

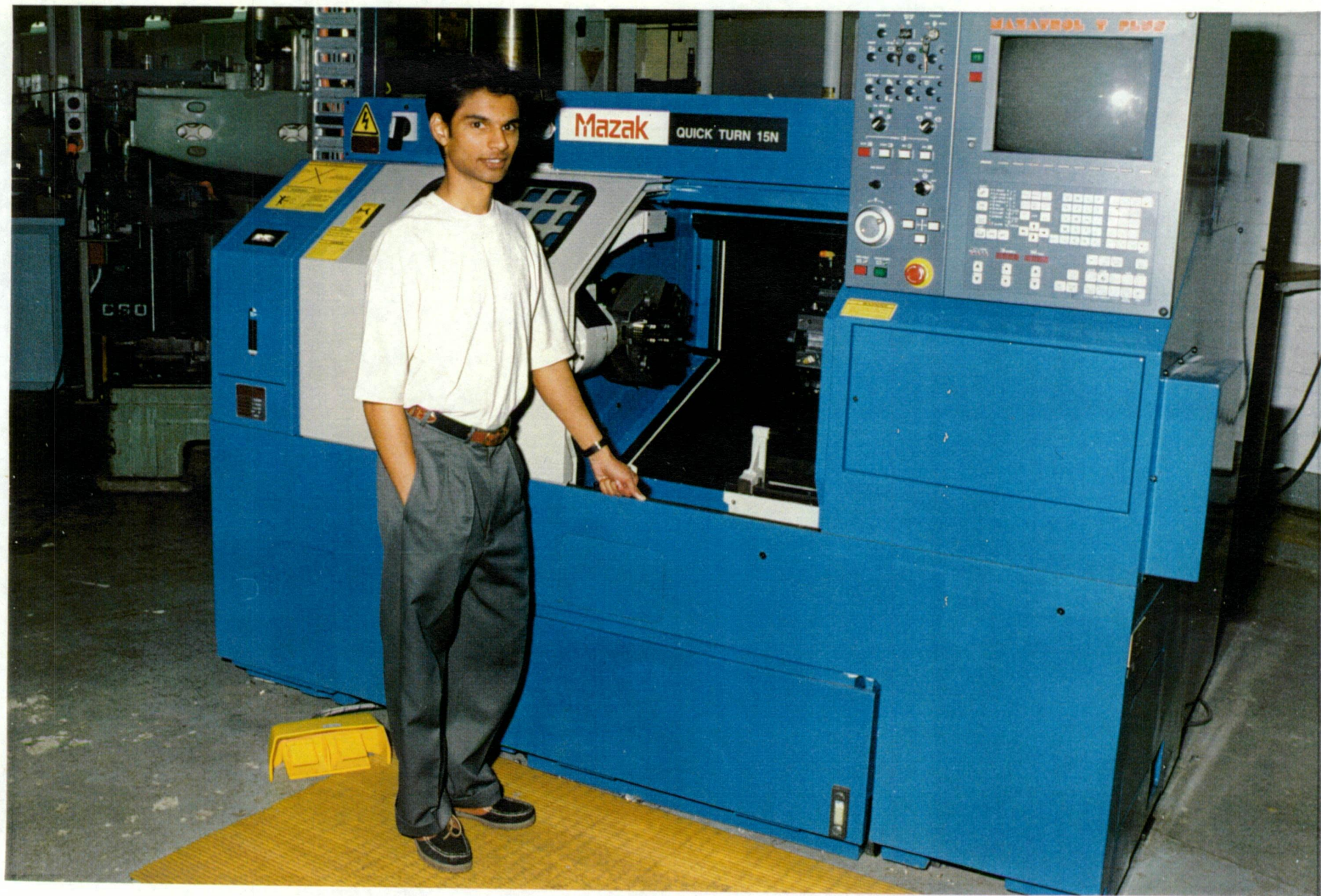
# Selection Of Optimum Machine Parameters For Maximum Production Rate (Minimum Time) Criteria In Single Pass Turning Operations

by

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# Abstract

The purpose of this work is to investigate and develop optimization techniques used for single pass turning operations on CNC machine lathes. The scope of this work is limited to the Maximum Production Rate Criterion (Minimum Time Criterion) for two machining variables, feed rate ( $f$ ) and machining speed ( $v$ ).

Further, a comparison of three methods of finding the optimum solution will be made. The three methods used are:

1. A combined mathematical and graphical based optimisation technique
2. Real time simulated optimization on a CNC lathe
3. Neural networks to obtain optimum cutting conditions

The comparison of optimum time with limited constraints using mathematical models and that of more optimised trends in CNC lathes give a better understanding of the accuracy of modern machine tools and limitations of models with limited constraints. Further, the neural network is also used as a decision making tool in determining the optimum cutting conditions. It is hoped that the neural network estimation of optimum cutting conditions are of reliable quantitative accuracy.

# Contents

	Page
Introduction	1
<b>Chapter 1: Literature Review</b>	4
1.1 Optimisation	9
1.2 Technological Constraints	10
1.2.1 Feed and Speed Constraints	11
1.2.2 Three Force Constraints	11
1.3 Optimisation Criteria	13
1.3.1(a) The Minimum Time Per Component (or Maximum Production Rate) Criteria	14
1.3.1(b) The Minimum Cost Per Component Criteria	14
1.3.1(c) The Maximum Profit Rate Criteria	15
1.4 Tool-Life Equations	19
1.5 Optimisation Techniques	24
1.6 Classical Modelling of Turning Operations	25
1.6.1 Single Pass Turning Without Constraints	26
1.6.2 Single Pass turning With Constraints	32
1.6.3 Multi-pass Turning Without Constraints	35
1.6.4 Multi-pass Turning With Constraints	37
1.6.4.1 Example of a Strategy Used For The Optimisation of Constrained Multi-Pass Turning Operations	37
1.7 Artificial Neural Networks	40
1.8 Concluding Remarks	50
<b>Chapter 2: Computer Integrated Manufacturing (CIM)</b>	53
2.1.1 Benefits of CAPP	54
2.1.2 Types of CAPP	54
2.1.2.1 Example of a Generative CAPP System	57
2.1.3 State of The Art CAPP Systems	57
2.2 Concluding Remarks	62
<b>Chapter 3: Unconstrained and Constrained Optimisation For Single Pass Rough Turning Operations</b>	64
3.1 Unconstrained Optimisation	65
3.2 Constrained Optimisation	72
3.3 Application of Mathematical Model	74
3.4 Results of Mathematical Model	76
3.5 Concluding Remarks	80

<b>Chapter 4: Real Time Optimisation On CNC Lathe</b>	<b>82</b>
4.1 Machine Tool and Tool-Workpiece Specifications	83
4.2 Description of Experimental Method	84
4.3 Discussion of Results	90
4.4 Concluding Remarks	92
 Final Concluding Remarks	 93
 Future Work	 95
 References	
 APPENDICES	
<i>Appendix 1 - Results of Mathematical Model (idealised optimisation) and         Time Trials on CNC machine</i>	
<i>Appendix 2 - Turning Operation Simulation Program Listing</i>	

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# Introduction

Metal machining is a process which has been in use since ancient times. In more recent times from about 1760 to 1860 there were many developments in machine tools in England during the period of the great industrial revolution where manufacturing techniques were needed to make components to an accuracy formerly not attainable.

Machining processes have developed to a very refined stage in the manufacturing industry today and its importance can in no way be underestimated. The machining process is probably the most important method by which metals and other materials are transformed into many of today's essential commodities. The importance and wide use of turning processes today represents a significant proportion of all machining operations. Hence, investigations for improving the efficiency and effectiveness of machining operations is of great value in a very competitive economic environment.

The need for reliable performance estimates is paramount especially from an economical point of view. The advent of CNC/NC machines in manufacturing has meant that time spent on actual machining components has significantly increased from less than 6% of the total available production time for conventional manufacturing systems to well above 77% for modern CNC/NC

machine tools [1]. With such a large increase in actual machining time the need to further improve and optimise machining times and costs becomes increasingly more important in modern manufacturing industry.

The selection of machining conditions such as feed and speed have traditionally relied on the experience of machine operators and on handbook recommendations which are known to be *feasible* solutions but not the *optimum* solution. In recent years attempts as evidence is seen in the literature review to develop computer software to determine optimum. An in-depth study of a complex computer-aided optimisation analysis and strategies for multiple constraint turning operations by a researcher [4] at the University of Melbourne has recently been carried out successfully. With the use of mathematical and graphical analysis detailed flow charts were drawn and implemented to determine global constrained optimum cutting conditions with given performance criteria. This information could in turn be integrated into systems such as computer-aided drawing (CAD) and computer-aided manufacturing (CAM) to result in a fully automatic manufacturing process incorporating optimisation conditions.

The optimization analysis for machining conditions carried out at the University of Melbourne proved to be surprisingly difficult, requiring intricate mathematical analysis and computer aided optimization strategies, which depend significantly on the mathematical functions and quantitatively reliable predications of machine performance characteristics, detailed specifications of machine tools, cutting tools and components as well as many practical constraints and process variables to be considered.

As materials improve with respect to cutting tools and workpiece materials, the availability and acquisition of empirically determined tool-life equations and related constant values for different tool-work combinations is difficult.

This work is aimed at studying and developing an optimisation technique for single pass turning operations to determine the optimum machine cutting condition for several tool-work combinations. The optimisation is based on the maximum production rate (minimum time per component) criteria and incorporates limited constraints such as the machine cutting speed and feed. Tool-workpiece combinations are limited to carbide tools only due to restrictions in the availability of tool-life data for necessary comparisons

# Chapter 1

## Literature Survey

In today's highly industrialised and mechanised society, we are surrounded by many mechanical marvels. Technical advances have come so far in recent years that in less than a century humankind has learned to fly, explored the deepest ocean and begun the exploration of space. Such technical achievements would not have been possible had human beings not learned to extract metals from the Earth and then shape them into useful products.

Many methods have been and are being used today to shape metals. However, only a small number of these methods produce the wide variety of items as do the processes of machining. In fact, machining is probably the most important method by which metals and other materials are transformed into the many products which are essential in today's high tech. society. This is based on the fact that some machining is involved in the production of almost any item one can think of. Even where machining is not directly involved, it is virtually always a necessary process in making the dies or fixtures used in the production operations.

Machining is basically a process of shaping materials using a variety of cutting tools. The material is shaved away in small pieces or chips (in one or more processes depending on the complexity of the job) uncovering the final size and shape of the workpiece.

In the last decade high precision machine tools have been combined with electronics and advancing computer technology which has enabled modern manufacturing to be computer controlled. The latter has led the way towards programmable automation and the field of computer based manufacturing systems such as computer integrated manufacturing (CIM), computer aided process planning (CAPP), flexible manufacturing systems (FMS), computer process control, computer aided handling and storage systems and computer networks for manufacturing.

Consumers today are better educated about technology and its limits. Their expectations (in terms of better value for money) of manufactured products have also increased. This demand for a better product by the consumer has forced the manufacturer to make products which are better designed. To the manufacturer this means that it is not only sufficient to design a product that satisfies its functional requirements (suitability for intended function, durability, and aesthetical appearance), but to also manufacture it easily and as cheaply as possible.

Auditing is one of the functions of the production activity and it is aimed at checking the designs from a manufacturing point of view. It is a very necessary function that enables the manufacturing department to design, select and/or provide the processes, operation sequence, tooling etc. to enable the product to be designed. The manufacturing department has various other responsibilities which include the designing of manufacturing systems, quality management systems, plant layouts, setting time standards and cost reduction programs.

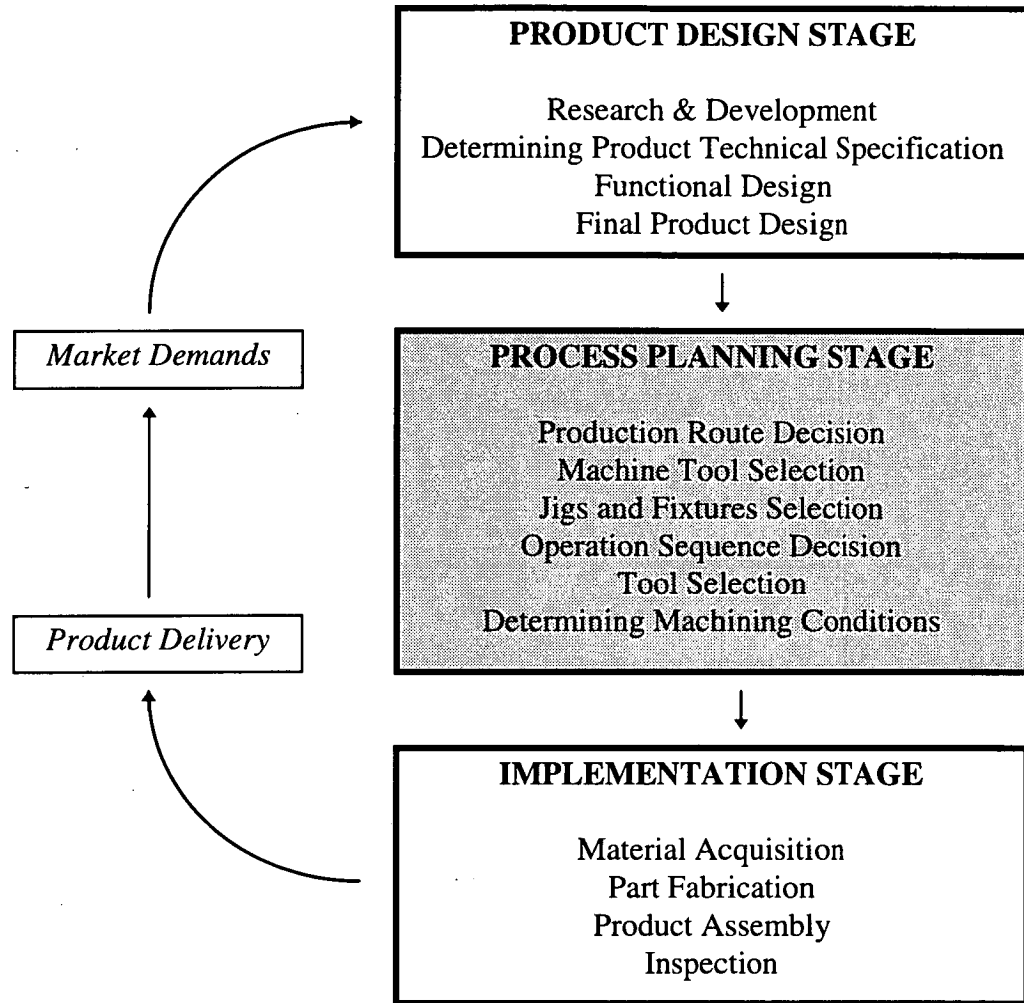
Evidently, a strong link exists between design and manufacturing requiring full cooperation between these two functions. The tendency today is to integrate the functional design and the design for manufacture at the early stages of the design process to prevent problems and extra costs at the manufacturing stage. Sometimes, the design of a product is reconsidered or even changed completely without altering the intended function. This process is termed “Value Engineering”.

Figure 1.1 gives a global view of the steps that are necessary in producing a product. The production cycle basically goes through three stages which are, the product design stage, the process planning stage and the implementation stage.

In particular, the process planning stage where functions such as production route decisions, machine tool selection, operation sequence decisions, tool selection, and determining machining conditions, has captured the interest of researchers in machining. The principle objective of research is the reliable estimation of performance characteristics such as the three force components, power, component surface finish and dimensional accuracy for a wide spectrum of practical machining operations involving numerous process variables.

It then becomes apparent that even a slight decrease in complexity or the number of steps in machining, or even an increase in tool life would result in substantial time, cost and/or material savings in each of the above stages in the production cycle.

It is evident that optimisation of machine parameters is a field in which lies great



**Figure 1.1** - Functions of integrated manufacturing systems (IMS).

interest and benefits. In recent years the benefits of this study and its applications have been realised by manufacturing industries. From a global point of view these benefits include

- Lower costs per component
- Higher volume economic production
- Decrease in waste material
- Better on-line production flow

- Better product consistency
- More efficient process planning
- Better customer service
- Better quality control on processes
- Decreased reliability on human operators
- Predictable tool replacement and machine service times

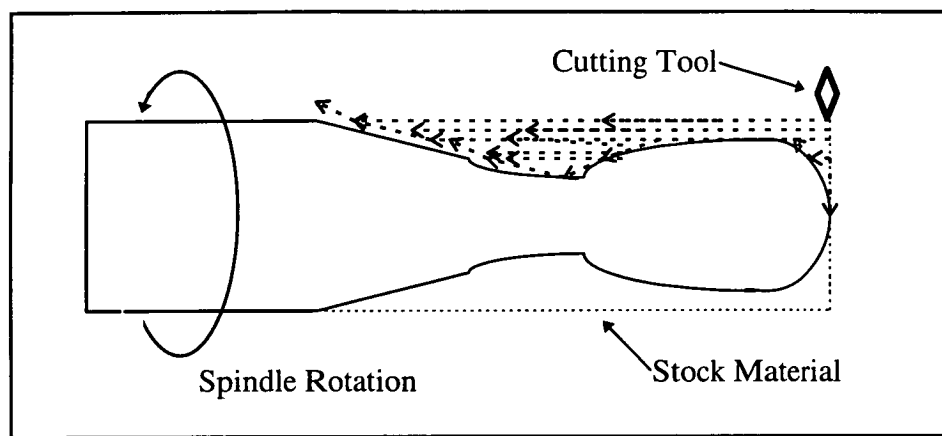
Traditionally, the values of process or machining variables such as feed, speed and depth of cut have been determined either by machine operators, based on their past experience, or by process/production planning engineers. The latter combine experience with handbook and tool manufacturer recommendations in arriving at detailed process plans including the selection of machining process variables such as machining speed and feed. However, both of these methods rely very much on personal experience and handbook recommendations which are known to be feasible but not the optimal solution.

The advent of CNC/NC machines in manufacturing has meant that time spent on actual machining components has significantly decreased from less than 6% of the total available production time for conventional manufacturing systems to well above 77% for modern CNC/NC machine tools [1]. It becomes even more evident then, that the need for optimising machine variables and process planning to improve production rates and component costs are necessary in today's highly competitive industrialised world.

In this chapter, several of the available optimisation techniques and a brief treatment of artificial neural networks are presented.

## 1.1 Optimisation

Optimisation is the process which seeks the best possible solution for a given manufacturing criteria. For example, consider the different ways in which the part shown in Figure 1.2 could be turned on a lathe.



**Figure 1.2** - Different cutting paths that could be used to obtain the part shown.

One can easily see at least 10 different patterns of the various paths in which to turn the stock material to obtain the finished product. Apart from these various paths, one can then choose the magnitude of the several machine parameters such as speed, feed and depth of cut. The combinations are numerous. However, only a few of the many combinations available will be feasible solutions, and only one of the feasible solutions will be the optimum solution.

Optimisation analysis of manufacturing has been studied since Gilbert's first work, *Economics of Machining* [2] in 1950. He introduced 'the maximum production rate' and 'the minimum production cost' criteria, under which optimal

machining speeds were analysed by developing mathematical models for a single stage manufacturing.

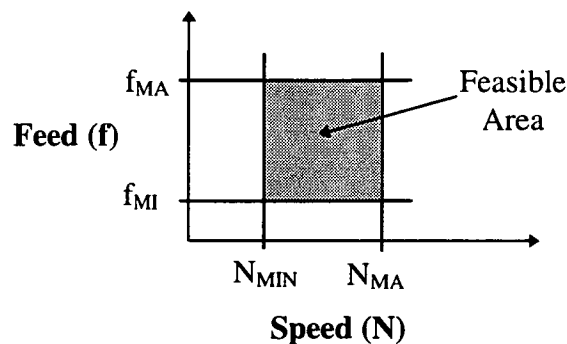
Single pass turning operations are possible and feasible in many situations depending on the limiting constraints, especially if the operation is restricted by the highest feed [3]. In single pass turning operations only one pass by the cutting tool is required to cut the stock material to the desired shape. However, it has been shown [3,4] that single pass turning is not always optimum. The more likely situation will be that the operation is subject to such practical constraints as available power, surface finish, minimum tool life, maximum permissible feed, and a range of allowable cutting speeds. In this latter case, two passes, or sometimes even three passes, can be cheaper or take less production time.

## **1.2 Technological Constraints**

Most of the reported work in economics of machining has been devoted to single pass turning using Taylor-type tool-life equations. However, many of the earlier researchers have not accounted for the technological constraints (such as the three cutting force and power constraints, surface finish constraints, and availability of machining performance and machine tool specification data) in the analysis. It is quite evident that when constraints are included in the analysis, the optimal cutting conditions selected will be different because of the constraint effect. In order to apply optimisation results for turning operations directly to practical machining operations, many technological constraints caused by machine tools and component specifications have to be considered since these constraints can affect both the optimisation strategy as well as the values of selected cutting conditions.

### 1.2.1 Feed and Speed Constraints

Maximum and minimum feeds ( $f_{\text{MAX}}$  and  $f_{\text{MIN}}$ ) and rotational speeds ( $N_{\text{MAX}}$  and  $N_{\text{MIN}}$ ) have to be determined in the design of a machine tool. The available rotational speeds  $N$  and feeds  $f$  should be first satisfied when optimum cutting conditions are selected. As shown in Figure 1.3, these constraints make up a rectangular feasible area.



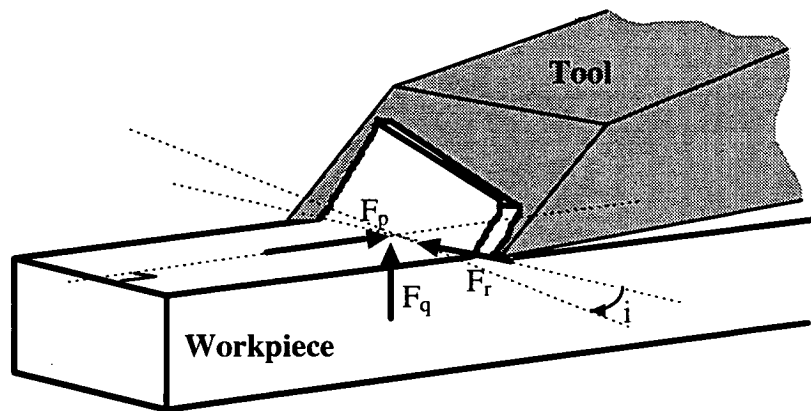
**Figure 1.3** - Feasible area in the speed-feed domain.

While any combination of machine speed and feed is not possible on a conventional machine tool (since these variables are controllable only in discrete step) they are infinitely variable for the modern NC/CNC machine tools. Therefore, during optimisation analysis, a continuous path can be plotted on the  $f$ - $N$  diagram enabling the optimum solution to be used in practice. Furthermore, the optimum solution can be determined to a high degree of accuracy.

### 1.2.2 Three Force Constraints

In most turning operations, forces acting between the tool and workpiece can be resolved into three components, the power force ( $F_p$ ), radial force ( $F_r$ ) and the

thrust force ( $F_q$ ) components (Figure 1.4) and are also important constraints when arriving at the constrained optimum cutting conditions.



**Figure 1.4** - Oblique cutting showing the three force components.

Excessive forces between the tool and workpiece are considered undesirable. The machine tool will rapidly wear out or even damage if it is overloaded with work. In addition, the toolholder and tool piece will give a maximum radial force limit, the workpiece deflection will restrict the maximum power force and thrust force, and the machine tool feed system rigidity will limit the maximum radial force [4]. However, it is known that the forces at the tool-work interface are affected by many variables such as speed, feed, depth of cut, tool geometry, and the tool and work materials. Thus, it is important that the cutting conditions selected will not only satisfy the economic criteria but also the force constraints.

Other constraints used in previous studies include low power/limiting spindle torque constraints, maximum power constraints, surface finish constraints, threshold of dynamic machine stability constraints, tool life constraints, and chip geometry constraints. The complexity of the resulting optimisation analysis and

strategy increases significantly as more constraints are included in the optimisation analysis.

In this work, only those constraints which impose limitations on the cutting conditions such as machining speed and feed rate is considered in the analysis.

### **1.3 Optimisation Criteria**

With regard to economics of manufacture, aspects such as the criterion for optimisation and tool-life equations for machining will first have to be clearly defined.

The criteria functions are of significant importance in studying the economics of machining. The type of criteria objective functions chosen would influence the optimum result. Numerous plausible criteria have been employed in the economics of machining studies, ranging from purely technological criteria, such as maximum material removal rate and the very popular maximum production rate, to the more financial criteria, such as minimum cost per component, maximum rate of return and maximum profit rate.

The most popular criterion employed in optimisation techniques previously reported [5-24] have been based on the minimum time per component (or maximum production rate) criteria, the minimum cost per component criteria, and the maximum profit rate criteria.

#### **1.3.1(a) The minimum time per component (or maximum production rate)**

**criteria:**

This criteria maximises the amount of products produced in a unit time interval; hence, it minimises the production time per unit piece. This criteria is adopted when an increase in physical productivity or productive efficiency is desired, neglecting the production cost needed and/or profit obtained and is given by

$$t = t_p + t_m + t_e = t_p + t_m + t_c \frac{t_m}{T} \quad (1.1)$$

where  $t$  = production time per unit piece

$t_p$  = loading, unloading, idle set up time per component

$t_m$  = machining time per component

$t_e$  = tool-replacement time

$t_c$  = time required to replace worn cutting tool with a new one

and  $T$  = tool life

**1.3.1(b) The minimum cost per component criteria:**

This criteria refers to producing a unit product at the least cost. The unit production cost is given by

$$\begin{aligned} u &= m_c + u_p + u_m + u_e + u_t + u_i \\ &= m_c + k_l t_p + (k_l + k_m) t_m + (k_l t_c + k_t) \frac{t_m}{T} \end{aligned} \quad (1.2)$$

where  $m_c$  = material cost

$u_p$  = preparation (or set-up) cost

$u_m$  = machining cost

$u_e$  = tool-replacement cost

$u_t$  = tool cost

$u_i$  = overhead costs

$k_l$  = direct labour cost and overhead

$k_m$  = machining overhead

and  $k_t$  = cost of cutting edge

It is evident that the governing equations for these two criteria are mathematically similar, and the optimisation strategies for selecting cutting conditions have been shown to be the same [4]. However, practically it is more advantageous to develop the solution strategy for the time per component objective function since this equation is simpler to use since it only requires time data.

### **1.3.1(c) The maximum profit rate criteria:**

This criteria maximises the profit in a given time interval. Okushima and Hitomi [26] used a profit ( $P_r$ ) objective function for producing  $N$  units in a constant time interval

$$P_r = (c-b)N - a \quad (1.3)$$

where  $a$  = fixed cost

$b$  = variable costs

and  $c$  = selling price per piece

In analysing the maximum profit rate ( $P_r$ ) criterion, Wu and Ermer [26] also developed an equation based on Marginal analysis

$$P_r = R - C \quad (1.4)$$

where  $R$  = total revenue per minute

and  $C$  = total cost per minute

Both the  $R$  and  $C$  terms are functions of the cutting speed. Armarego and Russel [6] formulated the equation for the maximum profit rate criterion in terms of time per component ( $t$ ) and cost per component ( $u$ )

$$P_r = \frac{(I - u)}{t} \quad (1.5)$$

where  $I$  = income per component (excluding material cost)

A similar maximum profit rate criterion as given in equation.(1.3) was employed by Boothroyd and Rusek [27]. They extended the optimisation analysis to allow for the effects of worker incentive schemes and batch production on the machining conditions. Although the three equations (1.3 - 1.5) were derived from different principles, the resulting equations are mathematically similar. The profit rate equations appear to be more complicated for use in mathematical analysis than the production rate and cost per component equations. So Chitale *et al.* [28] proposed a rate of return ( $R$ ) as a new objective criterion for machining optimisation analysis

$$R = \frac{I_c - u}{tu} \quad (1.6)$$

By comparison, this equation is even more complicated than those above because of the extra  $u$  term in the denominator.

The above three criteria are often used in optimisation analysis for single pass turning. Armarego and Wong [29], Iwata *et al.* [30], Kals and Hijink [31] have extended the  $t$  and  $u$  equations to multi pass turning using the general form; ie for  $t$

$$t = t_p + \sum_{i=1}^m t_{ci} \left( 1 + \frac{t_e}{t_i} \right) + m t_s \quad (1.7)$$

where  $m$  = number of passes

$t_{ci}$  = cutting time for the  $i_{th}$  pass

$t_s$  = tool reset time per pass

and  $t_i$  = tool-life using cutting conditions of the  $i_{th}$  pass

and for  $u$

$$u = x \left[ t_p + \sum_{i=1}^m t_{ci} \left( 1 + \frac{t_e}{t_i} \right) + m t_s \right] \quad (1.8)$$

where  $x$  = labour cost for running the machine tool

If the profit rate equation ( $P_r$ ) and the rate of return equation ( $R$ ) criteria are formulated for multi-pass turning, they will lead to an equation with many terms on both the numerator and denominator such that the mathematical analysis for finding the optimum conditions will be even more complex than equation. (1.7) and (1.8) [4]. Ghiassi *et al.* [32] and Malakoot *et al.* [33,34] optimised the three objectives (minimising total cost, maximising production rate and maximising quality of cut) subject to some constraints. But these were found to be more complex [4].

Although a variety of plausible criteria which have been discussed above can be used, the maximum production rate (minimum time per component) and minimum cost per component have been found to be the most popular criteria. In the economics of machine studies, the appropriate criterion to be used is dependent on the management policy and ease of implementation [4]. While higher management levels might place more emphasis on the maximum profit rate or the maximum rate of return criteria to justify the company investment, those closer to the manufacturing levels would usually prefer the maximum production rate criteria to meet certain deadlines or to reduce the bottle-neck in production lines. In a non-profit making organisation, the minimum cost per component criterion could be more appropriate. If time is more important than cost or profit, then the maximum production rate criterion should be used.

However, more attention has generally been placed on the problems of optimising conditions than in detailed analysis of the best criterion to be used. This is understandable in view of the difficulties in obtaining the necessary data or equations for the tool-life, practical constraints and the development of optimisation and experimental strategies. From the above survey, it is apparent that tool-life is the central element in economic machining. An understanding of the tool-life and the equations relating tool-life to the cutting conditions is therefore essential in the study of economics of machining if mathematical optimisation analysis and strategies are to be properly understood.

## 1.4 Tool-Life Equations

A tool's life can end by catastrophic failure of the cutting edge or by exceeding a critical wear level. Exceeding the critical wear level does not, in itself, result in immediate deterioration of the tool performance to the point of incurring economic penalties as would the catastrophic failure of the tool. Cutting may still be acceptable if the tool operates beyond its critical wear limit [4]. However, the economic penalties due to the propagation of tool wear are shown up by altering various process constraints such as deteriorating surface finish, increasing cutting forces, and increasing deflections and vibrations [4].

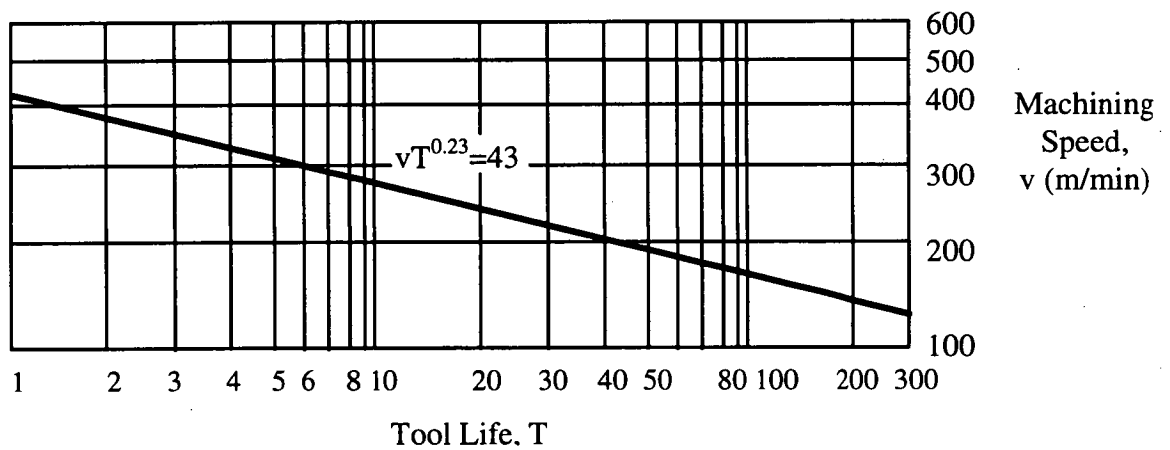
Catastrophic tool failure analysis has focused on tool failure distribution modelling and is primarily used to determine the optimal tool replacement interval [35], however these studies do not incorporate the influence of cutting conditions. Gradual wear tool failure is modelled as a function of the cutting conditions eg. Taylor equation. Therefore, this kind of wear failure is used in the optimisation of machining conditions. For optimisation of cutting conditions more emphasis has

been placed on the tool-life data and tool-life equations rather than on the tool failure criteria and tool wear mechanisms.

Various forms of empirical tool-life have been developed [36-38] by curve fitting experimental data obtained from tool-life investigations because of the absence of reliable theoretical tool-life models for quantitative prediction purposes. However, there have been considerable attempts to establish tool-life relationships, and tool-life equations can be classified into two categories

- Taylor-type equations
- Non-Taylor type equations

Earlier on this century Taylor conducted some experimental tool-life tests for single pass turning [39] and showed that the logarithmic tool-life ( $\log(T)$ ) is linearly related to the logarithmic cutting speed ( $\log(V)$ ), Figure 1.5.



**Figure 1.5** - The Taylor tool-life curve. It shows a linear relationship between tool life and machining speed on a bilogarithmic graph.

These results lead to the tool-life equation

$$vT^n = C \quad (1.9)$$

where  $v$  = machining speed

$T$  = tool life

$n$  = slope of the Taylor tool-life curve with respect to  
machining speed (constant)

and  $C$  = 1 min tool-life machine speed (constant)

This is the widely known Taylor's tool-life equation. After Taylor, other workers in the field developed tool-life equations similar to Taylor's equation. Taylor also proposed the idea of using speed  $v_T$  for a fixed tool-life  $T$  in turning operations ie when cutting speed  $v_T$  is used the tool-life will be  $T$  minutes. By adopting a standard test period of 20 minutes, Taylor gave the cutting speed equation

$$v_{20} = \frac{C_1 \left[ 1 - \frac{8}{7} \left( \frac{1}{32r^2} \right) \right]}{f^y \left[ \frac{48d}{32r} \right]^x} \quad (1.10)$$

where  $v_{20}$  = cutting speed for 20 minutes of the tool-life

$C_1$  = constant

$r$  = nose radius of the cutting tool (inches)

$f$  = feed rate (inches/rev)

$d$  = depth of cut (inches)

$$x = 0.4 + \frac{2.12}{5 + 32r}$$

and  $y = \frac{2}{15} + 0.06\sqrt{32r} + \frac{0.8(32r)}{192r + 288d}$

$v_T$  was used as a means of comparing the machinability of different materials. In the later Taylor-type tool-life equations it is noted that the nose radius ( $r$ ) was introduced to the equations since the nose radii in early tools were larger and hence less significant. Because of the complexity of equation 1.10, it was not used in practical operations [4].

