COMPUTER INTEGRATED MACHINING PARAMETER SELECTION IN A JOB SHOP USING EXPERT SYSTEMS AND ALGORITHMS

by

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(ABSTRACT)

The research for this dissertation is focused on the selection of machining parameters for a job shop using expert systems and algorithms. The machining processes are analyzed in detail and rule based expert systems are developed for the analysis of process plans based on operation and work-material compatibility, the selection of machines, cutting tools, cutting fluids, and tool angles. Data base design is examined for this problem. Algorithms are developed to evaluate the selection of machines and cutting tools based on cost considerations. An algorithm for optimizing cutting conditions in turning operations has been developed. Data framework and evaluation procedures are developed for other machining operations involving different types of machines and tools.

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CHAPTER 1 : INTRODUCTION

1.1 BACKGROUND

The job shop has come a long way since the early days of manufacturing engineering. The sophistication of machine tools, cutting tools, and other equipment for manufacturing have changed considerably for improvements in productivity and quality. The varieties of these machining parameters have also increased considerably. They possess varying degrees of operational specifications and capabilities which influence the cost and quality of manufacturing. The process planning function has thus become difficult mainly because of the complexity associated with the selection and specification of the machine tool, cutting tool, cutting fluid, and cutting angles required for the machining processes. Considerable cost savings can be accomplished from the proper selection of machining parameters, and the search for the optimal combination is not an easy one.

The selection of the optimal combination of machining parameters is complex for another reason. The information or knowledge that is necessary to make the proper choices is not well structured. This is because human expertise plays a large role in the make up of this knowledge. Heuristics or "rules of thumb" form the basis for most kinds of decision making when choosing from among various machining parameters. The influence that each machining parameter has on one another makes it very difficult for attributing any well defined structure to the knowledge. Human expertise leads to effective solutions when considering trade-offs that exist between the benefits and disbenefits associated with machining parameter selection. The process of capturing human expertise is not as simple as writing a computer program to output results based on structured information. It is even more difficult to find the underlying reasons behind human decision making in the machining environment. This process requires effort to find patterns that exist in selecting machines, tools, cutting fluids, and tool angles based on an in-depth analysis of manufacturing processes and systems.

1.2 HISTORY AND TRENDS

The machining of metals and non-metals has been practiced for over three thousand years, but the mechanics of the process are as yet imperfectly understood. Most of the developments and improvements in machining processes, until quite recently, have come from trial-and-error methods and empirical observation. Since World war II, however, there has been a gradual change in approach. Increasingly, analytical methods have been used to study the cutting process, and the application of these methods have resulted in major improvements. The use of conventional operations has increased considerably and some new processes have also come into industrial use. It is certain that future developments will rely heavily on a basic understanding of the fundamental mechanics of the machining process.

Machining is only one of the many types of manufacturing operations. Other operations include casting, forming, welding etc. Machining operations are often claimed to be the most important processes, as some machining is involved in the manufacture of any product. The expenditure on machining processes forms a considerable portion of a country's economy. Manufacturing technology has undergone a lot of change since the 1940's, as processes like metal forming, extrusion, and spinning have been developed since then. These "chipless" machining processes seemed to have put an end to the conventional machining processes, but the simplicity and economic nature of the latter tends to retain these processes in the modern industrial world. Material removal processes have been improved considerably in recent years. Machine tool performance has improved, and their control is better than ever. Cutting tool materials, machine tool speed and accuracy have been improved substantially. Several new processes like electrolytic machining and ultrasonic machining have been developed [114].

The early lathes were just workpieces rotated between the dead centers fixed on tree trunks, with a person holding the cutting tool in his hands. The French developed the lathe during the middle ages but the first successful slide rest and traversing saddle was created by Maudsley in England in 1797. The years from 1760 to 1860 gave rise to remarkable development in machine tools, especially in Britain. This was primarily due to the need to create components with accuracy, more than that needed before. John Wilkinson invented the planing machine in 1774, Maudsley developed the screw-cutting lathe and Joseph Whitworth improved the lathe. Whitworth was also responsible for developing the modern form of the twist drill [114].

Towards the second half of the nineteenth century Britain had laws which forbade machine tool manufacturers from practicing their expertise outside Britain. The Civil war thus forced American inventors to develop machine tools of their own. Eli Whitney is credited with developing the milling machine around the year 1818. The profile copying milling machine is also credited to him. Stephen Fitch built the turret lathe in 1845 and Joseph Brown developed the universal milling machine and cylindrical grinder in 1862 and 1864 respectively [114].

The work of F.W.Taylor in the United States [103] was an important milestone in the area of machining economics. He developed a relationship between tool life and machine speed, and this relationship is still in use today. The trend in research later shifted to the aspects of machine parameter optimization using several mathematical programming techniques.

1.3 SOME MACHINING OPERATIONS

This section will describe some of the machines commonly encountered on the job shop and their operations [115].

1.3.1 Lathe

Turning is a machining process in which a workpiece is rotated about its longitudinal axis on a machine tool called a lathe. Cutting tools mounted on the lathe are fed into the rotating workpieces to remove material and produce the required shape. The principal surfaces machined are concentric with the longitudinal axis of the workpiece [115].

Turning operations are defined as the removal of material from external surfaces on rotating workpieces. Related operations on external surfaces also performed on lathes include facing, chamfering, grooving, knurling, skiving, threading, and parting. Operations that can be performed on internal surfaces with a lathe include drilling, reaming, boring, threading and recessing [115].

Lathes are one of the most versatile machine tools available. Many different types of lathes of varying complexity are available to suit specific applications. The basic requirements for these lathes include features for holding and rotating the workpiece and holding and feeding the cutting tool. Figure 1 shows the basic configuration of the operation of the lathe.

Many factors influence the turning operation. The three major ones are the cutting speed, feed rate, and the depth of cut. Cutting speed V refers to the rotational speed of the lathe spindle and workpiece and can be expressed in revolutions per minute (rpm). For turning and most other machining operations, the cutting speed is generally given in surface feet per minute (sfm) or meters per minute (m/min), which is the rate at which the workpiece surface moves past the cutting tool. The surface speed equals the rotary speed N (rpm) of the spindle times the circumference of the workpiece, D [115].

Feed rate *f* is the rate at which the tool advances along its cutting path. It is expressed in inches or millimeters per minute or per revolution of the machine spindle. Depth of cut *d* is the thickness of the layer of material removed from the workpiece surface, expressed in inches or millimeters [115].

The cutting tool used in the turning operation and its orientation to the workpiece are important factors to consider. The cutting fluid flowing over the cutting zone influences the surface finish, and the cutting forces [115].

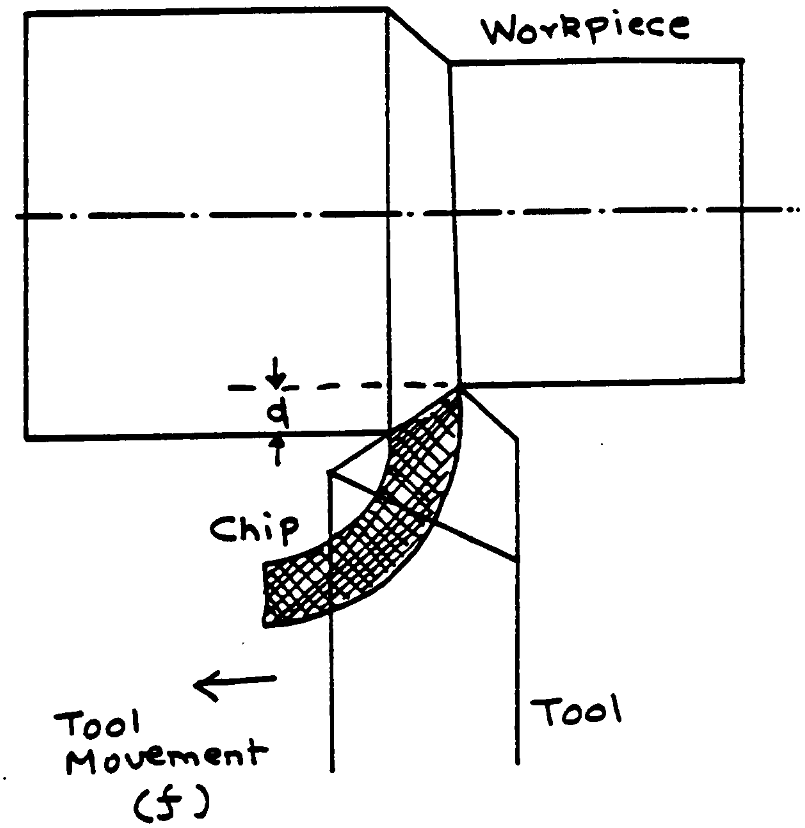


Figure 1. The Turning Process

1.3.2 Milling Machine

Milling is a machining process for removing material by relative motion between a workpiece and a rotating cutter having multiple cutting edges. In some applications, the workpiece is held stationary while the rotating cutter is moved past it at a given feed rate. In other applications, both the workpiece and cutter are moved in relation to each other and in relation to the milling machine. More frequently, however, the workpiece is advanced at a relatively low rate of movement or feed to a milling cutter rotating at comparatively high speed, with the cutter axis remaining in a fixed position. A characteristic feature of the milling process is that each milling cutter tooth takes its share of the stock in the form of small individual chips. Milling operations are performed on many different machines. Since both the workpiece and the cutter can be moved relative to one another, independently or in combination, a wide variety of operations can be performed by milling. Applications include the production of flat or contoured surfaces, slots, grooves, recesses, threads, and other configurations [115]. Figure 2 shows the milling operation.

