.5	45	*
233	0.2	1.5	45	*
221	0.3	1.5	45	*
209	0.3	3	45	*
186	0.4	3	45	*
142	0.6	3	45	*
119	0.8	3	45	*
190	0.3	6	45	*
166	0.4	6	45	*
130	0.6	6	45	*
107	0.8	6	45	*
182	0.3	8	45	*
162	0.4	8	45	*
126	0.6	8	45	*
103	0.8	8	45	*
226	0.1	1.5	60	*
218	0.2	1.5	60	*
207	0.3	1.5	60	*
196	0.3	3	60	*
174	0.4	3	60	*
133	0.6	3	60	*
111	0.8	3	60	*
178	0.3	6	60	*
155	0.4	6	60	*
122	0.6	6	60	*
100	0.8	6	60	*
170	0.3	8	60	*
152	0.4	8	60	*
118	0.6	8	60	*
96	0.8	8	60	*

APPENDIX F

CONTENTS OF DATA FILES AND JOB INPUT FILES

Two special characters, the hash and the asterisk ('#' and '*'), were included in the data files. In addition, in the main data file CUTD7_0.DBS and the job input file JOB[JobNumber].TXT, a colon (':') was included. Each of these characters served a purpose:

a) The hash

When the system accessed a data file, it treated the complete entry as an ASCII string. When moving along the string to retrieve the part of a string corresponding to a particular number, it counted the spaces between the numbers. However, proper names and ISO codes in a data file may have had different numbers of spaces, thus making space counting impractical. Therefore, where appropriate, the system counted hashes instead of spaces. This also allowed the system to find the ISO codes and names more simply, since it just looked between the appropriate hashes. Hashes were also used to keep similar blocks of values together, thus simplifying the search coding.

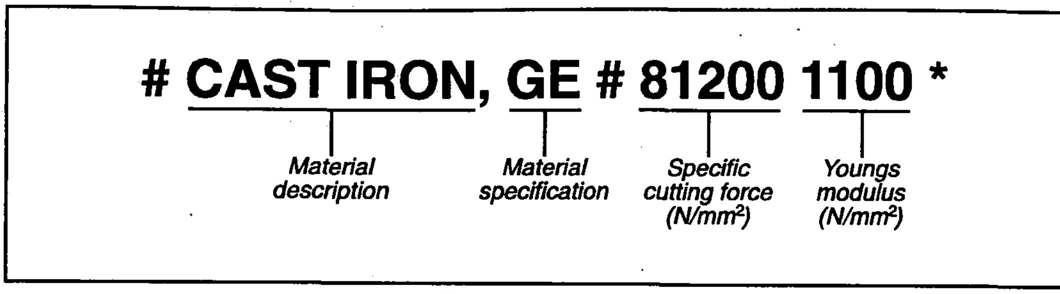
b) The asterisk

Asterisks were used for end-of-line markers. This was not strictly necessary in Turbo Pascal, since this includeed the standard library function end-of-line (eol). However, the asterisks permited programs written in other languages, which may not have included the library function end-of-line, to interrogate the data files and find the end of a line.

c) The colon

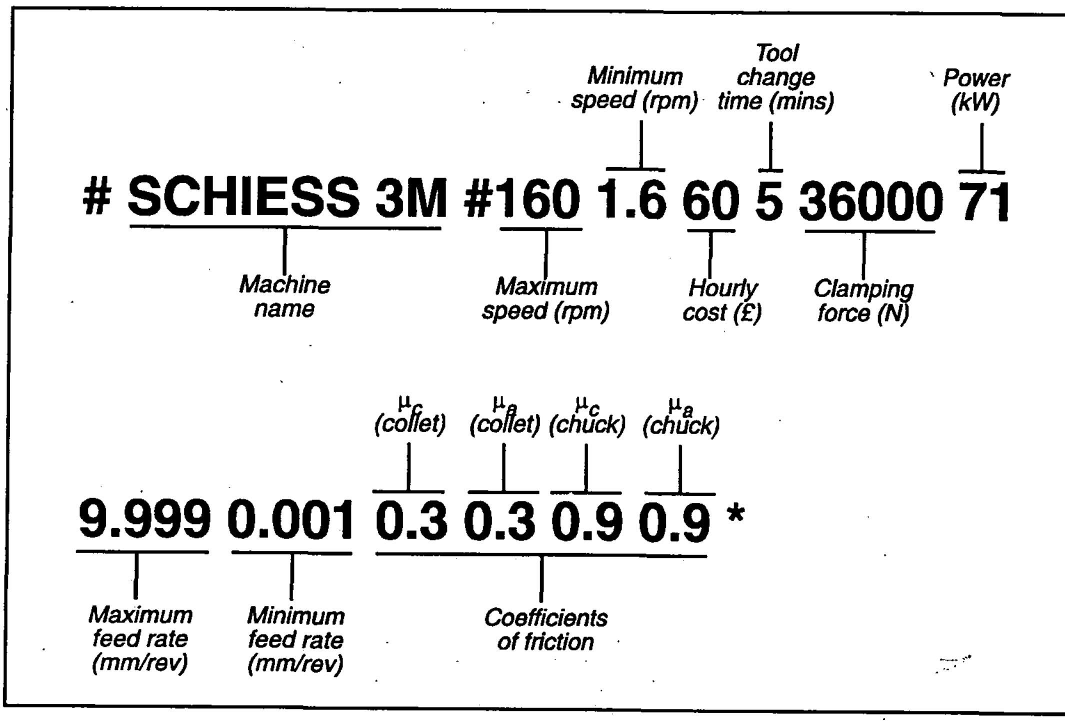
This was used to separate the insert ISO code from the ISO grade. Thus the system could separate the string into its component parts. In the job input file, the colon serveed a second function. It told the system whether the last line in the file was an insert or a holder/boring bar. In the latter case, the system then had to search the insert data file for all the suitable inserts in all grades. In addition, there may have been more than one holder/boring bar and the system would continue assembling tools for processing until it reached the end of the file. This facility is not used at present, since the output will only allow for one tool to be processed.

Note: In practice, when a data file was viewed, all parts of a record were on the same line. However, this was not true of the job input file.



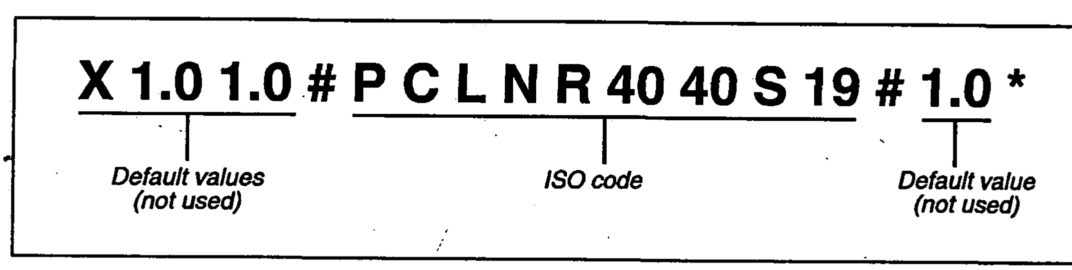
Box F.1

Typical entry in material data file, MATERIAL.DBS



Box F.2

Typical entry in machine data file, MACHINE.DBS



Box F.3

Typical entry in holder data file, HOLDER.DBS

X 1.0 1.0 # S 16 Q S C L C R 09 # 1.0 *

Default values (not used) — X 1.0 1.0
ISO code — S 16 Q S C L C R 09
Default value (not used) — 1.0

Box F.4

Typical entry in boring bar data file, BOREBAR.DBS

 # C N M G 19 06 16 # 1.0

ISO code — C N M G 19 06 16
Default value (not used) — 1.0

 # 0 15 0 # 1.0 0.75 *

P K M — 0 15 0
ISO grades — 0 15 0
Default value (not used) — 1.0
C_{le} — 0.75

Box F.5

Typical entry in insert data file, INSERT.DBS

 # R5 # SCHIESS 4M # CAST IRON, GE

Record number — R5
Machine name — SCHIESS 4M
Material description and specification — CAST IRON, GE

 # 1 0 1 0 1 0 1 0 # P C L N R 40 40 S 19

Boolean variable pairs (outside or inside diameter, roughing or finish cut, longitudinal turning or facing, continuous or intermittent cutting) — 1 0 1 0 1 0 1 0
Tool holder/boring bar ISO code — P C L N R 40 40 S 19

 # C N M G 19 06 16 : K15 # 30

Insert ISO code — C N M G 19 06 16
ISO grade — K15
Specified minimum tool life — 30

 # 123.286 1.280 9.313 # 123.2 0.6 5 T *

System data (cutting speed, feed rate and depth of cut) — 123.286 1.280 9.313
Approved data (cutting speed, feed rate, depth of cut and tool life indication) — 123.2 0.6 5 T

Box F.6

Typical entry in main data file, CUTD7_0.DBS

GE1

Job unique identifier

SCHIESS 5M

Machine name

CHUCK

Workholding

CAST IRON, GE

Material description and specification

956 850 75 580 500 20 6.4 0.1 0 1 12 850 0

Cut dimensions (component diameter in chuck/collet, component diamater before cut, length of component in chuck/collet, maximum distance from chuck/collet to tool, total length of cut, total depth of cut, surface finish, tolerance, required number of passes, batch size, work set-up time, general minimum outside diameter, general maximum inside diameter)

0 1 1 0 1 0 1 0 1 0

Boolean variable pairs (outside or inside diamater, roughing or finish cut, longitudinal turning or facing, solid or hollow component, continuous or intermittent cutting)

S 16 Q S C L C R 09

Boring bar or external holder ISO code

C N M G 19 06 16 : K15

Insert ISO code and ISO grade

Box F.7

Typical job input file, JOB[JobNumber].TXT

NOTE: The record number in file CUTD7_0.DBS (box C.6) has the same value as JobNumber in the job input file name.