After Taylor's experimental studies on tool-life other workers [40-43] attempted to follow this approach of first finding the effect of feed and depth of cut on cutting speed for a fixed tool-life and then the effect of cutting speed on tool-life for a given tool work combination and cutting conditions. The reported results were generally similar to Taylor's although the effect of nose radius of the cutting tool was omitted ie

$$v_T = \frac{C'}{f^p d^q} \quad (1.11)$$

where  $C'$ ,  $p$  and  $q$  are constants for the conditions tested.

Kronenberg [40] combined equations (1.9) and (1.11) into a single relationship and proposed the "extended cutting speed rule" equation

$$v = \frac{C_v \left( \frac{G}{5} \right)^g}{(1000A)^z \left( \frac{T}{60} \right)^y} \quad (1.12)$$

where  $C_v$  = tool-life constant

$$G = \text{slenderness ratio} = \frac{d}{f}$$

$$A = \text{area of cut} = df$$

and  $y, g, z = \text{empirical exponents with } z > g \text{ and } (z + g) < 1$

Thus equation (1.12) is similar to the extended Taylor's tool-life equation quoted in many books [44-48]

$$T = \frac{K}{V^{\frac{1}{n}} f^{\frac{1}{n_1}} d^{\frac{1}{n_2}}} \quad (1.13)$$

Comparing equation (1.12) and (1.13) the following relationships can be shown which highlight the similarities between Taylor's tool-life equation and Kronenberg's tool-life equation

$$K = \frac{60C_v^{\frac{1}{y}}}{5^{\frac{g}{y}} (1000)^{\frac{z}{y}}}; \quad n = y; \quad n_1 = \frac{y}{g + z}; \quad n_2 = \frac{y}{z - g} \quad (1.14)$$

From the equations above, it can be concluded that tool-life is affected by the cutting speed ( $v$ ), feed ( $f$ ) and depth of cut ( $d$ ).

Extended Taylor-type tool-life equations of the form

$$T = \frac{C}{v^{n_o} f^{m_o} d^n} \quad (1.15)$$

where  $C = \text{tool-life constant for the Taylor-type tool-life equations}$

$T = \text{tool-life}$

$v = \text{machining speed}$

$f = \text{feed rate}$

$d$  = depth of cut

$n_o$  = tool-life cutting speed exponent

$m_o$  = tool-life cutting feed exponent

and  $n$  = tool-life depth of cut exponent

have been favoured in optimisation analysis and have progressed to an advanced practical stage - but at a slow rate. The reason for this advancement is that additional factors such as feed rate, depth of cut, and cutting tool radius have been introduced to Taylor's initial tool-life equation (1.9).

As can be appreciated, a large number of tests must be carried out at different cutting speeds in order to establish a Taylor line with any degree of confidence. With the addition of these new factors, the testing is significantly more laborious. Compared to non Taylor-type tool-life equations, Kronenberg [49] found that about 70-80% of commonly used tool-work material combinations could be represented by the popular Taylor-type tool-life equation. Other reasons for the popularity of Taylor-type tool-life equations are its mathematical simplicity, and tool-life data for the extended Taylor's equation can also be obtained in the literature [40] and machining handbooks [43,47,48].

## 1.5 Optimisation Techniques

The question of which optimisation approach and technique to use arises. Undoubtedly many optimisation techniques exist and have been used. One technique which has been used at the University of Melbourne [4] over a few

decades quite successfully is the method of using classical mathematical calculus together with graphical representation in the cutting speed-feed domain to develop the optimisation analysis and is used in this work. There has also been a tendency to use numerical optimisation computer packages in attempting to arrive at required cutting conditions. However, numerical search techniques have the disadvantage of being unable to guarantee that a global optimum solution can be found since these techniques perform a pattern search with a random number generator as a starting point. The use of combined mathematical calculus and graphical representation of economic trends and constraints in the speed-feed domain has led to clearly defined constrained optimisation strategies with guaranteed global optimum solutions. Other techniques include geometric programming and dynamic programming, but share the same disadvantage as numerical search techniques in that they do not guarantee a global optimum solution.

In the later part of this study artificial neural networks (neural nets) is used and so a brief treatment of artificial neural networks follows.

## **1.6 Classical Modelling of Turning Operations**

Since Taylor's work [39], most other workers attempted at developing optimisation strategies for single pass turning operations which is the fundamental of optimisation of the integrated manufacturing system. It is not until recently that investigation in optimisation strategies for multi pass turning operations has been reported. All the material in the following sections is derived from first principles and through experimental work which has been done by pioneering researchers in

this field. As the focus is shifted from single pass to multi pass turning operations, and as constraints are considered, the mathematics become more complex and laborious. However, it is not the aim of this work to present the more complex conditions of turning operations, especially multi pass turning operations with constraints, but they are briefly looked at.

### 1.6.1 Single Pass Turning Without Constraints

Most of the reported work in economics of machining has been devoted to single pass turning operations using Taylor-type tool-life equations [4]. Single pass turning without constraints is the fundamental condition in turning operations. Everything else is an extension of this condition. Some other workers have used non-Taylor tool-life equations in their analysis but are not discussed in this work.

Hitomi [50] has shown the optimum machine speeds under the three evaluation criteria for a fixed depth of cut and a fixed feed rate to be

#### 1. The maximum production rate or minimum time machining speed ( $v_t$ ):

$$v_t = \frac{C}{\left[\left(\frac{1}{n} - 1\right)\right]^n} \quad (1.16)$$

where  $C$  = one minute machining speed (constant)

$n$  = slope of Taylor tool-life curve (constant)

The maximum production rate or minimum time tool life ( $T_t$ ):

$$T_t = \left(\frac{1}{n} - 1\right)t_c \quad (1.17)$$

where  $t_c$  = time required to replace a worn cutting edge with a new one

2. The minimum cost machining speed ( $v_c$ ):

$$v_c = C \left[ \frac{1}{\frac{1}{n} - 1} \cdot \frac{(k_l + k_m)}{k_l t_c + k_t} \right]^n \quad (1.18)$$

where  $k_l$  = direct labour cost and overhead

$k_m$  = machining overhead

and  $k_t$  = cost of cutting edge

The minimum cost tool-life ( $T_c$ )

$$T_c = \left(\frac{1}{n} - 1\right) \frac{k_l t_c + k_t}{k_l + k_m} \quad (1.19)$$

Using the partial derivatives  $\partial c / \partial v = 0$  and  $\partial c / \partial f = 0$ , Brown [7] and Armarego and Brown [8] have given the optimum speed and feed for minimum cost per component

$$T_{vc} = \frac{A}{v^{\frac{1}{n}} f^{\frac{1}{n_1}}} = \left(\frac{1}{n} - 1\right) \left(T_R + \frac{y}{x}\right) = \text{constant} \quad (1.20)$$

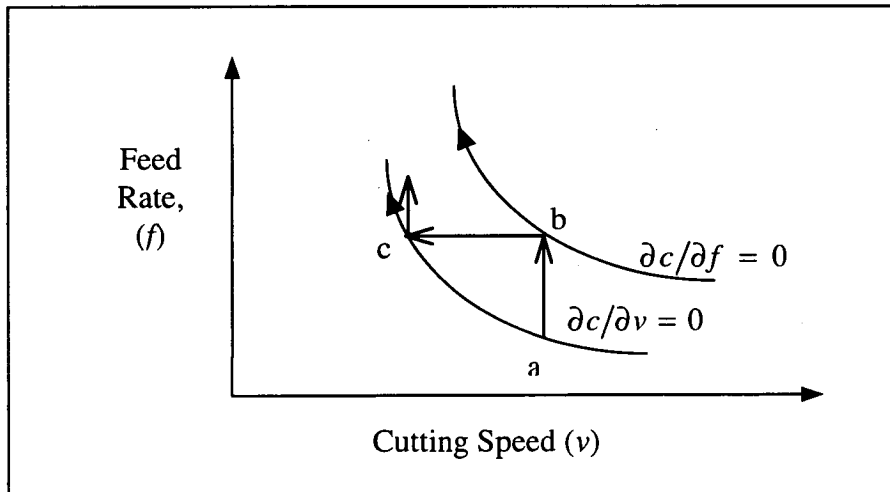
and 
$$T_{fc} = \frac{A}{v^{\frac{1}{n}} f^{\frac{1}{n_1}}} = \left( \frac{1}{n_1} - 1 \right) \left( T_R + \frac{y}{x} \right) = \text{constant} \quad (1.21)$$

where  $T_{vc}$  = economic tool-life for minimum cost per component when speed was the only variable

$T_{fc}$  = economic tool-life for minimum cost per component when feed was the only variable

and 
$$A = \frac{K}{d_T^{\frac{1}{n_2}}} = \text{constant}$$

They also found that as  $n \neq n_1$ , the two partial derivatives  $\partial c / \partial v = 0$  and  $\partial c / \partial f = 0$  could not be satisfied simultaneously and no unique global minimum occurred. In most practical cases  $1/n_1 < 1/n$ . Hence, the locus of  $\partial c / \partial v = 0$  would be on the left-hand side of the locus of  $\partial c / \partial f = 0$  on the  $V$ - $f$  diagram as shown in Figure 1.6.



**Figure 1.6** - Loci of the  $\partial c / \partial v = 0$  and  $\partial c / \partial f = 0$  curves in the  $V$ - $f$  domain.

The economic trend is shown by a-b-c, where the optimum occurs at higher feed rates and lower speeds. Similar trends have also been developed for the maximum production rate criteria [4].

3. The maximum profit rate machining speed ( $v_p$ ) is determined by:

$$(1-n)(k_t t_p + r_n t_c) v_p^{\frac{1}{n}} + \lambda(k_t - k_m t_c) v_p^{\frac{1}{n}-1} - n C^{\frac{1}{n}} (r_n + k_m t_p) = 0 \quad (1.22)$$

where  $r_n$  = unit net revenue (value added)

$$\lambda = \text{machining constant (for turning)} = \frac{\pi D L}{1000 s}$$

The maximum profit rate machining speed ( $v_p$ ) can be explicitly expressed from equation (1.22) for particular values of  $n$ . However, if the cutting speed is used as the only variable then the task becomes more complex and difficult resulting in the use of numerical methods to find the optimum speed. Using speed as the only variable and with the aid of computer analysis Wu and Ermer [26] found that the speed for maximum profit was between the speed for minimum cost ( $v_c$ ) and the speed ( $v_t$ ) for maximum production. As the unit revenue  $r_n$  is increased,  $v_p$  approaches  $v_t$  and deviates from  $v_c$  and vice-versa. Using the direct analytic approach, Armarego and Russell [6] considered speed and feed as the variables based on the maximum profit equation

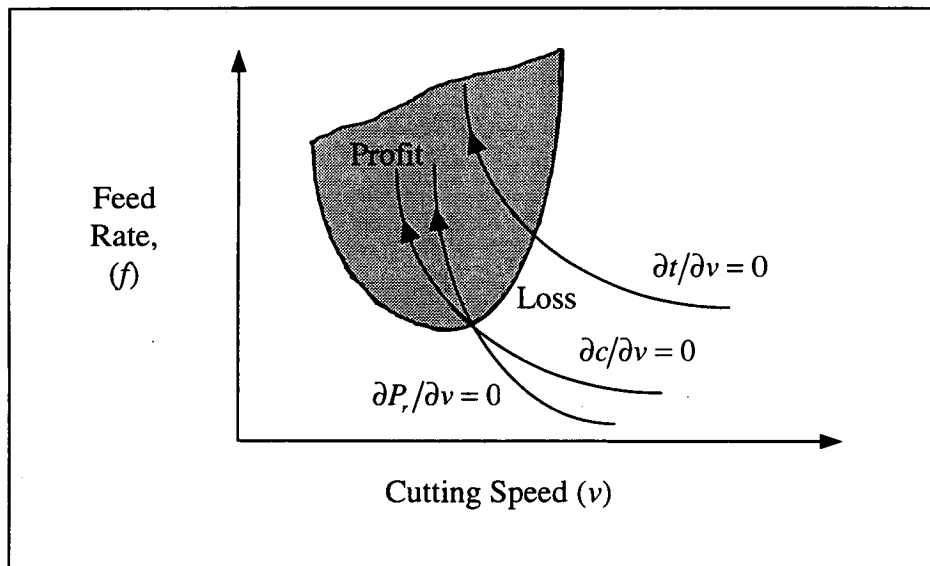
$$P_r = \frac{I - u}{t} \quad (1.23)$$

where  $I$  = income per component

$u$  = cost per component

and  $t$  = unit production time

The maximum profit speed ( $v_p$ ) and maximum profit feed ( $f_p$ ) were derived from the  $\partial P_r / \partial v = 0$  and  $\partial P_r / \partial f = 0$  equations. They showed that the high feed-low speed economic trends were also applicable to the maximum profit. By comparing  $\partial c / \partial v = 0$ ,  $\partial t / \partial v = 0$ , and  $\partial P_r / \partial v = 0$ , Armarego and [6] found that the  $\partial P_r / \partial v = 0$  and  $\partial t / \partial v = 0$  curves did not intersect the  $V$ - $f$  diagram. However, the  $\partial P_r / \partial v = 0$  curve intersected the  $\partial c / \partial v = 0$  curve where the profit rate was zero (Figure 1.7)



**Figure 1.7** - Loci of  $\partial t / \partial v = 0$ ,  $\partial c / \partial v = 0$ , and  $\partial P_r / \partial v = 0$  curves.

The authors also deduced that the often suggested cutting [7, 51, 52] could incur a loss between the minimum cost and maximum production rate curves (unless income was high). Hence, it is suggested that the cutting conditions selected should be in the profit region (Figure 1.7).

Hitomi [50] also assumed that it is reasonable from a practical stand-point that the machining speed for the maximum production rate is greater than that for the minimum production cost per piece produced ie

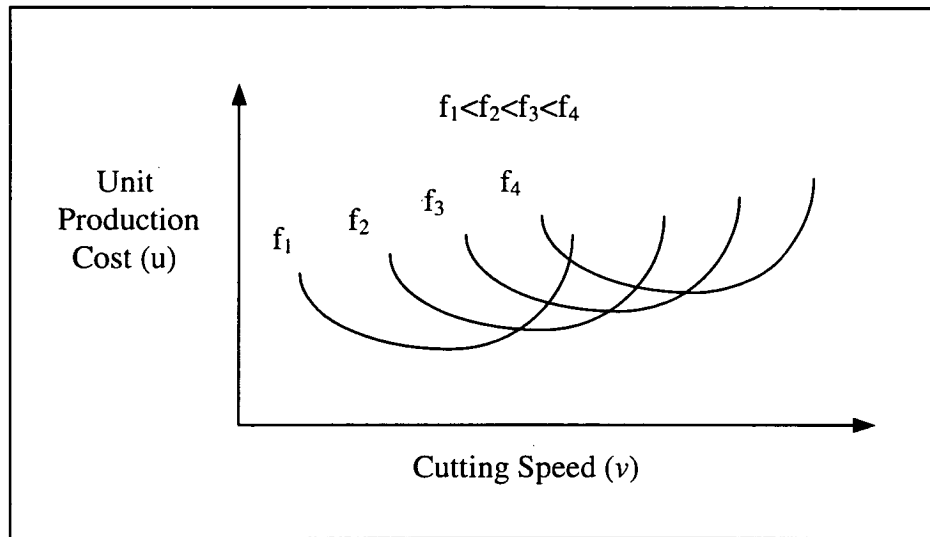
$$v_c < v_t \quad (1.24)$$

Any value of machining speed between these two optimum values is called the high efficiency speed and is preferable from a managerial stand-point. Hitomi [53, 54] also proved that the maximum profit rate machining speed ( $v_p$ ) exists in the high efficiency range and found the following relationship

$$v_c < v_p < v_t \quad (1.25)$$

Chisholm *et al* [55] found the effect of speed ( $v$ ) and feed ( $f$ ) on the cost per component with the aid of numerical and graphical techniques for specific demonstrations. Their observations led to the conclusion that lower minimum unit production costs ( $u$ ) were obtained when low speed was combined with high feed, as shown in Figure (1.8). Since then other workers [8, 56, 57] have shown similar trends.

The production time per component ( $t$ ) characteristics in the  $V$ - $f$  domain are essential for arriving at the constrained optimum solutions.



**Figure 1.8** - Cost per component versus cutting speed for a range of feeds.

### 1.6.2 Single Pass Turning With Constraints

In single pass turning operations without constraints the most significant economic trend for selecting the optimum cutting conditions is the high feed-low speed. However, when technological constraints are added to this simple case, the optimisation strategies will be different.

The use of technological constraints such as the machine tool speed and feed constraints, maximum tangential force, surface finish constraint, low power/limiting spindle torque constraints, maximum power constraints, threshold of dynamic machine stability constraints, tool life constraints, and chip geometry constraints have been demonstrated in previous work [4-8, 14-16, 21, 22, 29, 44, 58-65]. However, the constraint of most interest in this work is the machine tool feed-speed boundary constraint and is discussed below.

### 1. Optimisation strategies under Machine Tool Feed-Speed Boundary Constraints

Most researchers have pointed out that when selecting optimum cutting conditions, the highest feed and speed should not exceed the machine tool maximum tool maximum feed ( $f_{\max}$ ) and speed ( $V_{\max}$ ) limits [4]. The latter limit optimised cutting conditions in practice. Armarego and Wong [29] and Wong [63] presented the initial steps in selecting tool-work combinations and machine tool by superimposing known values of feeds and speeds of the machine tool with the  $\partial t / \partial v = 0$  curve as shown in Figure 1.9. If the  $\partial t / \partial v = 0$  curve was not in the machine feed-speed boundary (feasible area) the machine would be deemed unsuitable as shown in Figures 1.9 (a) and (b), otherwise Figure 1.9 (c). They further stated that the high feed-low speed selection was only applicable if  $0 < n < n_1 < 1$ , where  $n$  is the tool-life cutting speed exponent and  $n_1$  is the tool-life feed exponent. By varying the combinations of  $n$  and  $n_1$  Wong [63] was able to give a feed and speed selection strategy. However, he did not consider the effects of the machines minimum feed ( $f_{\min}$ ) and minimum speed ( $V_{\min}$ ) and the  $\partial t / \partial f = 0$  in his strategy, whereas Chia [15] and Armarego *et al* [17] noted these effects. As shown in Figure 1.10, five fundamental cases were observed in the  $V$ - $f$  domain. The case where the optimum cutting conditions lie on the machine tool minimum feed ( $f_{\min}$ ) and minimum speed ( $V_{\min}$ ) are shown in Figures 1.10 (a), (b) and (c). The cases where the optimum machine cutting conditions lie on the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  curves are shown in Figure 1.10 (b) and (e).

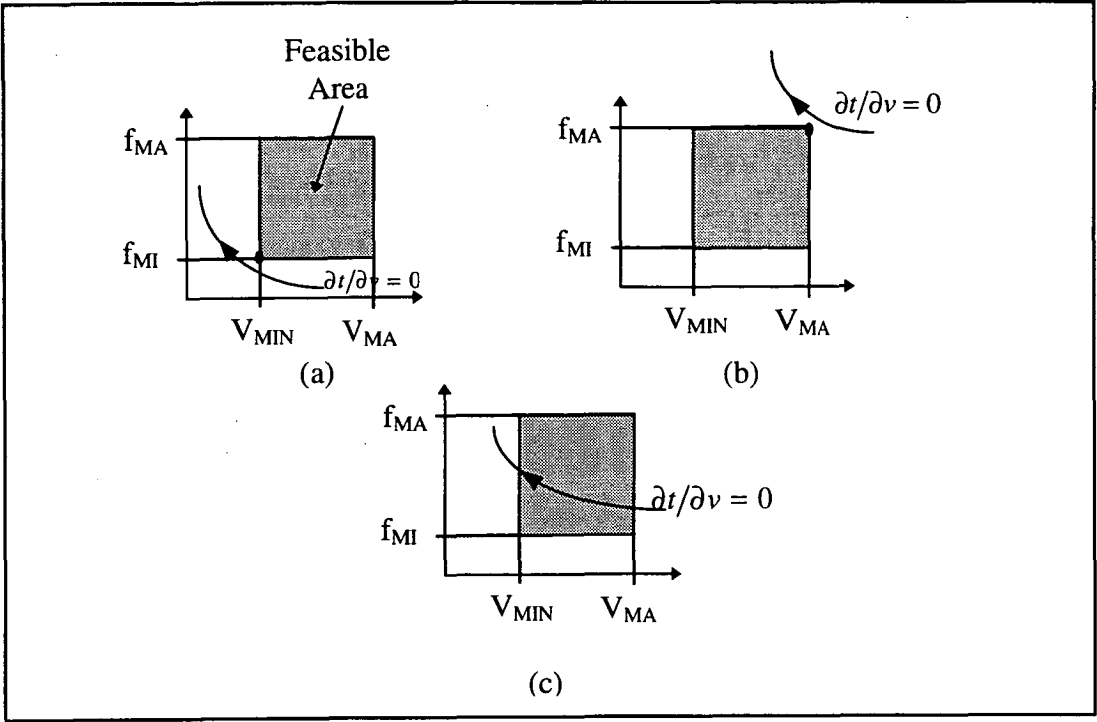


Figure 1.9 - Guide-line for preliminary selection for suitable machine tool [4].

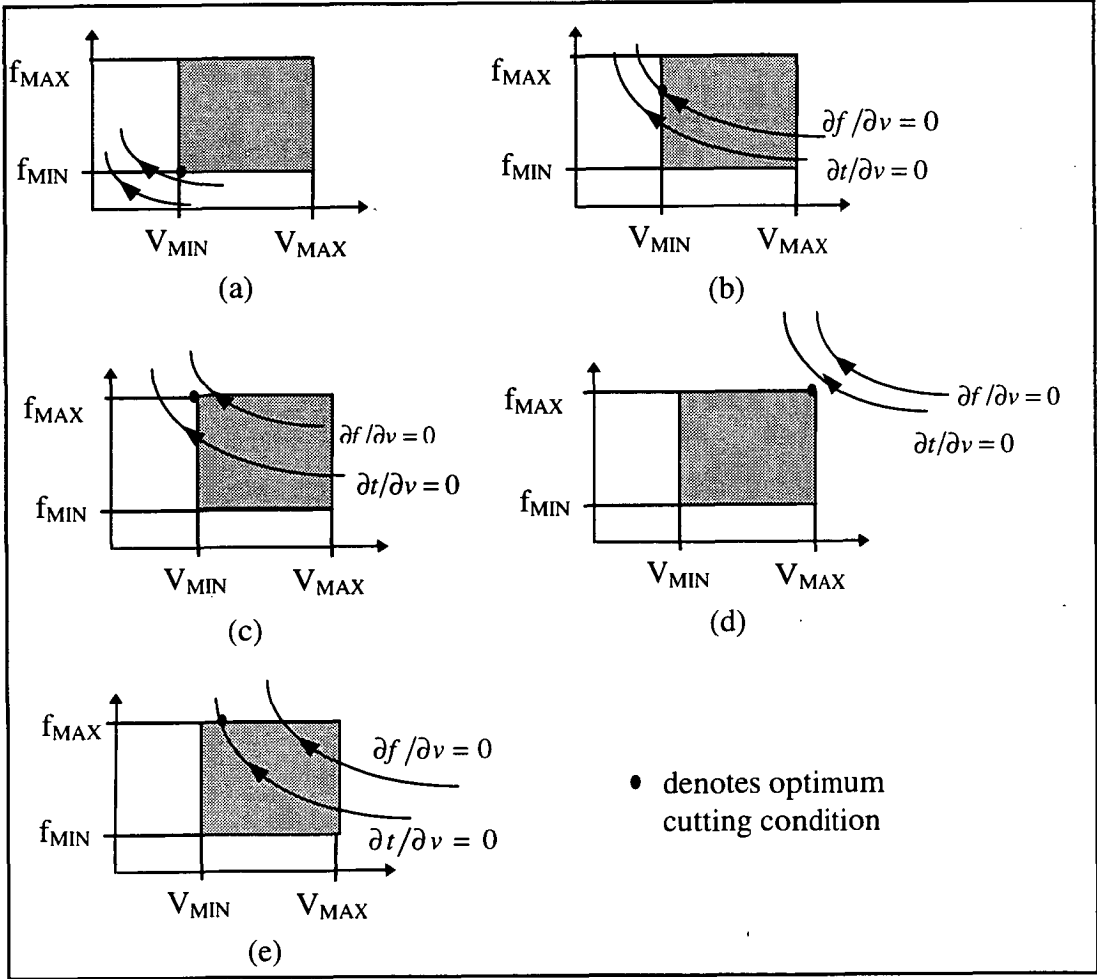


Figure 1.10 - Optimum cutting conditions under machine tool speed-speed boundaries [4].

### 1.6.3 Multi-Pass Turning Without Constraints

Single pass turning operations are not always superior to multi pass turning operations. They are optimum only if the operation is only restricted by the highest allowable feed, which is not the most general case [3]. When a large depth of cut is to be removed several passes (multi-pass operations) may have to be considered. The analysis of multi-pass turning optimisation is much more complicated than for single-pass turning operations since  $x$  speeds and  $x$  feeds for each of the  $x$  passes, the number of passes, and  $x-1$  depths of cut have to be determined.

The question that arises in multi-pass turning operations is which optimisation strategy to use. Workers such as Chia [15] claimed that the trends and optimisation strategies used for single-pass operations could be directly applied to each pass in multi-pass turning operations to establish the constrained optimum cutting speed and feed, allowing for the diameter variation in each pass. This approach could provide guide-lines for the optimum  $d_i$  (depth of cut in  $i^{\text{th}}$  pass) distribution and the optimum number of passes  $x$  although the numerical search techniques had to be used.

Kals and Hijink [31] suggested using equal depths of cut in each pass except for the last pass, while others such as Hinduja *et al* [66] suggested the use of the maximum possible depth of cut for all passes except for one. While these strategies gave the optimum solution for some cases they were not the result of rigorous optimisation analysis and numerical search techniques.

Unklesbay and Creighton [67] divided the total depth of cut into an appropriately selected integer number. Different combinations of these depth increments were then used to find the optimum depth of cut and the resulting optimum number of passes. Iwata *et al* [30] showed that the optimum depth of cut and the number of passes only slightly affected the optimum speed and feed. However, they used an equal depth of cut for each pass which Chia [15] claimed to be an unproven strategy.

Lambert and Walvekar [10] and Ermer and Kromodihargjo [11] combined linear programming with geometric programming to optimise multi-pass turning operations and used the Taylor tool-life equation, several practical constraints and minimum cost per component as the economic criteria in their optimisation analysis. The values of depth of cut for each pass were chosen arbitrarily and the optimum speed and feed were determined using geometric and linear programming procedures.

It has been shown that the analytic approach is superior to the 'trial and error' or numerical search techniques for optimising the cutting conditions in multi-pass turning operations, and that there is no guarantee that the global optimum solution will be found when using numerical search techniques [4]. Advantages of using the analytical approach are that clearly defined economic trends and characteristics for use in developing solution strategies which can be justified or modified when additional constraints have to be considered can be established [4]. Furthermore, the analytic approach can considerably reduce computer processing time [15, 22].

### **1.6.4 Multi Pass Turning With Constraints**

Constrained optimisation analysis and strategies for multi-pass turning operations with the multiple practical constraints of relevance to rough turning operations have been shown to be much more complicated than for the corresponding single pass analysis [4]. This is because the number of passes, the depth of cut, cutting speed and feed for each pass have to be determined to satisfy the selected economic criteria whilst not violating any of the constraints in every pass. This complex case is out the scope of this work. However, the next section is devoted to an example which demonstrates one of the current strategies used in the optimisation of constrained multi-pass turning operations.

#### **1.6.4.1 Example of a Strategy Used For The Optimisation of Constrained Multi-Pass Turning Operations:**

The following strategy for the optimisation of constrained multi-pass turning operations has been developed by Chua M.S., Rahman M., Wong Y.S., and Loh H.T.[68].

The main objectives of their work were:

- “(a) To study the effects of depth of cut, feed rate and cutting speed on the tool life, cutting forces and power consumption for TiN-coated carbide tools and Röchlin T4 medium carbon steel using design of experimental techniques.

- (b) To develop mathematical models to predict tool-life, cutting forces and power consumption as a function of depth of cut, feed rate and cutting speed within the operating region; and
- (c) To demonstrate the use of mathematical models in the determination of optimal cutting conditions using an optimisation technique.

The mathematical modelling of tool-life, cutting forces and power consumption models for a particular work and tool material involved lots of other factors, such as ways of holding the workpiece, the geometry of the cutting tool, etc.” However, to facilitate the experimental data collection Chua *et al* [68] only considered three dominant forces (depth of cut, cutting speed and feed rate) in the planning of the experiment. They planned the experimental programme using a complete  $3^3$  factorial design [69, 70]. The range of values of each factor were set at three levels - low, medium and high as shown in Figure 1.11. This setting gave a total of 27 experiments to be performed, each having a combination of different levels of factors as shown in Figure 1.12. The aim of this experiment is to measure the responses of tool-life, cutting forces and power consumption.”

Chua *et al* [68] postulated three mathematical models; the tool-life, cutting force and power consumption models which in general form are given by

$$Y = \phi(v, f, d) \quad (1.26)$$

where  $Y$  is the machining response,  $\phi$  is the response function, and  $v, f, d$  are the machine variables. Expressed in the non-linear form equation (1.26) becomes

$$Y = C v^{\alpha} f^{\beta} d^{\gamma} \quad (1.27)$$

“To facilitate the determination of constants and parameters, these mathematical models were linearised by performing a logarithm transformation. The logarithmic transformed mathematical models are given by

$$\ln Y = \ln C + \alpha \ln v + \beta \ln f + \gamma \ln d \quad (1.28)$$

The constants and parameters  $C$ ,  $\alpha$ ,  $\beta$  and  $\gamma$  were then solved by using multiple regression analysis [71]. For the purpose of developing the mathematical model, both the data for the machining responses and factors were logarithmically transformed.”

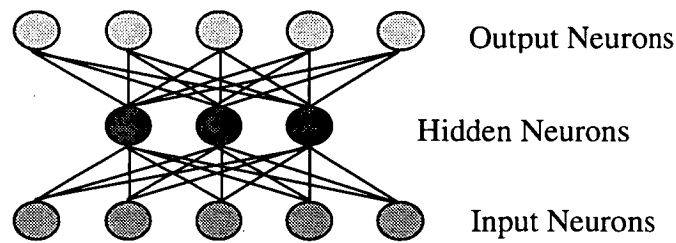
The mathematical models developed were used in the formulation of a multi-pass turning operation problem with the production time as the objective function subject to process constraints and solved using the sequential quadratic programming technique [72]. Using this technique the intermediate continuous solution for multi-pass turning was first determined by assuming that (i) the cutting conditions for each pass are the same and (ii) the workpiece diameter does not change during each pass of the cut. For this stage, cutting conditions of,  $m_o=2$ ,  $v=178$  m/min,  $f=0.25$  mm/rev and  $d=2.00$  mm, were used as the feasible starting point. The optimisation program computed an intermediate optimal solution with cutting conditions  $m_o=2.58$ ,  $v=212$  m/min,  $f=0.35$  mm/rev and  $d=1.553$  mm. Based on  $m_o$ , the lower and upper integers,  $m=2$  and  $m=3$ , respectively, were chosen as the number of passes of cut for the integer part of the multi-pass optimisation. The two-pass and three-pass turning optimisation problem for the same workpiece were automatically formulated and then solved by using the

intermediate optimal cutting conditions as the starting point. By comparing the production times, the cutting conditions for the two-pass operation was chosen to be optimal for turning this particular workpiece, 12.68 minutes as opposed to 14.37 minutes for the three pass operation. Chua *et al* found that the actual production time for the test was in accordance with the computed production time.

Based on the analysis of variance of each model, Chua *et al* found that the tool-life model was independent of the depth of cut as compared with the cutting force and power consumption models, which were dependent on the depth of cut, the feed rate and the cutting speed. They also found that the models developed were approximately 95% representative of this cutting process and the estimated parameters of each of the models were highly significant at the 99% level of significance within the operating range.

## 1.7 Artificial Neural Networks

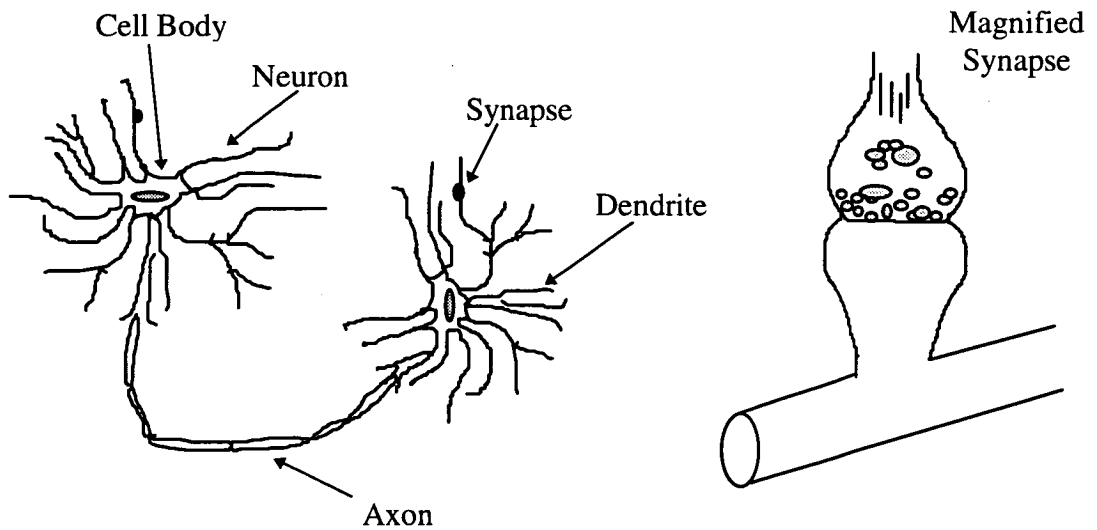
Neurons are nerve cells and neural networks are networks of such cells eg. the cerebral cortex of the brain. The notion of imitating the human neural processing system, cognitive capabilities and biological phenomena to model computation for artificial intelligence (AI) was introduced about 25 years ago. But it is not until recently that they are gaining recognition as a viable alternative to performing complex tasks such as decision making in multi faceted problems. Artificial neural systems are characterised as a distributed computational system comprising of a large number of processing units (Figure 1.11) each of which has selected characteristics of biological neurons connected to each other in a directed graph of varying configuration [73].