Milling is one of the most universal, yet complicated machining methods. The process has more variations in the kinds of machines used, workpiece movements, and types of tooling than any other basic machining method. Important advantages of removing material by milling include high stock removal rates, the capability of producing relatively smooth surface finishes, and a wide variety of cutting tools that are available. Cutting edges of tools can be shaped to form any complex surface [115].

There are so many variables influencing milling that it is difficult to predict results reliably. These variables include the size and shape of the workpiece, the work-material, milling operation, milling cutter, milling machine, the rigidity of the setup, and the pro-

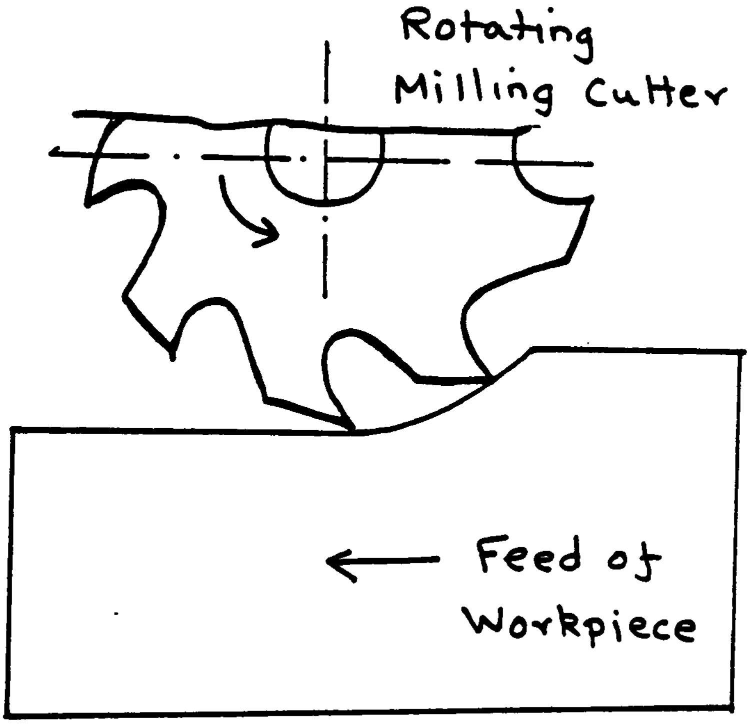


Figure 2. The Milling Process

duction rate, tolerance and surface finish requirements. An attempt must be made to establish the initial parameters for any milling operation, in spite of the existence of all these variables. These parameters include power and force requirements, cutting speed, feed rate, depth of cut, and cutting fluid to be used [115].

1.3.3 Drilling Machine

The production of holes by drilling is one of the oldest and the most widely used of all machining processes. Drilling is basically the production or enlarging of holes by the relative motion of a cutting tool and the workpiece. The cutting tool, the workpiece, or both, may rotate, with the tool generally being fed. Several different methods of drilling exist, including conventional, deep-hole and small-hole drilling. The choice of a method depends upon the size, depth, tolerance, and finish needed, production requirements, and the machines available to perform the operations. The cutting action of drilling is difficult and inefficient although it is fast and economical [115]. Figure 3 shows the drilling operation.

Obtaining maximum economy in the use of drills requires consideration of many factors. One important factor is selecting the proper drill for the specific application. The wide variety of drills available makes this selection process difficult. While a drill of almost any design can be used to produce a hole in almost any material, lower costs for production applications necessitate the use of the correct drill. Variables influencing the selection of the proper drill include the composition, hardness, and surface condition of the material to be drilled, the diameter and the depth of the holes to be produced, the accuracy, surface finish and production requirements, the type and condition of the machine to be used, and the rigidity of the setup. Once a drill has been selected, many

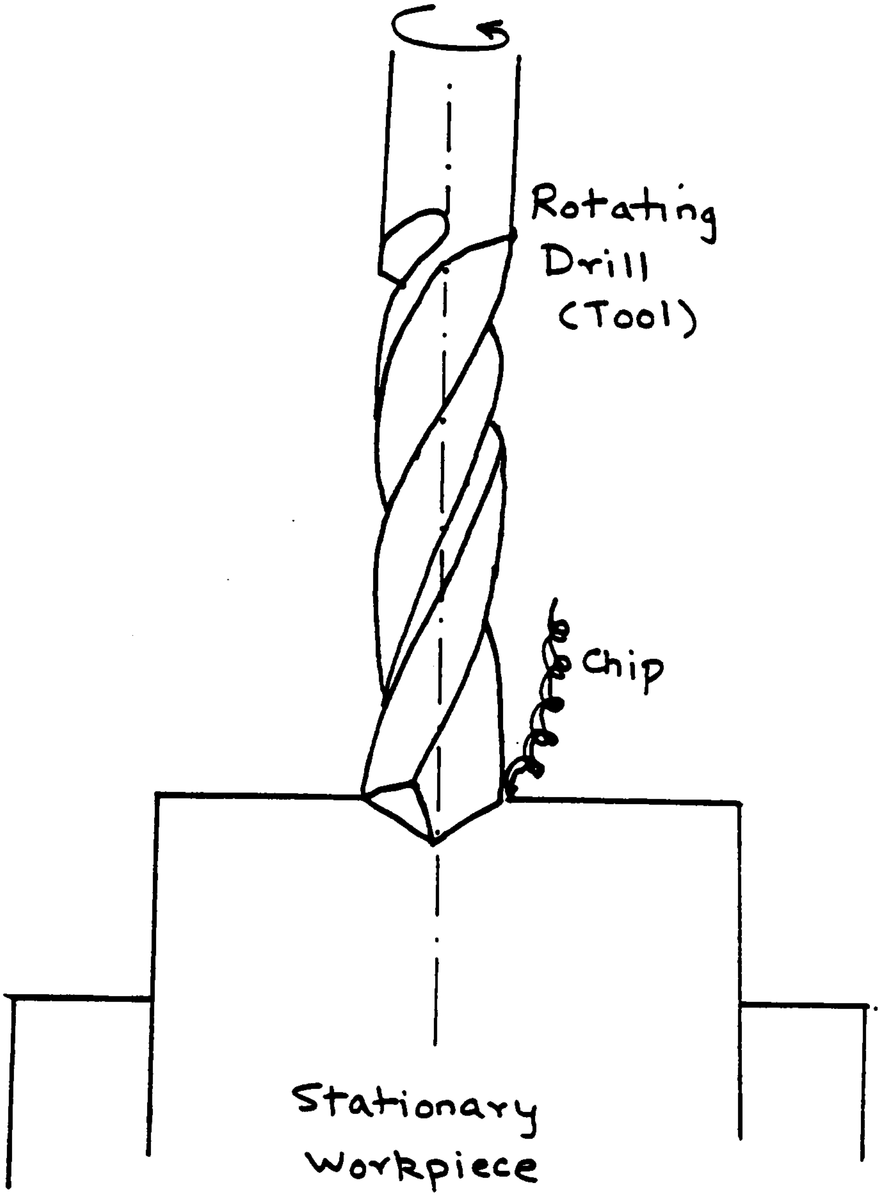


Figure 3. The Drilling Process

operating parameters must be established. These include power requirements, cutting speeds and feed rates, and the cutting fluid to be used [115].

1.3.4 Grinding Machines

Grinding is the most widely used single method of all the different categories of metalworking processes, when basing the comparison on the number of machine tools in use. In this respect, grinding exceeds even such basic processes as turning or drilling. It is an abrasive process, thereby distinguished from most other processes as it removes material by means of abrasive grains [115]. Figure 4 the grinding operation.