APPENDIX G

DIFFICULTIES WITH INDUSTRIAL TESTING

During the testing of System 3, the following sequence of events were recorded. PM (Production Manager), PP1 and PP2 (part programmers) and AP (apprentice) were all company employees.

Date	Harkers	Reyrolle
18 May 1992		
19 May 1992		System 3 installed. PP1 trained it its use. Problem reported
20 May 1992		
21 May 1992		System 3 reinstalled
22 May 1992		
	WEEKEND	
25 May 1992	Closed for shutdown	
26 May 1992	Closed for shutdown	
27 May 1992	Closed for shutdown	
28 May 1992	Closed for shutdown	
29 May 1992	Closed for shutdown	
	WEEKEND	
1 June 1992		
2 June 1992		
3 June 1992		Advised that PP1 was off sick for at least a fortnight. Spoke to PM about problem.
4 June 1992		Visited to discuss replacement personnel with PM. Agreed that PP2 would take over from PP1.
5 June 1992	System 3 installed. AP to be trained in its use.	
	WEEKEND	
8 June 1992	AP working in different department	Visited company
9 June 1992	AP working in different department	Visited company
10 June 1992	AP at college	
11June 1992	Visited company and trained AP in use of System 3	Visited company
12 June 1992		Advised no further progress
	WEEKEND	

Date	Harkers	Reyrolle
15 June 1992	Advised that machine had broken down	
16 June 1992	Advised that machine still down	
17 June 1992	AP at college	
18 June 1992		
19 June 1992	Advised that machine being used for grooving, which was not a suitable operation for testing	Advised no suitable jobs
	WEEKEND	
22 June 1992	Advised that an unscheduled job was now on the machine	Advised that there was no operator
23 June 1992		
24 June 1992		
25 June 1992		
26 June 1992		
	WEEKEND	
29 June 1992		
30 June 1992		
1 July 1992		Details of 8 jobs entered into System 3, with 5 jobs completed
2 July 1992		
3 July 1992		
	WEEKEND	

a) After seven weeks, only five jobs had been tested completely and these were all in one company (Reyrolle).

b) There were a number of days when there appears to have be no action. However, each time contact was made with a company employee, the date for the next contact was normally agreed. Great care was taken to avoid causing unnecessary disruptions to their other work, for example by making contact too frequently.

c) With Harkers, due to the size of their components, an unscheduled job on a machine could occupy a period of several days or even weeks.

APPENDIX H

RESULTS FOR SYSTEM 3

Harkers job group 1						
Job	**Cutting speed (m/min)**		**Feed rate (mm/rev)**		**Depth of cut (mm)**	
number	**Approved**	**System 3**	**Approved**	**System 3**	**Approved**	**System 3**
1	144	196	0.80	1.28	4.50	10.70
2	139	196	0.80	1.28	7.00	10.70
3	133	196	0.80	1.28	7.00	10.70
4	128	196	0.80	1.28	7.00	10.70
5	109	196	0.80	1.28	3.00	10.70
6	190	198	0.80	1.28	5.00	9.31
7	190	199	0.80	1.28	5.00	8.89
8	190	198	0.80	1.28	5.00	9.53
9	187	198	0.80	1.28	5.00	9.53
10	183	197	0.65	1.28	4.50	10.16
11	179	200	0.65	1.28	4.00	8.26
12	137	199	0.60	1.28	4.00	8.89
13	134	196	0.50	1.28	3.00	10.58
Mean	157±18	197±1	0.74±0.06	1.28±0.00	4.92±0.83	9.89±0.53
Mean %	±11%	±0%	±8%	±0%	±17%	±5%
SD	29	1	0.10	0.00	1.37	0.87

Table H.1

Results for System 3 - Harkers job group 1

Harkers job group 2						
Job	**Cutting speed (m/min)**		**Feed rate (mm/rev)**		**Depth of cut (mm)**	
number	**Approved**	**System 3**	**Approved**	**System 3**	**Approved**	**System 3**
14	147	198	1.00	1.28	2.00	8.26
15	64	211	0.80	1.09	6.00	6.35
16	110	200	0.80	1.28	6.00	6.35
17	153	204	0.60	1.28	3.00	9.53
18	128	204	0.40	1.28	4.00	10.80
19	132	198	0.80	1.28	5.00	9.53
20	149	196	0.60	1.28	3.00	9.88
Mean	126±29	201±5	0.71±0.18	1.25±0.07	4.14±1.46	8.67±1.62
Mean %	±23%	±2%	±25%	±5%	±35%	±19%
SD	31	5	0.20	0.07	1.57	1.75

Table H.2

Results for System 3 - Harkers job group 2

Harkers job group 3						
Job	**Cutting speed (m/min)**		**Feed rate (mm/rev)**		**Depth of cut (mm)**	
number	**Approved**	**System 3**	**Approved**	**System 3**	**Approved**	**System 3**
21	142	197	1.00	1.28	2.00	10.16
22	161	204	0.80	1.28	6.00	6.35
23	115	202	0.80	1.28	5.00	7.62
24	69	204	0.80	1.28	4.50	6.35
25	148	213	0.60	1.06	3.00	10.16
26	124	204	0.40	1.28	3.50	6.35
27	132	202	0.80	1.28	4.00	7.62
Mean	127±28	203±4	0.74±0.18	1.25±0.08	4.00±1.22	7.80±1.58
Mean %	±22%	±2%	±24%	±6%	±31%	±20%
SD	30	5	0.19	0.08	1.32	1.71

Table H.3

Results for System 3 - Harkers job group 3

Harkers job group 4						
Job	**Cutting speed (m/min)**		**Feed rate (mm/rev)**		**Depth of cut (mm)**	
number	**Approved**	**System 3**	**Approved**	**System 3**	**Approved**	**System 3**
28	121	198	1.00	1.28	7.00	9.31
29	121	199	0.10	1.28	6.00	8.89
30	103	198	0.65	1.28	9.00	9.53
31	119	198	1.00	1.28	6.00	9.53
32	117	197	1.00	1.28	8.00	10.16
33	114	200	1.00	1.28	8.00	8.26
34	110	199	1.00	1.28	10.00	8.89
35	113	196	0.80	1.28	8.00	10.58
36	95	204	0.40	1.28	5.00	6.35
37	94	204	0.30	1.28	5.00	6.35
38	152	204	0.40	1.28	5.50	6.35
39	91	204	0.30	1.28	5.00	6.35
40	149	204	0.40	1.28	5.00	6.35
41	85	204	0.30	1.28	5.00	6.35
42	90	204	0.30	1.28	5.00	6.35
43	87	204	0.30	1.28	5.00	6.35
44	148	216	0.80	1.01	5.00	10.67
45	136	205	0.25	1.18	3.00	9.14
46	148	196	0.80	1.28	5.00	10.63
Mean	115±11	202±2	0.58±0.15	1.26±0.03	6.08±0.85	8.23±0.85
Mean %	±10%	±1%	±27%	±2%	±14%	±10%
SD	23	5	0.32	0.07	1.77	1.76

Table H.4

Results for System 3 - Harkers job group 4

Harkers job group 5						
Job	Cutting speed (m/min)		Feed rate (mm/rev)		Depth of cut (mm)	
number	Approved	System 3	Approved	System 3	Approved	System 3
47	99	99	0.80	1.28	5.00	6.35
48	136	136	0.70	1.28	5.00	8.89
49	126	186	1.00	1.28	5.50	6.35
50	126	185	1.00	1.28	5.50	6.35
51	121	178	1.00	1.28	5.50	6.35
52	119	175	1.00	1.28	5.50	6.35
53	114	167	1.00	1.28	5.50	6.35
54	120	176	1.00	1.28	5.50	6.35
55	116	171	1.00	1.28	5.50	6.35
56	116	120	0.40	1.28	2.00	5.08
57	120	120	0.45	1.28	3.50	6.35
Mean	119±6	156±21	0.85±0.16	1.28±00	4.91±0.76	6.47±0.60
Mean %	±5%	±13%	±18%	±00%	±16%	±9%
SD	9	31	0.23	0.00	1.14	0.89

Table H.5

Results for System 3 - Harkers job group 5

Reyrolle job group A						
Job	Cutting speed (m/min)		Feed rate (mm/rev)		Depth of cut (mm)	
number	Approved	System 3	Approved	System 3	Approved	System 3
1	264	228	0.20	0.20	1.00	1.00
2	264	228	0.20	0.20	1.00	1.00
3	251	227	0.20	0.20	1.05	1.05
4	150	227	0.30	0.20	1.10	1.10
5	330	228	0.26	0.20	1.00	1.00
6	370	228	0.26	0.20	1.00	1.00
7	408	228	0.22	0.20	1.00	1.00
8	332	228	0.22	0.20	1.00	1.00
Mean	296±68	228±0	0.23±0.03	0.20±0.00	1.02±0.03	1.02±0.03
Mean %	±23%	±0%	±13%	±0%	±3%	±3%
SD	81	0	0.04	0.00	0.04	0.04