**Figure 1.11 - Artificial Neural System.**

Biologically each neuron is characterised by a cell body and thin branching extensions called dendrites and axons (Figure 1.12) which are specialised for inter-neuron transmission. The dendrites receive inputs from other neurons and the axon provides output to other neurons. Neurons receive electrochemical input signals from other neurons to which they are connected at sites on their surface, called synapses. The input signals are combined in various ways, triggering the generation of an output signal by the special region near the cell body. However, the interesting feature of the neurobiological phenomenon is the changing chemistry of synapse as information flows from one neuron to another. It is this special feature that researchers in this field of study have tried to emulate.

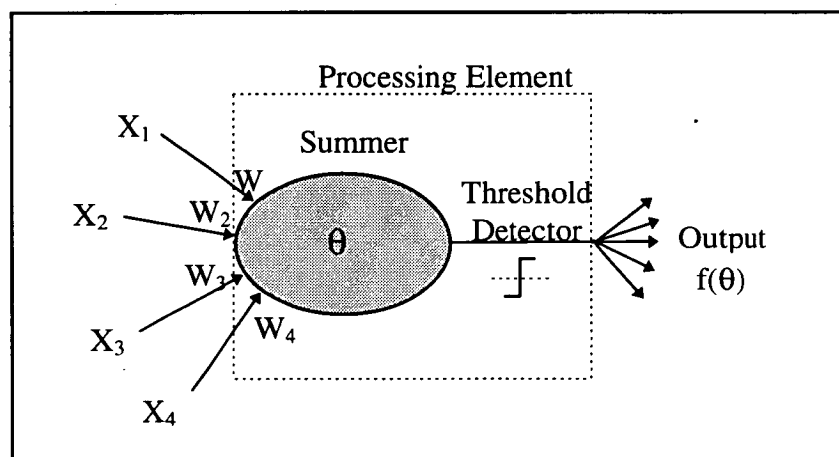
An idealised model of a neuron is shown in Figure 1.13. The processing elements are the fundamental building blocks of a neural network. They receive multiple input connections (which are links between the processing elements and carry signals between them - each connection may have a weight associated with it for altering the strengths of the signals passing through) and generate a single output



**Figure 1.12** - Neurons and their associated parts.

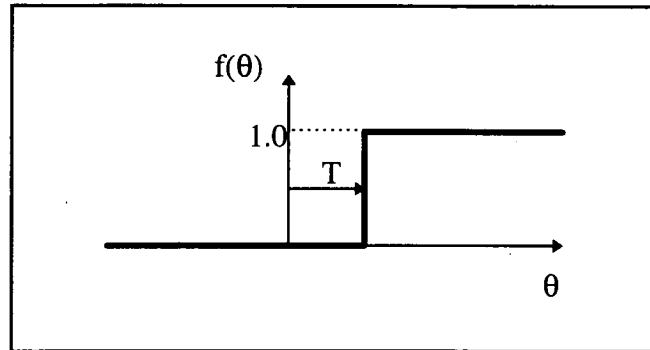
through the processing element which may fan out to many other processing elements. The processing element (synapse) consists of a summer and a threshold detector. The summer adds all the inputs after each of them has been multiplied with their corresponding weight

$$\theta = \sum_{i=1}^N W_i X_i \quad (1.29)$$



**Figure 1.13** - Functional model of a simulated neuron.

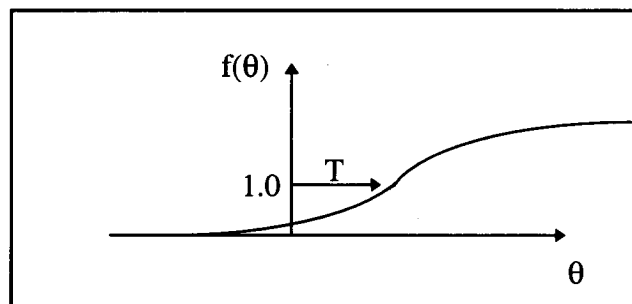
The output  $f(\theta)$  is a non-linear function. The simplest non-linear function is a threshold (Figure 1.14)



**Figure 1.14** Non-linear step threshold.

where  $f(\theta) = 0$  for  $\theta < T$   
 $f(\theta) = 1$  otherwise

However, a more useful non-linear function is the 'soft' threshold (Figure 1.15)



**Figure 1.15** - Non-linear 'soft threshold'.

Mathematically this can be described by the sigmoid function which varies smoothly from 0 to 1 or by the tanh (hyperbolic tangent) function which varies from -1 to +1. The sigmoid and the tanh functions are related by

$$\tanh(x) = 2\text{sigmoid}(2x) - 1 \quad (1.30)$$

The sigmoid can be used in the hidden layer of the NHM network and is given by

$$f(\theta) = \frac{1}{1 + \exp(-\theta)} \quad (1.31)$$

where  $\theta = \sum_{i=1}^n W_i X + \text{Threshold}$

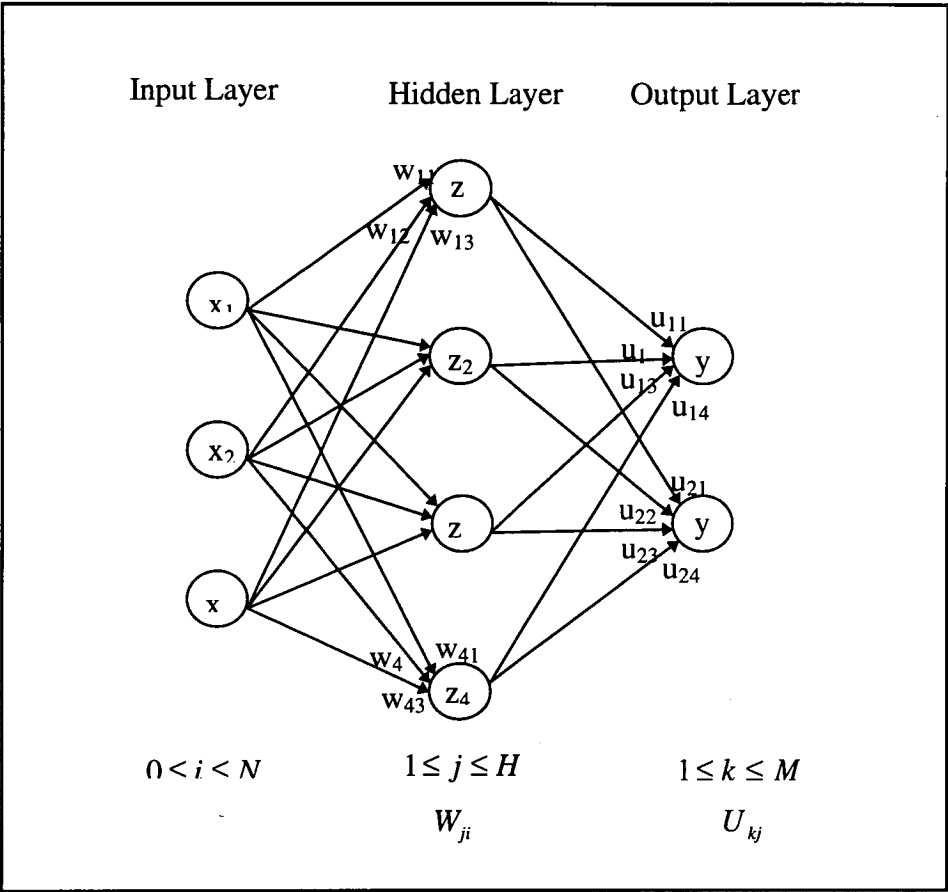
The differential of the sigmoid is given by

$$f'(\theta) = \frac{\exp(-\theta)}{[1 + \exp(-\theta)]^2} = \frac{1}{1 + \exp(-\theta)} * \frac{1 + \exp(-\theta) - 1}{1 + \exp(-\theta)} \quad (1.32)$$

or

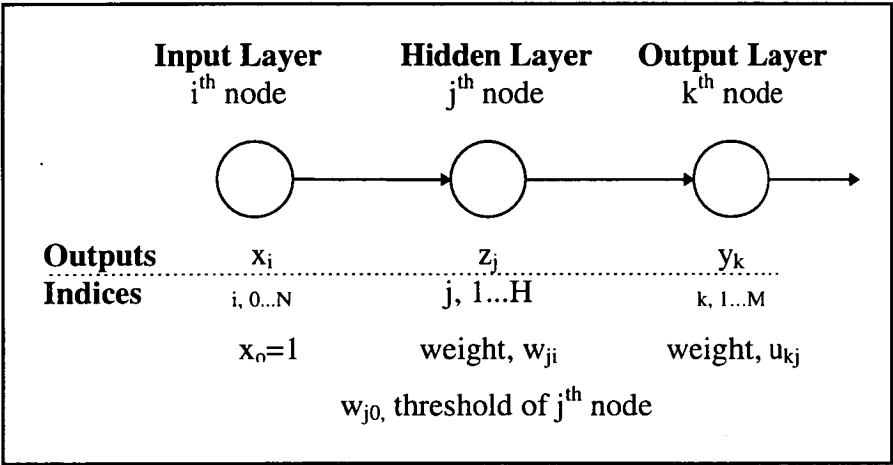
$$f'(\theta) = f(\theta)(1 - f(\theta)) \quad (1.33)$$

In this work one will use the 3-layer feedforward multi layered perceptron using backpropagation to simulate real time optimisation of machine cutting variables such as speed and feed using the minimum production time as the economic criteria. This type of neural network (Figure 1.16) is often called the NHM network, where N is the input layer, H is the hidden layer and M is the output later.



**Figure 1.16** - A standard back propagation network comprises 3 layers of processing elements, fully feed-forward connected.

Mathematically, Figure 1.16 can be represented by Figure 1.17



**Figure 1.17** - Symbolic representation of the NHM network.

The basic equations for a multilayered (NHM) network are

$$y_k = \sum_{j=1}^H u_{kj} z_j \quad (1.34)$$

$$Z_j = \frac{1}{1 + \exp(-\theta_j)} \quad (1.35)$$

$$\theta_j = \sum_{i=0}^N w_{ji} x_i \quad (1.36)$$

where  $y_k$ , represent the linear outputs,  $Z_j$  is the sigmoid function in the hidden layer only, and  $\theta_j$  represents the weighted sum.

The error is

$$E = \frac{1}{2} \sum_{k=1}^M (y - t_k)^2 \quad (1.37)$$

where  $t_k$  = true or desired value.

Equation 1.37 is the square root error not the RMS error.

The training task is to vary the weights  $w_{ji}$  and  $u_{kj}$  so that the error term (E) is a minimum.

If an input pattern is given to the system, the outputs can be calculated and the value for E can be derived. Using this result, the weights are then modified so that if the same input pattern is presented to the system, the network would output a smaller error ie

$$u_{kj}^{NEW} = u_{kj}^{OLD} + \Delta u_{kj} \quad (1.38)$$

and

$$w_{ji}^{NEW} = w_{ji}^{OLD} + \Delta w_{ji} \quad (1.39)$$

There are many ways of estimating the correction  $\Delta u_{kj}$  and  $\Delta w_{ji}$ , but the simplest and most commonly used is the method of “steepest descent”. This method is like being blindfolded on a hillside and you can move around and from the angle of your ankles you can tell which way is down and you can take a step in that direction. You can then test the direction and continue. The length of your step depends on how steep the hillside is. As it flattens off, your step becomes smaller. Mathematically this is

$$\Delta u_{kj} = -\eta \frac{\partial E}{\partial u_{kj}} \quad (1.40)$$

and

$$\Delta w_{ji} = -\eta \frac{\partial E}{\partial w_{ji}} \quad (1.41)$$

where  $\eta$  = ‘step length’ or ‘learning rate’ and is usually about 0.1.

The algorithm one would follow for backpropagation is as follows

- (a) Scale all inputs to 0..1 or  $\pm 1$ .
- (b) Set all  $w_{ji}$  and  $u_{kj}$  weights to random numbers in the range  $\pm 1$ .
- (c) Randomly pick an instance from the training set, ie one set of  $x_i$ ,  $i = 1..N$   
and the categories or values required at the outputs.
- (d) Feed the values through the net to get the  $k$  outputs.
- (e) Find the  $\delta k$  for each output.

(f) For each  $w_{ji}$  modify the weight using.

$$w_{ji}^{NEW} = w_{ji}^{OLD} + \Delta w_{ji} \quad (1.42)$$

$$\text{where} \quad \Delta w_{ji} = -\eta \frac{\partial E}{\partial w_{ji}}, \quad \eta=0.1$$

$$\text{and} \quad \frac{\partial E}{\partial w_{ji}} = z_j (1 - z_j) \cdot x_i \cdot \sum_{k=1}^M \delta_k \cdot u_{kj}$$

(g) For each  $u_{kj}$  modify the weight using

$$u_{kj}^{NEW} = u_{kj}^{OLD} + \Delta u_{kj} \quad (1.43)$$

$$\text{where} \quad \Delta u_{kj} = -\eta \frac{\partial E}{\partial u_{kj}}, \quad \eta=0.1$$

$$\text{and} \quad \frac{\partial E}{\partial u_{kj}} = \delta_k \cdot z_j$$

(h) Pick another instance from the training set and repeat from (d) until the net reproduces the training set or does not improve ( $10^4$  -  $10^8$  times is typical),[74].

The training set should be as large as possible (usually >3 times the number of weights). The test set is an independent set. It should also be noted that training can be a very slow process. The steepest descent algorithm only guarantees coverage when the learning rate goes to zero and the time to reach a solution then goes to infinity. If the net is going in the right direction at one step then do not change the direction completely in the next step. Modify the weight update to be

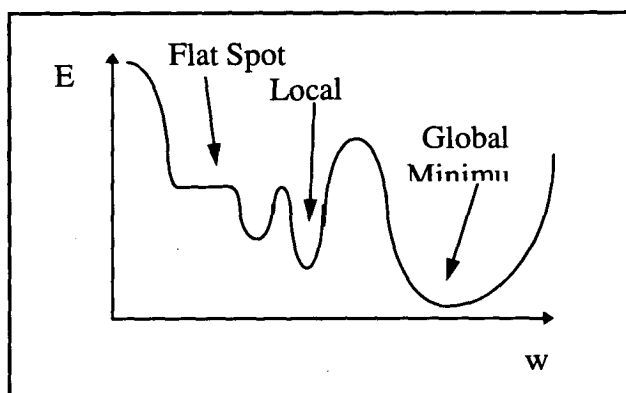
$$w^{t+1} = w^t + \eta \Delta w^t + \alpha \Delta w^{t-1} \quad (1.44)$$

The first two terms in equation 1.44 are as before, the third term is called the 'momentum',  $\alpha$ , and it can be as large as 0.9.

Also, the weight correction is proportional to the slope of the error surface ie

$$\Delta w \propto \frac{\partial E}{\partial w} \quad (1.45)$$

The slope may go to zero (flat spots) at points that are not at the bottom of holes (Figure 1.18), for instance at the top or on a shoulder.



**Figure 1.18** - Example of flat spots, local and global minimum.

The minimum that is found may not be the 'global' minimum but a 'local' minimum. There is very little that can be done in this case apart from exhaustively searching for the global minimum. However, if the local minimum solves the problem at hand then this case does not matter. If it does matter, then the search which have to begin again from a different set of random weights with the hope that a different minimum is found.

The momentum term can both speed up the training and help to push through local minima.

## **1.8 Concluding Remarks**

It is evident from the above survey that many researchers in the field of economics of machine operations have endeavoured to include practical constraints in their analysis to develop general trends in cutting operations. While the optimisation analysis of single-pass turning operations is relatively straightforward, the analysis of multi-pass turning operations has proven to be a complex task incorporating many parameters and certain economic criteria, which have to be satisfied simultaneously.

This thesis is aimed at developing cutting conditions for unconstrained and constrained single-pass turning operations using machine speed and feed rate as constraints. The optimisation analysis is based on the maximum production rate (minimum production time) criterion. Results that are obtained from the classical mathematical studies are compared to those obtained under the same conditions on a CNC machine (Mazak Quick Turn 15N) which includes optimisation hardware/software (Mazatrol T Plus). Finally, the use of a multilayer perceptron neural networks with back propagation is used as a decision making tool to obtain optimum cutting conditions for several tool-work combinations.

## Chapter 2

### Computer Integrated Manufacturing (CIM)

The technology that has had the greatest impact on manufacturing firms over the last few decades is computer technology applied to production systems [75]. One area to which this technology is applied is that of computer control. This includes, computer numerical control (CNC), flexible manufacturing systems (FMS) and robotics. Other applications of computer systems range from product design to manufacturing process planning and control. Furthermore, these applications include the business operations of the company (such as inventory use and planning, cost accounting, time scheduling, customer billing, etc.). These various functions constitute the information-processing cycle (because the common denominator that drives these functions is information in the forms of data and knowledge) that occurs in a manufacturing firm.

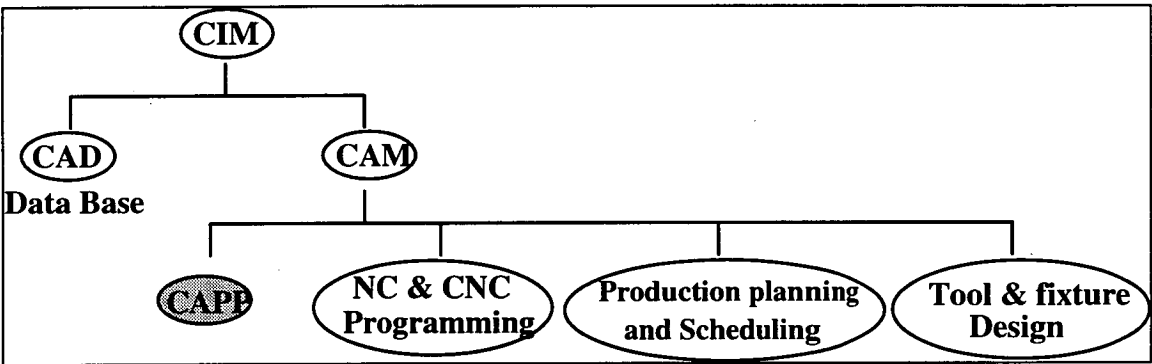
Computer integrated manufacturing uses the computer in the information processing cycle to integrate the different functions - design, manufacturing and business operations - into a unified, well-coordinated, and smooth running system.

The two main constituents of CIM are computer aided design (CAD) and computer aided manufacturing (CAM), which are commonly referred to as

CAD/CAM systems if the system supports manufacturing as well as design applications.

CAD is a design activity that involves the effective use of the computer to create, modify or document an engineering design with the use of an interactive computer graphics system.

CAM is the effective use of computer technology in the planning, management, and control of the manufacturing function. CAM can be effectively branched out into its separate components as shown in Figure 2.1 below.



**Figure 2.1** - CAPP in relation to other computer aided systems.

Other components such as computer aided quality control (CAQC), computer aided handling (CAH), and computer aided inspection (CAI) can be added under CAM. The computer aided process planning (CAPP) system is one of the key technologies which integrates the CAD and CAM systems. In particular, it is more important to develop a CAPP system which can generate a process plan based on the models of parts designed by an interactive system.

## 2.1 Computer Aided Process Planning

Computer aided process planning (CAPP) consists of determining the *sequence* of individual manufacturing processes and operations required to make a product. It produces the *route sheet* and the *operations sheet* that specify the process sequence right from inception to finish. CAPP represents a link between design and manufacturing in a CAD/CAM system and Cellular Manufacturing (see Types of CAPP). As shown in Figure 2.2 below, CAPP draws on all the design and manufacturing aspects of a part such as raw material selection, the standard operation sequence for that particular part, tool plan, cutting sequence etc to obtain a unified methodology to produce a part.

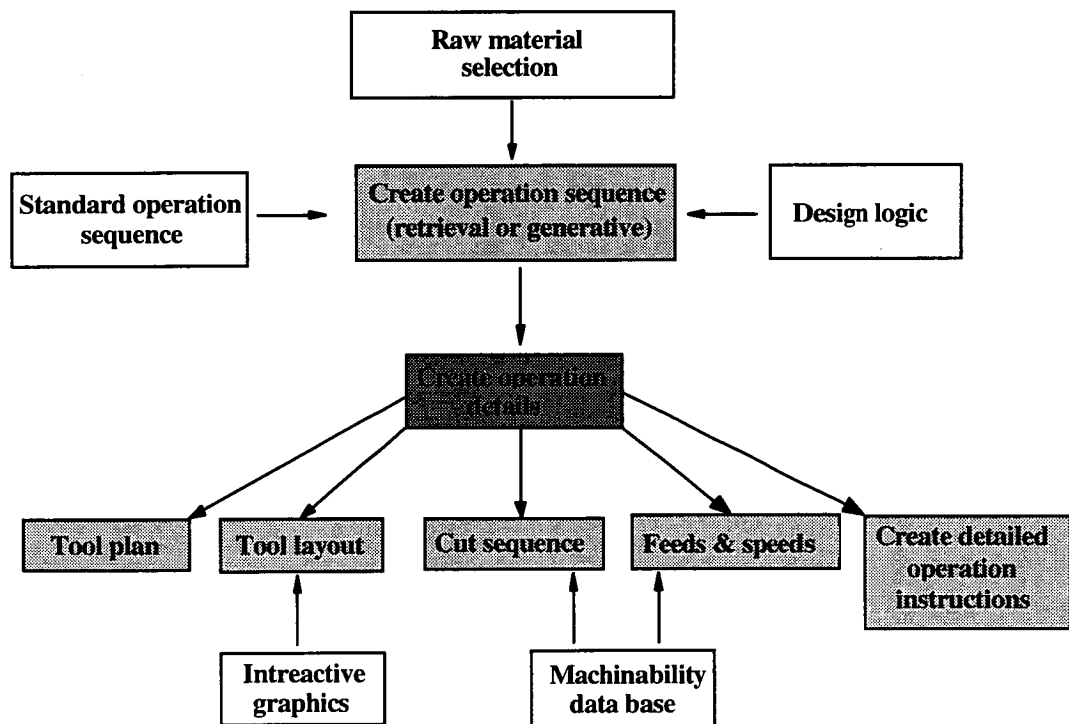


Figure 2.2 - CAPP can be variant or generative.

### 2.1.1 Benefits of CAPP :

1. Process rationalisation and standardisation :

- automated process planning leads to more logical and consistent process plans compared to manually set up process plans.

2. Increased productivity of process planners :

- due to systematic approach and the availability of standard process plans in the data files.

3. Reduced lead time for process planning.

4. Improved documentation/communication.

5. Incorporation of other application programs :

- eg cost estimating and work standards.

### 2.1.2 Types of CAPP :

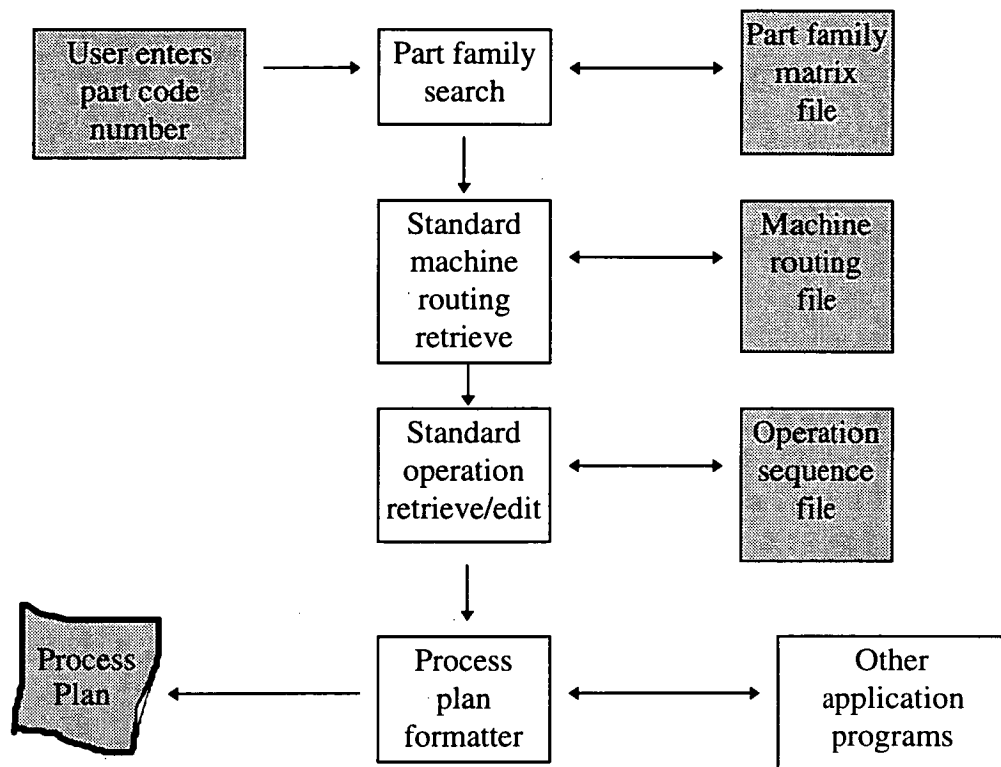
**Retrieval (*Variant*) process plans** use parts classification, coding and group technology (GT) as a foundation. In this approach, the parts produced in the plant are grouped into families, distinguished according to their design or manufacturing attributes. For each part family, a standard process plan is established since the parts in each family have certain similarities in shape and manufacture. The standard process plan is stored in computer files and then retrieved for new workparts which belong to that family (Figure 2.3). In order to do this, some form of parts classification and coding system such as polycodes and decision tree coding is required to organise the computer files and to permit efficient retrieval of the appropriate process plan for a new workpart.

*Polycodes* - each digit in this code has its own interpretation which does not depend on the preceding digit. This structure tends to be relatively long, but allows identification of specific part attributes, and is well suited to computer implementation.

*Decision tree coding* - also called hybrid coding, is the most advanced type of coding and combines both the design and manufacturing attributes. Most commercial parts coding systems are based on this method as it best serves the need of design and production.

There will invariably be some new parts for which editing of the existing process plan may be required. This is done when the manufacturing requirements of the new part vary slightly from the standard. The machine routing may be the same for the new part, but the specific operations required at each machine may be different. The complete process plan documents the operations as well as the sequence of machines through which the part must be routed (Figure 2.3). This type of CAPP system is sometimes referred to as a *variant system* because of the alterations that are made in the retrieved process plan.

Finally, the process formatter interprets and stores the information into a new process plan. At this stage other application programmes may be employed to add other information to the process plan, such as individual component and process costs.



**Figure 2.3** - Showing information flow in a retrieval-type computer-aided process planning system.

**Generative process plans** involves the use of computers which use a set of algorithms to create process plans from inception automatically and without human intervention (a data base is created based on the knowledge and experience gained through human process planners in computer programs). Inputs to the system include complete sets of specifications and drawings. This might involve the use of some form of part code number to summarise the workpart data, however, it does not involve the retrieval of existing standard plans. Generative CAPP systems on the contrary, synthesize the design of the optimum process sequence, and machine and time estimates based on the analysis of part geometry, material, type of surface finish required, and various other factors which would influence manufacturing decisions [76].

#### **2.1.2.1 Example of a generative CAPP system :**

GENPLAN [76] is close to a generative process planning system, but it requires a human planner to assist with some of the manufacturing decisions. Several versions of GENPLAN are available (one for parts fabrication and another for assembly), which means that it is not a system of universal applicability.

To operate the system, the planner enters a part classification code using a code scheme developed at Lockheed-Georgia. GENPLAN then analyses the characteristics of the part based on the code number (eg. part geometry, workpiece material, and other manufacturing related features) to synthesize an optimum process plan. It does not store standard process plans. Rather, it stores machine tool capabilities and it employs the logic and technological science of manufacturing. The output is a document specifying the sequence of operations, machine tools, and calculated process times. Process plans that required several hours to accomplish manually are now completed by GENPLAN in 15 minutes [76].

#### **2.1.3 State of the art CAPP systems :**

Iwata and Sugimura [77] in their research work developed an integrated CAD/CAPP system called CIMS (Computer Aided Integrated Manufacturing System) with know-hows of experienced process planners. The CIMS constructs the models of the parts interactively and generates the sequence of machine tools and the machining sequence on the basis of the information included in the models of the parts. The basic constitution of the CIMS is summarised in Figure 2.4 below.

This system consists of an interactive modelling subsystem, a knowledge base and a generative type process planning subsystem (Figure 2.4). The interactive modelling subsystem constructs the 3-D solid models of the parts which include both the geometrical and technological information such as material data, surface roughness data and accuracy data. These models are then directly transferred to

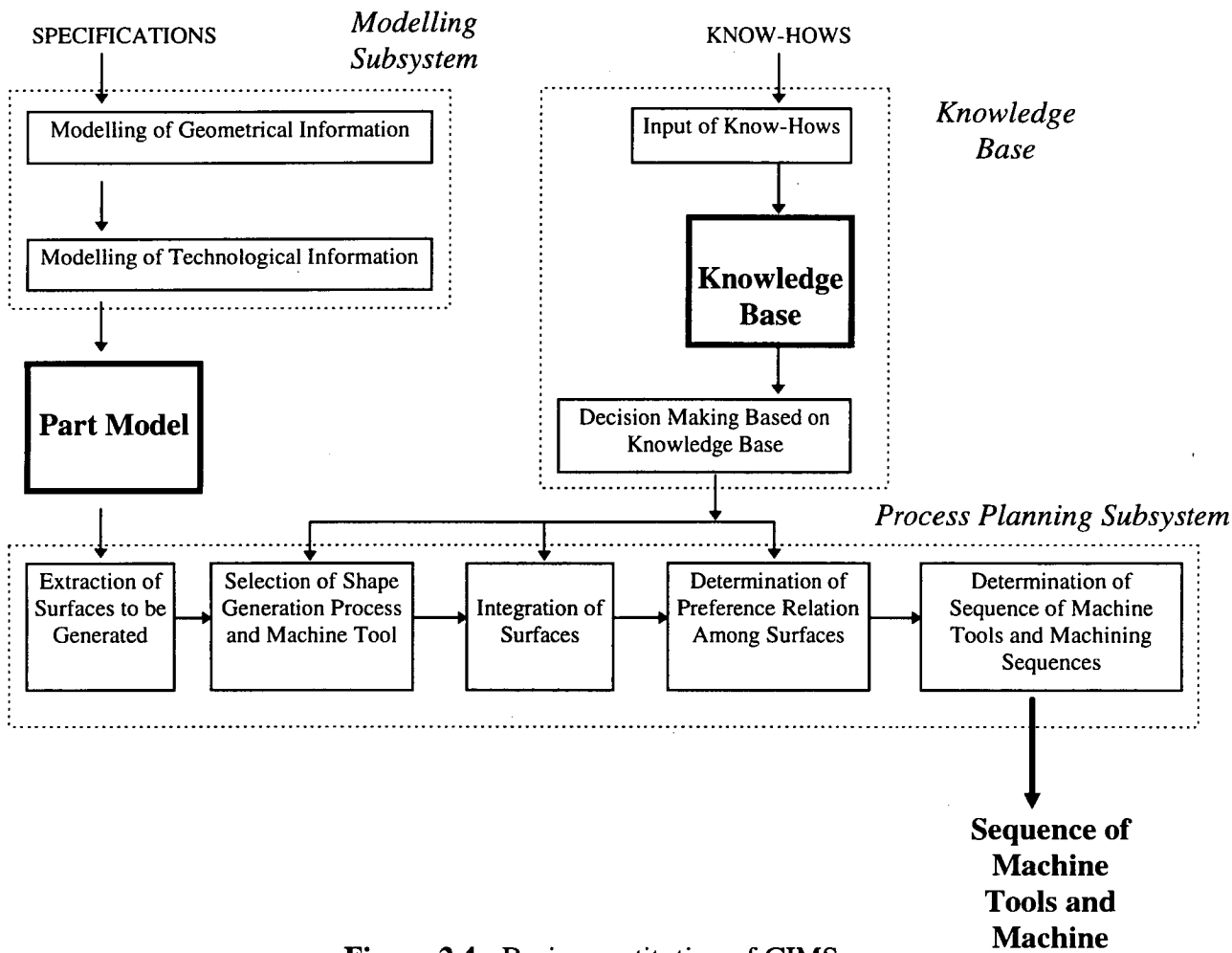


Figure 2.4 - Basic constitution of CIMS.

the process planning subsystem where the suitable sequence of machining tools and the machining sequence are generated based on the models of the finished part and the blank part constructed by the modelling subsystem. In the process planning stage the following steps are carried out :

1. All the surfaces to be machined are extracted by comparing the models of the finished part to the blank part.
2. Necessary combinations of the cutting motions, feed motions, and the geometries of the cutting edges are determined for each surface by analysing the geometry of the surface. Feasible machine tools are also selected.
3. If the surfaces are machined by one machining process, the surfaces are connected and integrated eg. the grooves and steps are recognised.
4. Based on the machining accuracy and the surface roughness, the preference relations among the machining processes of the surfaces are determined. The preference relations obtained here constrain the sequence of machine tools and the machine sequence.
5. Finally, by arranging the feasible machine tools and the surfaces under the constraints of the preference relations, the sequence of machine tools and the machining sequence are determined.

The five steps which are carried out in the process planning subsystem mentioned above can logically provide many feasible process plans. When this scenario exists, the process planning subsystem refers to the “knowledge base” when decision making based on the know-hows is required. This knowledge base consists of know-hows, which have been put into the system and stored in advance, of the experienced process planners and can be modified and expanded as required. Basically, the field of artificial intelligence is employed here to use

the knowledge base with the real time process planning in a series of IF - THEN type rules. All the rules are then designated a 1 (if Yes) or 0 (if No) and undergo a systematic procedure to determine the suitable sequence of machine tools and the machining sequence under certain constraints.