A rotating grinding wheel is "plunged" into a stationary or rotating workpiece and the abrasive grinding wheel removes material with each "plunge". The general operating parameters described previously for the other machines hold for the grinding machine [115].

1.4 ROLE OF RESEARCH IN THE MANUFACTURING SYSTEM

The typical manufacturing system associated with a job shop can be illustrated as in figure 5.

Job orders arrive into the shop randomly. Their process plans would indicate the operations that are to be performed, as well as their sequences. It is now necessary to select the machining parameters that are required to manufacture the product. This process is constrained by the availability of machines, cutting tools, and other parameters at the

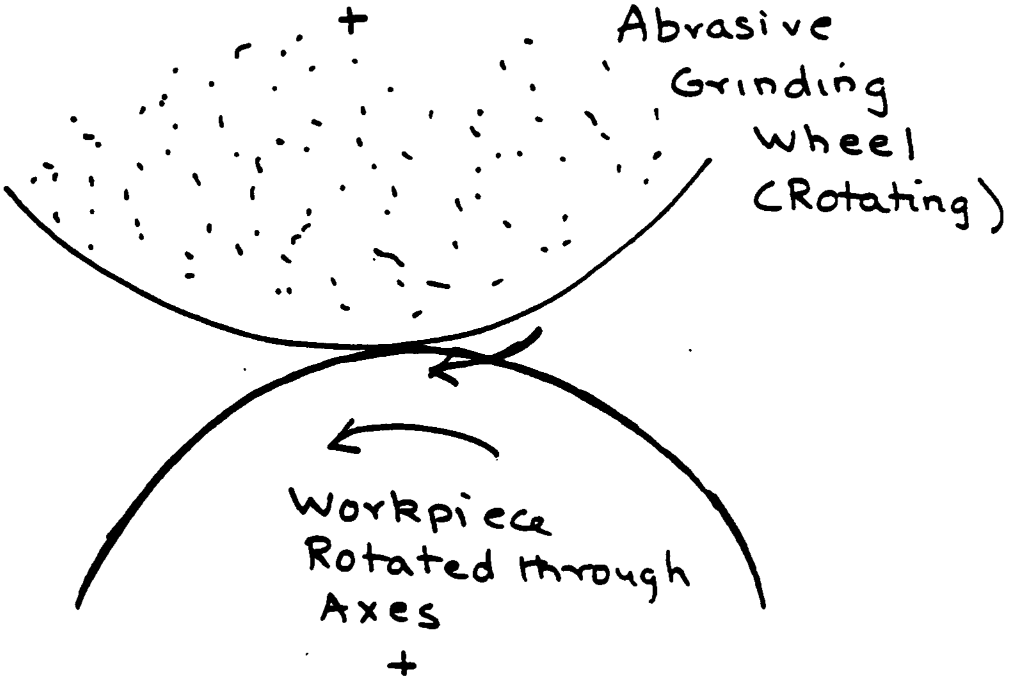


Figure 4. The Grinding Process

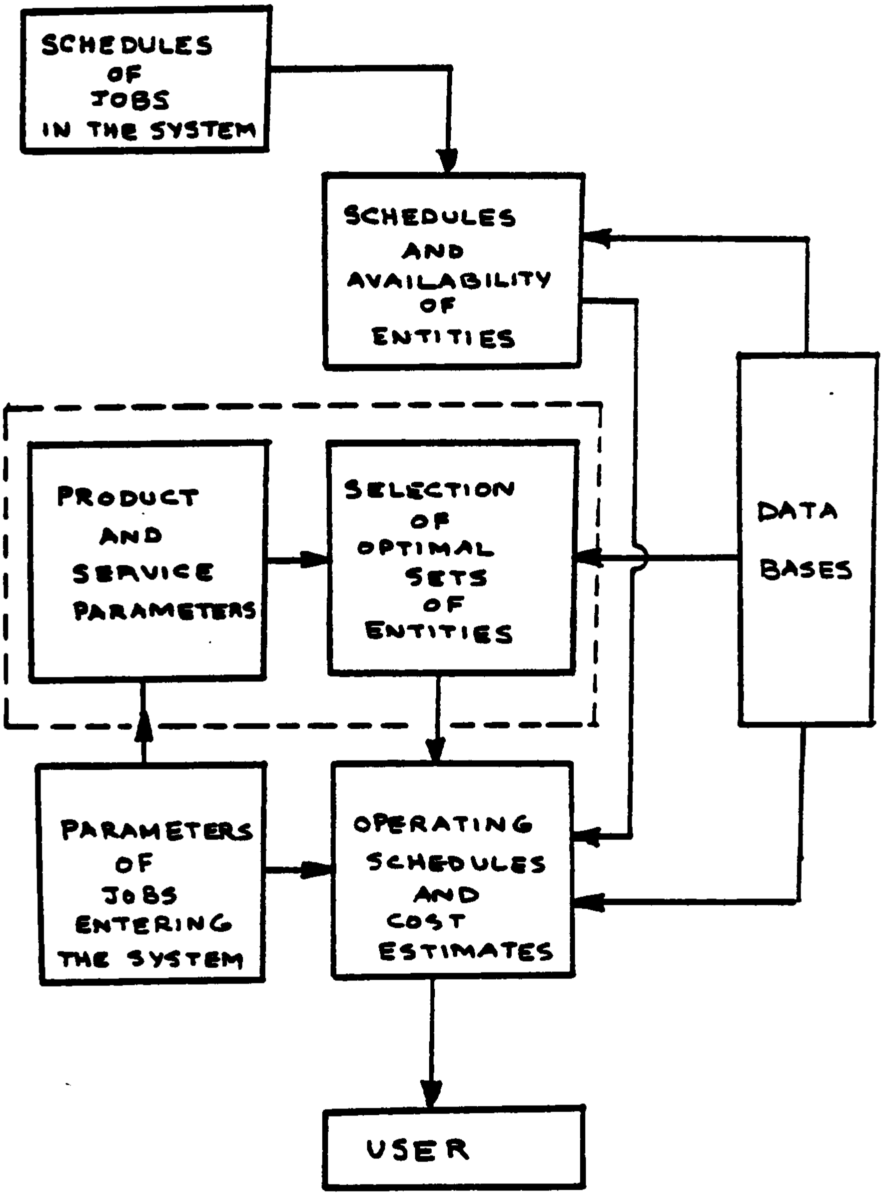


Figure 5. Role of Research in the Manufacturing System

required time. Their capacities would already have been committed to previous schedules for servicing other jobs already in the system.

For generating the schedules and availability of the machining parameters, information on the schedules of jobs already in the system is required. Then, the information about the sets of optimal machining parameters is required for generating the final operating schedules and cost estimates.

The subsystem for the selection of the optimal sets of machining parameters is fed with information about the product and service parameters. This input vector or a collection of them then forms an input to the subsystem which selects machining parameters for the various operations to be done on the job. The output vector resulting from this subsystem, along with the information on the schedules and availability now constitute an input into the final subsystem which determines the operating schedules and cost estimates.

All of the subsystems described above are interfaced with data bases which contain comprehensive information about the machining parameters. The subsystems themselves can be considered to be expert systems, high level computer programs etc. The general schematic described here represents a computer integrated manufacturing system for the job shop.

This research will concentrate on the development of the subsystem which determines the sets of optimal combination of machining parameters. The design of data bases and the development of generic expert systems and algorithms as components of this subsystem, will examined in detail.

1.5 OBJECTIVES OF THE RESEARCH

The research objectives are listed below.

1. Develop data requirements pertaining to the relevant machining parameters.

2. Develop expert systems to select sets of optimal machining parameters each machining operation. This includes the approval or rejection of process plans based on the compatibility between materials and operations, selection of machines, selection of tools, selection of cutting fluids, and the specification of tool angles.

3. Implement expert systems using the data for the relevant machining parameters in order to make the knowledge bases as generic as possible.

4. Develop a data framework for the design of an algorithm to evaluate machine and tool selection based on cost considerations.

5. Design and develop an heuristic for the determination of optimal cutting conditions for the turning operation, using geometric programming.

6. Implementation of the entire system.

1.6 CONCLUSION

This chapter has described the general nature of the manufacturing system in the job shop, and the specific aspects of this research, which is a component within the entire system. Chapter 2 will describe the literature search and examine the pros and cons of various methodologies adopted by other researchers in the field of manufacturing engineering and artificial intelligence. Chapter 3 will outline in detail, the methodology of research for the development of expert systems, data bases and algorithms. Chapter 4 will concentrate on the development of expert systems for the selection of machining parameters, and the analysis of process plans based on the compatibility between materials and operations. Chapter 5 will outline the development of the algorithms and the process of cost evaluation of machines and tools. Chapter 6 would deal with the implementation of the system and the analysis of results. The final chapter, namely 7, would indicate the conclusions and recommendations for future research.