Table H.6

Results for System 3 - Reyrolle job group A

Reyrolle job group B						
Job	**Cutting speed (m/min)**		**Feed rate (mm/rev)**		**Depth of cut (mm)**	
number	**Approved**	**System 3**	**Approved**	**System 3**	**Approved**	**System 3**
9	243	208	0.20	0.20	3.50	3.50
10	224	193	0.28	0.28	1.50	1.50
11	251	217	0.25	0.20	2.00	2.00
12	190	186	0.30	0.28	2.50	2.50
13	312	184	0.30	0.28	3.00	3.00
14	219	185	0.29	0.28	2.75	2.75
15	305	180	0.29	0.28	4.00	4.00
16	259	186	0.30	0.28	2.50	2.50
Mean	250±35	192±11	0.28±0.03	0.26±0.03	2.72±0.67	2.72±0.67
Mean %	±14%	±6%	±11%	±12%	±24%	±24%
SD	42	13	0.03	0.04	0.80	0.80

Table H.7

Results for System 3 - Reyrolle job group B

Reyrolle job group C						
Job	**Cutting speed (m/min)**		**Feed rate (mm/rev)**		**Depth of cut (mm)**	
number	**Approved**	**System 3**	**Approved**	**System 3**	**Approved**	**System 3**
17	231	197	0.20	0.20	3.50	7.00
18	219	189	0.28	0.28	2.00	2.00
19	219	189	0.28	0.28	2.00	2.00
20	330	199	0.30	0.28	1.00	1.00
21	330	189	0.28	0.28	2.00	2.00
22	328	189	0.29	0.28	1.82	2.00
23	267	189	0.30	0.28	1.82	2.00
Mean	275±49	192±4	0.28±0.03	0.27±0.03	2.02±0.69	2.57±1.84
Mean %	±18%	±2%	±12%	±10%	±34%	±71%
SD	53	4	0.03	0.03	0.74	1.99

Table H.8

Results for System 3 - Reyrolle job group C

APPENDIX I

ALTERNATIVE DATA CORRECTION METHODS

REGRESSION ANALYSIS

As an alternative to the mean and standard deviation correction method in chapter 8, at one stage regression analysis was assessed as a method for correcting the data. This was based on the assumption that there was a relationship between the corrected system data and the associated approved data for jobs from the same job group i.e. jobs with similar attributes. It was further assumed that the relationship was either linear or exponential.

In either case, the relationship was expressed in terms of a regression line. The assumed relationship was such that, for a specific parameter, if the two sets of data were plotted on a graph, a regression line could be drawn through the points and could be used to modify future values of system data. It should be noted that it was this method of data correction which was in use when the data in chapter 7 was collected from Reyrolle.

It would have been more usual to have used uncorrected data, in preference to corrected data. However, it was further assumed that there was a constant error between the uncorrected system data and the approved data[1]. By using the corrected data for the regression relationship, it was hoped to reduce the magnitude of the error as the number of jobs increased.

If regression analysis was not possible for the data, then the uncorrected data was used in its place. In practice, there were four possible graphs which could result

---

[1] A reasonably steady error was in fact observed in graphs 7.1 - 7.3 (chapter 7), and was implicit in the mean and standard deviation correction method in chapter 8.

from plotting approved data against corrected system data, where the corrected data may be replaced by uncorrected data, as just described. These four situations are shown in figure I.1 and can be described as:

i) Slope

This was the ideal situation, where data correction could take place. The approved data had sufficient different values, as did the system data. In this case, corrected data was used.

ii) Horizontal

Since the approved data only had a single value, regression was not possible and hence the uncorrected data was used.

iii) Vertical

Although the approved data had more than one value, the corresponding system data only had a single value. Again, the uncorrected data was used and regression was not possible.

iv) Undefined

The approved data had only a single value, as did the system data. Regression was not possible and hence the uncorrected data was used.

In the case of ii), iii) and iv) regression was not possible until the graph formed a slope i.e. until both sets of data had a sufficient number of different points to permit regression to take place.

Of the four graphs in figure I.1, the only one which could be used for data correction was the Slope. If any of the other graphs occurred, correction of the data was not possible. Under these circumstances, either the trend in the data had to change, or the data altered to produce a slope, before the data could be corrected. It was considered that this was not satisfactory.

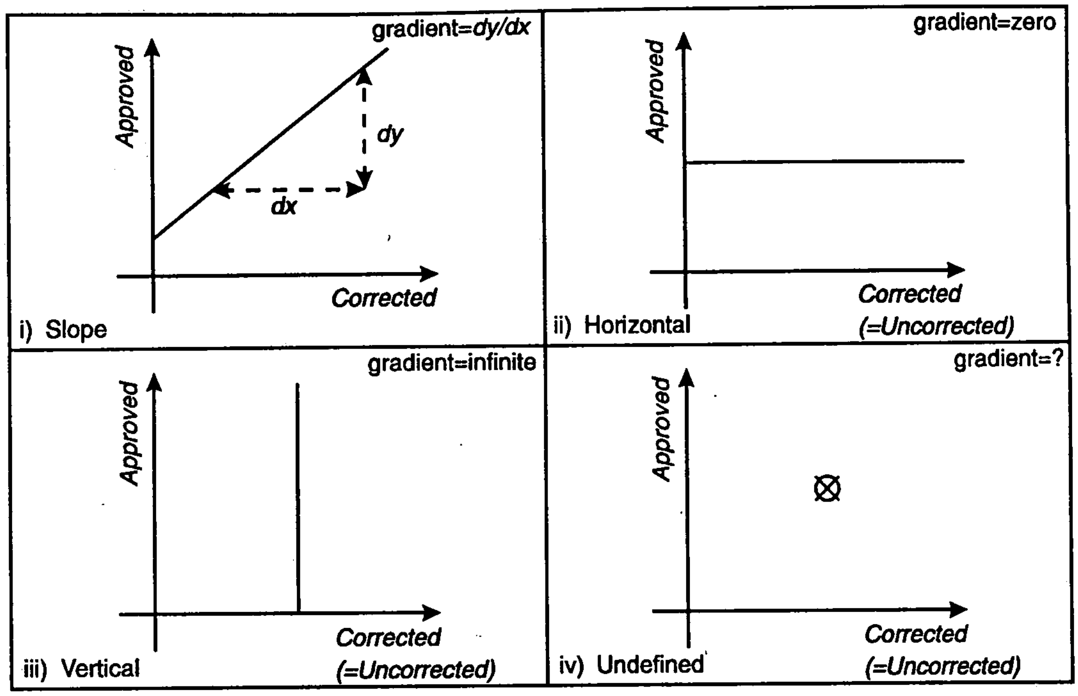


Figure I.1

Types of regression graphs

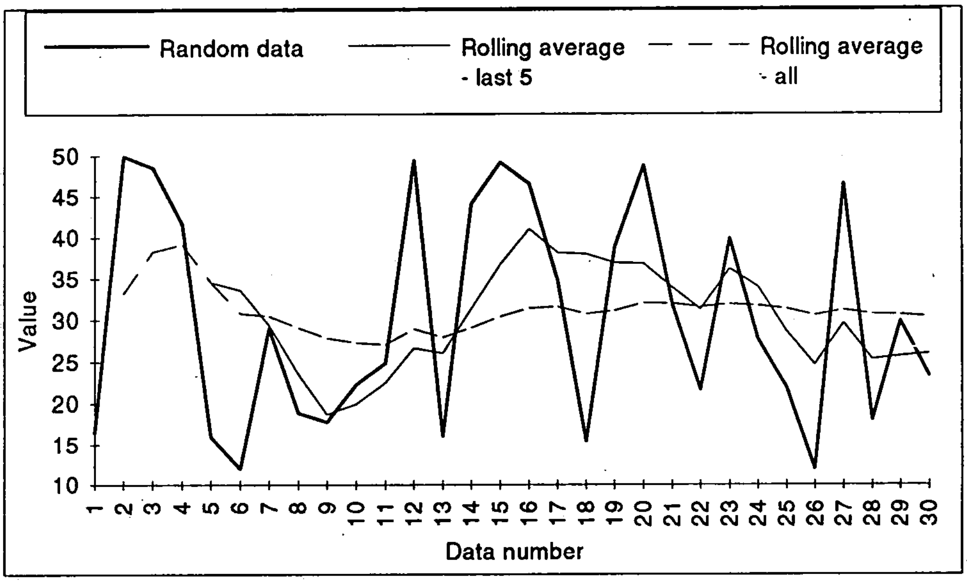
Again, to try to reduce the size of the error, corrected values of feed rate and depth of cut were used to calculate the required cutting speed. It was found that the results were extremely sensitive to the order in which jobs were processed. For one job group, it was found that for a certain order of jobs, a number of tools were rejected as technically unable to achieve the cut. When the order was changed, these tools became acceptable to the system.

ROLLING AVERAGE

The mean and standard deviation correction method (chapter 8) relied upon, amongst other factors, the rolling average of the approved data. In the circumstances, it might have seemed reasonable simply to use the rolling average of the approved data to provide suitable data for the job in question. There were two reasons why this was not found to be appropriate:

1) As the sample size increased, so the rolling average tended to smooth out any irregularities due to extreme data i.e. substantially larger or smaller than the mean. Consequently, the standard deviation of the rolling average was

significantly smaller than the standard deviation of the sample on which the rolling average was based. This is shown in graph I.1, where thirty random number between 10 and 50 were generated. Two rolling averages were then plotted: using all the points and the last five points. The reduction in standard deviations for the two rolling average plots can be seen quite clearly.



Graph I.1
Smoothing effect of the rolling average

2) By using the mean and standard deviation correction method in chapter 8, characteristics of the current job were included in the calculation. This would not be the case if the approved rolling average was used by itself.