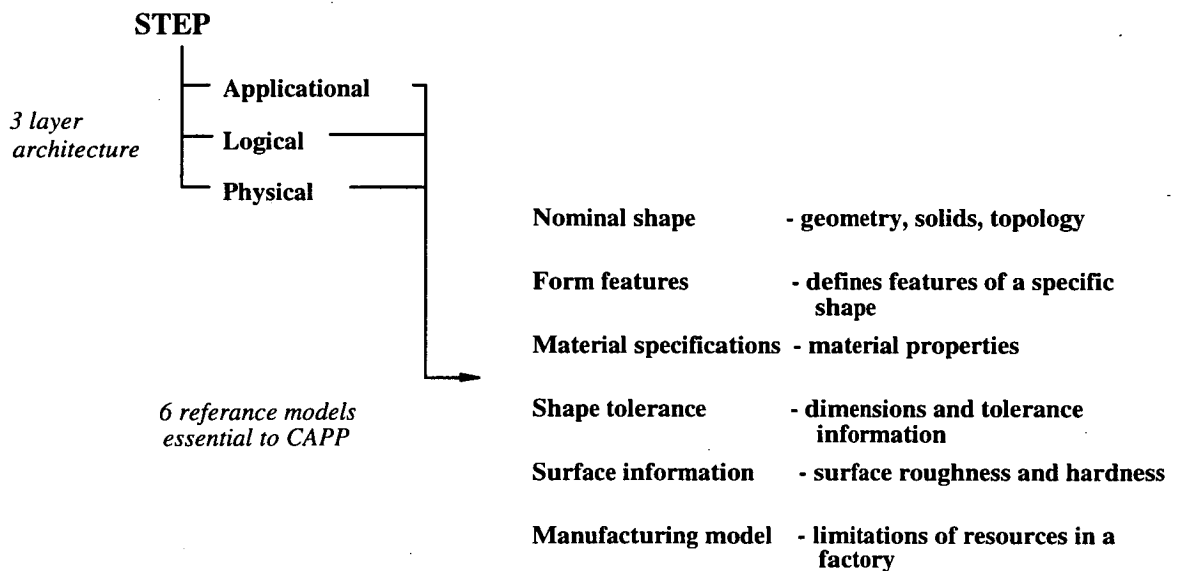
Currently, research is concentrated on graphical data conversion ie. CAD → CAPP interface. Current systems use solid models [78] since these models provide the most complete geometrical information output. Research to date concentrates on the aspects of feature modelling, feature extraction and feature refinement, using solid modeller information as a basis to create/extract the feature data, eg selection of cutting tools, speed, depth of cut and other performance parameters. Features of a given part include details like straight lines, curves, angles, holes, and their dimensions.

Neural networks seem to be the most effective mechanism for interpreting graphical data. With the advent of the STandard of the Exchange of Product Data (STEP), a new methodology exists for the development of CAPP systems. STEP is a neural product model data exchange mechanism that is capable of representing product definition data throughout the life cycle of a product. It is intended to be informationally complete for all engineering applications and to be interpretable by engineering applications.

Within STEP there exists a three layered architecture (Figure 2.5): application, logical and physical layers. The *application layer* develops a number of topical models specific to individual applications. The *logical layer* uses EXPRESS (an object-oriented information methodology), a language developed for defining

entities and their relationships with each other, describing all the topical models physically in the form of a schema [78]. The *physical layer* provides data structures to meet the data sharing and communication needs of the system.

Six reference models which are essential to CAPP can be identified using these three layers (Figure 2.5). The nominal shape model defines the entities used to create the shape of a part such as its geometry and topology. The form features and material specification models define features of a specific shape and describes material properties respectively. The shape tolerance model defines the dimension and tolerance information specified by ANSI Y14.5M - 1982 and ISO specifications. The surface information model defines information such as surface roughness and hardness. Finally, the manufacturing model defines the limitations of the resources within the factory eg. tools, machines, transportation mechanisms etc.



**Figure 2.5 - STEP structure.**

Attached to the inside back cover of this thesis is a copy of an on-screen simulation program. A listing of the program is given in Appendix 4. It is written in Qbasic and is compatible with G-Code. It is designed to simulate turning operations and to time the cutting operation. This program demonstrates the usefulness of simulation packages before conducting the operation practically as well as its place in CIM when integrated with other CIM components.

## 2.2 Concluding Remarks

It is evident that computer integrated manufacturing systems have developed to a very high level in the last 15 years. In particular, its various components such as CAD, CAPP and CAQC, and their compatibility, has improved in recent years to a level such that data transfer between the individual components is both accurate and efficient. Several packages are readily available today such as those offered by Sandvik - Coromant [79]. The latter offers products such as CoroPlan - a

machine operation planning system which helps the user to correctly choose the right tool and optimum cutting data, CoroTAS - a tool administration and logistics system for controlling tool stocks and tool flow to and from machines, CoroCAM - a graphical NC programming system linked to CoroPlan that generates and verifies NC programs for CNC machines based on an input of technology data from CoroPlan, and tool monitoring systems which comprise a range of sensors and associated control electronics to instantly inform the controller on detection of metal cutting problems. These systems together increase cutting efficiency, reduce planning time and ensure production consistency, increase machine utilisation, cut tool costs, ensure accurate tool data transfer, confirm methods before cutting, reduce machine waiting time, and recommend improvements to the management of the performance efficiency of machine tools.

The improvements made in integrating CAPP systems with technological data such as cutting speed and feed with the standard of the exchange of product data has led to almost fully automated production systems. However, the to develop a truly generic CAPP system lives on.

It is evident then, that further development of CIM systems is a worth while objective to attain more cost efficient production lined in manufacturing industry.

## Chapter 3

### Optimization for Single Pass Turning Operations

As mentioned in the literature survey, the study of unconstrained optimisation is a necessary component of arriving at constrained optimum solutions for single pass turning operations. This chapter covers in more detail the mathematical model developed for unconstrained single pass turning operations which is then applied to constrained optimisation. Thus the constraints specifically considered are the machine tool maximum and minimum spindle rotational speed and feed. The optimisation strategy is based on the minimum time per component (or maximum production rate) criteria. The optimised solutions generated by this model will then be compared to those obtained from real time simulations on a CNC lathe which uses handbook recommended parameter values and finally (if time permits) to those predicted by a trained neural network system. The purpose of this comparison is to demonstrate the value of using optimisation strategies as opposed to handbook recommendations and their potential application to the field of artificial intelligence.

### 3.1 Unconstrained Optimisation

In unconstrained optimisation for single pass turning operations with respect to maximum production rate, the unit production time ( $t$ ) has to be minimised with respect to the cutting speed ( $v$ ) and feed ( $f$ ) only since the depth of cut is constant in single pass turning.

Unit production time is expressed in general form as

$$t = t_p + t_m + t_e = t_p + t_m + t_c \frac{t_m}{T} \quad (3.1)$$

where  $t$  is the production time per unit piece,  $t_p$  is the loading, unloading, idle set up time per component,  $t_m$  is the machining time per component,  $t_e$  is the tool-replacement time,  $t_c$  is the time required to replace worn cutting tool with a new one and  $T$  is the tool life.

The tool-life  $T$  (min/edge) and the machining time tool-life cutting speed exponent(min piece) is dependant upon feed rates  $f$  (mm/rev) and machining speed  $v$  (m/min). The general equation used for the tool-life  $T$  is

$$T = \frac{C_0}{f^{\frac{1}{m_0}} v^{\frac{1}{n_0}}} \quad (3.2)$$

where  $m_0$  is the tool-life cutting speed exponent,  $n_0$  is the tool-life cutting speed exponent and  $C_0$  is the Taylor tool-life constant.  $m_0$ ,  $n_0$  and  $C_0$  values change for different tool-work combinations and can be found in Chinese handbooks [47,48,80].

Machining time  $t_m$  can be expressed as a function of machining speed and feed as

$$t_m = \frac{\lambda_o}{fv}, \quad \lambda_o = \lambda f \quad (3.3)$$

where  $\lambda_o$  is a machining constant.

Substituting equations (3.2) and (3.3) into equation (1.1), unit production time can be expressed as

$$t = t_p + \frac{\lambda_o}{fv} + t_c \frac{\lambda_o}{C_o} f^{\frac{1}{m_o}-1} v^{\frac{1}{n_o}-1} \quad (3.4)$$

Similarly, substituting equation (3.2) and (3.3) into equation (1.2), unit production cost can be expressed as

$$u = m_c + k_l t_p + (k_l + k_m) \frac{\lambda_o}{fv} + (k_l t_c + k_t) \frac{\lambda_o}{C_o} f^{\frac{1}{m_o}-1} v^{\frac{1}{n_o}-1} \quad (3.5)$$

Substituting  $m$  for  $\frac{1}{m_o} - 1$ ,  $n$  for  $\frac{1}{n_o} - 1$ ,  $a$  for  $\frac{t_c}{C_o}$  or  $\frac{(k_l t_c + k_t)}{(k_l + k_m) C_o}$ , and  $z$  for  $\frac{t}{\lambda_o}$  or

$\frac{u}{(k_l + k_m) \lambda_o}$  and omitting the constant terms  $\frac{t_p}{\lambda_o}$  or  $\frac{m_c + k_l t_p}{(k_l + k_m) \lambda_o}$  the following

general goal function is obtained:

$$z = \frac{1}{fv} + af^m v^n \quad (3.6)$$

Thus, although the values of the optimum cutting conditions eg speed and feed will be numerically different, the production time per component ( $t$ ) and production cost per component ( $u$ ) characteristics and optimisation strategies for selecting the optimum cutting conditions for these two criteria will be the same.

However, the mathematics is less complex for the production time per component and only time data is necessary to arrive at the optimum cutting conditions.

In single pass turning operations the cutting time ( $t$ ) is given by

$$t = \frac{\pi DL}{vf} \quad (3.7)$$

where  $D$  is the workpiece diameter,  $L$  is the length to be cut,  $v$  is the surface cutting speed and  $f$  is the feed rate.

The index constants  $m$  and  $n$  are usually related as  $0 < m < n$ , since in practice  $0 < n_o < m_o < 1$  from the stand point of metal cutting practice.

Unconstrained optimization (minimisation) of equation (3.6) is done by setting partial derivatives of this equation with respect to each of the decision variables, feed rate ( $f$ ) and machining speed ( $v$ ) equal to zero and thus obtaining

$$\frac{\partial z}{\partial f} = -\frac{1}{f^2 v} + amf^{m-1}v^n = 0 \quad (3.8)$$

$$\text{ie } amf^{m+1}v^{n+1} = 1 \quad (3.9)$$

and

$$\frac{\partial z}{\partial v} = -\frac{1}{fv^2} + amf^m v^{n-1} = 0 \quad (3.10)$$

$$\text{ie } amf^{m+1}v^{n+1} = 1 \quad (3.11)$$

From equations (3.8) and (3.10) the  $f$  - or  $v$  -minimum point for a fixed value of  $v$  or  $f$  is obtained as

$f$  -minimum point:

$$f^* = \frac{1}{(amv^{n+1})^{\frac{1}{m+1}}} \Bigg|_{v: \text{fixed}} \quad (3.12)$$

$v$  -minimum point:

$$v^* = \frac{1}{(anf^{m+1})^{\frac{1}{n+1}}} \Bigg|_{f: \text{fixed}} \quad (3.13)$$

If the values of  $v$  and  $f$  in equations (3.12) and (3.13) change, the loci of  $f$  and  $v$  are called the  $f$  -minimum line and  $v$  -minimum line respectively. The equations of these minimum lines are given as follows

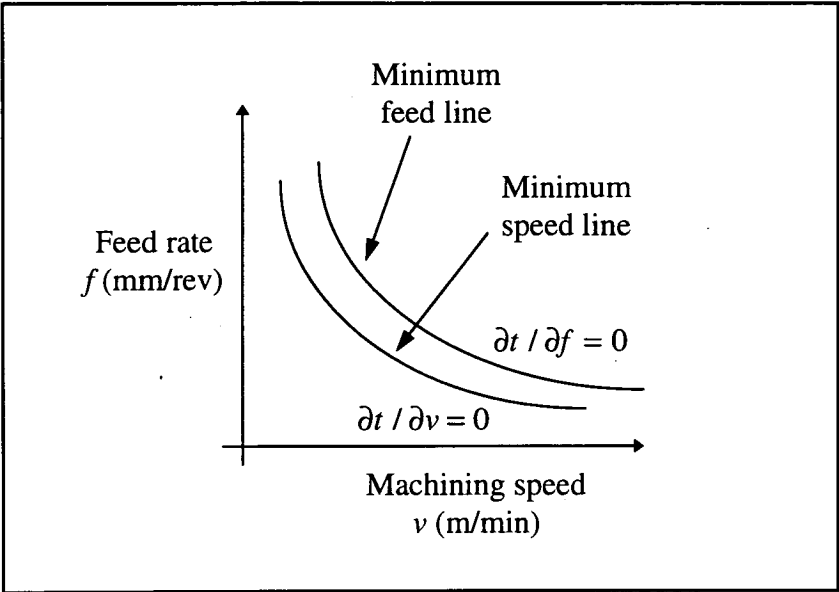
$f$  -minimum line:

$$f = \frac{1}{(am)^{\frac{1}{m+1}} v^{\frac{n+1}{m+1}}} \quad (3.14)$$

$v$  -minimum line:

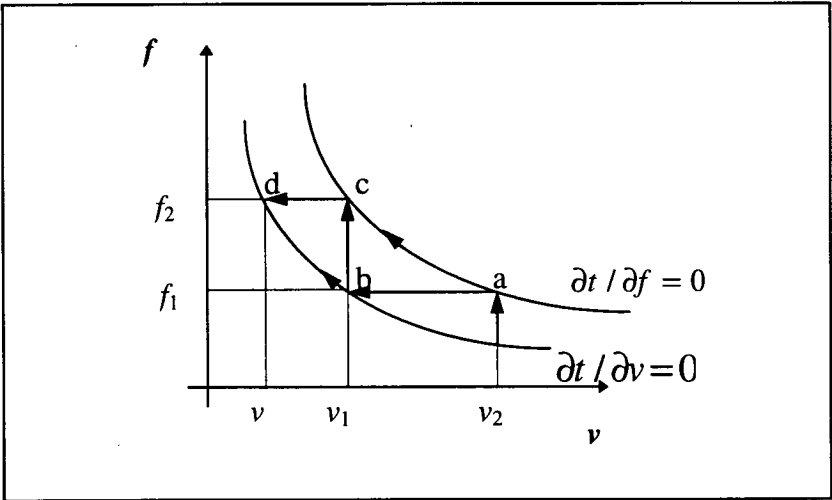
$$f = \frac{1}{(an)^{\frac{1}{m+1}} v^{\frac{n+1}{m+1}}} \quad (3.15)$$

In the practical case where  $0 < m < n$ , the  $f$  -minimum line always lies above the  $v$  -minimum line as shown in Figure 3.1.



**Figure 3.1** -  $f$  and  $v$  minimum lines in the speed- feed domain.  $z$ -value decreases infinitely as  $f \rightarrow \infty$  and  $v \rightarrow 0$ .

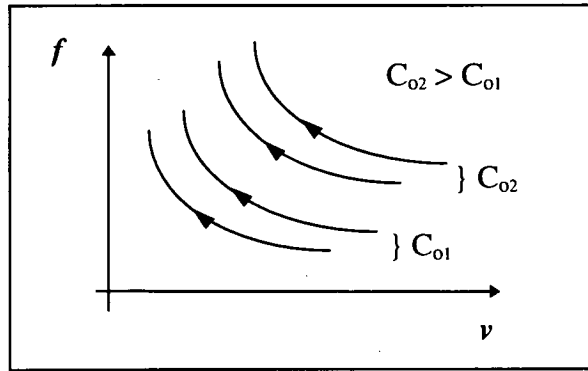
From equations (3.8) and (3.10), it can be shown that the bigger feed value will produce a smaller production time per component ( $t$ ) on the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci. The arrowhead in Figure 3.2 indicate the direction towards lower  $t$  values.



**Figure 3.2** -  $t$  characteristics and the loci of unconstrained optimum conditions

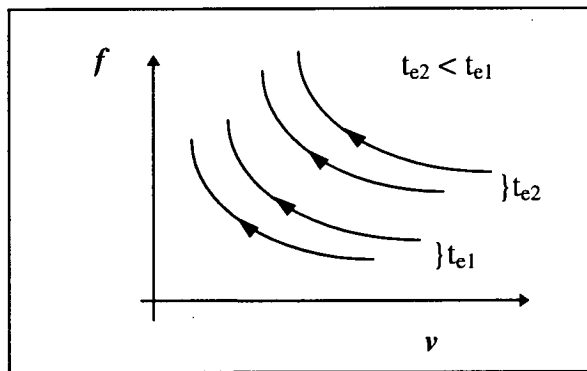
For a given feed when  $\frac{1}{n_o} > \frac{1}{m_o} > 1$ , the point on the  $\partial t / \partial v = 0$  loci always produces a minimum  $t$  value, and for a given speed the corresponding point on the  $\partial t / \partial f = 0$  loci always produces a minimum  $t$  value. In Figure 3.2, for a given speed  $v_1$ ,  $t(f_2)$  on the  $\partial t / \partial f = 0$  loci (point c) is minimum and for a given feed  $f_2$ ,  $t(v)$  on the  $\partial t / \partial v = 0$  loci (point d) is a minimum. The direction of the arrowhead (Figure 3.2) between the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci indicate the trends toward lower  $t$  values. Hence, it can be generalised that any point that lies between these two curves is a feasible solution but not the optimum solution. In Figure 3.2 the time per component ( $t$ ) at points a, b, c and d on the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci are in the sequence  $t_d < t_c < t_b < t_a$ . Upon observation of this fact, the time per component ( $t$ ) decreases as feed ( $f$ ) increases and the corresponding speed ( $v$ ) decreases.

It is found that for a given tool and workpiece combination and tool geometry (tip radius, insert thickness, insert shape etc), the values of  $n_o$ ,  $m_o$  and  $C_o$  will be constant and are available from the tool-life equation data in Chinese handbooks [47,48,80]. Further, when the time to replace a worn cutting tool ( $t_e$ ) and the depth of cut are fixed the positions of the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci remain fixed. However, on changing the tool-workpiece combinations and hence changing the values of  $n_o$ ,  $m_o$  and  $C_o$ , the positions of the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci will change in the  $v$ - $f$  domain, using the same values of  $t_e$  and depth of cut. From equations (3.14) and (3.15), when the value of  $C_o$  increases the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci shift towards higher  $v$ - $f$  values as shown in Figure 3.3.



**Figure 3.3** - Effect of  $C_o$  on the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci.

From equations (3.14) and (3.15), when the value of  $t_e$  increases the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci shift towards lower  $v$ - $f$  values as shown in Figure 3.4.

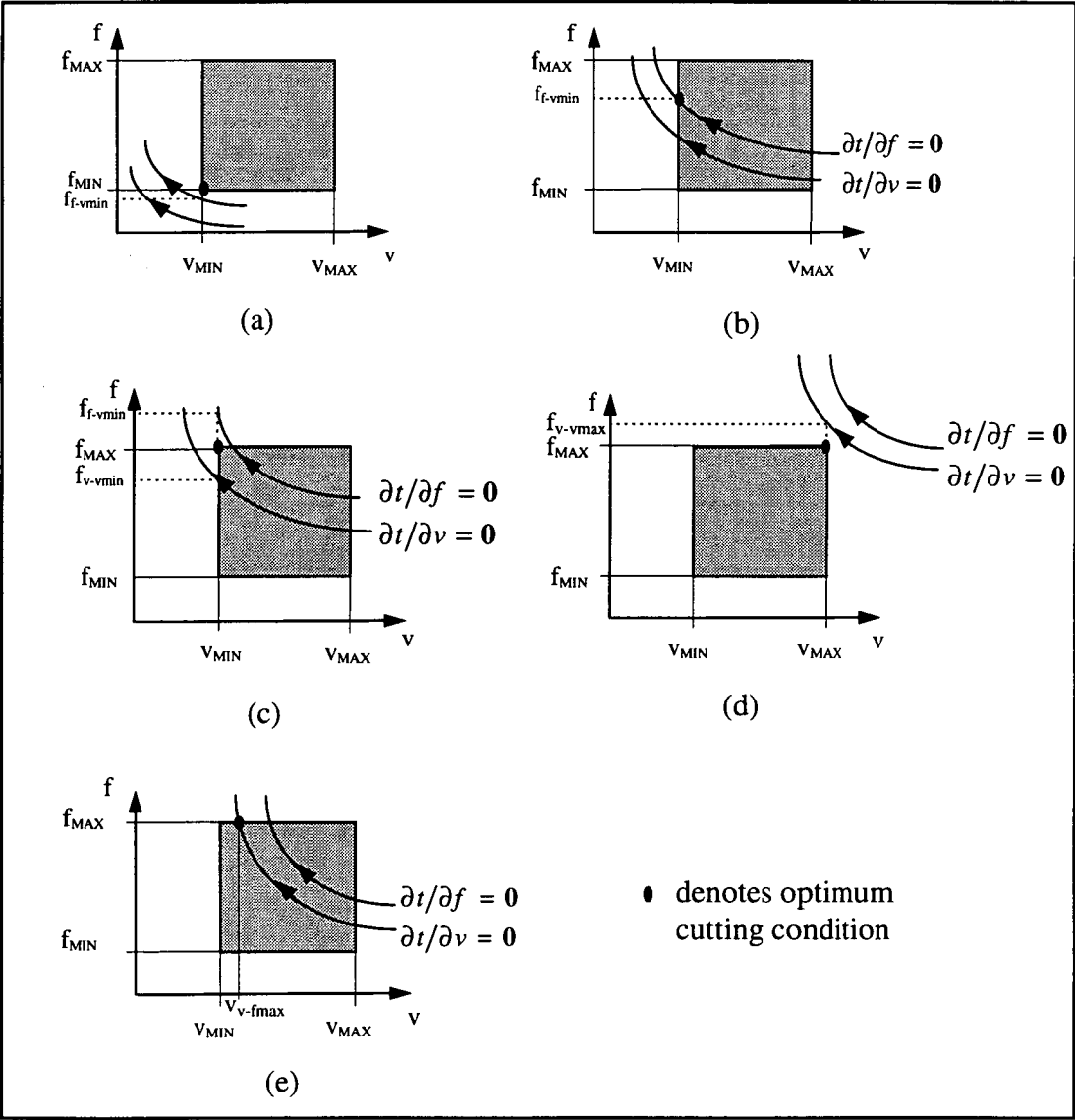


**Figure 3.4** - Effect of  $t_e$  on the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci.

From this study of  $t$  trends in the  $v$ - $f$  domain it is evident that to achieve optimised cutting conditions the general trend is to select high feed-low speed combinations when the usual tool-life equation exponent values apply ie when  $\frac{1}{n_o} > \frac{1}{m_o} > 1$ . A unique set of machining speed and feed rate cannot be determined for unconstrained minimisation of production time. The optimisation must be performed by taking into consideration practical manufacturing constraints to obtain constrained optimised solutions.

### 3.2 Constrained Optimisation

The two constraints that are used in this analysis are minimum and maximum feed rate ( $f$ ) and machining speed ( $v$ ), ie  $f_{\min} < f < f_{\max}$  and  $v_{\min} < v < v_{\max}$  respectively. These constraints are determined by the work diameter ( $D$ ) and the lowest and highest speeds of the spindle in the machine tool employed.



**Figure 3.5 - Optimum cutting conditions with feed and machine speed constraints.**

As already mentioned in the previous section, the optimum cutting conditions will be affected by the machine tool speed-feed boundary conditions. It was also noted in the previous section that the positions of the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci change relative to the machine speed-feed boundaries for different tool-workpiece combinations ie  $n_o$ ,  $m_o$  and  $C_o$ , using the same values of  $t_e$  and depth of cut. In total, five different general scenarios exist in the  $v$ - $f$  domain, which lead to distinctly different optimum solutions as shown in Figure 3.5. Within these five scenarios there exist many different relative positions of the  $\partial t / \partial f = 0$  and  $\partial t / \partial v = 0$  loci as well as the speed-feed boundaries in the  $v$ - $f$  domain depending on the tool-workpiece material combination used.

Defining  $f_{f-vmin}$  as the feed on the  $\partial t / \partial f = 0$  loci and  $v_{min}$

$f_{v-vmin}$  as the feed on the  $\partial t / \partial v = 0$  loci and  $v_{min}$

$f_{v-vmin}$  as the feed on the  $\partial t / \partial v = 0$  loci and  $v_{min}$

and  $v_{v-fmax}$  as the cutting speed on the  $\partial t / \partial v = 0$  loci and  $f_{max}$

The five scenarios shown in Figure 3.5 that can occur in the  $v$ - $f$  domain for different tool-workpiece combinations are:

- a. When the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci fall below  $f_{min}$  and  $v_{min}$ , the optimum solution is at  $f_{min}$  and  $v_{min}$ .
- b. When  $f_{min} < f_{f-vmin} < f_{max}$ , the optimum feasible solution is at  $f_{f-vmin}$  and  $v_{min}$ .
- c. When the maximum feed is in the range  $f_{v-vmin} < f_{max} < f_{f-vmin}$ , the optimum feasible solution is at  $f_{min}$  and  $v_{max}$ .

- d. When the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci are beyond the allowable range of machine speed and feed and maximum feed is in the range  $f_{\min} < f_{\max} < f_{v-\max}$ , the optimum solution is at  $f_{\max}$  and  $v_{\max}$ .
- e. When the speed  $v_{v-f_{\max}}$  is between  $v_{\min}$  and  $v_{\max}$ , the optimum solution is at  $f_{\max}$  and  $v_{v-f_{\max}}$  according to the trend along the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci.

This analysis has shown that even with two constraints ie speed and feed, there are several clearly definable solution types in the speed-feed domain which are dependant on the tool-workpiece combination with fixed values of cutting tool replacement time and the workpiece diameter.

### 3.3 Application of Mathematical Model

The mathematical modelling of finding the optimum cutting conditions is done using Microsoft Excel (Version 5). Equations 3.14 and 3.15 when defined and plotted plot the minimum speed and feed loci in the  $v$ - $f$  domain. Three tool - workmaterial combinations are used

Carbide-Carbon steel

Carbide-Cast iron

and

Carbide-Stainless steel

each with their associated  $n_o$ ,  $m_o$  and  $C_o$  values which are obtained from Chinese handbooks [43, 44, 80]. The tool replacement time ( $t_c$ ) was chosen to be 2 minutes. A machining speed ( $v$ ) range of  $10 < v < 710$  in steps of 10 m/min was

used to obtain a sample of speed-feed data points. The latter were then plotted to obtain the minimum speed and feed loci ie  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci in the  $v$ - $f$  domain. Finally, appropriate values of minimum and maximum feed and speed were overlayed on the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci to determine the optimum cutting speed and feed for the particular tool-workpiece combination. The production time per component  $t$  (sec) can then be calculated using

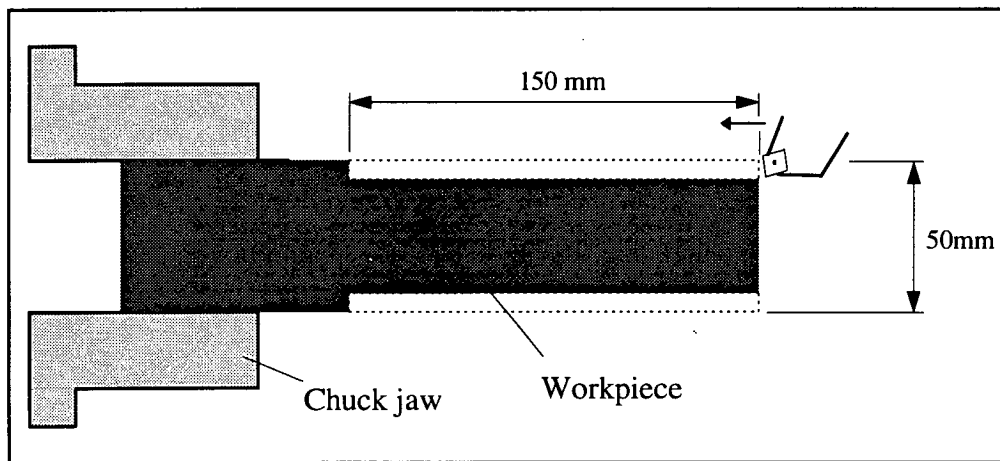
$$t = \frac{L}{fN} \quad (3.16)$$

where  $L$  = machining distance (mm)

$f$  = feed per revolution (mm/r)

$N$  = number of spindle revolutions (r/min)

The sample workpiece (Figure 3.6) has the following dimensions



**Figure 3.6** - workpiece geometry and dimensions.

The complete results from the mathematical model are listed in Appendix 1.

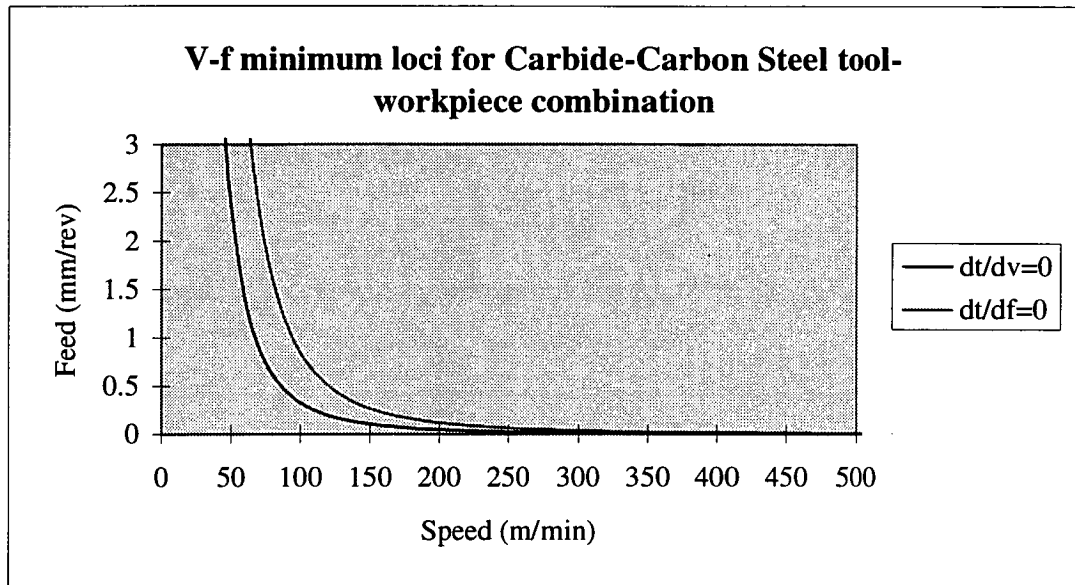
**3.4 - Results of Mathematical Model**

Table 3.1 shows the results of machining time per component for different speed-feed combinations. Note that a random value of feed is used for each value of machining speed since each value of machining speed has a range of feasible feeds associated with it (see Chapter 4, Section 4.2).

Table 3.1 - Machining time per component for Carbide-Carbon steel tool-work combination

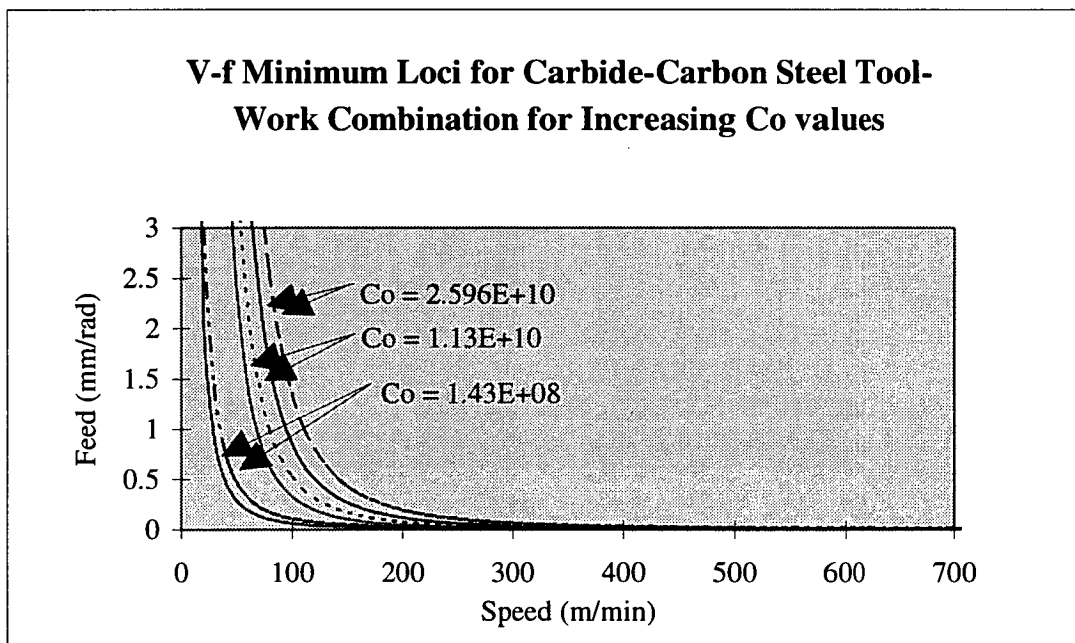
Table 3.1- Machining time obtained from mathematical model & real time simulations				
Co	Speed (m/min)	V-min		Time Random feed (sec)
		loc1	F-min	
2.60E+10	Feed1 (mm/rev)	2.60E+10	Feed1 (mm/rev)	
10	372.7283096	964.5799332	386.4752744	0.3657974
20	51.69599421	133.7835559	95.44333176	0.7406053
30	16.27784106	42.12526508	20.57637281	2.2901942
40	7.170037125	18.55526869	12.67561388	2.7882608
45	5.125505636	13.26424572	5.12550564	6.129332
50	3.79601454	9.823668763	6.025232968	4.692654
60	2.257674439	5.842613518	3.439941578	6.8495189
70	1.45499907	3.765379976	1.574544007	12.826573
80	0.994456788	2.57354496	1.553873138	11.372523
90	0.710888073	1.839700265	1.221234567	12.862364
100	0.526492731	1.36250537	0.841502933	16.799902
110	0.401257559	1.038410498	0.892909	14.39337
120	0.313130829	0.8103482	0.546056254	21.57465
130	0.249260709	0.6450509341	0.620021513	17.539301
140	0.201802935	0.522243834	0.504497887	20.015894
150	0.16578006	0.429020589	0.251725545	37.440689
160	0.137927362	0.356940865	0.285280453	30.972081
170	0.116041398	0.3003032396	0.266450134	31.21027
180	0.098597463	0.255159406	0.240472333	32.660646
190	0.084517106	0.218720989	0.205766982	36.160389
200	0.073022533	0.188974296	0.100970925	70.006128
210	0.063542952	0.164442183	0.105176199	64.006727
220	0.055652892	0.144023574	0.106236871	60.487333
230	0.049030695	0.126886054	0.112755696	64.512495
240	0.043430051	0.112392203	0.09508608	61.948986
250	0.038660134	0.100048181	0.076802518	73.628663
260	0.034571509	0.089467269	0.051979346	104.60639
270	0.031046	0.080343638	0.056702189	92.341898
280	0.027988297	0.072433327	0.045676591	110.53776
290	0.0253525503	0.0655359621	0.051953872	93.831027
300	0.022993062	0.0595303519	0.035064827	134.39077
310	0.020941682	0.054194772	0.034664437	131.55778
320	0.019129999	0.049506336	0.022265656	198.4161
330	0.017527774	0.045349603	0.01762033	243.12768
340	0.016094499	0.041650796	0.023514274	176.82835
350	0.014818302	0.038348139	0.0277710823	145.7622
360	0.013675092	0.035389636	0.021391989	183.57296
370	0.012647872	0.032731304	0.020488647	186.4865
380	0.0117222	0.030335766	0.019703741	188.81222
390	0.010885747	0.028171119	0.019171394	189.07935
400	0.010127947	0.026210014	0.023844908	148.21998
410	0.009439704	0.024428918	0.0222749756	151.566
420	0.008813165	0.022807503	0.009050681	371.90483
430	0.008241519	0.021328147	0.019973354	164.60497
440	0.007718844	0.01997552	0.013750683	233.66057
450	0.007239969	0.018736245	0.01171491	268.17044
460	0.00680037	0.017598611	0.007331567	419.18692
470	0.006396074	0.016552337	0.009798977	306.9614
480	0.006023582	0.01558837	0.013514489	217.93226
490	0.005679807	0.014698716	0.012688015	227.39067
500	0.005362013	0.013876301	0.011233116	251.70518
510	0.005067776	0.0131114847	0.008036468	344.92882
520	0.004794936	0.012408769	0.0073444243	370.17917
530	0.004541571	0.011733088	0.008398785	317.59237
540	0.004305962	0.011143356	0.00536693	487.80101
550	0.004086568	0.010575589	0.005060364	507.94647
560	0.003882009	0.010046212	0.004077637	619.10718
570	0.003691042	0.009552013	0.008917737	278.12041
580	0.003512551	0.009090095	0.005635654	432.50391
590	0.003345524	0.008657849	0.006505625	368.31663
600	0.00318905	0.008252911	0.004978475	473.27633
610	0.003043302	0.007873144	0.006303627	367.65631
620	0.002904531	0.0075116608	0.004827563	472.32694
630	0.002775056	0.007181541	0.003364972	666.86873
640	0.002653258	0.006866634	0.006834721	323.19276
650	0.002538571	0.006569543	0.004574862	475.41301
660	0.002430481	0.006289817	0.003972772	539.16893

Graph 3.1 shows the predicted trend between speed and feed ie as machining speed increases feed decreases.