CHAPTER 2 : LITERATURE SEARCH

2.1 THE MACHINING PROCESS : HISTORY

The earliest study of machining processes dates back to 1850. Engineers at that time were interested mainly in the mechanics of the cutting process and the improvements that could be obtained therein [114]. Cocquilhat was among the first to have analyzed the mechanics of the cutting process. He investigated the work content required to machine various materials including brass and iron [40]. The effect of tool geometry on the forces occurring in the cutting process was analyzed by Joessel [40]. In the early 1870's Time discovered that the deformation process during metal cutting was one of shear [40]. The following literature analysis was guided by [114].

Mallock in 1881 was the first to make a careful study of the process of chip formation and the effect of cutting fluids on cutting forces [40]. Zvorykin analyzed the forces and stresses occurring in the cutting zone, but Briks further improved his model that closely identified the forces and stresses using a form of shear plane deformation [114]. Reuleaux postulated that the mechanics of wood cutting and metal cutting were the same and showed the formation of cracks in the high temperature work material when cut by the tool [40]. This view was held by the machining community for a long time.

One of the most important work in the field of metal cutting was from F.W. Taylor [103] in 1907. He analyzed the aspects of tool wear and tool life and the effect of temperature on both. The development of the equation as a function of the tool life and the cutting speed is credited to him, and is still very much in use today. Along with White, Taylor was responsible for the development of high speed steel as a cutting tool material.

Rosenhein and Sturney [94] analyzed the process of chip formation in detail and categorized the various types of chips formed during the cutting process. The concept of the chip formation occurring in a shear plane was derived by Coker and Chakko [24]. Coker [23] has also investigated the stress distributions in the workpiece. The major developments in the analysis of metal cutting were by Ernst, Martellotti [33], Kronenberg [64], and Merchant [79,80,81]. Ernst and Martellotti analyzed the formation of the built-up-edge in metal cutting. Merchant was among the first to study the effect of chip formation of the surface finish of the component. He is also responsible for his milestone papers on the mechanics of metal cutting and his analytical considerations of the process from the stress-strain viewpoint.

The above mentioned research has been instrumental in contributing to the efficiency of the cutting process. The technical accomplishments gave rise to other forms of research, especially in the development of superior cutting tools, powerful and rigid machines, precision work holding devices, effective cutting fluids etc. The literature search on these developments over the years has not been conducted as they were not central to this research.

2.2 MACHINING PARAMETER SELECTION

Taylor's research on the tool life and its relationship to machine operating conditions was instrumental in the development of different kinds of machine tools with finely controllable cutting speeds and feeds. He also pioneered the development of improved cutting tools with long tool life prior to regrinding. This may have sparked off the need to analytically model the cutting process in terms of cost. Considerable research has been conducted on the optimization of cutting feed and speed of machine tools in order to minimize the cost of production or maximize the production rate. Since machine feeds and speeds were controllable within a few discrete steps in earlier days, it was important that the operating parameters of the machine be set at a level to maximize the tool life prior to regrinding. Several papers have been published in this area on unconstrained and constrained optimization using traditional mathematical programming techniques and geometric programming.

The optimization analysis for machine operating parameters has been studied since Gilbert's first work in 1950 [47]. He introduced the "maximum production rate" and "the minimum production cost", under which optimal machining speeds were analysed by developing mathematical models for a single stage manufacturing. Brown analysed unconstrained optimization in general and it is a milestone paper in this area [17]. Okushima and Hitomi [84] proposed a new criterion for manufacturing, namely the "the maximum profit" in a limited time interval, and theoretically derived the optimal machining speed under this criterion using the break-even analysis. Later this analysis was made using mathematical models by Wu and Ermer [109] and Hitomi [54]. Since 1966, this third criterion has been named "maximum profit rate" by Armerago and Russell [5].

The optimization of machining has been studied for the constrained and the unconstrained cases in the literature. Wu and Ermer [109] analyzed the unconstrained machining economics problem with maximum profit as the criterion. The objective was to determine the optimum machine operating conditions in this scenario. Numerous texts discuss the problem of unconstrained machine parameter optimization [9,13]. Mayer [75], Friedman and Tipnis [45], and Hitomi [55] have done research on the unconstrained problem.

The problem of unconstrained machining optimization was treated essentially from the viewpoint of differential calculus and later Geometric Programming (GP). GP was a very effective procedure suited for the machining problem in the sense that the computational complexity was reduced considerably. GP made it possible to consider the constrained optimization case and solve it efficiently.

Bhattacharya, Faria-Gonsalez and Ham [10] considered the constrained problem under the influence of two constraints. Ermer [34] has analyzed the constrained problem for the single pass turning operation for three different types of constraints. Later, Ermer and Kromordihardjo [36] extended the single pass to multi pass turning operations. Phillipson and Ravindran [89] have presented some numerical examples for the constrained machining economics problem. They introduced concepts like differential calculus, geometric programming and goal programming, which could be applied to the non-linear machining economics problem. They illustrated the use of logarithmic transformations in the applications to solving the machining problems. Abuelnaga [1] has summarized some optimization algorithms for metal cutting. Petropoulos [86] illustrates the use of GP in machining economics.

Walvekar and Lambert [107] and Beightler and Phillips [8] consider the application of geometric programming both for the constrained and unconstrained cases related to machining economics. Authors used different types of constraints to illustrate their models. Wysk, Davis and Agee [110] minimized the production time in their model. Feed, speed, depth of cut, and tool life were considered as the constraints. Tool life was assumed to be normally distributed and probabilistic tool failure was considered. The optimization method used a simple search procedure to determine the speed, feed and the depth of cut. Crookal and Venkataramani [26] have described a system for computer optimization of turning operations. They consider the aspects of multi-pass turning in their effort.

Mathematical programming techniques like Lagrange's method, Zoutendijk's method, Rosen's gradient projection method, penalty and barrier methods, can be used to solve the machining economics problem [7]. However, the major advantages offered by Geometric programming are not offered by these methods. For example, Lagrange's method will give rise to non-linear simultaneous equations, which by themselves are difficult to solve.

Bhattacharyya, Faria Gonsalez and Ham [10] have analyzed the problem of surface finish determination using regression methods for turning. The problem was to solve the constrained case for turning with just the surface finish constraint using the lagrangean multiplier approach. The Geometric programming application in machining has been presented by Phillips and Beightler [9], Walvekar and Lambert [107] and Ermer [34]. Ermer and Patel [35] and Milner [78] have used linear programming methods to solve the machining economics problem by using the criterion of maximum metal removal rate and different types of constraints. Ermer and Kromordihardjo [36] have applied separable programming with the aid of GP to analyze the machining problem. The combination of geometric programming and linear programming along with a grid refinement technique was used to iteratively solve the machining economics problem. The computational complexity of this procedure is offset by the accuracy and the ability to handle problems with more than one degree of difficulty.

The Sequential Unconstrained Minimization Technique (SUMT) was employed as a solution technique by Iwata etal [62], Hati and Rao [43]. Iwata, Murotsu, Iwatsubo, and Fujii [61] determine the machine operating conditions for the turning operation optimally with respect to minimum cost and maximum metal removal rate using probabilistic methods. Iwata etal have researched on multi-pass operations and determined the optimal cutting conditions using the techniques of dynamic programming. Probabilistic approach was adopted for the specification of the objective function and constraints, and the dynamic programming approach entailed the use of stages to determine the optimum cutting conditions corresponding to each pass.

Mayer etal [75] review the unconstrained machining economics problem using computer simulation methods for the determination of unit costs and production time using the general form of the tool life equation. Simulation with respect to alterations in the cutting speeds leads to the determination of the maximum production rate and minimum cost. Groover [49] has considered tool wear and surface roughness using models for the turning operation. Variation of the machine cutting conditions and the depth of cut was used with Monte Carlo simulation to determine the optimum cutting conditions.

Sunderam [102] and Phillipson [90] used goal programming techniques to model the multiple conflicting objectives arising within the machining model. The depth of cut and the cutting time were modeled as objectives by Sunderam, subject to two constraints.

Phillipson analyzed multi-stage machining systems with the goals of metal removal rate and tool life in his formulation, along with the constraints on the feed, speed and machine power. The approach has been illustrated for a rough turning operation.