APPENDIX J

RESULTS FOR SYSTEM 3 AND CORRECTED DATA

Harkers job group 1									
Job number	**Cutting speed (m/min)**			**Feed rate (mm/rev)**			**Depth of cut (mm)**		
	App	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**
1	144	196		0.80	1.28		4.50	10.70	
2	139	196		0.80	1.28		7.00	10.70	
3	133	196	140	0.80	1.28	0.80	7.00	10.70	6.38
4	128	196	136	0.80	1.28	0.80	7.00	10.70	6.63
5	109	196	132	0.80	1.28	0.80	3.00	10.70	6.71
6	190	198	120	0.80	1.28	0.80	5.00	9.31	4.18
7	190	199	159	0.80	1.28	0.80	5.00	8.89	3.97
8	190	198	187	0.80	1.28	0.80	5.00	9.53	4.82
9	187	198	197	0.80	1.28	0.80	5.00	9.53	4.83
10	183	197	195	0.65	1.28	0.80	4.50	10.16	5.52
11	179	200	199	0.65	1.28	0.66	4.00	8.26	3.48
12	137	199	192	0.60	1.28	0.64	4.00	8.89	4.12
13	134	196	176	0.50	1.28	0.60	3.00	10.58	5.72
Mean	157 ±18	197 ±1	167 ±20	0.74 ±0.06	1.28 ±0.00	0.75 ±0.05	4.92 ±0.83	9.89 ±0.53	5.12 ±0.76
Mean %	±11%	±0%	±12%	±8%	±0%	±7%	±17%	±5%	±15%
SD	29	1	30	0.10	0.00	0.08	1.37	0.87	1.14

Table J.1

Results for System 3 and corrected data - Harkers job group 1

Harkers job group 2									
Job number	Cutting speed (m/min)			Feed rate (mm/rev)			Depth of cut (mm)		
	App	Sys 3	Correct	App	Sys 3	Correct	App	Sys 3	Correct
14	147	198		1.00	1.28		2.00	8.26	
15	64	211		0.80	1.09		6.00	6.35	
16	110	200	88	0.80	1.28	1.01	6.00	6.35	4.51
17	153	204	101	0.60	1.28	0.91	3.00	9.53	6.24
18	128	204	117	0.40	1.28	0.74	4.00	10.80	5.86
19	132	198	114	0.80	1.28	0.55	5.00	9.53	4.81
20	149	196	117	0.60	1.28	0.63	3.00	9.88	5.01
Mean	126 ±29	201 ±5	108 ±16	0.71 ±0.18	1.25 ±0.07	0.77 ±0.24	4.14 ±1.46	8.67 ±1.62	5.29 ±0.91
Mean %	±23%	±2%	±14%	±25%	±5%	±31%	±35%	±19%	±17%
SD	31	5	13	0.20	0.07	0.19	1.57	1.75	0.73

Table J.2

Results for System 3 and corrected data - Harkers job group 2

Harkers job group 3									
Job number	Cutting speed (m/min)			Feed rate (mm/rev)			Depth of cut (mm)		
	App	Sys 3	Correct	App	Sys 3	Correct	App	Sys 3	Correct
21	142	197		1.00	1.28		2.00	10.16	
22	161	204		0.80	1.28		6.00	6.35	
23	115	202	159	0.80	1.28	0.85	5.00	7.62	4.47
24	69	204	124	0.80	1.28	0.83	4.50	6.35	3.77
25	148	213	89	0.60	1.06	0.73	3.00	10.16	5.62
26	124	204	99	0.40	1.28	0.82	3.50	6.35	3.21
27	132	202	104	0.80	1.28	0.67	4.00	7.62	3.89
Mean	127 ±28	203 ±4	115 ±35	0.74 ±0.18	1.25 ±0.08	0.78 ±0.09	4.00 ±1.22	7.80 ±1.58	4.19 ±1.14
Mean %	±22%	±2%	±30%	±24%	±6%	±12%	±31%	±20%	±27%
SD	30	5	28	0.19	0.08	0.08	1.32	1.71	0.92

Table J.3

Results for System 3 and corrected data - Harkers job group 3

Harkers job group 4									
Job	**Cutting speed (m/min)**			**Feed rate (mm/rev)**			**Depth of cut (mm)**		
number	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**
28	121	198		1.00	1.28		7.00	9.31	
29	121	199		0.10	1.28		6.00	8.89	
30	103	198	121	0.65	1.28	0.33	9.00	9.53	7.24
31	119	198	107	1.00	1.28	0.48	6.00	9.53	8.76
32	117	197	111	1.00	1.28	0.67	8.00	10.16	8.50
33	114	200	117	1.00	1.28	0.79	8.00	8.26	5.39
34	110	199	114	1.00	1.28	0.87	10.00	8.89	7.07
35	113	196	110	0.80	1.28	0.92	8.00	10.58	10.06
36	95	204	119	0.40	1.28	0.90	5.00	6.35	4.70
37	94	204	112	0.30	1.28	0.80	5.00	6.35	4.63
38	152	204	105	0.40	1.28	0.68	5.50	6.35	4.63
39	91	204	118	0.30	1.28	0.61	5.00	6.35	4.74
40	149	204	105	0.40	1.28	0.52	5.00	6.35	4.74
41	85	204	122	0.30	1.28	0.48	5.00	6.35	4.74
42	90	204	104	0.30	1.28	0.42	5.00	6.35	4.75
43	87	204	93	0.30	1.28	0.38	5.00	6.35	4.76
44	148	216	130	0.80	1.01	0.08	5.00	10.67	9.34
45	136	205	96	0.25	1.18	0.34	3.00	9.14	7.43
46	148	196	71	0.80	1.28	0.43	5.00	10.63	8.64
Mean	115 ±11	202 ±2	109 ±7	0.58 ±0.15	1.26 ±0.03	0.57 ±0.12	6.08 ±0.85	8.23 ±0.85	6.48 ±1.02
Mean %	±10%	±1%	±6%	±27%	±2%	±21%	±14%	±10%	±16%
SD	23	5	14	0.32	0.07	0.24	1.77	1.76	1.99

Table J.4

Results for System 3 and corrected data - Harkers job group 4

Harkers job group 5									
Job	**Cutting speed (m/min)**			**Feed rate (mm/rev)**			**Depth of cut (mm)**		
number	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**
47	99	99		0.80	1.28		5.00	6.35	
48	136	136		0.70	1.28		5.00	8.89	
49	126	186	179	1.00	1.28	0.72	5.50	6.35	7.00
50	126	185	159	1.00	1.28	0.94	5.50	6.35	5.11
51	121	178	147	1.00	1.28	0.99	5.50	6.35	5.04
52	119	175	141	1.00	1.28	0.99	5.50	6.35	5.04
53	114	167	136	1.00	1.28	0.99	5.50	6.35	5.05
54	120	176	137	1.00	1.28	0.99	5.50	6.35	5.07
55	116	171	134	1.00	1.28	0.99	5.50	6.35	5.09
56	116	120	118	0.40	1.28	0.99	2.00	5.08	4.75
57	120	120	118	0.45	1.28	0.92	3.50	6.35	4.95
Mean	119 ±6	156 ±21	141 ±15	0.85 ±0.16	1.28 ±00	0.95 ±0.07	4.91 ±0.76	6.47 ±0.60	5.23 ±0.50
Mean %	±5%	±13%	±10%	±18%	±00%	±7%	±16%	±9%	±10%
SD	9	31	19	0.23	0.00	0.09	1.14	0.89	0.67

Table J.5

Results for System 3 and corrected data - Harkers job group 5

Reyrolle job group A									
Job	**Cutting speed (m/min)**			**Feed rate (mm/rev)**			**Depth of cut (mm)**		
number	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**	**App**	**Sys 3**	**Correct**
1	264	228		0.20	0.20		1.00	1.00	
2	264	228		0.20	0.20		1.00	1.00	
3	251	227	263	0.20	0.20	0.20	1.05	1.05	1.00
4	150	227	253	0.30	0.20	0.20	1.10	1.10	1.08
5	330	228	173	0.26	0.20	0.28	1.00	1.00	1.00
6	370	228	245	0.26	0.20	0.27	1.00	1.00	1.00
7	408	228	339	0.22	0.20	0.27	1.00	1.00	1.00
8	332	228	403	0.22	0.20	0.25	1.00	1.00	1.00
Mean	296 ±68	228 ±0	279 ±85	0.23 ±0.03	0.20 ±0.00	0.24 ±0.04	1.02 ±0.03	1.02 ±0.03	1.01 ±0.03
Mean %	±23%	±0%	±30%	±13%	±0%	±15%	±3%	±3%	±3%
SD	81	0	81	0.04	0.00	0.04	0.04	0.04	0.04

Table J.6

Results for System 3 and corrected data - Reyrolle job group A

Reyrolle job group B									
Job number	Cutting speed (m/min)			Feed rate (mm/rev)			Depth of cut (mm)		
	App	Sys 3	Correct	App	Sys 3	Correct	App	Sys 3	Correct
9	243	208		0.20	0.20		3.50	3.50	
10	224	193		0.28	0.28		1.50	1.50	
11	251	217	249	0.25	0.20	0.20	2.00	2.00	2.75
12	190	186	220	0.30	0.28	0.29	2.50	2.50	3.04
13	312	184	201	0.30	0.28	0.30	3.00	3.00	3.24
14	219	185	232	0.29	0.28	0.30	2.75	2.75	2.88
15	305	180	213	0.29	0.28	0.30	4.00	4.00	3.76
16	259	186	265	0.30	0.28	0.30	2.50	2.50	2.49
Mean	250 ±35	192 ±11	230 ±25	0.28 ±0.03	0.26 ±0.03	0.28 ±0.05	2.72 ±0.67	2.72 ±0.67	3.03 ±0.46
Mean %	±14%	±6%	±11%	±11%	±12%	±18%	±24%	±24%	±15%
SD	42	13	24	0.03	0.04	0.04	0.80	0.80	0.44