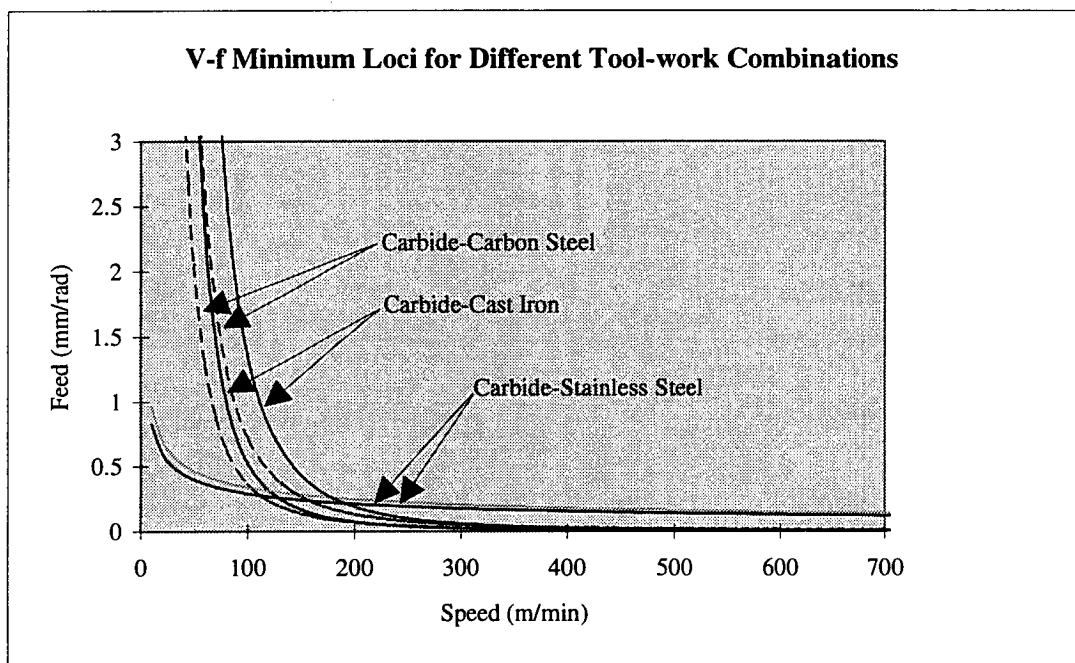
**Graph 3.1** - showing the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci in the  $v$ - $f$  domain.

Graph 3.2 below shows the trend as predicted earlier ie as  $C_o$  increases the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci shift towards higher speed and feed values.



**Graph 3.2** - showing predicted trends for increasing  $C_o$  values.

Finally Graph 3.3 shows the different  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci for different work materials. Note the stainless steel displays a much different loci in the v-f domain compared to carbon steel and cast steel. This behaviour can be explained by the fact that stainless steel is a relatively “sticky” material to cut ie it adheres to the tool when worked on. This property of stainless steel results in it being very sensitive to machining speed as displayed by the relatively flat curves in Graph 3.3.



**Graph 3.3** - showing the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci for different tool-work combinations.

Optimum cutting conditions can therefore be determined if the machine tools' maximum and minimum speeds and feeds are known. It should be noted that the maximum and minimum speeds and feeds for different CNC machine tools vary according to the capacity of the particular machine tool concerned.

### 3.4 Concluding Remarks

An optimisation strategy for selecting the optimum cutting speed and feed has been developed and discussed for single pass turning operations on CNC machine tools. The optimisation is based on the maximum production rate (minimum time per component) criteria in the analysis. The constraints used are the maximum and minimum feed rates, and the machine tools limiting speed ie  $v_{\min}$  and  $v_{\max}$ . The extended Taylor-type tool-life equation and data from comprehensive Chinese cutting data handbooks is used in the mathematical model. Standard tool-workpiece combinations such as carbide tool with carbon steel, cast iron and stainless steel and their associated coefficient values ( $1/n_0$  and  $1/m_0$ ) are used in the analysis as a basis for comparison for data obtained using a CNC machine tool.

The strategy adopted for this analysis is one that has been developed in earlier studies at Melbourne University. By using classical mathematics to facilitate an optimum solution in conjunction with graphical representation in the speed-feed domain, unique optimum cutting conditions ie speed and feed can be immediately determined.

It should be mentioned that additions of extra constraints such as the three force constraints, power and torque constraints would add significantly to the complexity of the analysis and have not been considered in this study.

Since the equations for time per component ( $t$ ) and cost per component ( $u$ ) are mathematically similar, the same solution strategy can be adopted in determining

optimum solutions by allowing for the tool changing time ( $t_c$ ) and the constant in the objective function. However, the optimum solutions will be different in value.

It was also apparent from the analysis that a reduction in tool changing time significantly reduces the time per component which indicates the need to improve tool changing times in industry, especially since it is a non-value adding operation. These results have highlighted the fact that adopting optimisation strategies is a worthwhile, cost saving exercise and that it should be used in the manufacturing industry to improve the efficiency of machining operations.

## Chapter 4

### Real Time Optimisation On CNC Lathe

In this chapter, the experimental procedure to obtain time data is described and presented. The purpose of gathering time data is to compare results obtained from the combined mathematical and graphical model to those obtained from real time simulations on a CNC lathe. The data also indicates the actual optimum cutting conditions for a given machine tool.

In Chapter 3 the optimisation of machine parameters for single pass turning operations using a combined mathematical and graphical model was analysed. The constraints used were the limiting machine spindle speed and feed rate. The popular Taylor-type tool-life equation was used in the analysis. The diameter effect was not considered in the analysis as it does not have an adverse effect in single pass turning operations. The maximum production rate criterion was used as the criteria objective function in obtaining the optimum cutting conditions.

It should be stressed again that the combined mathematical and graphical model uses only limiting machine spindle speed and feed rate as constraints. In contrast, the real time simulation on the CNC lathe uses several practical constraints in its decision making to obtain the optimum cutting conditions.

### 4.1 Machine Tool and Tool-Workpiece Specifications

**CNC Machine Tool:**

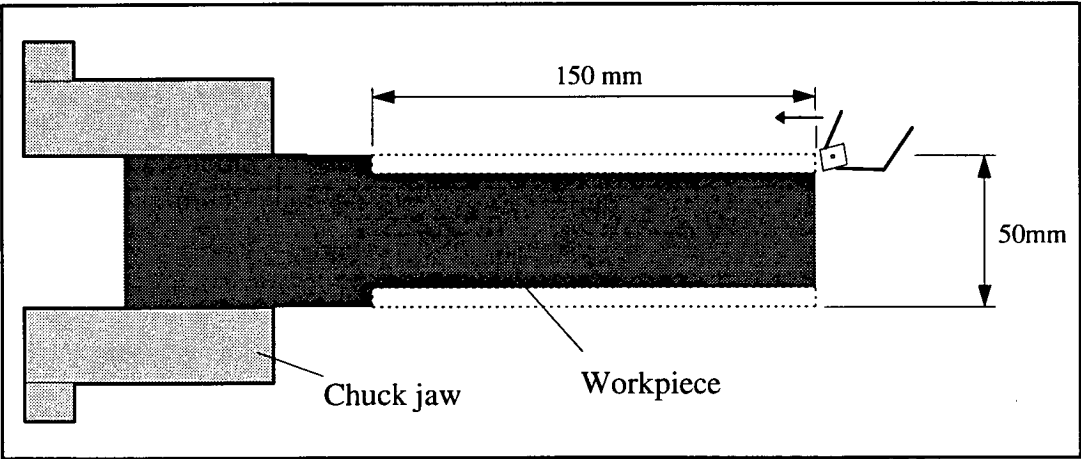
MAZAK Quick Turn 15N
(Model: SQT 15N by YAMAZAKI Machinery UK LTD.)
Control Unit: MAZATROL T PLUS
Speed Limits: 45-4500 (rpm)
Spindle Drive Motor = 11 kW
Maximum Length of Work = 451mm
Maximum Diameter of Work = 254mm

**Workpiece Specifications:**

The following tool-work combinations were used -

Tool-work Combination	1/n <sub>o</sub>	1/m <sub>o</sub>	C <sub>o</sub>
Carbide-Carbon steel (55 kg force per mm <sup>2</sup> )	5.0	1.75	2.60E+10
Carbide-Cast iron (forgable 150 BHN)	8.0	2.64	1.75E+13
Carbide-Stainless steel	3.0	6.67	3.41E+03

The geometry of the workpiece used in the simulation is shown in Figure 4.1.



**Figure 4.1** - workpiece geometry and configuration.

The cut diameter of 42mm which corresponds to a 4mm depth of cut was used for the single pass operation. The cut length used was 150mm.

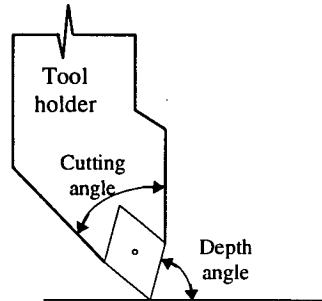
**Insert specifications:**

Right hand carbide insert -

Depth angle =  $95^\circ$

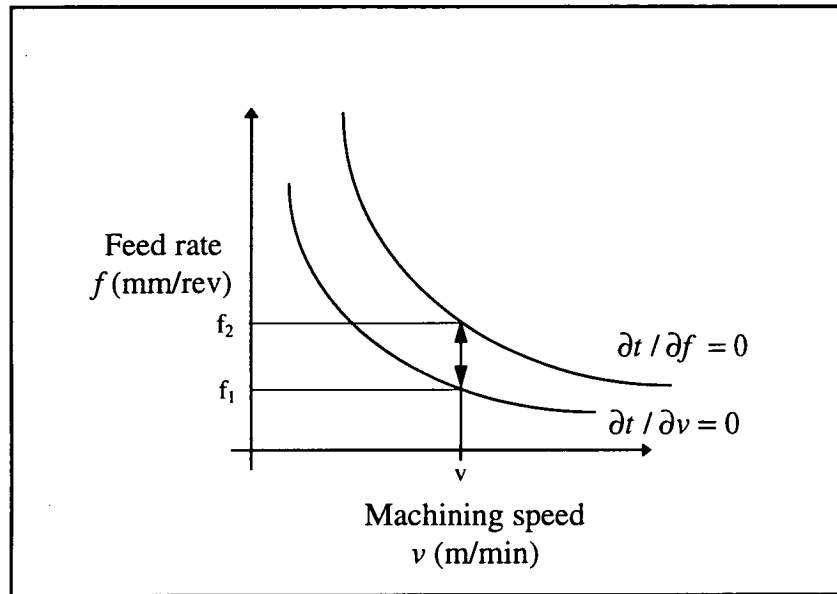
Cutting angle =  $80^\circ$

Nose radius = 0.8mm

**4.2 Description of Experimental Method**

In Chapter 3 the machining time per component were calculated for a range of machining speeds ( $v$ ). However, each value of speed had associated with it a range of feasible feed rates ( $f_1 - f_2$ ) between the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci ie the minimum speed and feed curves when the objective function ( $t$ ) is differentiated with respect to speed and feed, Figure 4.2.

In actual fact, an infinite number of feeds exists for any given value of machining speed. For the experiment to be viable, only one value of feed from the feasible feed range was randomly chosen. The speed range is determined by the minimum and maximum machine tool spindle speed ( $N_{\min}$  and  $N_{\max}$ ). Data from the machine tool was acquired in speed steps of 20m/min which enabled a total of approximately 30 measurements to be recorded.



**Figure 4.2** - feasible feed range for a given value of machining speed.

The MAZATROL control unit which is mounted onto the MAZAK Quick Turn 15N was used to simulate real time single pass turning operations. Speed and feed data obtained from the mathematical model were entered in the on-screen program and time trials for various combinations of speeds and feeds were performed and recorded.

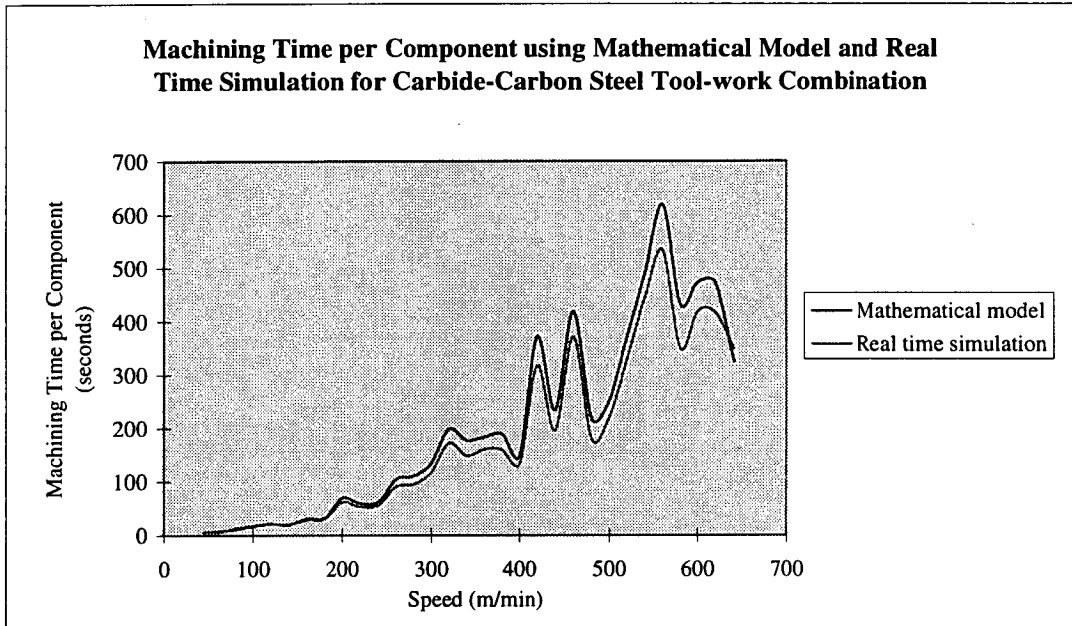
Table 4.1 shows the results obtained using the carbide-carbon steel tool-work combination. Full details of the results are presented in Appendix 1.

Unfortunately, the accuracy of simulated time was to the nearest second which meant that accurate comparisons could not be made with the time values obtained from the mathematical model. However, this is alright for the purpose of this comparison. It was also found that the MAZATROL T PLUS control unit could not facilitate feed values with more than three decimal places. This became a

Table 4.1 - Machining time obtained from the mathematical model and real time simulations					
Co	V-min loci 2.60E+10	F-min loci 2.60E+10	Random feed	Time (sec)	Real time (sec)
Speed (m/min)	Feedl (mm/rev)	Feedl (mm/rev)			
10	372.7283096	964.5799332	386.4752744	0.3657974	
20	51.69599421	133.7835559	95.44333176	0.7406053	
30	16.27784106	42.12526508	20.57637281	2.2901942	
40	7.170037125	18.55526869	12.67561388	2.7882608	6
45	5.125505636	13.26424572	5.12550564	6.129332	7
50	3.79601454	9.823668763	6.025232968	4.692654	
60	2.257674439	5.842613518	3.439941578	6.8495189	5
70	1.454999907	3.765379976	1.574540007	12.826573	
80	0.994456788	2.57354496	1.553873138	11.372523	13
90	0.710888073	1.839700265	1.221234567	12.862364	
100	0.526492731	1.36250537	0.841502933	16.799902	18
110	0.401257559	1.038410498	0.892909	14.39337	
120	0.313130829	0.8103482	0.546056254	21.57465	21
130	0.249260709	0.645059341	0.620021513	17.539301	
140	0.201802935	0.522243834	0.504497887	20.015894	21
150	0.16578006	0.429020589	0.251725545	37.440689	
160	0.137927362	0.356940865	0.285280453	30.972081	29
170	0.116041398	0.300302396	0.266450134	31.21027	
180	0.098597463	0.255159406	0.240472333	32.660646	31
190	0.084517106	0.218720989	0.205766982	36.160389	
200	0.073022533	0.188974296	0.100970925	70.006128	62
210	0.063542952	0.16442183	0.105176199	64.006727	
220	0.055652892	0.144023574	0.106236871	60.487333	54
230	0.049030695	0.126886054	0.112755696	54.512495	
240	0.043430051	0.112392203	0.09508608	61.948986	56
250	0.038660134	0.100048181	0.076802518	73.628663	
260	0.034571509	0.089467269	0.051979346	104.60639	91
270	0.031046	0.080343638	0.056702189	92.341898	
280	0.027989297	0.072433227	0.045676591	110.53776	95
290	0.025325503	0.065539621	0.051953872	93.831027	
300	0.022993062	0.059503519	0.035064827	134.39077	117
310	0.020941682	0.054194772	0.034664437	131.55778	
320	0.019129999	0.049506336	0.022265656	198.4161	172
330	0.017523774	0.045349603	0.01762033	243.12768	
340	0.016094499	0.041650796	0.023514274	176.82835	148
350	0.014818302	0.038348139	0.027710823	145.7622	
360	0.013675092	0.035389636	0.021391989	183.57296	161
370	0.012647872	0.032731304	0.020488647	186.4865	
380	0.0117222	0.030335766	0.019703741	188.81222	159
390	0.010885747	0.028171119	0.019171394	189.07935	
400	0.010127947	0.026210014	0.023844908	148.21998	133
410	0.009439704	0.024428918	0.022749756	151.566	
420	0.008813165	0.022807503	0.009050681	371.90483	317
430	0.008241519	0.021328147	0.019973354	164.60497	
440	0.007718844	0.01997552	0.013750683	233.66057	195
450	0.007239969	0.018736245	0.01171491	268.17044	
460	0.00680037	0.017598611	0.007331567	419.18692	372
470	0.006396074	0.016552337	0.009798977	306.9614	
480	0.006023582	0.01558837	0.013514489	217.93226	179
490	0.005679807	0.014698716	0.012688015	227.39067	
500	0.005362013	0.013876301	0.011233116	251.70518	220
510	0.005067776	0.013114847	0.008036468	344.92682	
520	0.004794936	0.012408769	0.007344243	370.17917	328
530	0.004541571	0.011753088	0.008398785	317.59237	
540	0.004305962	0.011143356	0.00536693	487.80101	443
550	0.004086568	0.010575589	0.005060364	507.94647	
560	0.003882009	0.010046212	0.004077637	619.10718	533
570	0.003691042	0.009552013	0.008917737	278.12041	
580	0.003512551	0.009090095	0.005635654	432.50391	349
590	0.003345524	0.008657849	0.006505625	368.31663	
600	0.00318905	0.008252911	0.004978475	473.27633	418
610	0.003042302	0.007873144	0.006303627	367.65631	
620	0.002904531	0.007516608	0.004827563	472.32694	417
630	0.002775056	0.007181541	0.003364972	666.86873	
640	0.002653258	0.006866634	0.006834721	323.19276	348
650	0.002538571	0.006569543	0.004574862	475.41301	
660	0.002430481	0.006289817	0.003972772	539.16893	695

problem at higher speed values where the feed did not vary much after three decimal places.

Graph 4.1 shows the time trend as machining speed increases. Note the normal distribution of the plot since the random value function in Excel 5.0 was used to randomly choose a feed value in the feasible feed range for a given speed value.



**Graph 4.1** - showing machining time per component increase as speed increases and feed decreases.

After time data from the real time simulation were recorded, a comparison between results obtained from the mathematical model and real time simulation was made. Table 4.2 makes a comparison between the machining time per component obtained by the mathematical model and the real time simulation by calculating the % deviation of the two values using

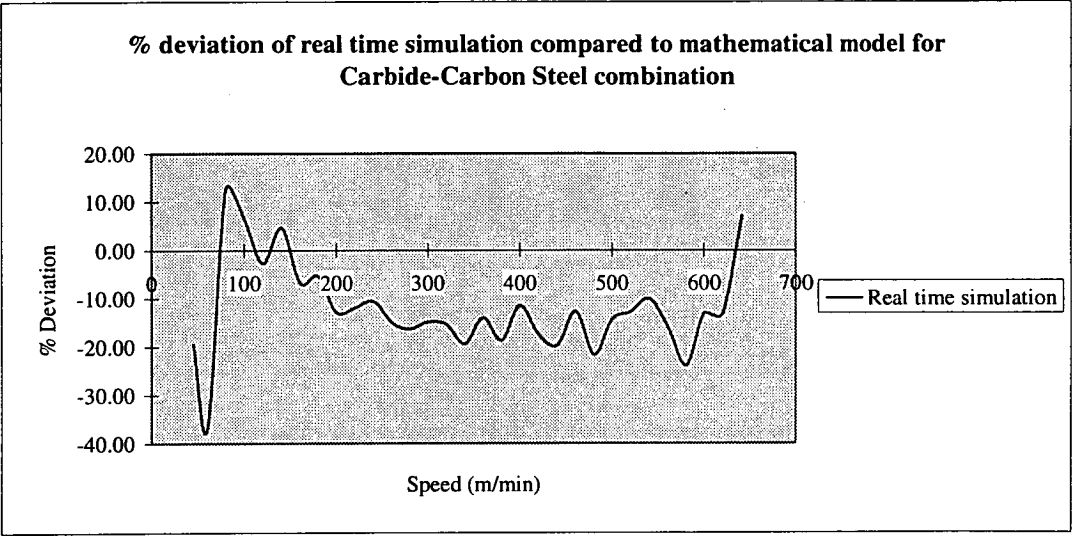
$$\% \text{ deviation} = \frac{t_{\text{simulated}} - t_{\text{math model}}}{t_{\text{simulated}}} \quad (4.1)$$

**Table 4.2 : comparison of machining time/component between mathematical model and real time simulation.**

Speed (m/min)	Time (seconds)		% Deviation
	Mathematical model	Real time simulation	
45	6.13	5.13	-19.49
60	6.85	5	-36.99
80	11.37	13	12.52
100	16.80	18	6.67
120	21.57	21	-2.74
140	20.02	21	4.69
160	30.97	29	-6.80
180	32.66	31	-5.36
200	70.01	62	-12.91
220	60.49	54	-12.01
240	61.95	56	-10.62
260	104.61	91	-14.95
280	110.54	95	-16.36
300	134.39	117	-14.86
320	198.42	172	-15.36
340	176.83	148	-19.48
360	183.57	161	-14.02
380	188.81	159	-18.75
400	148.22	133	-11.44
420	371.90	317	-17.32
440	233.66	195	-19.83
460	419.19	372	-12.68
480	217.93	179	-21.75
500	251.71	220	-14.41
520	370.18	328	-12.86
540	487.80	443	-10.11
560	619.11	533	-16.16
580	432.50	349	-23.93
600	473.28	418	-13.22
620	472.33	417	-13.27
640	323.19	348	7.13

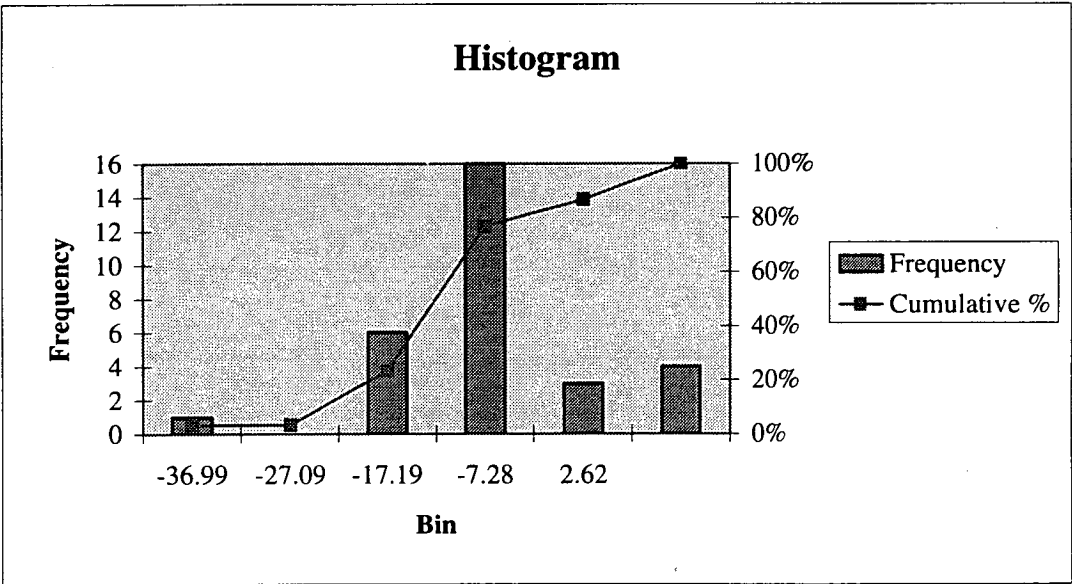
Note that a machining speed range of 45-640 m/min has been chosen. These are in fact the minimum and maximum machining speeds available on the MAZAK Quick Turn 15N CNC machine.

Graph 4.2 shows the percentage deviation between the machining time per component obtained from the mathematical model and the real time simulation.



**Graph 4.2** - percentage deviation between real time simulation and mathematical model.

However a more useful form of comparison is a histogram which indicates the frequency of occurrences within a percentage deviation value eg Graph 4.3 shows that there were 16 out of 30 occurrences where the real time simulation deviated from the mathematical model with a deviation of around -7% ie a lower machining time per component.



**Graph 4.3** - frequency of percentage deviation.

### 4.3 Discussion of Results

From the results of the mathematical model and time trials on the MAZAK CNC machine (Appendix 1) the following observations can be made.

All test results for the mathematical model conform with the theoretical predictions eg an increase in  $C_0$  values pushes the  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci towards higher machine speeds and feed values.

The optimum machining time per component for the three tool-work combinations using the mathematical model are (Table A1.1-A3.1 in Appendix 1):

Tool-work combination	Optimum Cutting Conditions		Optimum time
	Feed (mm/rev)	Speed (m/min)	
Carbide-Carbon steel	5.126	45	6.13 sec
Carbide-Cast steel	2.688	45	9.29 sec
Carbide-Stainless steel	0.487	45	64.56 sec

Note that all the optimum cutting times occur when machining speed is minimum and feed is maximum as predicted by the mathematical model.

When the turning operations were simulated in real time on the MAZATROL control unit, the machining time per component closely matched those obtained by the mathematical model. The plots of machining time per component vs speed for both methods are shown on Page X of Appendix 1. From these plots, the machining times per component ( $t$ ) from real time simulation were mostly less than those predicted by the mathematical model. The carbide-stainless steel tool-work combination displayed a reverse trend for time data. The most probable explanation for this behaviour could be because of the relatively flat  $\partial t / \partial v = 0$  and  $\partial t / \partial f = 0$  loci in the  $v$ - $f$  domain since stainless steel is a “sticky” material

which results in it being very sensitive to machining speed as in Graph 3.3. Further, since feed rates were randomly chosen for a give machining speed, the normal distribution does not have much variation for the very narrow feed range displayed by the carbide-stainless steel tool-work combination.

A more accurate comparison of the machining time per component was made by considering the percentage deviation between the mathematical model and time trials on the CNC machine. It was expected since the beginning that the real time simulation would provide a better solution than the mathematical model since the latter only considers two practical constraints while the MAZAK Quick Turn 15N CNC machine considers several practical restraints such as maximum allowable spindle torque, maximum power etc. So the  $t$  values generated by the CNC machine were considered to be the optimum values. The comparison revealed that the CNC machine generated lower  $t$  values over the normal operation range of practical machining. Tables A4-A6 in Appendix 1 shows that at extreme values of machining speed ie at a minimum of 45m/min and at approximately 640m/min for carbon steel, 600m/min for cast iron and 550m/min for stainless steel, the time values tend to be erratic for all tool-work combinations.

The histogram analysis revealed that 23 simulated time values out of a total data of 30 readings deviated by greater than -7.2% (for carbide-carbon steel tool-work combination) ie simulated time values were lower than time values predicted by the mathematical model (Page XI in Appendix 1). Further, the whole test sample had a mean value of -12.15% ie on average the real time simulation cut the same

component in 12.15% faster than the mathematical model predicted. Figures for the other tool-work combinations were:

	Percentage Deviation
Tool-work combination	Average
Carbide-Cast steel	-12.02%
Carbide-Stainless steel	-2.58

These results are indeed quite significant. With an average deviation of approximately -12% for carbon steel and cast iron and -3% for stainless steel, the mathematical model represents a very good fit to the actual cutting conditions.

#### 4.4 Concluding Remarks

Real time simulation of single pass turning was conducted on the MAZAK CNC machine tool. Tests were run in accordance with the machine tools' allowable machine parameters ie not to violate the maximum and minimum machine speed and feed.

When the results of time trials on the MAZAK CNC machine tool were compared to those obtained by using the mathematical model, both the results correlated surprisingly well. However, the production time per component obtained by the CNC machine tool was biased towards under-predicting the time. The latter highlights the fact that the CNC machine tool takes into consideration more than just speed and feed constraints to obtain its optimum cutting conditions.

## Final Concluding Remarks

This study has shown the advantage in time saving and hence cost savings of using optimised solutions for the simple case of single pass turning operations even when using only machine speed and feed as constraints. Even though single pass turning is not always better than multi-pass turning operations, its applications are never-the-less plentiful.

In order to obtain the optimum cutting conditions a strategy was developed by analysing the  $t$  (machining time per component) characteristics, formulating a mathematical model, and by using graphical representation in the speed-feed domain. From the literature survey the complexity of the analysis for single pass turning operations increased with each addition of a new constraint on the analysis was demonstrated.

The Taylor tool-life equation was used in the analysis and seems to have been the correct choice in incorporating it in the objective criteria function which was the maximum production rate criteria. Subsequently, it was found that the two most popular criteria functions are the maximum production (minimum production time per component) criteria and the minimum cost per component criteria.

The results of this study raise the important question of whether such detailed strategies make a significant difference to the economics of manufacture. In some cases the percentage deviation of machining time per component was so small that

it would be hard to warrant the need for such complex analysis and this is possibly the reason why so many machine operators still rely on “experience” in choosing cutting conditions.

The biggest difficulty in conducting this study was the fact that it was hard to acquire tool-life cutting data such as  $1/n_o$ ,  $1/m_o$ , and  $C_o$  values for different tool-work combinations. The comparisons made between the mathematical model and real time simulation are not indicative of a very accurate comparison between the two methods. However the results displayed the expected trends and on comparison were surprisingly good.

The optimisation of machine parameters for single pass turning operations is a worthwhile quest especially today where the amalgamation of computers in manufacturing industry is becoming more and more rampant. With reference to Computer-integrated manufacturing (CIM) and in particular computer-aided design (CAD)/Computer-aided manufacturing (CAM) systems and computer-aided process planning the optimisation of machining parameters is a very important element in these large systems where other forms of optimisation such as the optimum selection of jigs and fixtures, optimum logistics of materials to save production time etc need to work together to optimise the whole manufacturing process from inception to the finished product.

Due to time restrictions, the author could not train the neural network system to predict optimum cutting conditions.

## Future Work

A few shortcomings were encountered during this study. The first critical aspect was the unavailability of tool-life data for different tool-work combinations. Constant values for tool-work combinations used in this study were acquired through word of mouth and with the aid of another researchers [4] work. This type of data is difficult to acquire due to the nature it is obtained by. Data such as tool-life cutting speed and feed coefficients is only obtainable after laborious tool-life tests and only a few sources exist such as the Chinese handbooks referred to in this work. Furthermore, even if data were available for conventional tool-work combinations it would have been hard in this case to verify the results obtained since new tool-work combinations such as those using ceramic inserts are utilised in CNC machines to take full advantage of their power and speed. For example, the MAZAK CNC machine used in this study only had parameters for carbide and ceramic inserts in its data bank. Hence the comparisons made in this only give indication to the general trend of behaviours when comparing different method of analysis ie mathematical model and real time simulated trials. Tool-life data obtained from the Chinese handbooks did not fully specify the work material and cutting tool. So more effort needs to be made in obtaining similar tool-work combinations by carrying out an extensive search for such data.

The depth of cut was kept constant in this study so that its effect was not considered in the economic objective function. This was intended for the purpose

of this study. However, it was noted that depth of cut has a significant bearing in obtaining the optimum cutting conditions. For practical situations the depth should be considered in the analysis.