Hough and Gofforth [56,57] use a second order tool life equation along with a posylognormal objective function to solve machining problems with the aid of a "Branch and Bound" method. This method determines the optimum solutions by the process of adding constraints iteratively to the approach considered in the model. Gupta etal [50] consider probabilistic tool life for operations on multi station synchronous machines for the determination of optimum cutting conditions and effective tool changing schemes. Sekhon [97] uses a simulation approach for machining problem by attributing random variational characteristics to both the workpiece and the cutting tool. The tool life constants were varied to test different percentages of hardness of the workpiece. The minimum cost and the maximum production rate criterias were used to determine the optimum cutting conditions for the turning operation. Average values of hardness tool life exponents tend to reduce the difference between predicted and optimum cutting conditions, according to the authors.

Tsai [106] has developed a heuristic for solving the machining economics problem. The method converts the objective function in terms of one dual variable and unconstrained optimization using differential calculus is employed. The heuristic considers the status of the dual variables for treating any infeasibility in the dual solution.

As seen in this literature survey, several researchers have analyzed the machining parameter selection problem entirely from the perspective of the cutting speeds and feeds of machine tools. Geometric Programming comes out to be the best method to handle the problem. This is mainly due to the following reasons :

- The duals reflect the underlying technological factors of the process.
- The ratio of the duals to obtain the optimal solution gives an insight into the values of the cost factors without actually solving for the speeds and feeds.
- Given a reasonable degree of difficulty, the solution procedure is not complex.

This research will aim to develop heuristics that will make the GP approach simpler to implement in the machining environment.

So far the literature search has concentrated on research material pertaining to the selection of machine operating parameters. Not much research has been done on the selection of other machining parameters like machine, cutting tool, cutting fluid etc. Literature tends to consider the selection of entities to service products to be manufactured only in terms of cost. The combined use of human experience and optimization approaches for selection processes in a manufacturing environment thus assumes importance.

2.3 PROCESS PLANNING

Process planning is the function of generating the sequence of manufacturing operations on a product from its initial state to the final state, and specifying the machine, tooling, and operating parameters required to manufacture it. It is a link between the product design and the manufacturing personnel in the shop floor.

CAM-I was responsible for the most extensively used process planning system (CAPP) [101]. MIPLAN is another such system produced by the ORI [101]. Wysk developed APPAS (Automated Process Planning and Selection) for planning the operations of milling and hole drilling. GENPLAN [19] is a generative process planning system developed within Lockheed. It is applicable to both fabrication and assembly operations and it uses a GT coding technique. COBAPP is a system developed by Phillips [87] for cutting operations involving rotational parts. A system called CIMS/MODE [60] is a computer aided generative type process planning system designed to link CAD and CAM. ACAPS [32] uses GT coding in its function for automated process planning.

This research assumes that a partial process plan is available prior to the selection of machining process parameters. One of the aims of the research is to make process planning more effective by providing a framework to consider manufacturability with respect to actual shop conditions and equipment.

2.4 EXPERT SYSTEMS AND APPLICATIONS

Machinability data bank design was the first concept to evolve within the framework of a systems approach to metal cutting optimization. Friedman etal [44] describe the evolution of the entire machining system with particular emphasis on the design of machinability data banks. They also mention that optimization, being in a conceptual stage, should be developed to aid the modular approach to the problem. Eversheim etal [37] explain the aspects of computer aided planning and optimization of cutting data, time and costs. They concentrate on process planning without the use of expert systems.

Artificial Intelligence research has concentrated on solving engineering problems which normally require considerable human effort, and also the development of computationally efficient and intelligent modules. Robotics, natural language processing, and expert systems are components of AI. Expert systems are tools to help automate human decision making processes. The use of data bases, knowledge bases, and inference engine enable expert systems to solve problems that require significant human expertise owing to their complexity. The following literature analysis has been much aided by [116].

Reinstein [92] has analyzed the architecture of expert systems with specific input into the difference that exists with respect to traditional problem solving scenarios and their implications. Farreny [38] has researched into existing expert systems and has described them in relation to the principles of concatenation, filtering, monotone, and non-monotone knowledge as applied in their construction. Gevarter [46] has worked on similar aspects with special emphasis on the general aspects related to expert system applications, trends, research necessities, and future.

Rychener [96] has prepared a well documented bibliography on the various aspects relating to specific expert systems as well as introductory material on artificial intelligence. Kastner and Hong [63] illustrate the applications of expert systems within the field of operational research. Gondran [48] has presented a treatise on expert systems emphasizing their role, application areas and the pros and cons of adopting expert system approaches to problem solving.

A tutorial on the organization of expert systems for solving problems has been provided by Stefik etal [100]. The paper analyzes small problems which require limited searching and which include static and deterministic data, as well as large problem structures which use variant data and render the search space to be quite large. Hayes-Roth [52] has also done similar research and provided an overview of the field of expert systems application along with theoretical implications on engineering applications. The human interface with computers for expert system applications has been examined for their development as well as support tools. Yaghmai etal [111] examine expert systems in terms of developmental and applications issues.

The success of expert systems in specific application areas has been outlined by Morris [82]. Ellis [31] has analyzed in depth about expert system development and applications for several kinds of problems, with emphasis on their future and economic viability. McCarteny [71] addresses the problem of capturing expertise in the development of expert systems. Shaw [99] has detailed the transformation of data bases into expert systems by means of an interface which leads to queries in both directions.

Expert system application in the areas of geological prospecting, medical diagnosis, computer testing, and mathematical analysis has been examined in detail by Addis [2]. Alty and Coombs[4] describe expert system applications in relation to computing or information technology by analyzing conventional expert system issues in the first part followed by the application software. Data processing, predicate calculus, inference mechanisms have been examined with software descriptions on MYCIN, DENDRA, MOLGEN etc.

Campbell [18] outlines the development and applications of expert systems along with their rule structure, both for inferencing and guiding the path of the inference engine. The limitations and advantages of expert system approaches in contrast with other problem solving methods has been presented.

2.5 EXPERT SYSTEMS IN MANUFACTURING

Application of expert systems in manufacturing automation encompass the spectrum from the design of the product through to the automated manufacturing using a robot.

GUMMEX is a process planning system for rubber products, as described by Iudica [59]. The system uses forward chaining to generate the specification of manufacturing processes and support activities required in the production of rubber components. The programs include rule modules, graphics interfaces, and inference mechanisms. Lu [70] has considered the applications of expert systems for automated manufacturing in regard to the robustness required of manufactured products and the relation between emperical approaches to achieve this using expert systems. A case is made for the contribution that expert systems can make in the areas of manufacturing productivity and quality.

The applications of expert systems for robotics and automated manufacturing has been outlined by Lacoe [66]. The key aspects of integrating expert systems into existing manufacturing technology have been examined. Chester, Lamb and Dhurjatl [22] present FALCOM, an expert system for examining alarm signals and other plant data. The network existing between components in FALCOM is the moving force behind the expert system's operations. Failure of components, failure conditions, and error in data can easily be identified by FALCOM. Crandall [25] has described VALVEFIND, an expert system that aids in the selection of valves using specialized expertise.

An expert system simulation model for the analysis of reciprocating compressor performance has been outlined by Law [68]. The system considers several performance parameters, and supports the design function.

Liebowitz [69] has examined the development of expert systems for specifying functional necessities of software for NASA Goddard's Command Management system. The selection of tools for processing using numerical control machine tools has been accomplished using expert systems, as outlined in [104]. The system, written in PASCAL, affords an improvement over manual selection based on manufacturing and tool room expertise. Blanning [11] has analyzed the development of expert systems for decision making in the managerial environment.

Process planning is the bridge between the design and manufacturing functions. The conversion of product design into manufacturing instructions is very crucial, as it influences several factors that affect productivity and product quality. The process of capturing the knowledge of the expert process planner for the development of expert systems has been examined in [104].

Mayer, Young, and Phillips [76] show that artificial intelligence can be used well to solve manufacturing problems. Davies and Darbyshire [27] have shown that process planning is easily performed using the application of expert systems. They have developed EXCAP, which is a computer aided process planning system. Barkocy [5] and Phillips [87] have indicated that CAD and CAM could be linked through the use of generative process planning and using expert systems. Matsuhina [74] has used expert system to integrate CAD and CAM. Chang [20] has developed a totally integrated process planning system which performs the function of automated process planning for several operations.

Kinoglu etal [117] illustrate the development of an expert system used for manufacturing process analysis which is capable of inferencing in the face of uncertainty using numerical procedures. Frame structures and constraint propagations are used in a framework where products are represented in frames of data.