Table J.7

Results for System 3 and corrected data - Reyrolle job group B

Reyrolle job group C									
Job number	Cutting speed (m/min)			Feed rate (mm/rev)			Depth of cut (mm)		
	App	Sys 3	Correct	App	Sys 3	Correct	App	Sys 3	Correct
17	231	197		0.20	0.20		3.50	7.00	
18	219	189		0.28	0.28		2.00	2.00	
19	219	189	215	0.28	0.28	0.28	2.00	2.00	1.86
20	330	199	232	0.30	0.28	0.28	1.00	1.00	0.06
21	330	189	301	0.28	0.28	0.35	2.00	2.00	2.18
22	328	189	323	0.29	0.28	0.32	1.82	2.00	2.07
23	267	189	325	0.30	0.28	0.31	1.82	2.00	1.98
Mean	275 ±49	192 ±4	279 ±64	0.28 ±0.03	0.27 ±0.03	0.31 ±0.04	2.02 ±0.69	2.57 ±1.84	1.63 ±1.10
Mean %	±18%	±2%	±23%	±12%	±10%	±11%	±34%	±71%	±68%
SD	53	4	52	0.03	0.03	0.03	0.74	1.99	0.89

Table J.8

Results for System 3 and corrected data - Reyrolle job group C

APPENDIX K

EXPERIMENT TO TEST THE RATIO OF CUTTING FORCES

K.1 INTRODUCTION

In section 6.2.1 it was hypothesised that the ratios between the three cutting forces F_V, F_S and F_a would be approximately constant for a specific tool, irrespective of the material being cut i.e.:

$$\frac{F_{V(material\ 1)}}{F_{S(material\ 1)}} \cong \frac{F_{V(material\ 2)}}{F_{S(material\ 2)}} \qquad \text{Equ K.1}$$

$$\frac{F_{V(material\ 1)}}{F_{a(material\ 1)}} \cong \frac{F_{V(material\ 2)}}{F_{a(material\ 2)}} \qquad \text{Equ K.2}$$

(equations 6.4 - 6.5, section 6.2.1)

This hypothesis was based on the assumption that, for a specific cut, the magnitude of the resultant force was governed by the material, while the direction of the resultant was decided by the tool geometry. The tool geometry also governed how the resultant force was distributed in the x, y and z directions. It was considered necessary to test this hypothesis and therefore an experiment was arranged.

Wherever possible, it was considered desirable for the combination of factors in each test to be as close as possible to what might be termed "standard conditions". In this context, "standard conditions" should be taken to mean that the combinations of tool, material and cutting conditions would be those that might reasonably be chosen on a shop floor, based on published information such as tool manufacturer's recommendations and other reference sources e.g. Metcut (1972). In practice, this was not essential, since the objective of this thesis was for any combination, recommended or not, to be considered for tool selection purposes.

K.2 OBJECTIVES

The objective of the experiment was primarily to test whether, for a range of materials being machined with geometrically identical tools at a specified feed rate S and depth of cut a and with other factors remaining constant, the ratio between the cutting forces (F_V/F_S and F_V/F_a) would remain approximately constant.

K.3 EXPERIMENTAL DESIGN

There were a number of factors to consider i.e.:

1) tools,
2) materials,
3) machine tool,
4) cutting conditions,
5) cutting fluid.

However, two of these (machine tool and cutting fluid) were eliminated by means of blocking. Using more than one machine tool may or may not have influenced the results. However, to ensure that this was not the case, all tests were carried out on the same machine.

Cutting fluid had the potential to influence the tests, by altering the fluid attributes such as direction, aiming point and flow rate. However, not using cutting fluid could also influence the outcome, since tools might be more prone to built up edges (which effectively alters the tool geometry) or premature failure if the cuts were dry. In the event, it was found that the cuts were satisfactory without cutting fluid and hence the tests were conducted dry.

The remaining three factors were each defined by one or more attributes e.g.:

Factor	**Attributes**
Tools	1. Geometry e.g. approach angle κ, included angle ε, nose radius r_e
	2. Chipbreaker type C_b
	3. ISO carbide grade

Materials	1. Mechanical properties e.g. yield strength, hardness, Young's modulus E 2. Machinability e.g. specific cutting force K_s, typical tool life T
Cutting conditions[1]	1. Feed rate S 2. Depth of cut a or 1. Roughing cut 2. Semi-roughing cut 3. Finish cut

It will be seen that the potential number of levels for each factor was extremely large. It was unrealistic to test all combinations of all factors and hence the number of levels of each factor was limited to a maximum of three. It was considered that whilst this would not definitely prove the force ratio hypothesis, it would certainly indicate whether there was any basis for the hypothesis or not. With three factors, two of them with three levels (cutting conditions and materials) and two levels for the third factor (tools), eighteen cutting test results were required, as summarised in table K.1.

	Material 1	**Material 2**	**Material 3**
Tool 1	1. Roughing cut 2. Semi-rough cut 3. Finish cut	1. Roughing cut 2. Semi-rough cut 3. Finish cut	1. Roughing cut 2. Semi-rough cut 3. Finish cut
Tool 2	1. Roughing cut 2. Semi-rough cut 3. Finish cut	1. Roughing cut 2. Semi-rough cut 3. Finish cut	1. Roughing cut 2. Semi-rough cut 3. Finish cut

Table K.1

Summary of cutting tests

Such an experiment is a $3 \times 3 \times 2$ factorial design. Each test can be designated *ABC*, where *A* represents the material level, *B* represents the tool level and *C* represents the cutting conditions level. This notation is summarised in figure K.1. In terms of the objectives, it was expected to show that the same force ratios applied for *xBC*

[1] The reason why the cutting speed V was not considered was because cutting forces were a function of feed rate and depth of cut only (section K.4).

tests, where x represented the change in the material, for a fixed tool B and cutting conditions C.

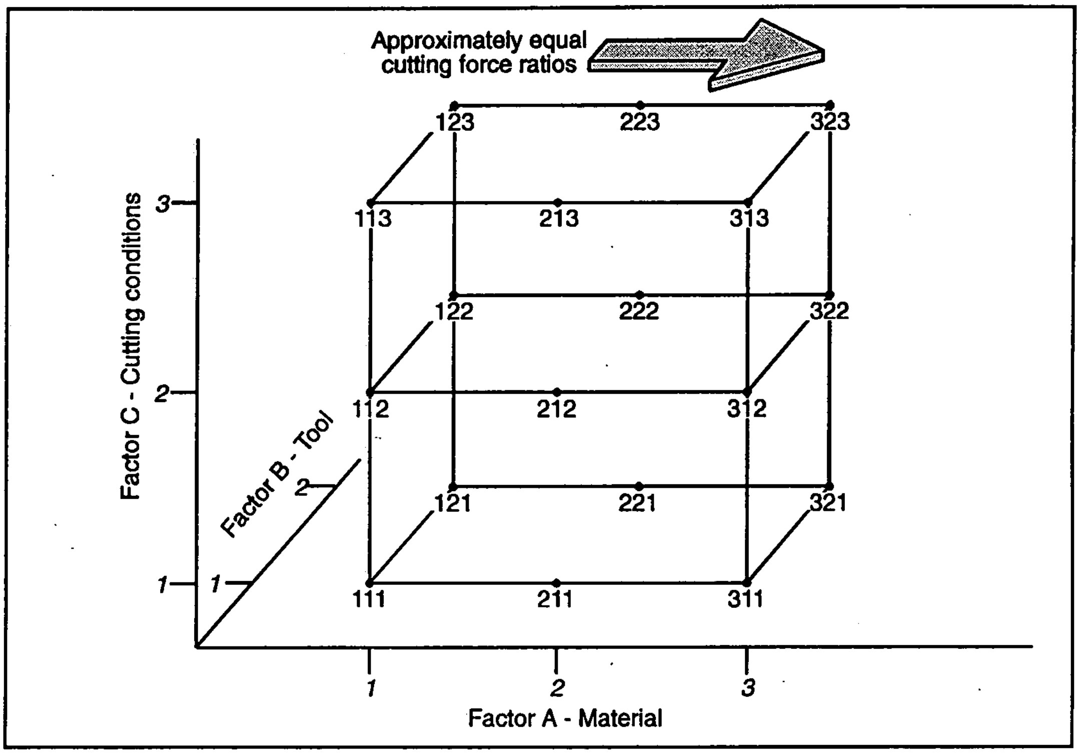


Figure K.1

Designation of factor levels and test numbers (based on Montgomery (1991))

K.4 FACTOR DESIGN

The test pieces (material) had to meet a number of requirements:

1) they had to be rigid when being cut,

2) they had to have a reasonably homogeneous structure e.g. no mill scale, hard skin, etc.,

In selecting the tools and cutting conditions, a number of criteria had to be met:

1) All tools had to be capable of both roughing and finishing cuts. This meant that inserts had to have a reasonable included or plan angle to ensure that they did not fail during the roughing cuts.

2) Each set of cutting conditions had to be reasonable for all of the

tool/material combinations. In this case, "reasonable" was taken to refer to tool life. Since tools were not specifically tested to failure, to ensure that this criteria was met, all cutting conditions selections were guided by tool manufacturer's catalogues recommendations.