Further study could be done on improving the optimised cutting conditions for single pass turning operations by considering more constraints such as the machines' maximum power, limiting spindle torque and also surface finish.

Due to lack of time, the author could not train the neural network system to predict the optimum cutting conditions and make the network recognise the tool-work combination in use when values of cutting conditions were entered into the system.

Finally, it should be stressed once again that the importance of finding and using optimum cutting conditions in economic manufacture is high and that seeking optimum solutions to practical turning operations is a very worth while quest.

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# APPENDIX 1 - Results of Mathematical Model (idealised optimisation) and Time Trials on CNC Machine

Machining time per component using real-time

Machining time per component using mathematical model

$t_c$
2

$t_c$  = tool changing time (mins/edge)

**Table A1 - Carbide-Carbon steel**

Work (kgforce/sq mm) = 55

$m_o$	0.57
$n_o$	0.2
$m$	0.75438596
$n$	4
$a$	7.7042E-11
$1/(m+1)$	0.57
$(n+1)/(m+1)$	2.85

Table A1.1- Machining time obtained from mathematical model					
	$V$ -min loci	$F$ -min loci	Random feed	Time (sec)	Real time (sec)
Co	2.60E+10	2.60E+10			
Speed (m/min)	Feed1 (mm/rev)	Feed2 (mm/rev)			
10	372.728310	964.579933	386.475274	0.37	
20	51.695994	133.783556	95.443332	0.74	
30	16.277841	42.125265	20.576373	2.29	
40	7.170037	18.555269	12.675614	2.79	6
45	5.125506	13.264246	5.125506	6.13	7
50	3.796015	9.823669	6.025233	4.69	
60	2.257674	5.842614	3.439942	6.85	5
70	1.455000	3.765380	1.574540	12.83	
80	0.994457	2.573545	1.553873	11.37	13
90	0.710888	1.839700	1.221235	12.86	
100	0.526493	1.362505	0.841503	16.80	18
110	0.401258	1.038410	0.892909	14.39	
120	0.313131	0.810348	0.546056	21.57	21
130	0.249261	0.645059	0.620022	17.54	
140	0.201803	0.522244	0.504498	20.02	21
150	0.165780	0.429021	0.251726	37.44	
160	0.137927	0.356941	0.285280	30.97	29
170	0.116041	0.300302	0.266450	31.21	
180	0.098597	0.255159	0.240472	32.66	31
190	0.084517	0.218721	0.205767	36.16	
200	0.073023	0.188974	0.100971	70.01	62
210	0.063543	0.164442	0.105176	64.01	

Optimum

220	0.055653	0.144024	0.106237	60.49	54
230	0.049031	0.126886	0.112756	54.51	
240	0.043430	0.112392	0.095086	61.95	56
250	0.038660	0.100048	0.076803	73.63	
260	0.034572	0.089467	0.051979	104.61	91
270	0.031046	0.080344	0.056702	92.34	
280	0.027989	0.072433	0.045677	110.54	95
290	0.025326	0.065540	0.051954	93.83	
300	0.022993	0.059504	0.035065	134.39	117
310	0.020942	0.054195	0.034664	131.56	
320	0.019130	0.049506	0.022266	198.42	172
330	0.017524	0.045350	0.017620	243.13	
340	0.016094	0.041651	0.023514	176.83	148
350	0.014818	0.038348	0.027711	145.76	
360	0.013675	0.035390	0.021392	183.57	161
370	0.012648	0.032731	0.020489	186.49	
380	0.011722	0.030336	0.019704	188.81	159
390	0.010886	0.028171	0.019171	189.08	
400	0.010128	0.026210	0.023845	148.22	133
410	0.009440	0.024429	0.022750	151.57	
420	0.008813	0.022808	0.009051	371.90	317
430	0.008242	0.021328	0.019973	164.60	
440	0.007719	0.019976	0.013751	233.66	195
450	0.007240	0.018736	0.011715	268.17	
460	0.006800	0.017599	0.007332	419.19	372
470	0.006396	0.016552	0.009799	306.96	
480	0.006024	0.015588	0.013514	217.93	179
490	0.005680	0.014699	0.012688	227.39	
500	0.005362	0.013876	0.011233	251.71	220
510	0.005068	0.013115	0.008036	344.93	
520	0.004795	0.012409	0.007344	370.18	328
530	0.004542	0.011753	0.008399	317.59	
540	0.004306	0.011143	0.005367	487.80	443
550	0.004087	0.010576	0.005060	507.95	
560	0.003882	0.010046	0.004078	619.11	533
570	0.003691	0.009552	0.008918	278.12	
580	0.003513	0.009090	0.005636	432.50	349
590	0.003346	0.008658	0.006506	368.32	
600	0.003189	0.008253	0.004978	473.28	418
610	0.003042	0.007873	0.006304	367.66	
620	0.002905	0.007517	0.004828	472.33	417
630	0.002775	0.007182	0.003365	666.87	
640	0.002653	0.006866	0.006835	323.19	348
650	0.002539	0.006570	0.004575	475.41	
660	0.002430	0.006290	0.003973	539.17	695
670	0.002329	0.006026	0.005796	364.06	
680	0.002232	0.005777	0.005201	399.72	
690	0.002141	0.005541	0.002416	848.08	
700	0.002055	0.005319	0.003347	603.34	
710	0.001974	0.005108	0.004115	483.83	

tc
2

tc = tool changing time (mins/edge)

Table A2 - Carbide-Cast iron

Forgable 150 BHN

mo	0.5
no	0.2
m	1
n	4
a	1.87441E-10
1/(m+1)	0.5
(n+1)/(m+1)	2.5

Table A2.1- Machining time obtained from mathematical model					
	V-min loci	F-min loci	Random feed	Time (sec)	Real time (sec)
Co	1.07E+10	1.07E+10			
Speed (m/min)	Feed 1	Feed 2			
10	115.488095	230.976189	159.083436	0.89	
20	20.415604	40.831207	33.323718	2.12	
30	7.408565	14.817129	12.642947	3.73	
40	3.609003	7.218006	3.804214	9.29	11
45	2.688475	5.376949	2.688475	11.69	13
50	2.065914	4.131828	2.954641	9.57	
60	1.309662	2.619323	1.397159	16.86	17
70	0.890824	1.781649	1.195217	16.90	
80	0.637988	1.275975	0.652450	27.08	27
90	0.475260	0.950519	0.873956	17.97	
100	0.365205	0.730411	0.394136	35.87	33
110	0.287777	0.575553	0.346272	37.12	
120	0.231518	0.463035	0.347782	33.87	32
130	0.189530	0.379061	0.221645	49.06	
140	0.157477	0.314954	0.208099	48.52	44
150	0.132528	0.265057	0.160328	58.78	
160	0.112781	0.225563	0.141881	62.28	56
170	0.096920	0.193841	0.118644	70.09	
180	0.084015	0.168030	0.126216	62.23	56
190	0.073393	0.146786	0.095878	77.61	
200	0.064560	0.129120	0.067929	104.06	92
210	0.057146	0.114293	0.101208	66.52	
220	0.050872	0.101744	0.074061	86.77	76
230	0.045522	0.091043	0.087742	70.05	
240	0.040927	0.081854	0.078157	75.37	67
250	0.036956	0.073912	0.040243	140.52	
260	0.033505	0.067009	0.057058	95.29	84

Optimum

270	0.030488	0.060976	0.043004	121.76	
280	0.027838	0.055677	0.028047	180.02	154
290	0.025500	0.051000	0.045698	106.68	
300	0.023428	0.046856	0.028233	166.91	145
310	0.021584	0.043168	0.030205	150.98	
320	0.019937	0.039874	0.035642	123.95	109
330	0.018461	0.036922	0.030721	139.45	
340	0.017133	0.034267	0.022435	185.34	162
350	0.015936	0.031871	0.018544	217.82	
360	0.014852	0.029704	0.024312	161.53	141
370	0.013869	0.027737	0.021232	179.95	
380	0.012974	0.025948	0.024269	153.29	133
390	0.012158	0.024317	0.014630	247.77	
400	0.011413	0.022825	0.020990	168.38	145
410	0.010729	0.021459	0.017705	194.75	
420	0.010102	0.020204	0.010861	309.91	286
430	0.009525	0.019050	0.010206	322.13	
440	0.008993	0.017986	0.013519	237.67	195
450	0.008502	0.017003	0.013773	228.11	
460	0.008047	0.016094	0.008134	377.86	326
470	0.007626	0.015252	0.012178	247.00	
480	0.007235	0.014470	0.010974	268.38	228
490	0.006871	0.013743	0.007393	390.25	
500	0.006533	0.013066	0.011412	247.77	219
510	0.006217	0.012435	0.008099	342.28	
520	0.005923	0.011846	0.009185	296.00	257
530	0.005647	0.011295	0.006608	403.66	
540	0.005390	0.010779	0.008917	293.61	247
550	0.005148	0.010296	0.007185	357.72	
560	0.004921	0.009842	0.006938	363.85	306
570	0.004708	0.009416	0.008256	300.42	
580	0.004508	0.009016	0.005258	463.55	418
590	0.004319	0.008638	0.008489	282.27	
600	0.004142	0.008283	0.008184	287.91	
610	0.003974	0.007948	0.006797	340.96	
620	0.003816	0.007631	0.007452	306.00	
630	0.003666	0.007332	0.004268	525.79	
640	0.003524	0.007049	0.005835	378.54	
650	0.003390	0.006781	0.006245	348.29	
660	0.003263	0.006527	0.006086	351.93	
670	0.003143	0.006286	0.004680	450.85	
680	0.003029	0.006058	0.005707	364.30	
690	0.002920	0.005840	0.005505	372.16	
700	0.002817	0.005634	0.003298	612.31	
710	0.002719	0.005438	0.002932	679.19	

tc
2

tc = tool changing time (mins/edge)

Table 3 Carbide-Stainless Steel

mo	0.15
no	0.33
m	5.6667
n	2.0303
a	0.0006
1/(m+1)	0.15
(n+1)/(m+1)	0.4545

Table A3.1- Machining time obtained from mathematical model					
	V-min loci	F -min loci	Random feed	Time (sec)	Real time (sec)
Co	3.41E+03	3.41E+03			
Speed (m/min)	Feed 1	Feed 2			
10	0.964005	0.826445	0.944605	149.66	
20	0.703473	0.603090	0.678231	104.22	
30	0.585067	0.501581	0.520178	90.59	
40	0.513352	0.440099	0.480249	73.59	65
45	0.486591	0.417157	0.486591	64.56	58
50	0.463837	0.397649	0.443477	63.76	
60	0.426947	0.366023	0.414171	56.89	51
70	0.398055	0.341255	0.359417	56.19	
80	0.374614	0.321158	0.326993	54.04	49
90	0.355085	0.304416	0.349658	44.92	
100	0.338480	0.290181	0.328130	43.08	40
110	0.324130	0.277878	0.286292	44.89	
120	0.311560	0.267102	0.284006	41.48	38
130	0.300429	0.257559	0.298591	36.42	
140	0.290477	0.249027	0.282251	35.78	34
150	0.281509	0.241339	0.272453	34.59	
160	0.273371	0.234362	0.264847	33.36	31
170	0.265940	0.227992	0.256811	32.38	
180	0.259120	0.222145	0.227383	34.54	33
190	0.252829	0.216752	0.225550	32.99	
200	0.247003	0.211757	0.242295	29.17	28
210	0.241585	0.207112	0.237748	28.32	
220	0.236530	0.202779	0.223494	28.75	27
230	0.231799	0.198722	0.219174	28.04	
240	0.227358	0.194915	0.202833	29.04	28
250	0.223178	0.191332	0.214837	26.32	
260	0.219235	0.187951	0.201682	26.96	26

Optimum

270	0.215506	0.184754	0.196075	26.70
280	0.211973	0.181725	0.186897	27.01
290	0.208618	0.178849	0.207131	23.54
300	0.205428	0.176115	0.179740	26.22
310	0.202389	0.173509	0.183673	24.83
320	0.199489	0.171023	0.199157	22.18
330	0.196719	0.168648	0.169620	25.26
340	0.194067	0.166375	0.166489	24.97
350	0.191527	0.164197	0.176542	22.88
360	0.189090	0.162108	0.184574	21.28
370	0.186750	0.160101	0.163537	23.36
380	0.184500	0.158172	0.179473	20.73
390	0.182334	0.156316	0.172220	21.05
400	0.180248	0.154527	0.160671	22.00
410	0.178236	0.152803	0.168734	20.44
420	0.176294	0.151138	0.167733	20.07
430	0.174419	0.149530	0.164965	19.93
440	0.172606	0.147976	0.158640	20.25
450	0.170852	0.146472	0.152348	20.62
460	0.169153	0.145016	0.163258	18.82
470	0.167508	0.143605	0.167497	17.96
480	0.165912	0.142237	0.151169	19.48
490	0.164365	0.140910	0.160369	17.99
500	0.162862	0.139622	0.157191	17.99
510	0.161403	0.138371	0.146405	18.93
520	0.159984	0.137155	0.146486	18.56
530	0.158605	0.135973	0.151265	17.63
540	0.157263	0.134822	0.149639	17.50
550	0.155957	0.133703	0.137748	18.66
560	0.154685	0.132612	0.137729	18.33
570	0.153445	0.131549	0.140971	17.59
580	0.152237	0.130514	0.143725	16.96
590	0.151059	0.129503	0.139160	17.22
600	0.149909	0.128518	0.138638	17.00
610	0.148787	0.127556	0.146573	15.81
620	0.147692	0.126617	0.141703	16.09
630	0.146621	0.125699	0.130391	17.21
640	0.145575	0.124802	0.131669	16.78
650	0.144553	0.123926	0.142584	15.25
660	0.143553	0.123069	0.126842	16.89
670	0.142576	0.122231	0.140202	15.05
680	0.141619	0.121410	0.121452	17.12
690	0.140682	0.120607	0.137381	14.91
700	0.139765	0.119821	0.120529	16.76
710	0.138867	0.119051	0.128514	15.49

Percentage deviation in machining time per component between mathematical model and real time simulation.

Carbide-Carbon steel tool-work combination

**Table A4 :** Comparison of machining time/component between mathematical model and real time simulation.

Speed (m/min)	Time (seconds)		% Deviation
	Mathematical model	Real time simulation	
45	6.13	5.13	-19.49
60	6.85	5	-36.99
80	11.37	13	12.52
100	16.80	18	6.67
120	21.57	21	-2.74
140	20.02	21	4.69
160	30.97	29	-6.80
180	32.66	31	-5.36
200	70.01	62	-12.91
220	60.49	54	-12.01
240	61.95	56	-10.62
260	104.61	91	-14.95
280	110.54	95	-16.36
300	134.39	117	-14.86
320	198.42	172	-15.36
340	176.83	148	-19.48
360	183.57	161	-14.02
380	188.81	159	-18.75
400	148.22	133	-11.44
420	371.90	317	-17.32
440	233.66	195	-19.83
460	419.19	372	-12.68
480	217.93	179	-21.75
500	251.71	220	-14.41
520	370.18	328	-12.86
540	487.80	443	-10.11
560	619.11	533	-16.16
580	432.50	349	-23.93
600	473.28	418	-13.22
620	472.33	417	-13.27
640	323.19	348	7.13

Average = -12.15

Carbide-Cast iron tool-work combination

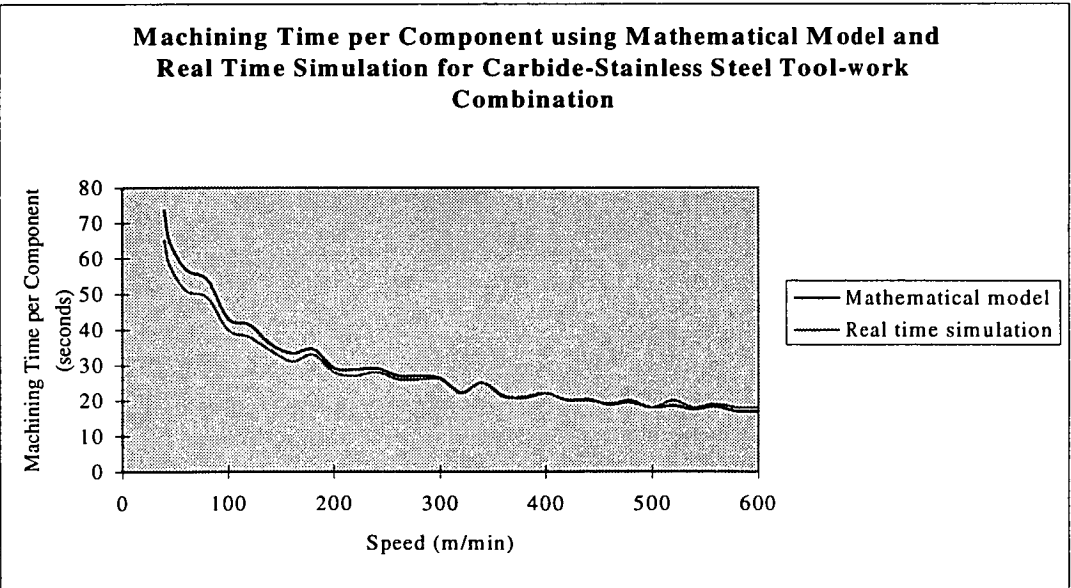
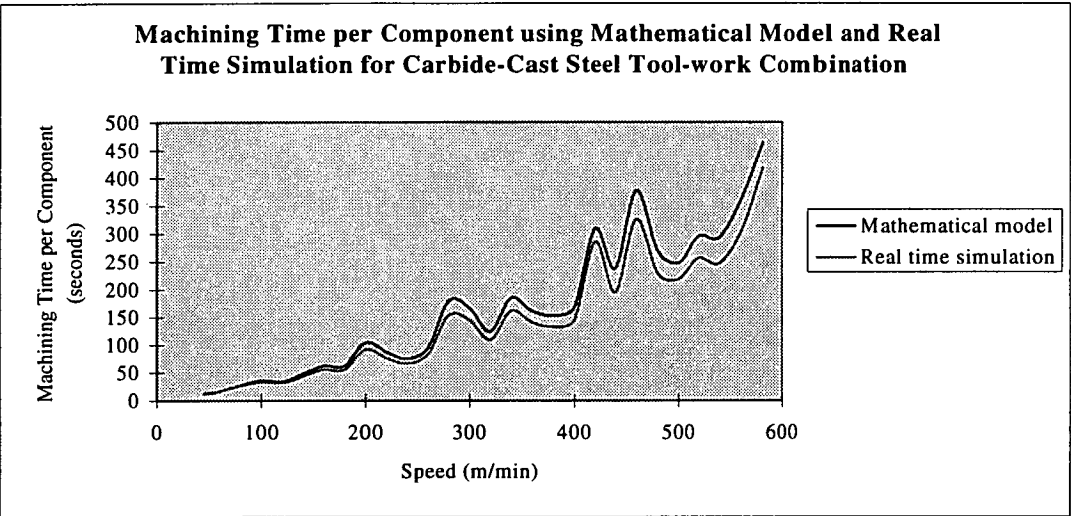
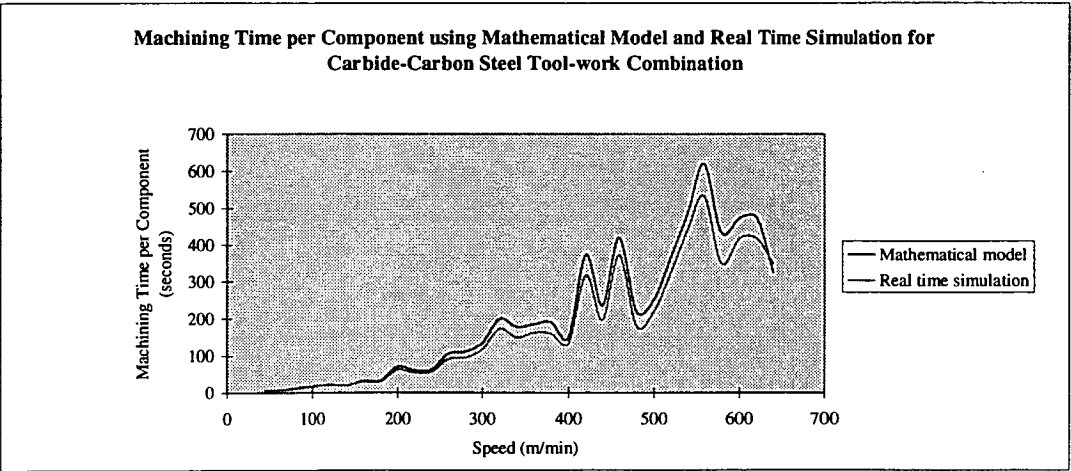
<b>Table A5 : Comparison of machining time per component between mathematical model and real time simulation.</b>			
Speed (m/min)	Time (seconds)		% Deviation
	Mathematical model	Real time simulation	
45	11.69	13	10.12
60	16.86	17	0.80
80	27.08	27	-0.31
100	35.87	33	-8.69
120	33.87	32	-5.86
140	48.52	44	-10.28
160	62.28	56	-11.21
180	62.23	56	-11.12
200	104.06	92	-13.11
220	86.77	76	-14.17
240	75.37	67	-12.49
260	95.29	84	-13.45
280	180.02	154	-16.90
300	166.91	145	-15.11
320	123.95	109	-13.72
340	185.34	162	-14.40
360	161.53	141	-14.56
380	153.29	133	-15.26
400	168.38	145	-16.13
420	309.91	286	-8.36
440	237.67	195	-21.88
460	377.86	326	-15.91
480	268.38	228	-17.71
500	247.77	219	-13.14
520	296.00	257	-15.17
540	293.61	247	-18.87
560	363.85	306	-18.91
580	463.55	418	-10.90
Average			-12.02

Carbide-Stainless steel tool-work combination

**Table A6 : Comparison of machining time per component between mathematical model and real time simulation.**

Speed (m/min)	Time (seconds)		% Deviation
	Mathematical model	Real time simulation	
40	73.59	65	-13.22
45	64.56	58	-11.31
60	56.89	51	-11.55
80	54.04	49	-10.29
100	43.08	40	-7.71
120	41.48	38	-9.16
140	35.78	34	-5.23
160	33.36	31	-7.62
180	34.54	33	-4.67
200	29.17	28	-4.19
220	28.75	27	-6.49
240	29.04	28	-3.72
260	26.96	26	-3.69
280	27.01	26	-3.90
300	26.22	26	-0.84
320	22.18	22	-0.83
340	24.97	25	0.10
360	21.28	21	-1.31
380	20.73	21	1.29
400	22.00	22	0.01
420	20.07	20	-0.34
440	20.25	20	-1.27
460	18.82	19	0.92
480	19.48	20	2.58
500	17.99	18	0.07
520	18.56	20	7.20
540	17.50	18	2.80
560	18.33	19	3.53
580	16.96	18	5.78
600	17.00	18	5.58
Average			-2.58

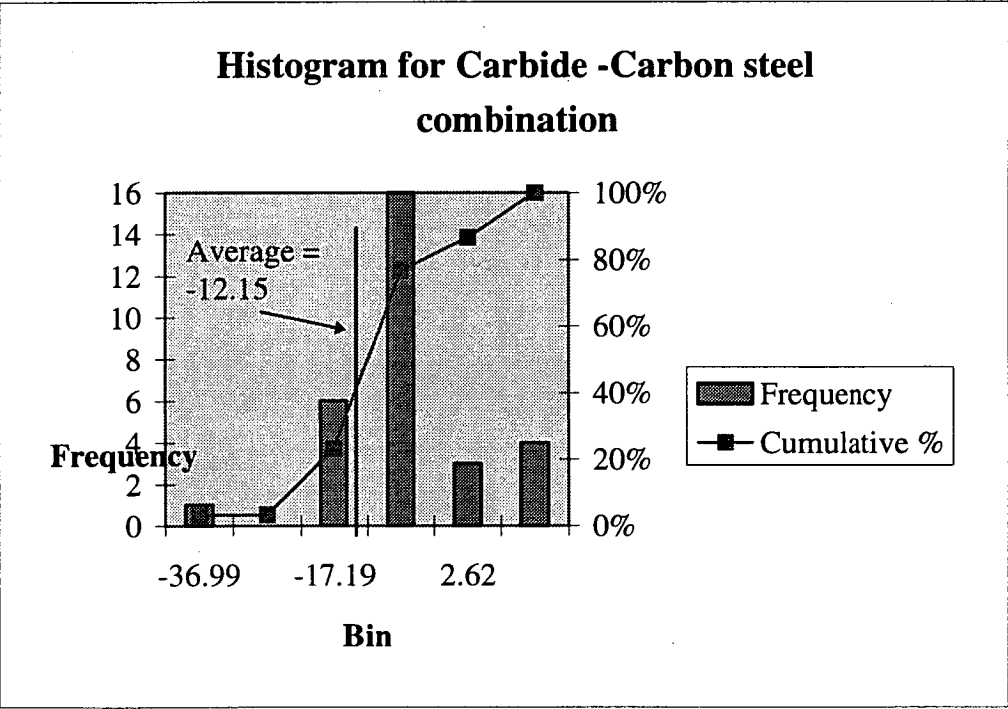
Graphs showing the time trends for different tool-work combinations:



Histograms showing frequency of occurrence for a given percentage deviation and the average percentage deviation for each tool-work combination:

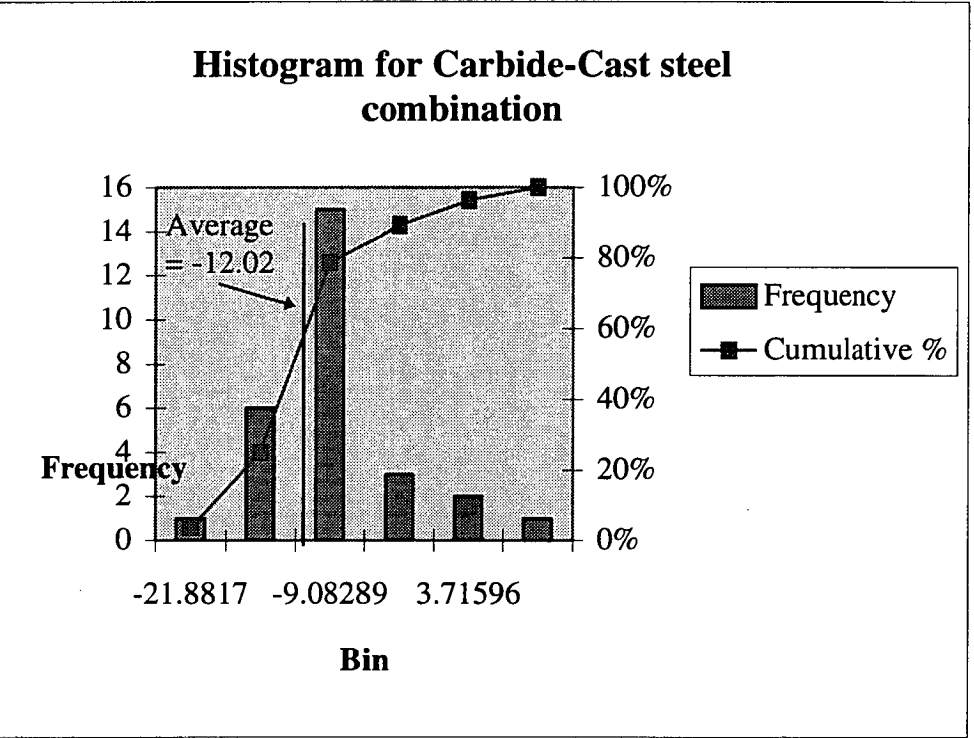
Carbide-Carbon steel tool-work combination

<i>Bin</i>	<i>Frequency</i>	<i>Cumulative %</i>
-36.99037829	1	3.33%
-27.08849254	0	3.33%
-17.18660678	6	23.33%
-7.284721027	16	76.67%
2.617164729	3	86.67%
More	4	100.00%



Carbide-Cast iron tool-work combination

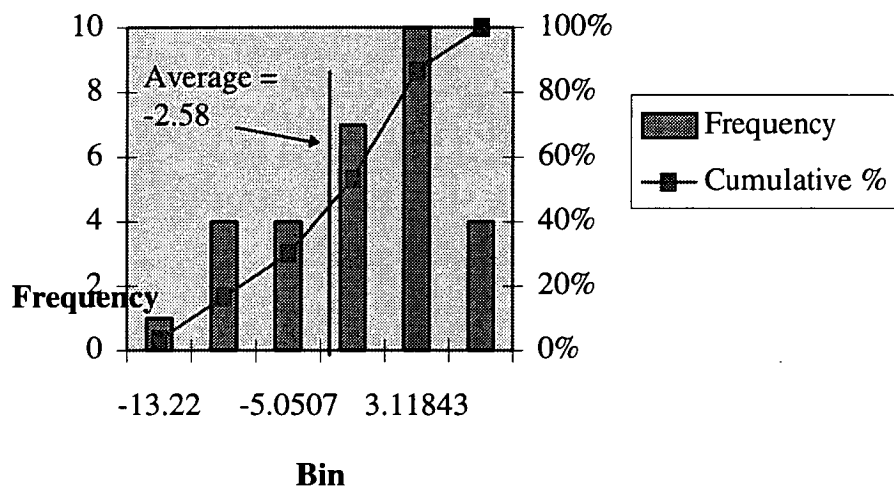
Bin	Frequency	Cumulative %
-21.8817394	1	3.57%
-15.48231459	6	25.00%
-9.082889792	15	78.57%
-2.683464989	3	89.29%
3.715959813	2	96.43%
More	1	100.00%



## Carbide-Stainless steel tool-work combination

<i>Bin</i>	<i>Frequency</i>	<i>Cumulative %</i>
-13.21979965	1	3.33%
-9.135243187	4	16.67%
-5.050686725	4	30.00%
-0.966130264	7	53.33%
3.118426198	10	86.67%
More	4	100.00%

## Histogram for Carbide-Stainless steel combination



## APPENDIX 2 - Turning Simulation Program

The following program listing is an example of how on screen simulations of turning operations work. The program was written by the department of Mechanical Engineering (University of Tasmania) in Qbasic. It is demonstrated on disk 1 which is attached to the inside back cover of this thesis. To run the program type: A:\> qbasic, then open file CNC.bas and select START from the RUN menu. The demonstration programs and the parameters are

1. Demo1: Dia = 20mm, distance from chuck jaw = 50.5mm
2. Demo2: Dia = 31.6mm, distance from chuck jaw = 40mm
3. Demo3: Dia = 20mm, distance from chuck jaw = 50.5mm
4. Demo4: Dia = 20mm, distance from chuck jaw = 50.5mm

The code can be best edited using any Turbo Pascal editor for quick editing.

CNC.bas is an introduction screen.