PATRIARCH [83] uses an expert/DSS system for automating the routine parts of the manager's job. The expert system forms part of a scheduling and sequencing system which aims to forecast, plan and deliver products in a manufacturing firm. ISIS [43] is an expert system designed for job shop scheduling. Constraint directed approach is used for the development of the system which considers organizational as well as physical constraints.

Markus etal [73] examine the development of expert systems for fixture design using the workpiece shape, process, and support locations. The system, called MODBWILD, is capable of generating drawings for the the selected fixtures. Fisher [41] discusses the various expert systems available for use within the manufacturing domain. Edosomwan [30] articulates ten design rules for developing Knowledge based expert systems.

2.6 ANALYSIS

There is not much literature present on the direct application of expert systems for machine parameter selection. CAPIS [55] is a system that posseses the framework for machining optimization and job scheduling, but does not use expert system concepts. The system optimizes machining parameters using empirical equations and trial and error methods. The system may not be useful in a large scale environment. COMP [95] is an expert system in the metal cutting area. It has no provisions for optimization except for providing the user with graphs and figures to accomplish this.

Wysk and Wang [108] describe the development of an expert system for machine data selection. The system selects machine operating parameters based on emperical equations. Hsu [58] describes the development of rules for machine parameter selection, based on the conditions which are reported in handbooks.

The contributions of this research in contrast with existing literature in this area are as follows.

1. Development of expert systems with generic knowledge bases.
2. Development of rules by an in-depth analysis of "cause and effect" with respect to machining parameters.
3. Development of an expert system for the analysis of process plans. based on the compatibility between operations and materials.
4. Development of heuristics based on the principle of geometric programming for the optimization of cutting conditions pertaining to the turning operation.
5. Development of a data framework and algorithm for the cost evaluation of machines and tools.

CHAPTER 3 : RESEARCH METHODOLOGY

3.1 KNOWLEDGE BASED EXPERT SYSTEMS

In the previous chapters it had been shown that the machining parameter selection problem is quite ill-structured. There is definitely the need to solve the problem using domain dependent knowledge and heuristic rules. In this chapter, the research methodology for selecting entities to support product manufacturing will be developed.

In the past, human expertise has played a significant role in the operation of manufacturing and service industries. Human expertise can be retained only be adequate training, and even then the patterns that exist in human behavior to solve problems can be unpredictable and difficult to document. Moreover, expertise obtained in this form could be easily lost due to relocation of the experts in the manufacturing environment.

Knowledge based expert systems represent the expert's heuristic reasoning that emulate the behaviour of humans in solving problems usually thought to require experts for their resolution [30]. They represent a new solution approach that utilizes the best of the research done in the field of artificial intelligence in the past. This new problem solving approach aids considerably in the critical decision making processes found in the field of engineering.

Knowledge based expert systems have always been a favorite tool of engineers and scientists in the arena of manufacturing engineering [70]. The decision making processes in manufacturing are critical in the sense that the product cost and quality depend heavily on them. Knowledge about the inference procedures and the expert level activity therein can be used effectively to aid engineers when faced with complex decision making environments.

There are however serious challenges to this new technology in the sense that many do not think that it is a better approach when compared with traditional methods. The reason behind this is that they do not clearly realize and understand the true potential of this tool. While many knowledge based expert systems are being developed for various engineering applications, it is very important to examine the foundations of this approach to reveal its true significance for the problem at hand. It is necessary to use this powerful tool where the traditional methods are inadequate and integrate it with these methods if the overall solution methodology can be made more effective.

The integration and interaction between people, machines and computers characterizes the complex nature of the manufacturing activity. Any manufacturing facility will have basic equipment that are required for the manufacturing activities. Under operating conditions, these equipments generate substantial amount of information. This information is being used by the engineers in the shop to arrive at critical decisions. At present, automation is widely used for managing the equipment and the information that they generate. For example, considerable automation has been brought into the manufacturing facility at the equipment level in the form of robotics, CAD/CAM, CNC machines, etc. Information is now being managed by sophisticated data base systems, interactive graphics facilities, MAP etc. These efforts to automate the factory have contributed to increase in productivity and quality and made manufacturing industries much more competitive than they were before.

Human expertise is still used for analyzing the information and reaching decisions when required. Knowledge based expert systems are aimed to automate the process of analyzing the information and aiding the human to arrive at decisions quickly and efficiently. Full or partial automation of the decision making processes in manufacturing can lead to a great increase in productivity and quality.

The popularity of applying expert systems to address manufacturing problems is mainly due to the fact that they provide knowledge to aid in decision making, not just information and data [118]. Traditional software can only generate information and data using appropriate input, and this has to be analyzed by the engineers based on their experience and "rules of thumb". Knowledge based expert systems address the decision making process directly by capturing the domain dependent knowledge and treating them with inference procedures.

Computer programs are quite effective in dealing with structured information, in that they can process it using numerical techniques and other methods for providing numbers and figures which can be good decision making tools. Since the efficiency of manufacturing processes depends on domain dependent and deterministic knowledge, it is necessary to integrate expert systems with traditional methods for efficient problem solving.

Unexpected changes to the equipment in the manufacturing facility often leads to changes in the structure of the information that they generate. Often traditional software needs to be modified to suit these changes in the information. Expert systems, if built with separation between the data and the knowledge base, can easily adapt to these changing conditions.

The research methodology for this dissertation begins with the choice of a direction to proceed. Due to the above mentioned reasons, the use of expert systems and algorithms are adopted as tools for this research.

3.2 COMPONENTS OF A KNOWLEDGE BASED EXPERT SYSTEM

Knowledge based expert systems comprise of the following components.

1. A Knowledge Base contains rules which reflect the domain dependent knowledge and the expert level heuristics.

2. The Inference Engine provides control in using the knowledge base when solving problems. The strategies for quick and efficient problem solving are in here.

3. The Working Memory consists of the relevant data that pertains to the problem at hand. Some knowledge bases are developed with the data inherent in them, but it is very useful to have a strong separation between the knowledge base and the data bases related to the problem, and provide the interface whenever necessary.

Figure 6 illustrates the typical components of a knowledge based expert system.

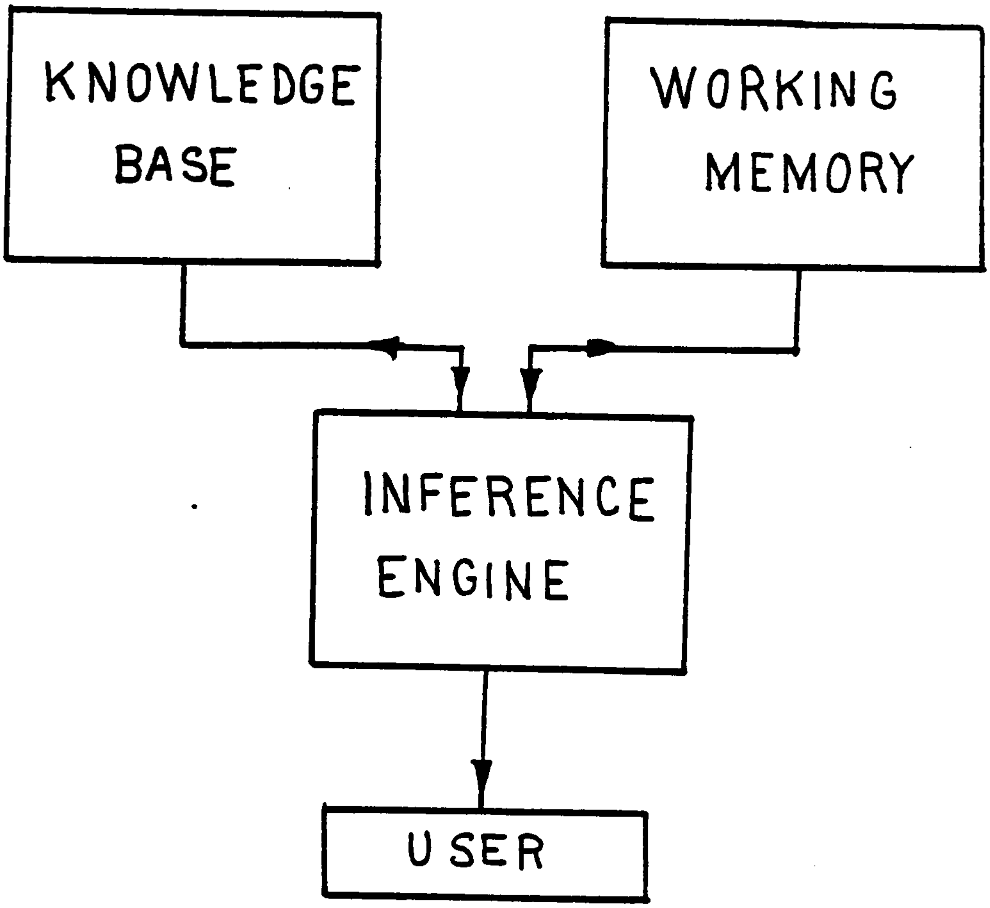


Figure 6. Components of an Expert System

3.3 EXPERT SYSTEM MODEL FOR MANUFACTURING

The present expert system approach for solving manufacturing problems is mainly to use heuristic knowledge. The knowledge base contains rules which pertain to the domain dependent knowledge and expert heuristics. The inference engine then proceeds to use backward or forward chaining methods to arrive at the decisions. This approach is very effective if the domain dependent or expert knowledge is entirely heuristic. If some deterministic knowledge is required to evaluate the decision making alternatives, then it is necessary to provide an interface between expert systems and the traditional methods of using deterministic knowledge. The proposed model is shown in figure 7.
The user inputs the required product and service parameters. The user can also make the expert system read the relevant data from data bases. Since the interface between the inference engine and data bases is still a major research issue, forward chaining can be employed to read in the relevant data from the data bases into the expert system consultation.