3) Tools should not fail nor show significant wear during a test, since a worn tool would result in different cutting forces, compared to an unworn tool.

4) Each tool, including the insert ISO grade, had to be capable of machining all three materials.

5) The insert nose radius had to be suitable for both finishing and roughing cuts.

6) Tools had to be sufficiently rigid to eliminate the effects of vibration.

The two ISO tools and corresponding inserts chosen are shown in table K.2.

Attribute	**Tool 1**	**Tool 2**
Manufacturer	Sandvik Coromant	Sandvik Coromant
Holder ISO code	PCLNR 1616H12-M	PTGNR 1616H16
Insert ISO code	CNMA 120408	TNMA 160408
Insert shape	Diamond	Triangular
Approach angle κ	95°	90°
Included angle ε	80°	60°
ISO Chipbreaker/fixing C_b	A	A
Insert size	12 mm	16 mm
Nose radius r_e	0.8 mm	0.8 mm
Insert grade	Sandvik GC4015	Sandvik GC4015
Chipbreaker design	None	None
Holder shank size*	16 mm×16 mm	16 mm×16 mm
Overall tool length	100 mm	100 mm
**The actual shank size required for the dynamometer was 3/4"×3/4". The nearest standard metric size that would fit was 16mm× 16mm.*		

Table K.2
Details of tools

The three materials were chosen to have a variety of mechanical and machining properties, whilst capable of being machined with the same cutting speed. Details of the three materials used are shown in table K.3.

	Material 1	Material 2	Material 3
BS970 1955	EN1A	EN8	EN16
BS970 Part 1 1971	230M07	080M40	605M36
Description	Leadbearing freecutting non-alloy steel	Medium tensile steel	Manganese molybdenum alloy steel
Condition supplied	Bright drawn bar	Bright drawn bar	Bright bar, hardened and tempered in S condition
Hardness	See table K.6	See table K.6	See table K.6
Relative machinability index*	150 approx.	45 approx.	29 approx.
**Macreadys (1990)*			

Table K.3
Details of materials

The three cutting conditions were selected to represent a roughing, a semi-roughing and a finish cut. Each set of cutting conditions had to be suitable for each tool with each material. The cutting speed was kept constant for all three sets of cutting conditions. This was because from equations B.6 - B.8 (appendix B) and 6.1 - 6.3 (section 6.2.1) the cutting forces were a function of feed rate and depth of cut only i.e. $F_V,\ F_S,\ F_a = f(S,\ a)$. The details of the three cuts are shown in table K.4.

	Cut 1	Cut 2	Cut 3
Type of cut	Roughing cut	Semi-roughing cut	Finish cut
Cutting speed, *V* (m/min)	58.4	58.4	58.4
Rotational speed, *n* (rpm)	310	310	310
Feed rate, *S* (mm/rev)	0.28	0.2	0.14
Depth of cut, *a* (mm)	3.5	2.5	1.5

Table K.4
Details of cuts

K.5 EQUIPMENT

The equipment used for the tests was:

1) Dean Smith and Grace lathe type 17, serial no. 34176-6-62
2) Kistler three component piezoelectric measuring platform type 9257A, serial no. 58776
3) Kistler 3 channel amplifier assembly type 5801, serial no. 17706, consisting of three Kistler charge amplifiers type 5001 and three Kistler galvo amplifiers type 5211
4) Southern Instruments UV recorder type M1300, serial no. 858

The UV recorder was able to record all three axes simultaneously.

K.6 PREPARATION

Each specimen was a solid bar 60 mm diameter, faced off to 150 mm long and uniquely numbered. All specimens of each material were cut from the same bar, which ensured reasonable uniformity of structure and composition. To confirm that each material was different, each specimen was hardness tested using the Rockwell "B" (HRB)[1] method at the centre of the end-face, which effectively gave a number of readings along the centre-line of the bar from which the material was cut.

Each specimen was held in a chuck at one end but, due to the physical constraints of the test rig, it was not possible to support the free end with a centre. Each specimen was used for a roughing, semi-roughing and a finish cut with a single tool type (figure K.2). Therefore each replication required two specimens of each material i.e. one for each tool. Eight specimens of each material were prepared, thus allowing two spares of each.

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[1] It had been intended to hardness test the surfaces of the specimens as well. However, the Rockwell method is only suitable for flat surfaces.

Randomisation of the tests was achieved in two stages:

1) The order of the specimens within each material type was randomised independently, selecting six out of each set of eight specimens,

2) The tool/material order was randomised and material specimens allocated from their randomised order.

This process was repeated for each replication. The randomised test details are shown in table K.5.

Test	Cut type	Tool	Mat'l	Specimen	Test	Cut type	Tool	Mat'l	Specimen
Replication 1									
1	Rough	2	1	4	**10**	Rough	1	1	8
	Semi-rough	2	1	4		Semi-rough	1	1	8
	Finish	2	1	4		Finish	1	1	8
2	Rough	2	3	5	**11**	Rough	2	3	4
	Semi-rough	2	3	5		Semi-rough	2	3	4
	Finish	2	3	5		Finish	2	3	4
3	Rough	1	3	3	**12**	Rough	1	2	6
	Semi-rough	1	3	3		Semi-rough	1	2	6
	Finish	1	3	3		Finish	1	2	6
4	Rough	1	2	4	**Replication 3**				
	Semi-rough	1	2	4	**13**	Rough	2	2	7
	Finish	1	2	4		Semi-rough	2	2	7
5	Rough	2	2	8		Finish	2	2	7
	Semi-rough	2	2	8	**14**	Rough	1	2	2
	Finish	2	2	8		Semi-rough	1	2	2
6	Rough	1	1	1		Finish	1	2	2
	Semi-rough	1	1	1	**15**	Rough	1	1	6
	Finish	1	1	1		Semi-rough	1	1	6
Replication 2						Finish	1	1	6
7	Rough	2	2	3	**16**	Rough	1	3	1
	Semi-rough	2	2	3		Semi-rough	1	3	1
	Finish	2	2	3		Finish	1	3	1
8	Rough	2	1	3	**17**	Rough	2	3	2
	Semi-rough	2	1	3		Semi-rough	2	3	2
	Finish	2	1	3		Finish	2	3	2
9	Rough	1	3	8	**18**	Rough	2	1	7
	Semi-rough	1	3	8		Semi-rough	2	1	7
	Finish	1	3	8		Finish	2	1	7

Table K.5

Randomised details of cutting tests

In Test 11, specimen 4 was a substitution for specimen 7. Specimen 7 was suspected of containing impurities, since it overloaded the recording equipment. By the time the cut had passed the region with the impurities, there was insufficient material to complete all three cuts and hence one of the spare specimens was used. A fresh insert was also used.

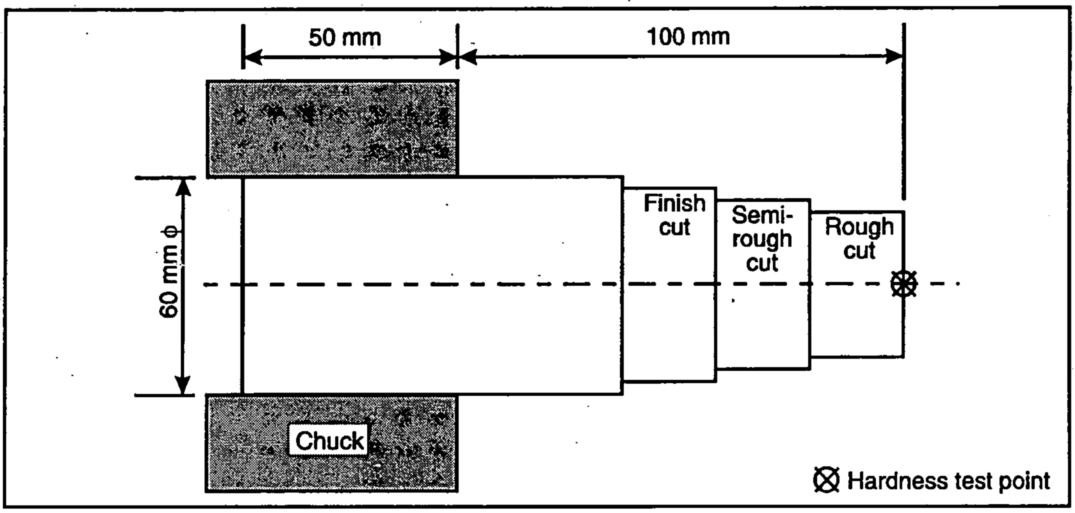


Figure K.2
Experimentation set-up

K.7 PROCEDURE

Each specimen was subjected to a roughing, semi-roughing and a finish cut at the specified cutting conditions (table K.4). This reduced to a minimum any material differences for a set of force ratios (F_V/F_S and F_V/F_a). For each cut a new insert cutting edge was used. This was to eliminate the effects of any damage caused to the cutting edge during the previous test. Additionally, after each test the cutting edge was visually inspected to determine it's condition and whether it had suffered any obvious damage. All cuts were made without cutting fluid (section K.3). The UV recorder output was three simultaneous traces, one for each axis. This was turned on just prior to the tool engaging with the specimen. After testing, each specimen was hardness tested in the centre of the end face.

The output from the tests for each tool/material/cutting parameters combination were the three cutting forces F_V, F_S and F_a. From this information, the force ratios (response variables) F_V/F_S and F_V/F_a were calculated. Since there were three replications of each test, the mean ratios for each test were also calculated.