### CNC.bas

```
10 CLS
20 SCREEN 1, 1
30 COLOR 9, 9
40 LOCATE 5, 7: PRINT "CNC LATHE SIMULATION PACKAGE"
41 LOCATE 9, 8: PRINT ".. Linear Interpolation ..": LOCATE 11, 7: PRINT ".. Circular
    Interpolation ..": LOCATE 13, 11: PRINT ".. Screw Cutting ..": LOCATE 15, 11: PRINT "..
    Screen Editor .."
44 LOCATE 17, 6: PRINT ".. RS232 Interface Routines .."
50 LOCATE 25, 1: PRINT TAB(8); "PRESS SPACEBAR TO CONTINUE ";
60 DRAW "BM 40,44": DRAW "C1R240C1D4C1L240C1U4": PAINT (43, 46), 1
70 LOCATE 18, 1
90 PSET (0, 0)
100 A = 0: B = 10: C = 199: D = 10: E = 199
110 GOSUB 170: PAINT (5, 5), 2: PSET (0, 0), 2
120 A = 0: B = 319: C = 10: D = 319: E = 10: GOSUB 170: PAINT (15, 5), 2: PSET (309, 0), 2
130 A = 0: B = 10: C = 199: D = 10: E = 199: GOSUB 170: PAINT (310, 15), 2
140 DRAW "BM10,159": DRAW "C1R299C1D30C1L299C1U30": PAINT (12, 161), 1
141 LINE (35, 166)-STEP(244, 10), 0, BF: LOCATE 22, 6: PRINT "MANUFACTURING
    ENGINEERING DEPARTMENT"
150 A$ = INKEY$: IF A$ = "" GOTO 150
160 CHAIN "C:\COLIN\ASCIIMENU.BAS"
170 DRAW "C2 U" + STR$(A) + "C2 R" + STR$(B) + "C2 D" + STR$(C) + "C2 L" + STR$(D)
    + "C2 U" + STR$(E): RETURN
```

MENU.bas displays the menu screen for the package. It's options include :

- 1.Enter Edit mode
- 2.Send a programme to the Lathe
- 3.Get a programme from the Lathe
- 4.Get a paper printout
- 5.Get a simulated tool trace
- 6.Enter Interactive Mode
- 7.Get a Catalogue
- 8.Quit from programme

### MENU.bas

```
1 DIM N$(250)
4 ON ERROR GOTO 999
5 SCREEN 0: WIDTH 40
10 COLOR 4, 7, 4: CLS : LOCATE 2, 5: COLOR 7, 9, 4: PRINT SPACES$(31): ON KEY(1)
    GOSUB 8000: KEY(1) ON: KEY 9, "GOTO 5000" + CHR$(13)
20 LOCATE 3, 5: PRINT " CHOOSE ONE OF THE FOLLOWING ": LOCATE 4, 5: PRINT
    SPACES$(31): COLOR 0, 7, 4
30 PRINT
40 PRINT " 1.Enter Edit mode.": PRINT
50 PRINT " 2.Send a programme to the Lathe.": PRINT
60 PRINT " 3.Get a programme from the Lathe.": PRINT
70 PRINT " 4.Get a paper printout.": PRINT
80 PRINT " 5.Get a simulated tool trace.": PRINT
90 PRINT " 6.Enter Interactive Mode.": PRINT
95 PRINT " 7.Get a Catalog.": PRINT
97 PRINT " 8.Quit from programme": PRINT
100 COLOR 7, 9, 4: LOCATE 22, 5: PRINT SPACES$(31): : LOCATE 24, 5: PRINT
    SPACES$(31): : LOCATE 23, 5: INPUT " ENTER THE APPROPRIATE NUMBER";
    N$: COLOR 0, 7, 4
105 X = VAL(N$)
106 IF X = 8 THEN CLS : PRINT : PRINT "To return to the operating system (DOS)": PRINT "
    type .... SYSTEM ": PRINT : END
110 IF X = 1 THEN CHAIN "C:\COLIN\ASCII\EDITOR19.BAS"
120 IF X = 2 THEN CHAIN "C:\COLIN\ASCII\BMLATHE.BAS"
130 IF X = 3 THEN CHAIN "C:\COLIN\ASCII\LATHEIBM.BAS"
135 IF X = 4 THEN 190
140 IF X = 5 THEN CHAIN "C:\COLIN\ASCII\SOLID.BAS"
150 IF X = 6 THEN CHAIN "C:\COLIN\ASCII\INTER2.BAS"
160 IF X = 7 THEN CLS : FILES "*.": PRINT : COLOR 7, 9, 4: LOCATE , 2, 1: PRINT
    SPACES$(38): LOCATE , 2, 1: PRINT " DO YOU WISH TO DELETE ANY
    PROGRAMME? ": LOCATE , 2, 1: PRINT SPACES$(38): COLOR 0, 7, 4: PRINT :
    LOCATE , 15, 1: INPUT "Y/N"; Y$: IF ASC(Y$) = 89 OR ASC(Y$) = 121 THEN 400
170 GOTO 10
190 COLOR 0, 7, 4: CLS
200 LOCATE 5, 5: PRINT " IS YOUR PROGRAMME ON DISC? (D)": PRINT : PRINT
    TAB(15); "OR": PRINT : PRINT TAB(5); " IN THE LATHE MEMORY? (L)": PRINT :
    LOCATE , 15: INPUT N$
210 IF ASC(N$) = 76 THEN CLS : GOTO 300
215 IF ASC(N$) = 68 THEN 220
217 GOTO 190
220 PRINT : PRINT TAB(3); "WHAT IS THE NAME OF YOUR PROGRAMME?": PRINT :
    LOCATE , 15: INPUT N$
230 OPEN N$ FOR INPUT AS #1: LPRINT CHR$(14); " " "N$
```

```
240 INPUT #1, A$: LPRINT A$: PRINT A$: IF EOF(1) THEN 260
250 GOTO 240
260 CLOSE #1: GOTO 10
300 COLOR 0, 7, 4: CLS : COLOR 7, 1, 4: LOCATE 1, 1: PRINT STRING$(40, " "); : PRINT
    "SET UP THE LATHE TO TRANSMIT THROUGH THE"; : PRINT "THE RS232
    PORT AND MAKE CERTAIN THAT THE"; : PRINT " PRINTER IS CONNECTED
    AND SWITCHED ON. "; : PRINT STRING$(40, " ");
305 COLOR 0, 7, 4: LOCATE 8, 2: PRINT "WHEN THE LAST BLOCK OF DATA HAS
    BEEN": LOCATE 10, 3: PRINT "PRINTED, HOLD THE Ctrl KEY DOWN AND":
    LOCATE 12, 3: PRINT "PRESS THE BREAK KEY TO EXIT THE IBM": LOCATE 14, 9:
    PRINT "FROM THE RECEIVE MODE."
306 LOCATE 16, 4: PRINT "THEN PRESS THE FUNCTION KEY F9 TO": LOCATE 18, 10:
    PRINT "RETURN TO THE MENU."
307 LOCATE 22, 3: COLOR 7, 1, 4: PRINT STRING$(36, " "); : LOCATE 23, 3: PRINT " YOU
    MAY COMMENCE TRANSMITTING DATA "; : LOCATE 24, 3: PRINT "      WHEN
    YOU ARE READY.      "; : LOCATE 25, 3: PRINT STRING$(36, " ");
310 CLOSE #1: L = 0: OPEN "COM1:300,E,7,1,RS,CS,DS,CD,LF,PE" FOR RANDOM AS #1
320 ON COM(1) GOSUB 350
330 COM(1) ON
345 GOTO 330
350 INPUT #1, N$
360 COM(1) OFF
370 L = L + 1: PRINT N$: LPRINT N$
380 RETURN
400 PRINT : LOCATE , 10: INPUT "WHAT PROGRAMME "; N$: KILL N$: GOTO 160
500 COM(1) OFF: CLOSE #1: L = 0: GOTO 10
999 CLOSE #1
1000 IF ERR = 25 THEN CLS : LOCATE 8, 2: PRINT "CHECK THAT YOUR PRINTER IS
    CONNECTED ": LOCATE 10, 11: PRINT "AND SWITCHED ON.": LOCATE 12, 5:
    PRINT "WHEN ALL IS CORRECT PRESS THE": LOCATE 14, 8: PRINT "SPACEBAR
    TO START AGAIN.": COM(1) OFF: CLOSE #1
1110 FOR N = 1 TO 3: BEEP: NEXT N
1115 IF ERR = 25 THEN A$ = INKEY$: IF A$ = " " THEN RESUME 4 ELSE GOTO 1115
1120 IF ERR = 53 THEN CLS : LOCATE 8, 8: PRINT "FILE NOT FOUND - REENTER":
    RESUME 220
1130 ON ERROR GOTO 0
5000 CLOSE #1: CHAIN "C:\COLIN\ASCII\MENU"
8000 CHAIN "C:\COLIN\ASCII\MENU"
```

SOLID.bas executes the 5th option (simulate a tool trace) in the menu. It calls upon a preprogrammed G-Code from the data base and performs functions such as clockwise and anti-clockwise circular interpolation, straight line and step interpolation, tool and workpiece drawing routines on screen, setting the timer on and off for the turning operation, and the actual simulation on screen.

### SOLID.bas

```

10 SCREEN 0: WIDTH 40: DIM N$(250): M% = 60: DIM T%(100): ON KEY(9) GOSUB 8000:
    KEY(9) ON
13 TOOL3I$ = "M+0,-9 M-1,0 M-0,+8 M-1,-1 M+0,-7 M-1,0 M+0,+6 M-1,-1 M+0,-5"
14 TOOL2I$ = "M-1,-1 M+2,0 M+0,-1 M-2,0 M-1,-1 M+4,0 M+0,-1 M-4,0 M-1,-1 M+6,0 M+0,-
    1 M-6,0 M-1,-1 M+8,0 M+0,-1 M-8,0"
15 TOOL1I$ = "M+0,6 M+1,1 M+0,-6 M+1,1 M+0,+6 M+1,1 M+0,-6 M+1,1 M+0,+6 M+1,1
    M+0,-6"
16 TOOL2I$ = "M-1,+1 M+2,0 M+0,1 M-2,0 M-1,+1 M+4,0 M+0,1 M-4,0 M-1,+1 M+6,0 M+0,1
    M-6,0 M-1,+1 M+8,0 M+0,1 M-8,0"
17 TOOL3I$ = "M+0,9 M-1,0 M-0,-8 M-1,+1 M+0,+7 M-1,0 M+0,-6 M-1,+1 M+0,+5"
18 TOOL1I$ = "M+0,-6 M+1,-1 M+0,6 M+1,-1 M+0,-6 M+1,-1 M+0,6 M+1,-1 M+0,-6 M+1,-1
    M+0,6"
20 COLOR 0, 7, 2: CLS : LOCATE 2, 4: PRINT "WHAT IS THE NAME OF YOUR
    PROGRAMME.": LOCATE 4, 15: COLOR 4, 7, 2: INPUT N$: PRINT : COLOR 0, 7, 2:
    PRINT " WHAT IS THE DIAMETER OF YOUR WORK.": LOCATE 8, 15: COLOR 4, 7,
2: INPUT D$: D = VAL(D$): PRINT : COLOR 0, 7, 2
30 PRINT " WHAT IS ITS POSITION IN RELATION TO": PRINT : LOCATE , 12: PRINT
    "THE CHUCK JAWS.": COLOR 4, 7, 2: LOCATE 14, 15: INPUT D$: LE = VAL(D$)
40 PRINT : IF D > 200 OR LE > 350 THEN PRINT " YOUR MEASUREMENTS ARE
    GREATER THAN THE": LOCATE 18, 9: PRINT "CAPACITY OF THE LATHE.":
    PRINT CHR$(7): LOCATE , 10: COLOR 0, 2, 2: PRINT "PLEASE ENTER AGAIN.":
    FOR D1 = 1 TO 4000: NEXT D1: GOTO 20
50 COLOR 0, 7, 2: PRINT " DO YOU WANT SINGLE BLOCK <S> OR": LOCATE 18, 11:
    PRINT "AUTOMATIC MODE <A>": LOCATE 20, 15: COLOR 4, 7, 2: INPUT S$
60 D1 = 100
80 GOSUB 3020
160 CX = 310: CY = 180: X1 = 310: Y1 = 180
170 OPEN N$ FOR INPUT AS #1
180 I% = I% + 1: INPUT #1, N$(I%): IF EOF(1) THEN 200
190 GOTO 180
200 CLOSE #1
205 startTime& = TIMER
210 LOCATE 22, 1
215 IF S$ = "S" THEN PRINT "PRESS THE SPACEBAR TO SINGLE STEP"
220 FOR N = 1 TO I%
221 IF S$ = "S" THEN GOSUB 6000
222 LOCATE 20, 7: PRINT SPACES$(33);
225 LINE (46, 149)-STEP(L, 12), 0, B: LOCATE 22, 1: PRINT SPACES$(116);
226 L = LEN(N$(N)) * 8 + 3: LINE (46, 149)-STEP(L, 12), 2, B
230 LOCATE 20, 7: PRINT N$(N); : IF S$ = "S" THEN GOTO 250
240 FOR D1 = 1 TO 1000: NEXT D1
250 IF ASC(N$(N)) = 40 THEN GOTO 617
255 LOCATE 22, 1
260 L% = LEN(N$(N)): IF L% = 0 THEN 617
280 B$ = RIGHT$(N$(N), L% - A%): B% = ASC(B$): IF B% < 65 OR B% = 78 THEN 400
290 C% = ASC(RIGHT$(N$(N), L% - (A% + 1))): IF A% <> L% - 2 THEN F% =
    ASC(RIGHT$(N$(N), L% - (A% + 2)))
300 IF B% = 83 THEN PRINT " -SPINDLE SPEED="; VAL((RIGHT$(B$, LEN(B$) - 1)));

```

```

310 IF B% = 84 THEN PRINT "TOOL NO. "; MID$(B$, 2, 1); " WITH OFFSET NO. ";
    MID$(B$, 3, 2); : GOSUB 2038
320 IF B% = 71 THEN GOSUB 770
360 IF B% = 88 THEN GOSUB 1000: Y = 80 + J / 2
365 IF B% = 90 THEN GOSUB 1000: X = 30 + J: IF G% = 29 THEN X = J
370 IF B% = 73 THEN GOSUB 1000: I = J
380 IF B% = 75 THEN GOSUB 1000: K = J
390 IF B% = 82 THEN GOSUB 1000: R = J: IF G% <> 29 THEN GOSUB 1100: GOTO 400
391 IF B% = 68 THEN GOSUB 1000: D = 80 + J / 2
392 IF B% = 67 THEN GOSUB 1000: C = J / CO
393 IF B% = 72 THEN GOSUB 1000: H = J
394 IF B% = 80 THEN GOSUB 1000: P = J
395 IF B% = 77 THEN GOSUB 1010
400 A% = A% + 1: IF A% < L% THEN 280
402 IF G% = 0 THEN 617
403 IF G% = 28 THEN 615
490 REM DRAWING ROUTINES
500 CX = X1: CY = Y1: IF X1 > 300 OR Y1 > 180 THEN 505
502 DRAW "BM" + STR$(INT(X1)) + "," + STR$(INT(Y1)): DRAW "C0 X" +
    VARPTR$(TOOL$)
505 IF G% = 29 THEN R = 0: GOSUB 1080: GOTO 615
507 IF G% = 30 THEN R = 0: GOSUB 1091: GOTO 615
508 IF G% = 52 THEN G% = 4: X = 310: Y = 180
510 IF R = 0 THEN R = SQR(K ^ 2 + I ^ 2)
520 IF R > 0 THEN PX = X1 + K: PY = Y1 + I: FOR CX = X1 TO X STEP -.5: GOSUB 690:
    GOSUB 650: NEXT CX: I = 0: K = 0: R = 0: GOTO 610
530 IF X < X1 AND Y < Y1 THEN FOR CX = X1 - G% TO X STEP -G%: CY = CY - (Y1 - Y) /
    (X1 - X) * G%: GOSUB 650: NEXT CX
540 IF X > X1 AND Y < Y1 THEN FOR CX = X1 + G% TO X STEP G%: CY = CY - (Y1 - Y) /
    (X - X1) * G%: GOSUB 650: NEXT CX
550 IF X < X1 AND Y > Y1 THEN FOR CX = X1 - G% TO X STEP -G%: CY = CY + (Y - Y1) /
    (X1 - X) * G%: GOSUB 650: NEXT CX
560 IF X > X1 AND Y > Y1 THEN FOR CX = X1 + G% TO X STEP G%: CY = CY + (Y - Y1) /
    (X - X1) * G%: GOSUB 650: NEXT CX
570 IF Y = Y1 AND X < X1 THEN FOR CX = X1 TO X STEP -G%: GOSUB 650: NEXT CX
580 IF Y = Y1 AND X > X1 THEN FOR CX = X1 TO X STEP G%: GOSUB 650: NEXT CX
590 IF X = X1 AND Y < Y1 THEN FOR CY = Y1 TO Y STEP -G%: GOSUB 650: NEXT CY
600 IF X = X1 AND Y > Y1 THEN FOR CY = Y1 TO Y STEP G%: GOSUB 650: NEXT CY
610 IF CX > 300 OR CY > 180 THEN X1 = X: Y1 = Y: GOTO 617
615 DRAW "BM" + STR$(INT(X)) + "," + STR$(INT(Y)): DRAW "C2 X" +
    VARPTR$(TOOL$): X1 = X: Y1 = Y
617 A% = 0: N$ = "": NEXT N
618 endTime& = TIMER
    PRINT
    PRINT endTime& - startTime&: "Seconds elapsed"
    PRINT "PRESS SPACE BAR TO RETURN TO THE MENU"; :
619 A$ = INKEY$: IF A$ = "" GOTO 619
620 IF A$ = " " THEN CHAIN "C:\COLIN\ASCII\MENU.BAS" ELSE GOTO 619
640 FOR D1 = 1 TO 10: SOUND 100, 10: NEXT D1
650 REM DRAWING ROUTINES
665 IF G% = 1 OR G% = 2 OR G% = 3 OR G% = 29 OR G% = 30 THEN SOUND 100, 1
666 DRAW "BM" + STR$(INT(CX)) + "," + STR$(INT(CY)): DRAW "C2 X" +
    VARPTR$(TOOL$)
670 CZ = CY - 79: IF 70 - CZ < 10 THEN CZ = 60
671 CZ = 82 - CZ
672 DRAW "BM" + STR$(INT(CX)) + "," + STR$(INT(CZ)): DRAW "C0 X" +
    VARPTR$(TOOL$): DRAW "BM" + STR$(INT(CX)) + "," + STR$(INT(CY)): DRAW
"C0 X" + VARPTR$(TOOL$)
675 RETURN

```

```

690 REM G2 AND G3 COORDS
700 S = R ^ 2 - (CX - PX) ^ 2: IF S < 0 THEN S = S * -1
705 IF G% = 2 THEN CY = PY + SQR(S): GOTO 720
710 CY = PY - SQR(S)
720 RETURN
730 REM G2 OR G3?
740 IF C% = 50 THEN G% = 2: GOTO 760
750 G% = 3
760 RETURN
770 IF C% = 48 THEN G% = 4: GOTO 910
780 IF C% = 49 THEN G% = 1: GOTO 910
790 IF C% = 50 AND F% = 56 THEN G% = 28: GOTO 910
800 IF C% = 50 AND F% = 57 THEN G% = 29: GOTO 910
805 IF C% = 51 AND F% = 48 THEN G% = 30: GOTO 910
810 IF C% = 50 THEN G% = 2: GOTO 910
820 IF C% = 51 THEN G% = 3: GOTO 910
830 IF C% = 55 AND F% = 49 THEN PRINT " -METRIC MODE";
840 IF C% = 55 AND F% = 48 THEN PRINT " -INCH MODE";
850 IF C% = 57 AND F% = 52 THEN PRINT " -FEED RATE IN UNITS/MIN.";
860 IF C% = 57 AND F% = 53 THEN PRINT " -FEED RATE IN UNITS/SPINDLE
      REVOLUTION";
870 IF C% = 57 AND F% = 48 THEN PRINT " -ABSOLUTE DIMENSIONS.";
880 IF C% = 57 AND F% = 49 THEN PRINT " -RELATIVE DIMENSIONS.";
890 IF C% = 53 AND F% = 48 THEN PRINT " -ZERO POINT OF POSITION REGISTER SET
      TO THESE VALUES.";
895 IF C% = 53 AND F% = 50 THEN PRINT " -AXIS POSITIONING. MACHINE
      REFERENCED."; : G% = 52: GOTO 910
900 G% = 0
910 RETURN
1000 J = VAL(RIGHT$(N$(N), L% - (A% + 1))) * CO: RETURN
1010 IF C% = 48 THEN PRINT " -MACHINE HALT - PRESS THE RETURN KEY TO
      CONTINUE"; :
1013 IF A$ = "13" THEN CLS : D1 = 100: LE = VAL(RIGHT$(N$(N + 1), LEN(N$(N + 1)) -
      1)): GOSUB 3020
1020 IF C% = 50 THEN PRINT " -END OF PROGRAMME": GOTO 618
1030 IF C% = 51 THEN PRINT " -SPINDLE ON - FORWARD";
1040 IF C% = 53 THEN PRINT " -STOP SPINDLE";
1050 IF C% = 52 THEN PRINT " -SPINDLE ON - REVERSE";
1060 IF C% = 54 THEN PRINT " -TOOL CHANGE";
1070 G% = 0: RETURN
1075 DRAW "BM" + STR$(X1) + "," + STR$(Y1): DRAW "C0 X" + VARPTR$(TOOL$)
1080 CY = D: FOR CP = 1 TO C: CY = CY + H / C / 1.5: FOR K = X1 TO X1 + X STEP -P: CX
      = K: GOSUB 650: NEXT K: I = CY: CY = D - H * .4: FOR CX = CX TO X1 STEP P:
      GOSUB 666: NEXT CX: DRAW "BM" + STR$(CX) + "," + STR$(CY): DRAW "C2 X"
      + VARPTR$(TOOL$): GOSUB 2010: DRAW "BM" + STR$(CX) + "," + STR$(CY):
      DRAW "C0 X" + VARPTR$(TOOL$)
1090 CY = I: NEXT CP: X = X1: Y = Y1: DRAW "BM" + STR$(X) + "," + STR$(Y): DRAW
      "C0 X" + VARPTR$(TOOL$): I = 0: K = 0: RETURN
1091 FOR CX = X1 TO X1 - X STEP -P: GOSUB 666: NEXT CX
1092 CY = D: FOR CP = 1 TO C: CY = CY + H / C / 1.5: FOR K = X1 - X TO X1 STEP P: CX =
      K: GOSUB 650: NEXT K: I = CY: CY = D - H * .4: FOR CX = X1 TO X1 - X STEP -P:
      GOSUB 666: NEXT CX: DRAW "BM" + STR$(CX) + "," + STR$(CY): DRAW "C2 X"
      + VARPTR$(TOOL$): GOSUB 2010: DRAW "BM" + STR$(CX) + "," + STR$(CY):
      DRAW "C0 X" + VARPTR$(TOOL$)
1093 CY = I: NEXT CP: FOR CX = X1 - X TO X1 STEP P: GOSUB 650: NEXT CX: X = X1: Y
      = Y1: DRAW "BM" + STR$(X) + "," + STR$(Y): DRAW "C0 X" +
      VARPTR$(TOOL$): I = 0: K = 0: RETURN
1100 REM TEST

```

```

1110 AN = 3.141593 - ATN((Y - Y1) / (X1 - X)) - ATN(SQR(R ^ 2 - (SQR((X1 - X) ^ 2 + (Y -
    Y1) ^ 2) / 2) ^ 2) / (SQR((X1 - X) ^ 2 + (Y - Y1) ^ 2) / 2))
1120 IF G% = 3 THEN K = COS(AN) * R: I = SIN(AN) * R: RETURN
1130 K = (COS(AN) * R + (X1 - X)) * -1: I = (SIN(AN) * R - (Y - Y1)) * -1: RETURN
2010 IF S$ = "S" THEN D$ = INKEY$: IF D$ = "" GOTO 2010
2015 GOTO 2030
2020 GOSUB 640
2030 RETURN
2038 IF T2% = 0 THEN T2% = 1: T1% = VAL(MID$(B$, 2, 1)): GOTO 2045
2040 T1% = VAL(MID$(B$, 2, 1)): DRAW "BM" + STR$(M%) + ",0": DRAW "C2 X" +
    VARPTR$(TOOL$): IF T% = T1% + 1 THEN 2080
2042 IF T% = 5 AND T1% = 3 THEN 2080
2045 IF T1% = 1 THEN TOOL$ = TOOL1$: TOOLI$ = TOOL1I$: M% = 60
2050 IF T1% = 2 THEN TOOL$ = TOOL2$: TOOLI$ = TOOL2I$: M% = 145
2060 IF T1% = 3 THEN TOOL$ = TOOL3$: TOOLI$ = TOOL3I$: M% = 232
2070 DRAW "BM" + STR$(M%) + ",0": DRAW "C0 X" + VARPTR$(TOOL$)
2080 RETURN
3020 CO = D1 / D: P = LE * CO: IF P + 30 > 280 THEN D1 = D1 - 1: GOTO 3020
3025 CLS : SCREEN 1, 1
3026 DEF SEG : POKE &HFE, 0
3027 CLS
3030 D% = INT(D * CO)
3035 PSET (0, 0): A = 10: B = 160: X = 1: F = 2: GOSUB 5000: D = 60 - D% / 2
3036 DRAW "BM10," + STR$(INT(D)): B = 20: GOSUB 5000: D = D + 10
3037 DRAW "BM20," + STR$(INT(D)): B = 10: GOSUB 5000:
3038 D = 80 + D% / 2: DRAW "BM10," + STR$(INT(D)): B = 20: GOSUB 5000
3039 B = 10: DRAW "BM20," + STR$(INT(D)): GOSUB 5000
3040 D = 80 - D% / 2: DRAW "BM10," + STR$(INT(D))
3041 B = D%: A = P + 19: F = 1: GOSUB 5000
3043 DRAW "BM1,80": FOR N = 1 TO 18: READ X, Y: DRAW "BM" + STR$(X) + ",0":
    DRAW "C2 R" + STR$(Y): NEXT N
3045 LOCATE 1, 5: PRINT "T1="; : DRAW "BM60,0": DRAW "C2 X" +
    VARPTR$(TOOL1$)
3050 LOCATE 1, 15: PRINT "T2=": DRAW "BM145,0": DRAW "C2 X" +
    VARPTR$(TOOL2$)
3060 LOCATE 1, 26: PRINT "T3=": DRAW "BM232,0": DRAW "C2 X" +
    VARPTR$(TOOL3$)
3065 GET (60, 0)-(68, 11), T%
4090 RETURN
5000 DRAW "C1 R" + STR$(INT(A)) + "D" + STR$(INT(B)) + "L" + STR$(INT(A)) + "U" +
    STR$(INT(B)): PAINT STEP(2, 2), F, X: RETURN
5010 DATA 1,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5,20,
    5,5,5,20,5,5,5,20,5,5,5,20,5,5,5
6000 A$ = INKEY$: IF A$ = "" GOTO 6000
6005 IF ASC(A$) = 13 THEN A$ = "13": GOTO 6020
6010 IF A$ <> " " GOTO 6000
6020 RETURN
8000 CHAIN "C:\COLIN\ASCIIMENU.BAS"

```

INTER2.bas allows the user to input the G-Code and material specifications such as the type of material being machined, workpiece diameter and length, and the type of cutting tool to be used.