The rules begin to get executed by the backward chaining procedure. This is the sequential process of finding the goal to be achieved and then determining whether the conditions that cause the goal to be achieved are met. The output consists of the list of entities within the manufacturing environment that have been selected to service the product to be manufactured. In chapter 4, this methodology will be applied to the selection of machining parameters.

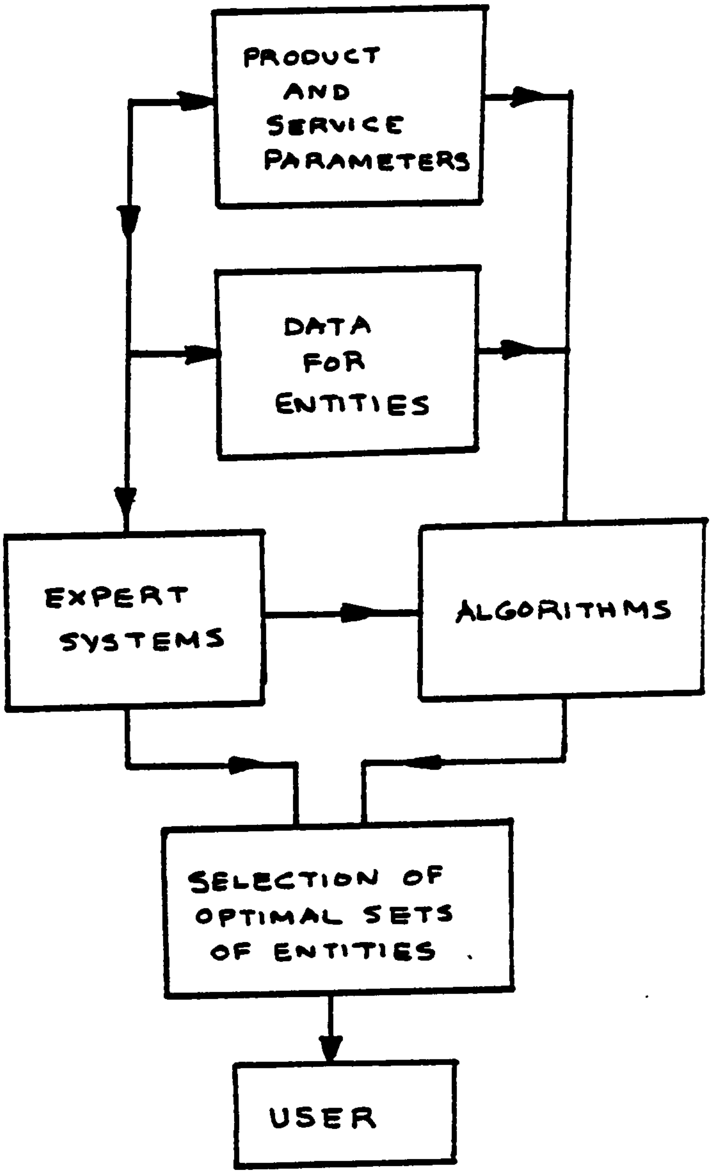


Figure 7. Proposed Model

3.4 DATA REQUIREMENT

The data has to capture all relevant aspects of the entities and conform with the requirements of the expert system. In the manufacturing environment, it is possible to have many kinds of data bases in existence. These data bases, used for scheduling, cost estimating etc., can also easily be used by the system used for the selection of entities. The main problem will be to extract the relevant data from these large data bases.

Since the efficiency of expert systems can be judged by how fast they make decisions, the data retrieval problem can be handled well from inside the expert system, using the forward chaining procedure. Rules could be developed to retrieve data values based on the relational aspects of data. This way the time of data retrieval can be kept to a minimum. The advantage of providing such front-end data retrieval procedures within the knowledge base is mainly to accomplish data base interface with the expert system.

Often new data is developed as the consultation of the expert system proceeds. This type of data may be required for the selection of some kinds of entities. In this case rules can be developed to retrieve such data in consultations, where applicable. The variables for which the data is required assume special importance. These variables could take on one value or multiple values of data. The expert systems should be developed to allow multiple values of data for these variables, when required.

The data for the entities should be filled in a matrix structure. For example, if machines were the entity, then the rows would be the different attributes for the machines, and the columns would be the various types of machines themselves. When each machine is considered individually, then the data for that machine would assume the dimension of a vector. The data can be arranged in any order as that does not play a role in the effectiveness of the execution of the expert systems. It should be noted that apart from the data types mentioned above, provision should be made for accommodating data which could be generated as the expert system consultation proceeds.

The type of data required on each entity has to reflect the function of that particular entity. The selection or rejection of any entity depends on whether or not it can provide the desired function to the product. So in essence we are trying to match the product attributes to the specific data on the functional capabilities of the entity. When formulating the fields for the data on the entities it is necessary to estimate the functional characteristics either in numerical or in symbolic terms.

Direct matching of the attributes of the product and the functional capabilities of some entities may not always lead to conclusions. This is because the functions of these entities are dependent on many factors pertaining to the product and service parameters. In this case, explicit data requirement is not necessary, but the use of rules to match several product and service parameters would lead to the selection of these entities. For example, in the machining environment, cutting fluid selection cannot be done in the same manner as machine selection. A machine would be selected by comparing its functional characteristics with the product and service parameters. A cutting fluid would be selected by matching service and product parameters with specific pre-determined values. This matching process leads to a conclusion on the general nature of the cutting condition, and based on this condition the cutting fluid type would be selected. Since the only data requirement for the cutting fluid is just the type of environment in which it works best, this data can be embedded into the rules of the expert system as opposed to reading it from a data base.

3.5 RULES DEVELOPMENT

The development of rules is a very important part in the design of expert systems. The rules have to be based on an accurate analysis of the domain dependent knowledge and the expert heuristics. The rules also have to be as generic as possible with respect to the selection of the entities. The general structure of the rules are in the "IF-THEN" format, with the use of "AND, OR" wherever applicable.

In backward chaining, the organization and sequence of the rules play a role in the efficiency of execution of the expert system. In forward chaining, the use of pseudo variables are sometimes necessary to direct the path of the inference engine along a desired path. This can be easily done by having some major conditions to be met for the pseudo variable to assume a specified value. If the pseudo variable does indeed assume the desired value, then the relevant goals are pursued. This way the expert system need not find all the goals, but find only those that are sought by the user. Thus, the use of forward chaining to retrieve data and pursue selected goals, along with the execution of the rules by backward chaining leads to an efficient methodology for the selection of entities.

The rules should have conditions and conclusions. If a set of rules are being developed for the selection of a particular entity, then it is sometimes effective to have stages in the selection of the entity, as opposed to having one rule with a number of conditions. This way the conditions can be split up into levels of importance, and as the consultation of the expert system proceeds, considerable savings in time may be obtained. This approach can help the user understand the selection process in a much better fashion. This is also important when using commercially available expert system shells, as they may have an upper limit on the number of conditions that can incorporated into any rule. For example, machines may be selected based on the feasibility of accommodation of the component on the machine. If the machine were feasible for this requirement, then it can be analyzed for the fulfillment of the surface finish and tolerance requirements.

An in-depth analysis of the manufacturing situation is inevitable. The knowledge from experts, handbooks or other sources should be analyzed in detail. Sometimes heuristic knowledge can be rationalized by considering the scientific aspects of the problem or by observing a pattern in such knowledge. After rationalizing this kind of knowledge, it can be expressed in the form of conditions and conclusions. This may be complex at times, as not all types of knowledge can be readily put in this form. As the conditions begin to develop, the premise of the conditions need to be either a variable (field) from a data base, fixed number, or a symbolic expression. It is advantageous to make the premise of the conditions a variable (field) in a data base simply because this contributes to the generic nature of the rules.