K.8 RESULTS

The results of the hardness tests are given in table K.6.

	Hardness (HRB)		
	Material 1	**Material 2**	**Material 3**
Specimen 1	88	Specimen not used	109
Specimen 2	Specimen not used	102.5	109
Specimen 3	88	101	109
Specimen 4	88.5	103.5	107
Specimen 5	Specimen not used	Specimen not used	108
Specimen 6	87	103	Specimen not used
Specimen 7	88	102	Specimen not used
Specimen 8	89	103.5	110
Average hardness	**88.08**	**102.58**	**108.67**

Table K.6

Hardness test results for specimens

To convert the height of each of the traces (mm) from the UV recorder into force (N), it was necessary to multiply by the factors shown in table K.7. The resulting forces are shown in table K.8.

	Output from charge amplifiers (N/V)			**Output from galvo amplifiers (V/cm)**			**Overall multiplication factors (N/cm)**		
	F_V	F_S	F_a	F_V	F_S	F_a	F_V	F_S	F_a
Rough	1000	1000	200	2	1	1	2000	1000	200
Semi-rough	1000	1000	200	2	1	1	2000	1000	200
Finish	500	5000	200	2	1	1	1000	500	200

Table K.7

Conversion factors for traces from UV recorder

		Material 1			Material 2			Material 3		
Replication		1	2	3	1	2	3	1	2	3
Roughing cut										
F_V (N)	Tool 1	3800	3600	4100	4600	4500	4900	4000	4600	5000
	Tool 2	4000	4300	3900	5200	5100	4800	4500	4500	5200
F_S (N)	Tool 1	1300	1250	1350	1700	1500	1700	1500	1450	1450
	Tool 2	1300	1200	1200	1750	1700	1650	1500	1500	1550
F_a (N)	Tool 1	430	390	360	520	410	450	490	500	410
	Tool 2	410	410	390	510	500	500	500	450	490
Semi-roughing cut										
F_V (N)	Tool 1	2300	2300	1900	3000	2500	2900	3000	2900	2500
	Tool 2	2200	2400	2100	3400	3400	2500	3200	3200	2700
F_S (N)	Tool 1	700	600	600	950	900	950	800	850	850
	Tool 2	600	650	650	1000	950	900	900	850	900
F_a (N)	Tool 1	230	200	220	260	310	310	270	270	280
	Tool 2	200	230	240	280	260	330	270	320	310
Finish cut										
F_V (N)	Tool 1	800	850	950	1100	1050	1200	1000	1100	1250
	Tool 2	800	800	950	1100	1150	1100	1100	1200	1350
F_S (N)	Tool 1	350	300	275	425	400	400	400	450	425
	Tool 2	300	325	300	375	400	375	400	425	475
F_a (N)	Tool 1	230	210	150	250	210	220	250	260	220
	Tool 2	190	200	150	210	240	230	260	220	240

Table K.8

Cutting forces from cutting tests

All of the inserts cutting edges were examined visually at the end of the tests. None of the cutting edges showed signs of excessive wear, damage or a built-up edge.

K.9 CALCULATIONS AND ANALYSIS

Based on the values of the cutting forces determined experimentally in table K.8, the ratios of F_V/F_S and F_V/F_a were calculated. The ratios are shown in table K.9. The mean ratios, based on the ratios for the three replications, are shown in table K.10 and graph K.1. Table K.10 also shows the overall mean ratio for the three materials together and the deviation from this overall mean for the three materials, expressed as a percentage, where the deviation was defined as:

$$\text{Deviation } (\%) = \left[\left(\frac{\text{Mean ratio}}{\text{Overall mean ratio}} \times 100\right) - 100\right]$$

		Material 1			Material 2			Material 3		
Replication		1	2	3	1	2	3	1	2	3
Roughing cut										
F_V/F_S	Tool 1	2.92	2.88	3.04	2.71	3.00	2.88	2.67	3.17	3.45
	Tool 2	3.08	3.58	3.25	2.97	3.00	2.91	3.00	3.00	3.35
F_V/F_a	Tool 1	8.84	9.23	11.39	8.85	10.98	10.89	8.16	9.20	12.20
	Tool 2	9.76	10.49	10.00	10.20	10.20	9.60	9.00	10.00	10.61
Semi-rough cut										
F_V/F_S	Tool 1	3.29	3.83	3.17	3.16	2.78	3.05	3.75	3.41	2.94
	Tool 2	3.67	3.69	3.23	3.40	3.58	2.78	3.56	3.76	3.00
F_V/F_a	Tool 1	10.00	11.50	8.64	11.54	8.06	9.35	11.11	10.74	8.93
	Tool 2	11.00	10.43	8.75	12.14	13.08	7.58	11.85	10.00	8.71
Finish cut										
F_V/F_S	Tool 1	2.29	2.83	3.45	2.59	2.63	3.00	2.50	2.44	2.94
	Tool 2	2.67	2.46	3.17	2.93	2.88	2.93	2.75	2.82	2.84
F_V/F_a	Tool 1	3.48	4.05	6.33	4.40	5.00	5.45	4.00	4.23	5.68
	Tool 2	4.21	4.00	6.33	5.24	4.79	4.78	4.23	5.45	5.63

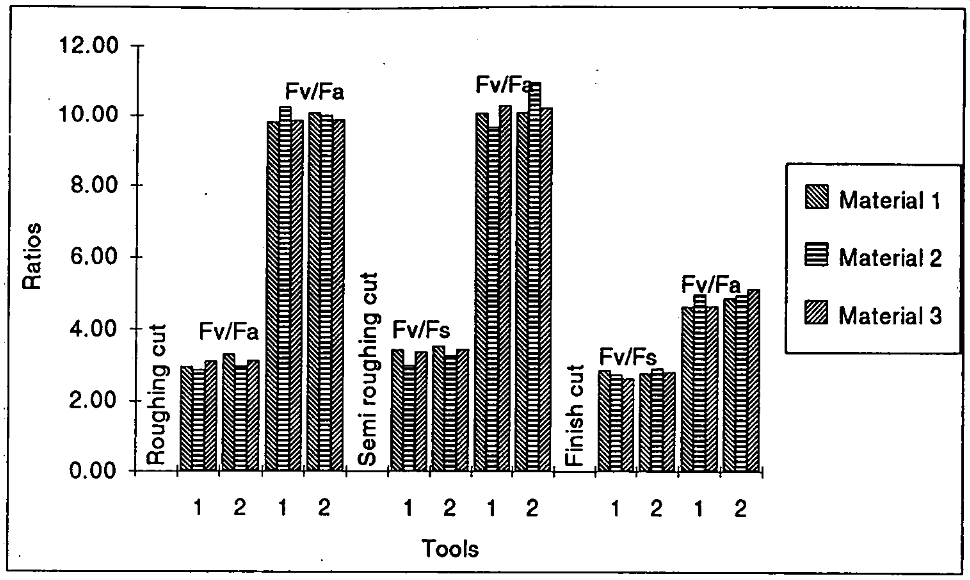
Table K.9

Ratios of cutting forces

		Mean force ratios from tests			Overall means	Percentage deviations from overall means		
		Mat'l 1	Mat'l 2	Mat'l 3		Mat'l 1	Mat'l 2	Mat'l 3
Roughing cut								
F_V/F_S	Tool 1	2.95	2.86	3.10	2.97	-0.73%	-3.56%	4.29%
	Tool 2	3.30	2.96	3.12	3.13	5.63%	-5.34%	-0.29%
F_V/F_a	Tool 1	9.82	10.24	9.85	9.97	-1.51%	2.68%	-1.17%
	Tool 2	10.08	10.00	9.87	9.98	0.98%	0.15%	-1.13%
Semi-roughing cut								
F_V/F_S	Tool 1	2.95	2.86	3.10	2.97	5.04%	-8.21%	3.17%
	Tool 2	3.30	2.96	3.12	3.13	3.60%	-4.55%	0.96%
F_V/F_a	Tool 1	9.82	10.24	9.85	9.97	0.59%	-3.34%	2.74%
	Tool 2	10.08	10.00	9.87	9.98	-3.19%	5.18%	-1.99%
Finish cut								
F_V/F_S	Tool 1	2.86	2.74	2.63	2.74	4.25%	-0.13%	-4.12%
	Tool 2	2.76	2.91	2.81	2.83	-2.23%	3.04%	-0.81%
F_V/F_a	Tool 1	4.62	4.95	4.64	4.74	-2.46%	4.54%	-2.08%
	Tool 2	4.85	4.94	5.10	4.96	-2.32%	-0.51%	2.83%

Table K.10

Means of cutting force ratios and percentage deviation from the overall means



Graph K.1
Cutting force ratios

K.10 DISCUSSION AND CONCLUSIONS

The results in tables K.9 and K.10 confirmed that the hypothesis was justified. With one exception, the deviation of the ratios for different materials from the overall means (based on all three materials) were less than ±6% from the overall mean concerned. In many cases they were considerably less than this.

Judging by table K.6, the specimens for a particular material were reasonably similar, at least in terms of hardness. Nevertheless, table K.8 showed quite a variation in the recorded forces. In part this was undoubtedly due to the method for recording data i.e. a paper trace from a UV recorder, since one possible source of error was the accuracy with which the heights of the traces were able to be measured. In some cases, an error of 1 mm could produce an error of 200 N (table K.7). An improved recording method may well have produced better results. Nevertheless, the results were considered sufficiently accurate to justify the hypothesis that, for a given tool geometry, the ratio between the three cutting forces is approximately the same, irrespective of material.