#### INTER2.bas

```
10 DIM P%(20): DIM S%(16004): ON KEY(9) GOSUB 7000: KEY(9) ON
20 DIM N$(250): SCREEN 0: WIDTH 40: CX = 310: CY = 180: X1 = 310: Y1 = 180
30 COLOR 0, 7, 2: CLS: COLOR 0, 4, 2: PRINT " BEGIN ALL COMMENTS WITH A
    BRACKET. ";: PRINT SPACE$(40): : PRINT " DO NOT USE BRACKETS WHEN
    ENTERING CODE.";
50 GOSUB 1200
60 COLOR 0, 7, 2: LOCATE 10, 1: PRINT "ENTER PROGRAMME NAME": GOSUB 1050: IF
    D% = 1 GOTO 60
70 GOSUB 1170
80 GOSUB 1100: LOCATE 10, 1: PRINT "ENTER MATERIAL TYPE.": GOSUB 1050: IF D%
    = 1 GOTO 80
90 GOSUB 1170
100 GOSUB 1100: LOCATE 10, 1: PRINT "ENTER OUTSIDE": PRINT "DIAMETER OF
    MATERIAL": GOSUB 1050: IF D% = 1 GOTO 100
110 GOSUB 1110: IF D1% = 0 GOTO 100
120 N$ = N$ + " O.D.": GOSUB 1170
130 GOSUB 1100: LOCATE 10, 1: PRINT "ENTER DISTANCE FROM": PRINT "END OF
    WORK PIECE": PRINT "TO CHUCK JAWS.": GOSUB 1050: IF D% = 1 GOTO 130
140 GOSUB 1110: IF D1% = 0 GOTO 130
150 N$ = N$ + " FROM CHUCK": GOSUB 1170
160 GOSUB 1100: LOCATE 10, 1: PRINT "SELECT METRIC(G71)": LOCATE 11, 9: PRINT
    "OR": PRINT " INCH(G70).": GOSUB 1050
170 GOSUB 1100: LOCATE 10, 1: PRINT "SELECT ABSOLUTE(G90)": LOCATE 11, 9:
    PRINT "OR": PRINT "INCREMENTAL(G91).": GOSUB 1050
180 GOSUB 1100: LOCATE 10, 1: PRINT "SELECT FEED MODE": PRINT: PRINT "
    UNITS/MIN.(G94)": PRINT " UNITS/REV.(G95)": GOSUB 1050
190 N$ = A$: GOSUB 1170: A$ = ""
200 GOSUB 1100: LOCATE 10, 1: PRINT "ENTER G50 CODE,": PRINT "FOLLOWED BY":
    PRINT "X AND Z VALUES.": GOSUB 1050: GOSUB 1110: IF D1% < 2 GOTO 200
210 N$ = A$: GOSUB 1170: GOSUB 1270
220 GOSUB 1100: LOCATE 10, 1: PRINT "SELECT SPINDLE SPEED": PRINT "USING
    CODE(S).": GOSUB 1050: N$ = A$
230 GOSUB 1100: LOCATE 10, 1: PRINT "SELECT DIRECTION OF": PRINT "SPINDLE
    ROTATION": PRINT: PRINT " FORWARD(M3).": PRINT " REVERSE(M4).": GOSUB
    1050: N$ = A$: GOSUB 1170
240 GOSUB 1100: LOCATE 10, 1: PRINT "ENTER TOOL NUMBER": PRINT "USING
    CODE(T) AND": PRINT "OFFSET NUMBER.": GOSUB 1050: B$ = N$: N$ = A$:
    GOSUB 1170
250 GOSUB 1100: LOCATE 12, 1: PRINT "DO YOU WISH TO ALTER": PRINT "ANY
    LINE(Y/N)?": PRINT: INPUT "", N$: IF N$ <> "" THEN GOSUB 1200 ELSE GOTO 250
260 IF ASC(N$) = 89 OR ASC(N$) = 121 THEN GOSUB 1100: GOSUB 1210: GOTO 250
270 D = VAL(RIGHT$(N$(3), LEN(N$(3)) - 1)): LE = VAL(RIGHT$(N$(4), LEN(N$(4)) - 1)):
    B$ = RIGHT$(N$(8), 4): DI = D
290 D1 = 100
300 CO = D1 / D: P = LE * CO: IF P + 30 > 280 THEN D1 = D1 - 1: GOTO 300
310 D% = INT(D * CO): B$ = RIGHT$(N$(8), LEN(N$(8)) - 4)
320 SCREEN 1, 1: GOSUB 1480: GET (1, 1)-(300, 190), S%
340 LOCATE 21, 1: INPUT "SELECT FEED RATE USING CODE(F). ", B$: OP$ = B$:
    GOSUB 1110: IF D1% = 0 THEN GOSUB 6000: GOTO 340
350 LOCATE 21, 1: PRINT "ENTER CODE G0 FOR FIRST TOOL MOVEMENT.": : G% = 4:
    LOCATE 23, 19: INPUT A$
```

```
360 LOCATE 21, 1: GOSUB 6000: LOCATE 21, 1: INPUT "ENTER X COORDINATE. X=",
    YC$: OP$ = YC$: X$ = YC$: GOSUB 1110: IF D1% = 0 THEN GOSUB 6000: GOTO
    360
370 LOCATE 22, 1: INPUT "ENTER Z COORDINATE. Z=", XC$: OP$ = XC$: Z$ = XC$:
    GOSUB 1110: IF D1% = 0 THEN LOCATE 22, 1: PRINT STRING$(60, " ");: GOTO
    370
390 GOSUB 720: GOSUB 1230: IF ASC(Y$) = 89 OR ASC(Y$) = 121 THEN X1 = X: Y1 = Y:
    GOTO 550
400 GOTO 530
410 GOSUB 6000: PRINT "ENTER A G CODE TO POSITION THE TOOL": LOCATE , 10:
    PRINT "OR TO MAKE A CUT?": LOCATE , 15: INPUT A$: GOSUB 6000: IF A$ =
    "G28" OR A$ = "G29" OR A$ = "G27" OR A$ = "G30" THEN GOSUB 9060: IF A$ =
    "G28" OR A$ = "G27" THEN GOTO 525
411 IF A$ = "G29" OR A$ = "G30" THEN GOSUB 740: GOTO 525
420 LOCATE 22, 1: INPUT "X=", YC$: OP$ = YC$: IF YC$ = "" THEN YC$ = STR$((Y - 80) /
    CO * 2): GOTO 450
430 GOSUB 1110: IF D1% = 0 THEN GOSUB 6000: GOTO 420
440 X$ = YC$
450 LOCATE 22, 14: INPUT "Z=", XC$: OP$ = XC$: IF XC$ = "" THEN XC$ = STR$((X - 30)
    / CO): GOTO 480
460 GOSUB 1110: IF D1% = 0 THEN LOCATE 22, 10: PRINT STRING$(10, " ");: PRINT
    STRING$(20, " ");: GOTO 450
470 Z$ = XC$
475 IF A$ = "G52" THEN G% = 4
480 IF A$ = "G0" THEN G% = 4
490 IF A$ = "G1" THEN G% = 1
500 IF A$ = "G2" THEN G% = 2: GOSUB 1460
510 IF A$ = "G3" THEN G% = 3: GOSUB 1460
520 GOSUB 720: IF A$ = "G0" AND VAL(XC$) = X3 AND VAL(YC$) = Y3 THEN GOSUB
    9020: GOTO 526
522 IF A$ = "G52" AND VAL(XC$) = 0 AND VAL(YC$) = 0 THEN GOSUB 9020: GOTO 526
525 GOSUB 1230
526 IF ASC(Y$) = 89 OR ASC(Y$) = 121 THEN X1 = X: Y1 = Y: GOTO 550
530 PUT (1, 1), S%, PSET
540 R$ = "": GOSUB 6000: PRINT "REENTER ALL BLOCK DATA": GOSUB 1090: GOSUB
    6000: GOTO 410
550 GET (1, 1)-(300, 190), S%: IF A$ = "G28" OR A$ = "G29" OR A$ = "G30" THEN 595
560 X2$ = "X" + X$: IF X$ = X1$ THEN X2$ = "": IF G% = 2 OR G% = 3 THEN X2$ = "X" +
    X$
570 Z2$ = "Z" + Z$: IF Z$ = Z1$ THEN Z2$ = "": IF G% = 2 OR G% = 3 THEN Z2$ = "Z" + Z$
580 X1$ = X$: Z1$ = Z$
590 IF A$ = "G0" OR A$ = "G52" THEN GOSUB 1330
595 GOSUB 1530
597 IF F% = 2 THEN F% = 0: GOSUB 6000: GOTO 340
620 IF F% <> 1 THEN 410
630 GOSUB 6000: INPUT "ENTER SPINDLE STOP CODE(M5). ", A$: GOSUB 1530: GOSUB
    6000: INPUT "ENTER END OF PROGRAMME CODE(M2). ", A$: GOSUB 1530
640 N$ = RIGHT$(N$(1), LEN(N$(1)) - 1)
650 OPEN N$ FOR OUTPUT AS #1
660 FOR N = 1 TO N%
670 PRINT #1, N$(N)
680 NEXT N
690 CLOSE
700 GOSUB 6000: PRINT "YOUR PROGRAMME HAS NOW BEEN SAVED AS": LOCATE ,
    8: PRINT "*** "; N$; " ***": PRINT "PRESS SPACEBAR TO RETURN TO THE
    MENU"
705 A$ = INKEY$: IF A$ <> " " THEN 705
710 CHAIN "C:\COLIN\ASCII\MENU.BAS"
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720 Y = 81 + VAL(YC$) / 2 * CO: X = 30 + VAL(XC$) * CO: Y$ = "": IF G% = 2 OR G% = 3
    THEN GOSUB 1020
725 IF A$ = "G52" AND VAL(XC$) = 0 AND VAL(YC$) = 0 THEN X = 30 + X3 * CO: Y = 81
    + Y3 / 2 * CO
730 IF X1 > 300 OR Y1 > 180 THEN 750
740 DRAW "BM" + STR$(X1) + STR$(Y1): DRAW "C0 X" + VARPTR$(TOOLS$)
750 CX = X1: CY = Y1
755 IF A$ = "G29" THEN G% = 29: GOSUB 3000: GOTO 870
756 IF A$ = "G30" THEN G% = 30: GOSUB 3012: GOTO 870
760 IF R = 0 THEN R = SQR(K ^ 2 + I ^ 2)
770 IF R > 0 THEN PX = X1 + K: PY = Y1 + I: FOR CX = X1 TO X STEP -.5: GOSUB 970:
    GOSUB 920: NEXT CX: I = 0: K = 0: R = 0: GOTO 860
780 IF X < X1 AND Y < Y1 THEN FOR CX = X1 - G% TO X STEP -G%: CY = CY - (Y1 - Y) /
    (X1 - X) * G%: GOSUB 920: NEXT CX
790 IF X > X1 AND Y < Y1 THEN FOR CX = X1 + G% TO X STEP G%: CY = CY - (Y1 - Y) /
    (X1 - X) * G%: GOSUB 920: NEXT CX
800 IF X < X1 AND Y > Y1 THEN FOR CX = X1 - G% TO X STEP -G%: CY = CY + (Y - Y1) /
    (X1 - X) * G%: GOSUB 920: NEXT CX
810 IF X > X1 AND Y > Y1 THEN FOR CX = X1 + G% TO X STEP G%: CY = CY + (Y - Y1) /
    (X - X1) * G%: GOSUB 920: NEXT CX
820 IF Y = Y1 AND X < X1 THEN FOR CX = X1 TO X STEP -G%: GOSUB 920: NEXT CX
830 IF Y = Y1 AND X > X1 THEN FOR CX = X1 TO X STEP G%: GOSUB 920: NEXT CX
840 IF X = X1 AND Y < Y1 THEN FOR CY = Y1 TO Y STEP -G%: GOSUB 920: NEXT CY
850 IF X = X1 AND Y > Y1 THEN FOR CY = Y1 TO Y STEP G%: GOSUB 920: NEXT CY
860 IF CX > 300 OR CY > 180 THEN 880
870 DRAW "BM" + STR$(X) + "," + STR$(Y): DRAW "C2 X" + VARPTR$(TOOLS$)
880 A% = 0: N$ = "": RETURN
920 IF CX > 300 OR CY > 180 THEN RETURN
925 DRAW "BM" + STR$(CX) + STR$(CY): DRAW "C2 X" + VARPTR$(TOOLS$)
930 IF G% = 1 OR G% = 2 OR G% = 3 OR G% = 29 OR G% = 30 THEN SOUND 100, 1
940 CZ = CY - 80: IF 70 - CZ < 10 THEN CZ = 60
945 CZ = 81 - CZ
950 DRAW "BM" + STR$(CX) + STR$(CZ): DRAW "C0 X" + VARPTR$(TOOLS$): DRAW
    "BM" + STR$(CX) + STR$(CY): DRAW "C0 X" + VARPTR$(TOOLS$)
960 RETURN
970 REM G2 AND G3 COORDS
980 S = R ^ 2 - (CX - PX) ^ 2: IF S < 0 THEN S = S * -1
990 IF G% = 2 THEN CY = PY + SQR(S): GOTO 1010
1000 CY = PY - SQR(S)
1010 RETURN
1020 AN = 3.141593 - ATN((Y - Y1) / (X1 - X)) - ATN(SQR(R ^ 2 - (SQR((X1 - X) ^ 2 + (Y -
    Y1) ^ 2) / 2) / (SQR((X1 - X) ^ 2 + (Y - Y1) ^ 2) / 2))
1030 IF G% = 3 THEN K = COS(AN) * R: I = SIN(AN) * R: RETURN
1040 K = (COS(AN) * R + (X1 - X)) * -1: I = (SIN(AN) * R - (Y - Y1)) * -1: RETURN
1050 COLOR 0, 7, 2: PRINT : INPUT "", N$: OP$ = N$: GOSUB 1200: IF N% > 3 THEN A$ =
    A$ + N$: GOTO 1070
1060 LOCATE 14, 1: IF LEFT$(OP$, 1) <> "(" THEN BEEP: COLOR 1, 4, 2: PRINT "YOU
    HAVE NOT STARTED": PRINT : PRINT "WITH A BRACKET!": PRINT : PRINT
    "ENTER AGAIN.": GOSUB 1090: D% = 1: GOTO 1080
1070 D% = 0
1080 RETURN
1090 FOR D1 = 1 TO 2500: NEXT D1: RETURN
1100 COLOR 0, 7, 2: LOCATE 10, 1: FOR D1 = 1 TO 14: FOR D2 = 1 TO 20: PRINT " "; :
    NEXT D2: PRINT : NEXT D1: RETURN
1110 D1% = 0: FOR D1 = 1 TO LEN(OP$): IF ASC(MID$(OP$, D1, 1)) = 46 THEN D1% =
    D1% + 1
1120 NEXT D1: IF N% = 5 AND D1% < 2 THEN 1140
1130 IF D1% > 0 THEN 1160

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1140 BEEP: COLOR 0, 4, 2: LOCATE 23, 1: PRINT "DECIMAL OMITTED": GOSUB 1090: IF
    N% < 7 THEN A$ = "": GOSUB 1100
1150 COLOR 0, 7, 2
1160 RETURN
1170 N% = N% + 1: N$(N%) = N$: C% = C% + 1: P%(N%) = C%: GOSUB 9000
1172 COLOR 0, 7, 2: LOCATE 6 + C%, 21: PRINT STRING$(19, " "): LOCATE 6 + C%, 21:
    COLOR 7, 1, 2: IF N% < 5 THEN PRINT STR$(N%); : COLOR 0, 7, 2: PRINT " ";
    N$(N%): IF RI$ = "" THEN RETURN ELSE C% = C% + 1: LOCATE 6 + C%, 24: PRINT
    RI$: RI$ = "": N$(N%) = C$: RETURN
1180 COLOR 7, 1, 2: PRINT STR$(N%); : COLOR 0, 7, 2: IF F% > 0 THEN PRINT " ";
    N$(N%): RETURN
1190 N$(N%) = "N0" + RIGHT$(STR$(N% - 4), LEN(STR$(N% - 4)) - 1) + " " + N$: GOSUB
    9000: PRINT " "; N$(N%): IF RI$ = "" THEN A$ = "": RETURN
    1195 C% = C% + 1: LOCATE 6 + C%, 25: PRINT RI$: RI$ = "": A$ = "": N$(N%) =
    C$: RETURN
1200 COLOR 0, 4, 2: LOCATE 3, 1: FOR N = 1 TO 19: LOCATE N + 3, 21: PRINT " ": NEXT
    N: RETURN
1210 LOCATE 13, 1: PRINT "WHAT LINE?": PRINT : INPUT "", F%: GOSUB 1200: GOSUB
    1100: LOCATE 12, 22: PRINT : PRINT "ENTER AMMENDED CODE": PRINT : COLOR
    7, 1, 2: PRINT STR$(F%); : COLOR 0, 7, 2: INPUT "", N$: GOSUB 1200: G% = N%: N%
    = F% - 1: C% = P%(F% - 1)
1220 GOSUB 1170: N% = G%: RETURN
1230 GOSUB 6000
1231 IF A$ = "G28" OR A$ = "G27" THEN Y$ = "Y": GOTO 1240
1235 LOCATE 22, 1: PRINT "IS THIS WHERE YOU WANTED TO MOVE(Y/N)?: LOCATE
    , 15: INPUT Y$: RETURN
1240 IF N% < 14 THEN N$ = "N0" + RIGHT$(STR$(N% - 4), LEN(STR$(N% - 4)) - 1): GOTO
    1260
1250 N$ = "N" + RIGHT$(STR$(N% - 4), LEN(STR$(N% - 4)) - 1)
1260 IF A$ = "" THEN 1265
1262 IF ASC(A$) = 40 THEN N$ = ""
1265 RETURN
1270 X = 0: IF N% < 7 THEN N$ = N$(6)
1280 X = X + 1: IF MID$(N$, X, 1) <> "X" THEN 1280
1290 Y3 = VAL(MID$(N$, X + 1, LEN(N$) - X))
1300 X = X + 1: IF MID$(N$, X, 1) <> "Z" THEN 1300
1310 X3 = VAL(MID$(N$, X + 1, LEN(N$) - X))
1320 RETURN
1330 IF VAL(XC$) = X3 AND VAL(YC$) = Y3 OR A$ = "G52" AND VAL(XC$) = 0 AND
    VAL(YC$) = 0 THEN F% = 1: GOTO 1336
1332 F% = 0: RETURN
1336 GOSUB 6000: PRINT "IS THIS THE END OF YOUR PROGRAMME(Y/N).": LOCATE ,
    15: INPUT Y$: IF Y$ = "Y" THEN 1400
1338 GOSUB 1400: GOSUB 1530
1340 GOSUB 6000: INPUT "DO YOU WISH TO REVERSE THE BLANK.(Y/N) "; Y$: IF Y$ =
    "Y" THEN GOSUB 6000: INPUT "ENTER SPINDLE STOP CODE. (M5) "; A$: GOSUB
    1530: GOSUB 6000: INPUT "ENTER PROGRAMME HALT CODE. (M0) "; A$: GOSUB 1530:
    GOTO 1410
1350 GOSUB 6000: PRINT "ENTER G50 CODE FOLLOWED BY X AND Z": INPUT "
    VALUES. ", N$: OP$ = N$: GOSUB 1110: IF D1% < 2 THEN 1350
1360 GOSUB 1270: A$ = N$: GOSUB 1530
1370 GOSUB 6000: PRINT "ENTER NEW TOOL NUMBER WITH OFFSET ZERO.":
    LOCATE , 15: INPUT A$: GOSUB 6000: INPUT "ENTER TOOL CHANGE CODE
    (M6). ", B$: B$ = A$ + B$: A$ = "": GOSUB 2038: GOSUB 1530
1380 GOSUB 6000: INPUT "SELECT SPINDLE SPEED USING CODE (S). ", A$: GOSUB
    6000: PRINT "SELECT DIRECTION OF SPINDLE ROTATION": PRINT "
    FORWARD. (M3)": INPUT " REVERSE. (M4) ", B$: F% = 2: RETURN
1400 GOSUB 6000: PRINT "CANCEL TOOL AND OFFSET BY ENTERING": INPUT "TOOL
    NUMBER AND OFFSET ZERO.", B$: F% = 1: RETURN
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1410 GOSUB 6000: PRINT "ENTER DISTANCE FROM END OF WORKPIECE": INPUT "TO
      CHUCK JAWS. "; N$: OP$ = N$: GOSUB 1110: IF D1% = 0 THEN 1410
1415 RESTORE: D1 = 100: D = D1: COLOR 0, 1
1420 CO = D1 / D: P = VAL(N$) * CO: IF P + 30 > 280 THEN D1 = D1 - 1: GOTO 1420
1430 D% = INT(D * CO): SCREEN 1, 1: CLS : GOSUB 1480: A$ = "(" + N$ + " FROM
      CHUCK JAWS": GOSUB 1530: GOTO 1350
1450 GOSUB 6000: BEEP: PRINT "YOU HAVE ENTERED INCORRECT DATA": GOSUB
1090: : R = 0: I = 0: K = 0: RESUME 540
1460 LOCATE 22, 28: INPUT "R=", RC$: OP$ = RC$: GOSUB 1110: IF D1% = 0 THEN
      LOCATE 22, 28: PRINT STRING$(10, " "): LOCATE 23, 1: PRINT STRING$(20, " "):
      GOTO 1460
1470 R = VAL(RC$) * CO: R$ = "R" + RC$: RETURN
1480 TOOL1$ = "M+0,6 M+1,1 M+0,-6 M+1,1 M+0,+6 M+1,1 M+0,-6 M+1,1 M+0,+6 M+1,1
      M+0,-6"
1481 TOOL2$ = "M-1,+1 M+2,0 M+0,1 M-2,0 M-1,+1 M+4,0 M+0,1 M-4,0 M-1,+1 M+6,0
      M+0,1 M-6,0 M-1,+1 M+8,0 M+0,1 M-8,0"
1482 TOOL3$ = "M+0,9 M-1,0 M-0,-8 M-1,+1 M+0,+7 M-1,0 M+0,-6 M-1,+1 M+0,+5"
1483 TOOL1I$ = "M+0,-6 M+1,-1 M+0,6 M+1,-1 M+0,-6 M+1,-1 M+0,6 M+1,-1 M+0,-6 M+1,-
      1 M+0,6"
1484 TOOL2I$ = "M-1,-1 M+2,0 M+0,-1 M-2,0 M-1,-1 M+4,0 M+0,-1 M-4,0 M-1,-1 M+6,0
      M+0,-1 M-6,0 M-1,-1 M+8,0 M+0,-1 M-8,0"
1485 TOOL3I$ = "M+0,-9 M-1,0 M-0,+8 M-1,-1 M+0,-7 M-1,0 M+0,+6 M-1,-1 M+0,-5"
1486 TOOL$ = TOOL1$: TOOLI$ = TOOL1I$
1487 PSET (0, 2): A = 10: B = 156: X = 1: F = 2: GOSUB 5000: D = 60 - D% / 2: DRAW
      "BM10," + STR$(D): B = 20: GOSUB 5000: D = D + 10: DRAW "BM20," + STR$(D): B =
      10: GOSUB 5000: D = 80 + D% / 2: DRAW "BM10," + STR$(D): B = 20: GOSUB 5000: B
      = 10: DRAW "BM20," + STR$(D): GOSUB 5000
1490 D = 80 - D% / 2: DRAW "BM10," + STR$(D): B = D%: A = P + 19: F = 1: GOSUB 5000
1500 DRAW "BM1,80": FOR N = 1 TO 18: READ X, Y: DRAW "BM+" + STR$(X) + ",0":
      DRAW "C2 R" + STR$(Y): NEXT N
1510 LOCATE 1, 5: PRINT "T1="; : DRAW "BM60,0": DRAW "C2 X" +
      VARPTR$(TOOL1$)
1520 LOCATE 1, 15: PRINT "T2=": DRAW "BM145,0": DRAW "C2 X" +
      VARPTR$(TOOL2$)
1524 LOCATE 1, 26: PRINT "T3=": DRAW "BM232,0": DRAW "C2 X" +
      VARPTR$(TOOL3$)
1526 GOSUB 2038
1528 RETURN
1530 N% = N% + 1: GOSUB 1240: N$(N%) = N$ + " " + A$ + X2$ + Z2$ + R$ + B$ + A1$:
      GOSUB 6000: PRINT "  YOUR CODE FOR THIS OPERATION IS": L =
      LEN(N$(N%)) * 8 + 9: LOCATE 23, 8: PRINT N$(N%); : B$ = "": A$ = "": R$ = "":
      X2$ = "": Z2$ = "": A1$ = ""
1540 LINE (49, 174)-STEP(L, 10), 2, B: LOCATE 25, 1: PRINT "  PRESS THE SPACEBAR
      TO CONTINUE";
1541 A$ = INKEY$: IF A$ <> " " GOTO 1541
1542 LOCATE 25, 1: PRINT SPACE$(34); : RETURN
2038 IF T2% = 0 THEN T2% = 1: T1% = VAL(MID$(B$, 2, 1)): GOTO 2045
2040 T1% = VAL(MID$(B$, 2, 1)): DRAW "BM" + STR$(M%) + ",0": DRAW "C2 X" +
      VARPTR$(TOOL$): IF T% = T% + 1 THEN 2080
2042 IF T% = 5 AND T1% = 3 THEN 2080
2045 IF T1% = 1 THEN TOOL$ = TOOL1$: TOOLI$ = TOOL1I$: M% = 60
2050 IF T1% = 2 THEN TOOL$ = TOOL2$: TOOLI$ = TOOL2I$: M% = 145
2060 IF T1% = 3 THEN TOOL$ = TOOL3$: TOOLI$ = TOOL3I$: M% = 232
2070 DRAW "BM" + STR$(M%) + ",0": DRAW "C0 X" + VARPTR$(TOOL$): GET (1, 1)-
      (300, 190), S%
2080 RETURN
3000 CY = D: FOR CP = 1 TO C: CY = CY + H / C / 1.5: FOR K = X1 TO X1 + X STEP -P: CX
      = K: GOSUB 920: NEXT K: I = CY: CY = D - H * .4: FOR CX = CX TO X1 STEP P:
      G% = 99: GOSUB 920: G% = 29: NEXT CX: DRAW "BM" + STR$(CX) + STR$(CY):

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DRAW "C2 X" + VARPTR$(TOOL$): DRAW "BM" + STR$(CX) + STR$(CY): DRAW
"C0 X" + VARPTR$(TOOL$)
3010 CY = I: NEXT CP: X = X1: Y = Y1: DRAW "BM" + STR$(X) + STR$(Y): DRAW "C0 X"
+ VARPTR$(TOOL$): I = O: K = 0: R = 0: RETURN
3012 CY = D: FOR CP = 1 TO C: CY = CY + H / C / 1.5: FOR K = X1 - X TO X1 STEP P: CX =
K: GOSUB 920: NEXT K: I = CY: CY = D - H * .4: FOR CX = X1 TO X1 - X STEP -P:
G% = 99: GOSUB 920: G% = 30: NEXT CX: DRAW "BM" + STR$(CX) + STR$(CY):
DRAW "C2 X" + VARPTR$(TOOL$): DRAW "BM" + STR$(CX) + STR$(CY): DRAW
"C0 X" + VARPTR$(TOOL$)
3013 CY = I: NEXT CP: FOR CX = X1 - X TO X1 STEP P: GOSUB 925: NEXT CX: X = X1: Y
= Y1: DRAW "BM" + STR$(X) + STR$(Y): DRAW "C0 X" + VARPTR$(TOOL$): I = O:
K = 0: R = 0: RETURN
3020 IF A$ = "G28" OR A$ = "G27" THEN GOSUB 1530: RETURN
3030 GOSUB 740: GOSUB 1530: RETURN
5000 DRAW "C=X;R=A;C=X;D=B;C=X;L=A;C=X;U=B;": PAINT STEP(2, 2), F, X: RETURN
5010 DATA 1,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5,20,5,5,5
6000 LOCATE 21, 1: PRINT SPACE$(119): : LOCATE 24, 1: PRINT SPACE$(39): : LOCATE
21, 1: RETURN
7000 GOSUB 6000: LOCATE 25, 1: PRINT SPACE$(39): : LOCATE 21, 1: INPUT "DO YOU
WISH TO SAVE THIS CODE ?", Y$: IF Y$ = "Y" THEN GOTO 640 ELSE CHAIN
"C:\COLIN\ASCIIMENU.BAS"
8000 CHAIN "C:\COLIN\ASCIIMENU.BAS"
9000 IF LEN(N$(N%)) > 16 THEN C$ = N$(N%): R1$ = RIGHT$(N$(N%), LEN(N$(N%)) -
16): N$(N%) = LEFT$(N$(N%), 16)
9010 RETURN
9020 GOSUB 6000: PRINT "THE TOOL IS NOW IN THE HOME POSITION": GOSUB 1231:
RETURN
9060 IF A$ = "G29" OR A$ = "G30" THEN 9070 ELSE INPUT "D=", X2$: OP$ = X2$: GOSUB
1110: IF D1% = 0 THEN LOCATE 21, 1: PRINT STRING$(20, " "): GOSUB 9080:
LOCATE 21, 1: GOTO 9060
9061 D = 81 + VAL(X2$) * CO / 2: X2$ = "D" + X2$: LOCATE 21, 10: INPUT "C=", Z2$: C =
VAL(Z2$): Z2$ = "C" + Z2$
9063 LOCATE 21, 16: INPUT "H=", R$: OP$ = R$: GOSUB 1110: IF D1% = 0 THEN LOCATE
21, 16: PRINT STRING$(10, " "): GOSUB 9080: GOTO 9063
9064 H = VAL(R$) * CO: R$ = "H" + R$
9065 LOCATE 21, 23: INPUT "W=", B$: IF B$ = "" THEN 9066 ELSE OP$ = B$: GOSUB
1110: IF D1% = 0 THEN LOCATE 21, 23: PRINT STRING$(10, " "): GOSUB 9080:
GOTO 9065
9066 IF B$ <> "" THEN B$ = "W" + B$
9067 LOCATE 21, 32: INPUT "A=", A1$: IF A1$ = "" THEN 9069 ELSE OP$ = A1$: GOSUB
1110: IF D1% = 0 THEN LOCATE 21, 31: PRINT STRING$(7, " "): GOSUB 9080:
GOTO 9067
9068 IF A1$ <> "" THEN A1$ = "A" + A1$ ELSE RETURN
9069 RETURN
9070 INPUT "Z=", X2$: OP$ = X2$: GOSUB 1110: IF D1% = 0 THEN LOCATE 21, 1: PRINT
STRING$(10, " "): GOSUB 9080: LOCATE 21, 1: GOTO 9070
9071 X = VAL(X2$) * CO: X2$ = "Z" + X2$
9072 LOCATE 21, 10: INPUT "X=", Z2$: IF Z2$ = "" THEN 9073 ELSE OP$ = Z2$: GOSUB
1110: IF D1% = 0 THEN LOCATE 21, 10: PRINT STRING$(10, " "): GOSUB 9080:
GOTO 9072
9073 IF Z2$ <> "" THEN Z2$ = "X" + Z2$
9074 LOCATE 21, 20: INPUT "R=", R$: IF R$ = "" THEN 9075 ELSE OP$ = R$: GOSUB
1110: IF D1% = 0 THEN LOCATE 21, 20: PRINT STRING$(10, " "): GOSUB 9080:
GOTO 9074
9075 IF R$ <> "" THEN R$ = "R" + R$
9076 LOCATE 21, 30: INPUT "P=", B$: OP$ = B$: GOSUB 1110: IF D1% = 0 THEN LOCATE
21, 30: PRINT STRING$(8, " "): GOSUB 9080: GOTO 9076
9079 P = VAL(B$) * CO: B$ = "P" + B$: RETURN
9080 LOCATE 23, 1: PRINT STRING$(15, " "): RETURN

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EDITOR 19.bas allows the user to modify and correct the G-Code for the selected job.

**EDITOR19.bas**

```
10 KEY 15, CHR$(&H40) + CHR$(&O1)
20 ON KEY(15) GOSUB 1070
30 KEY(15) ON
40 ON KEY(11) GOSUB 1080
50 KEY(11) OFF
60 ON KEY(14) GOSUB 1090: KEY(14) OFF
70 N$ = "0"
80 ON ERROR GOTO 1110
90 REM Write a new programme or Edit an existing one
100 SCREEN 0: COLOR 4, 7, 2: WIDTH 40: KEY OFF
110 DIM N$(250): CLS
120 LOCATE 10, 10: COLOR 4, 9, 2: PRINT "          ": LOCATE 11, 10: PRINT "
    INSTRUCTIONS Y/N ? ": LOCATE 12, 10: PRINT "          ": LOCATE 11, 33
130 LOCATE 14, 17, 1: INPUT ""; Y$
140 IF Y$ = "" GOTO 120
150 IF ASC(Y$) = 89 OR ASC(Y$) = 121 THEN GOTO 780
160 IF ASC(Y$) = 78 OR ASC(Y$) = 110 THEN 180
170 GOTO 120
180 COLOR 4, 7, 2
190 CLS : LOCATE 2, 12: COLOR 1, 14, 2: PRINT "          ": LOCATE 3, 12: PRINT " DO
    YOU WANT TO ": LOCATE 4, 12: PRINT ; "          ": LOCATE 8, 7: COLOR 4, 7, 2:
    PRINT "WRITE A NEW PROGRAMME? (1)"
200 PRINT : PRINT TAB(16); "OR": PRINT : PRINT TAB(7); "EDIT AN EXISTING ONE?
    (2)"
210 PRINT : PRINT TAB(16); "OR": PRINT : PRINT TAB(7); "RETURN TO THE MENU?
    (3)": PRINT : LOCATE 18, 16
220 INPUT ""; Y$
230 IF Y$ = "1" GOTO 520
240 IF Y$ = "2" GOTO 270
250 IF Y$ = "3" THEN CHAIN "C:\COLIN\ASCIIMENU.BAS"
260 GOTO 180
270 CLS : LOCATE 2, 11: COLOR 1, 14, 2: PRINT "          ": LOCATE 3, 11: PRINT "
    WHAT PROGRAMME ? ": LOCATE 4, 11: PRINT ; "          ": LOCATE 8, 11:
    COLOR 4, 7, 2
280 INPUT NA$: OPEN NA$ FOR INPUT AS #1: L% = 1
290 INPUT #1, N$(L%): IF EOF(1) THEN 310
300 L% = L% + 1: GOTO 290
310 CLOSE #1: N$(L% + 1) = CHR$(255): N$(L% + 2) = CHR$(255): GOTO 580
320 CLS : LOCATE 2, 12: COLOR 1, 14, 2: PRINT "          ": LOCATE 3, 12: PRINT " DO
    YOU WANT TO ": LOCATE 4, 12: PRINT ; "          ": LOCATE 8, 16: COLOR 4, 7,
    2: PRINT "EDIT? (1)": LOCATE 10, 18: PRINT "OR": LOCATE 12, 16: PRINT "SAVE? (2)":
    LOCATE 14, 18: PRINT "OR"
330 LOCATE 16, 9: PRINT "RETURN TO THE MENU? (3)": LOCATE 18, 19
340 INPUT ""; A$
350 IF A$ = "1" THEN 580
360 IF A$ = "2" THEN 400
370 IF A$ = "3" THEN CHAIN "C:\COLIN\ASCIIMENU.BAS"
380 GOTO 320
390 REM ***** SAVE *****
400 CLS : LOCATE 10, 4: PRINT "ENTER A NAME FOR THIS PROGRAMME ": LOCATE
    12, 10: COLOR 1, 7, 2: INPUT NA$
410 N = 0: OPEN NA$ FOR OUTPUT AS #1
420 N = N + 1
430 IF N$(N) <> CHR$(255) THEN PRINT #1, N$(N): GOTO 420
```

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450 CLOSE
460 CLS : LOCATE 1, 6: COLOR 4, 1, 3: PRINT "THIS CODE HAS BEEN SAVED AS":
    LOCATE 3, 9: COLOR 1, 7, 2: PRINT "**** "; : COLOR 4, 1, 3: PRINT NA$: : COLOR 1,
    7, 2: PRINT " ****": X = 1
470 X = X + 1: IF N$(X) <> "" THEN PRINT N$(X): GOTO 470
475 GOSUB 480: CHAIN "C:\COLIN\ASCITMENU.BAS"
480 LOCATE 25, 5: COLOR 2, 13, 7: PRINT "PRESS THE SPACEBAR TO CONTINUE"; :
490 A$ = INKEY$: IF A$ = "" THEN 490
500 IF A$ = " " THEN RETURN
510 REM ***** WRITE A NEW PROGRAMME *****
520 CLS : COLOR 1, 14, 7: LOCATE 2, 10, 1: PRINT " BEGIN WRITING NOW "
530 L% = L% + 1: N$ = "": X = L%
540 COLOR 1, 14, 2: PRINT L%; : COLOR 1, 7, 2: PRINT " ";
550 LOCATE , , 1: INPUT "", N$(L%)
560 IF TRAP = 27 THEN N$(L%) = CHR$(255): N$(L% + 1) = CHR$(255): TRAP = 0: GOTO
    320
570 GOTO 530
580 REM ***** EDIT *****
590 COLOR 1, 7, 0: CLS : FOR L% = 1 TO 16: COLOR 0, 4, 0: PRINT L%; : COLOR 1, 7, 0:
    PRINT TAB(7); N$(L%): NEXT L%: N$ = "": L% = L% - 16: GOSUB 690
600 KEY(11) ON: KEY(14) ON: KEY(15) ON: LOCATE 22, 11: INPUT "", A$
610 IF TRAP = 27 THEN TRAP = 0: KEY(11) OFF: KEY(14) OFF: GOTO 320
620 IF A$ = "" GOTO 600
630 IF A$ = "RENUMBER" THEN X2 = 0: LOCATE 19, 1, 1: COLOR 0, 5, 0: PRINT "PLEASE
    WAIT - RENUMBERING"; : GOTO 980
640 IF ASC(A$) = 68 THEN P = VAL(RIGHT$(A$, LEN(A$) - 1)): FOR X = P TO 199: N$(X)
    = N$(X + 1): NEXT X: N$(X) = "": CLS : GOSUB 690: L% = L% - 1: GOSUB 700
650 IF ASC(A$) = 67 THEN GOSUB 750: L% = L% - 1: GOSUB 700: GOTO 600
660 IF VAL(A$) > 0 THEN L% = VAL(A$) - 1: CLS : GOSUB 690: GOSUB 700: GOTO 600
670 IF ASC(A$) = 65 THEN KEY(11) OFF: KEY(14) OFF: GOSUB 710: IF TRAP = 27 THEN
    TRAP = 0: GOTO 320
680 GOTO 600
690 COLOR 0, 5, 0: LOCATE 19, 1, 1: PRINT "Edit Mode": COLOR 0, 4, 0: LOCATE 22, 1, 1:
    PRINT "COMMAND ?"; : N$ = "": COLOR 1, 7, 0: RETURN
700 LOCATE 1, 1: FOR X = 1 TO 16: COLOR 0, 4, 0: L% = L% + 1: PRINT L%; : COLOR 1, 7,
    0: PRINT TAB(7); N$(L%): NEXT X: L% = L% - 15: RETURN
710 KEY(11) OFF: KEY(14) OFF: LOCATE 19, 1, 1: COLOR 0, 5, 0: PRINT "Append Mode"; :
    P = VAL(RIGHT$(A$, LEN(A$) - 1))
720 LOCATE 22, 11, 0: COLOR 0, 7, 0: PRINT SPACES$(29): LOCATE 22, 11, 0: INPUT "",
    N$: IF TRAP = 27 THEN RETURN
730 FOR X = 250 TO P + 2 STEP -1: N$(X) = N$(X - 1): NEXT X: N$(P + 1) = N$
740 COLOR 1, 7, 0: CLS : LOCATE 19, 1, 1: COLOR 0, 5, 0: PRINT "Append Mode": COLOR
    0, 4, 0: LOCATE 22, 1, 1: PRINT "COMMAND": P = P + 1: GOSUB 700: N$ = "":
    GOTO 720
750 LOCATE 19, 1, 1: COLOR 0, 5, 0: PRINT "Cursor Edit Mode";
760 P = VAL(RIGHT$(A$, LEN(A$) - 1))
770 LOCATE P - L% + 1, 7, 1: COLOR 1, 7, 0: INPUT "", N$(P): CLS : GOSUB 690: RETURN
780 COLOR 1, 7, 2: CLS : COLOR 4, 9, 2: LOCATE 2, 10: PRINT "WRITING A NEW
    PROGRAMME"
790 PRINT : COLOR 1, 7, 2: PRINT "1.Line numbers are automatically entered"; : PRINT
    "2.corrections may be made to a line by": PRINT " using the BACKSPACE key at the
    top of": PRINT " the keyboard. "; : COLOR 4, 7, 2: PRINT CHR$(27)
800 COLOR 1, 7, 2: PRINT " The BACKSPACE key deletes characters ": PRINT " so that new
    characters can be entered.";
810 PRINT "3.The Left and Right Cursor keys on the": PRINT " Numeric Key Pad will move the
    cursor": PRINT " left or right without deleting": PRINT " characters. ": PRINT " To
    make corrections, position the "
820 PRINT " cursor and then retype the new ": PRINT " character."
830 PRINT " Press the ENTER key when your line is": PRINT " correct and complete. "
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840 PRINT "4.The Ins (INSERT) and Del (DELETE) keys"; : PRINT " can also be used to
    correct a line": PRINT " before the ENTER key is pressed"
850 PRINT "5.To SAVE or EDIT a programme, press": PRINT " the ESC and RETURN keys.":
    GOSUB 960
860 COLOR 1, 7, 2: CLS : COLOR 4, 9, 2: LOCATE 2, 10, 1: PRINT "EDITING A
    PROGRAMME": COLOR 1, 7, 2: PRINT : PRINT "1.Entering a line number puts that
    line": PRINT " at the top of the screen."
870 PRINT "2.Pressing the Cursor Up or Cursor Down": PRINT " keys on the Numeric key pad
    moves": PRINT " the screen UP or DOWN one line.": PRINT " NOTE - The RETURN
    key must be pressed": PRINT " before this can take effect."
880 PRINT "3.Entering D followed by a line number": PRINT " DELETES that line."
890 PRINT "4.Entering A followed by a line number": PRINT " puts the Editor into the APPEND
    Mode.": PRINT " This allows extra lines to be inserted": : PRINT " after that line.
    Additions continue": PRINT " until the ESC and RETURN keys are"
895 PRINT " pressed."
900 PRINT " NOTE - While you are in the APPEND": PRINT " Mode, you cannot EDIT or
    DELETE": PRINT " previously written lines. To do this": PRINT " you must exit the
    APPEND Mode by": PRINT " pressing the ESC and RETURN keys."
910 GOSUB 960: COLOR 1, 7, 2: CLS : PRINT
920 PRINT "5.Entering C followed by a line number": PRINT " allows alterations to be made":
    PRINT " to that line."
930 PRINT " Use the BACKSPACE key or the Cursor": PRINT " Editing keys to position the
    cursor": PRINT " for Editing."
940 PRINT "6.Entering RENUMBER and then ": PRINT " RETURN, will renumber all N
    numbers.": : PRINT "7.Pressing the ESC key and then RETURN": PRINT " will exit the
    EDIT Mode."
950 GOSUB 960: COLOR 1, 7, 2: CLS : GOTO 120
960 LOCATE 24, 5, 1: COLOR 4, 9, 2: PRINT "PRESS THE SPACEBAR TO CONTINUE": :
    A$ = INKEY$: IF A$ = "" GOTO 960
970 COLOR 1, 7, 2: CLS : RETURN
980 FOR X = 1 TO 250
990 IF N$(X) = "" THEN 1050
995 IF LEN(N$(X)) = 1 THEN 1050
1000 IF ASC(N$(X)) <> 78 THEN 1050
1010 N$ = N$(X): X1 = 1: X2 = X2 + 1: N1$ = "N"
1020 IF ASC(RIGHT$(N$, LEN(N$) - X1)) < 58 THEN X1 = X1 + 1: IF X1 = LEN(N$) THEN
1030 ELSE GOTO 1020
1030 IF X2 < 10 THEN N1$ = "N0"
1040 N$(X) = N1$ + RIGHT$(STR$(X2), LEN(STR$(X2)) - 1) + " " + RIGHT$(N$, LEN(N$) -
    X1)
1050 NEXT X
1060 GOTO 590
1070 PRINT "Esc": : TRAP = 27: RETURN
1080 TRAP = 11: COLOR 1, 7, 0: CLS : GOSUB 690: GOSUB 700: RETURN
1090 TRAP = 11: COLOR 1, 7, 0: CLS : L% = L% - 2: IF L% < 0 THEN L% = 0
1100 GOSUB 690: GOSUB 700: RETURN
1110 FOR N = 1 TO 5: BEEP: NEXT N
1120 IF ERR = 53 THEN CLS : LOCATE 8, 8: PRINT "FILE NOT FOUND - REENTER":
    LOCATE 10, 12: RESUME 280
1130 IF ERR = 9 THEN CLS : LOCATE 4, 1: PRINT " YOU CANNOT WRITE MORE THAN
    250 LINES!": PRINT : PRINT : PRINT " PRESS THE SPACEBAR TO SAVE OR
    EDIT": L% = L% - 1: GOTO 1150
1140 RESUME 0
1150 A$ = INKEY$: IF A$ = "" GOTO 1150
1160 IF A$ = " " THEN RESUME 320
1170 GOTO 1150
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