The results were not compared with results based on the data in the file FORC.DAT. The reason for this is that it was not known how those results were derived, except that cutting fluid was used, which suggested that they were more appropriate for standard shop floor practice. Whilst the data in LIFE.DAT was known to be valid for the conditions used, since it originated from a reputable source (UMIST, England), a comparison between LIFE.DAT and this set of tests would not necessarily have been valid.

The primary objective of the experiment was to demonstrate the similar ratios between the cutting forces. Although these tests were restricted to ferrous materials (primarily so that comparisons could be made whilst maintaining the same conditions), there was no reason to believe that such results were not applicable to non-ferrous materials. Hence the conclusion drawn from the experiment was that the ratio between cutting forces, for a specified set of cutting conditions, was approximately similar for the same tool, irrespective of material.

APPENDIX L

REASONS FOR SYSTEM 3 AND DATA CORRECTION

The introduction of System 3 was driven by the need to fulfil the objectives of the work. These objectives were (section 1.4):

1) the input variables should be readily available,
2) the system should have the ability to accept any material and to consider any material with any tool,
3) cutting data similar to accepted company practice should be produced,
4) the system should be industrially acceptable.

System 2 could realistically only meet the third objective. The primary difference between Systems 2 and 3 was that System 2 required a greater quantity of more varied input data. Furthermore, some of this data had to be available for a wide range of tool/material combinations, including combinations that had never been used before. If the data was not readily available, experiments to derive data were not considered a practical alternative in an industrial environment (section 6.1). One solution was to use data for a similar situation (substitute data). The accuracy of this method depended on what substitute data was available. Irrespective of the source of the data, System 2 relied on it to function and thus it had to be available. There was also the need to enter the data, once it had been obtained.

The transition from System 2 to System 3 required three changes, to allow the work to meet the objectives. These related to the cost data, the insert constraints and the tool life data file LIFE.DAT. The cost data presented no problem, since it was simply a matter of blocking off that part of the algorithm (including the input) and modifying the output (section 7.4). A similar philosophy related to the insert constraints (section 7.2), but in this case the introduction of data correction was necessary to maintain the results within the limits specified by the approved data.

The situation with respect to the data file LIFE.DAT was somewhat different. The System 2 version of LIFE.DAT contained data for a variety of materials (section 6.3). Where System 2 required specific data that was not already stored in the file, it was necessary to enter suitable data into the file. This relied on the data being available, although it was likely that in some circumstances the data had never even been produced. Where data was not available, for whatever reason, substitute data had to be used (section 6.3). Irrespective of the source of the data, there still remained the problem of entering it into the data file. The amount of data was not inconsiderable; sufficient quantity was required to permit multiple regression with four variables. System 3 overcame these shortcomings by the use of a standard file, which contained data for one tool/material combination only. This data was modified to suit the circumstances, by means of an algorithm.

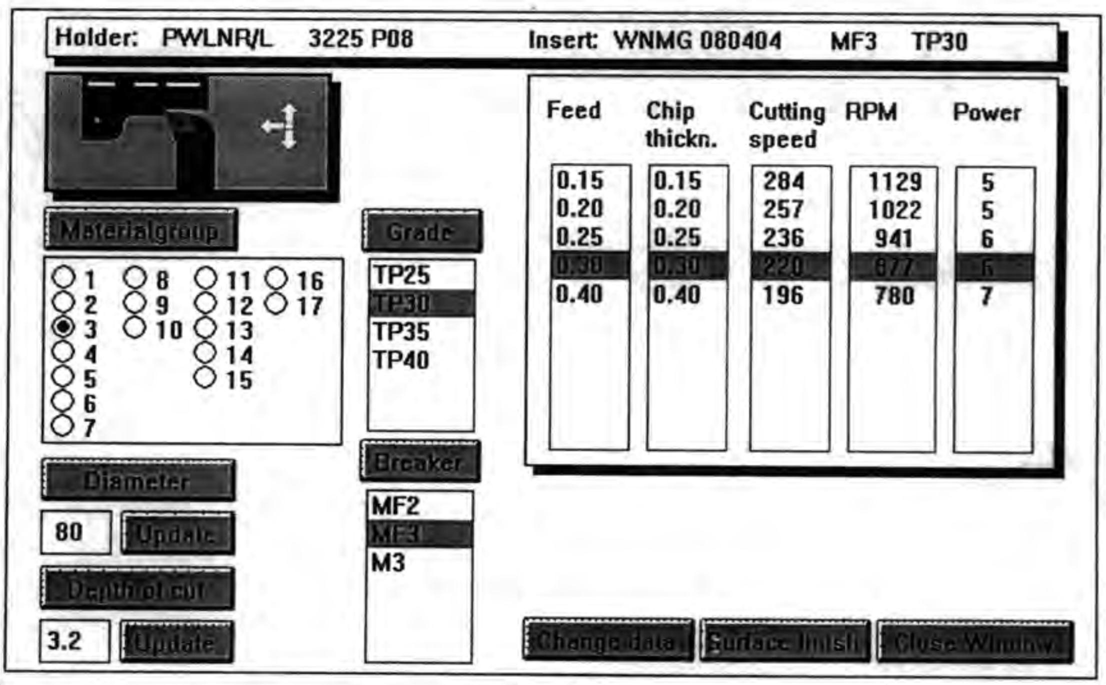
There was one other major difference between Systems 2 and 3. System 3 was the first attempt to use shop floor data for data correction purposes. In the event, the initial method used for data correction was shown not to be very effective (sections 7.5.2 and appendix I) and a different method adopted (chapter 8). Nevertheless, this use of fed back shop floor approved data was an important step forward, since the methods used do not appear to have been reported in the literature thus far (section 2.9).

In summary, System 3 allowed to work to meet the objectives specified. It was much more flexible than System 2 and hence provided a much more robust system, which was capable of dealing with any tool/material combination, but without the need to enter specific data that was hard to obtain. Unlike System 2, the prospect of being unable to run System 3 due to lack of data was greatly reduced. Consequently, System 3 was much more industrially acceptable than System 2, which was one of the objectives.

APPENDIX M

CONSTRUCTION OF TABLES 7.2 AND 7.3

The data in table 7.2 and 7.3 was used to modify the data in the file LIFE.DAT, so that the cutting speeds in LIFE.DAT were suitable for the ISO insert grade and material for the job in question. The tables were based on data taken from a computer program (Seco (1996)). The program was designed to provide recommended cutting conditions for various holder/insert/chipbreaker/ISO grade/material combinations in an assortment of different holder and insert sizes, primarily for ferrous materials. A typical output screen is shown in box M.1.



Box M.1

Output screen for Seco cutting data program (Seco (1996))

To arrive at the screen, the operation (in this case turning and facing) was selected, followed by the tool holder and then the insert, with associated chipbreaker and ISO grade. Once within the output screen, the material, ISO grade and chip breaker could be changed to obtain different conditions. Changing the diameter only changed the rpm, whilst depth of cut only influenced power. The 'Surface finish' button provided information on the surface finish obtainable with the different feed rates shown, whilst the 'Change data' button allowed the user to alter the cutting speed or feed rate, up to a certain percentage. The other parameter would then change to suit. However, the main difference between Seco (1996) and LIFE.DAT was that no indication of tool life was given in the program.

To construct table 7.2, data for a variety of tools and insert grades, but for a single material (Seco material group 3), was obtained from the Seco program. This material group was used since it was the same as that used in the file LIFE.DAT. This data was categorised by feed rate. Each entry in the table was the mean for all the data with the same attributes of feed rate, material and ISO insert grade, irrespective of holder and insert types. Hence each entry in table 7.2 was the average of a number of values obtained from the Seco program. Conversely, table 7.3 included data for a wide range of materials with differing values of specific cutting force K_s. In this case, the averaging process was irrespective of ISO insert grades, as well as holder and insert type. The data used for table 7.2 was a sub-set of the data used for table 7.3.

Examination of LIFE.DAT showed that a number of different feed rates had been used; 0.1, 0.2, 0.3, 0.4, 0.6 and 0.8 mm/rev. Consequently these feed rates were used in tables 7.2 and 7.3. This allowed the average cutting speeds to correspond to a particular feed rate in LIFE.DAT. The statistics of tables 7.2 and 7.3 are shown in table K.1.

	Table 7.2	Table 7.3
Total number of results from Seco (1996):	1459	11666
Mean number of Seco (1996) results used in table entries:	37	227
Total number of holder/insert/chip-breaker combinations:	226	
ISO tool holder types:	CSSNR, MRGNR, PCLNR, PSSNR, PSSNR, PWLNR, SCLCR, SSDCN	
ISO insert types:	CNMG, CNMA, CNMM, SNMG, SNMA, SNMM, WNMG, WNMA, WNMM, RNMG, RNMA, SNUN, SPMR, SPUN, CCMT, SCMT	
Seco chipbreaker types:	None, FF1, F1, F2, MF2, MF3, M3, M4, M5, MR5, MR7, R4, R6, R8, RR9	
ISO insert grades:	P10, P15, P20, P25, P30, P35, P40	P05, P10, P15, P20, P25, P30, P35, P40
Seco material groups (Seco (1996)):	3 - structural steels, ordinary carbon steels	1 - very soft "tacky" steels 3 - structural steels, ordinary carbon steels 4 - high carbon steels, ordinary low-alloy steels 5 - normal tool steels 6 - difficult tool steels 8 - easy-cutting stainless steels 9 - moderately difficult stainless steels 10 - stainless steel difficult to machine

Table M.1

Statistics of tables 7.2 and 7.3

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