3.6 INFERENCE ENGINE DEVELOPMENT

The inference engine provides the control structure to the expert system. When programming in computer language, the computer code has to reflect the inference procedure, but if a commercial expert system shell is used, the arrangement of the rules reflects the control structure.

Let us consider a particular entity and analyze the arrangement of rules for its selection. When a value for a particular goal is being pursued by the expert system, it is necessary to search through a finite number of rules before the goal is reached. In this process, it is advantageous to place the rules whose conclusions lead to sub-goals for which the probability of attainment is high. For example, if the properties of the material to be selected are such that a large proportion of materials fall into this category, then the rules for the selection of this type of material should be placed at the beginning.

If the probability of attaining all sub-goals are equal, the rules could be arranged in the order of increasing number of conditions. This is because the inference engine goes from one rule to another sequentially for selecting that particular entity, and savings in execution time can be achieved in this manner.

There could also be levels of these entities and the selection process can be conducted at each level if necessary. In this case, a tree structure can be attributed to the selection process, as shown in figure 8.

It is also important to realize that in manufacturing, there is no "one best" entity that is capable of performing the required function. The design of the expert system should be such that as many entities are selected as possible. This is because, if only one entity were selected, and for some reason it is not possible to make it available for manufacturing the product, the selection process is rendered useless. This situation is typical to manufacturing, as it is often dictated by the dynamic nature of some critical constraints.

3.7 ALGORITHM DEVELOPMENT

It is important to understand why algorithms are necessary for solving problems in a manufacturing environment. Expert systems, as seen in this chapter, are capable of analyzing heuristic data very effectively. When decision alternatives are to be compared on cost or other quantitative basis, algorithms prove to be much more effective. This

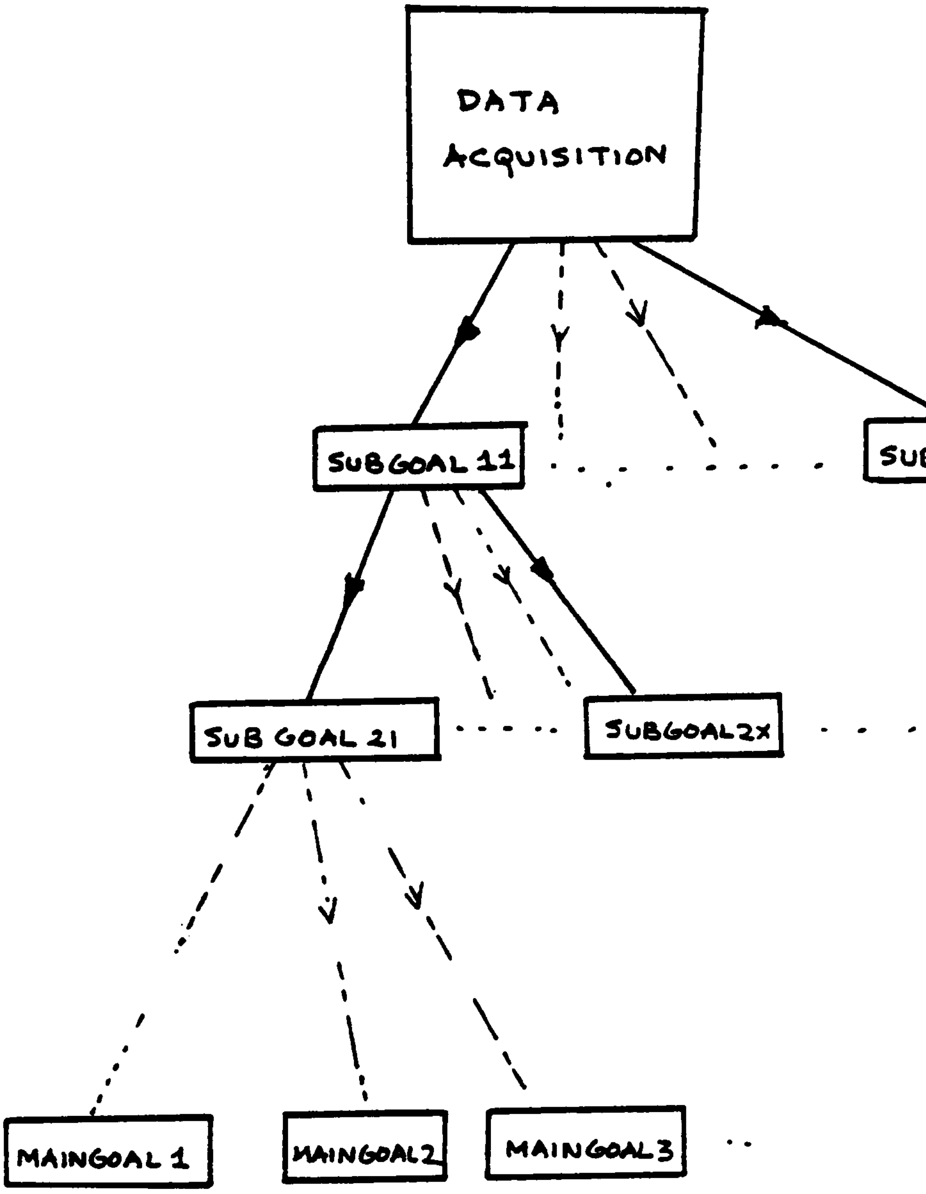


Figure 8. Inference Tree Structure

is especially true in the case where the choice between alternatives reduces to the value of a cost function which has to be optimized with respect to several constraints.

In manufacturing, the selection of entities to service a product to be manufactured often involves the computation of several factors. The selection is then based on the effect that these factors have on the overall cost. For example, the selection of cutting tools for manufacturing a component can be done easily using expert systems, as heuristic knowledge plays a large role in this aspect. However, after several cutting tools have been selected for the same function, the choice should be based on the cost of tool usage, which is a combination of the cost of tools used, and the tool changing cost. These costs depend largely on the tool-life equation and the operating conditions of the machine tool. Hence the problem is one of optimization rather than subjective reasoning.

The primary selection of entities should be done by the expert systems. The sets of entities selected should now be evaluated by the algorithms. The data for the algorithms should be in a matrix format. The general philosophy here is to find the entities selected earlier by the expert systems for a particular product, and then compute the "effectiveness" for each of those sets of entities by means of algorithms.

The output from the expert systems needs to be put in a data format suitable for retrieval by the algorithm. Since the expert systems are used to select entities, the output can be coded in 0,1 format for ease of use by the algorithm. Apart from this type of data, many other types of data are required for the cost evaluation process. This may include explicit cost data, or data on parameters which can be directly or indirectly used to compute costs using functions. The data on some types of entities are required more for use by the algorithm than by the expert systems. This is because some entities contribute most to the cost of manufacturing, while others do not. It is also necessary to have a numerical coding system for describing the various types of entities.

After all the data requirements have been identified, the algorithm has to be designed to have a modular approach for evaluating each entity separately or together with other types of entities for the desired manufacturing condition. The output from the algorithms should specify the selection of each entity, the necessity of any other entity for support, and the itemized cost values for each entity.

3.8 CONCLUSION

This chapter describes the general methodology of this research. It also indicates the techniques that one could adopt to design expert systems and algorithms for the selection of entities to conform to product manufacture in a manufacturing environment. In the next chapter, we will see the application of this methodology to the specific problem of the selection of machining parameters.

CHAPTER 4 : EXPERT SYSTEM MODELS FOR MACHINING PARAMETER SELECTION

In the last chapter, we had seen the general research methodology for entity selection in product manufacturing. In this chapter, a specific application of this methodology, namely the selection of machining parameters, will be examined. The machining parameters considered in this research are the machines, cutting tools, cutting fluids, and tool angles. An expert system for analyzing process plans for operation, work-material compatibility will also be developed.

4.1 COMPONENTS FOR THE MODEL

The model is restricted to an hypothetical example of a job shop. The restrictions apply mainly to the machines, operations, and cutting tool types. There is no restriction on the type of work-material being considered for the component to be manufactured.

The machines considered in this research are as follows.

1. Engine lathe

2. Turret lathe

3. Single spindle automatic lathe

4. Numerical control lathe

5. Horizontal milling machine

6. Vertical milling machine

7. Numerical control milling machine

8. Vertical drill press

9. Radial drilling machine

10. Turret drilling machine

11. Horizontal boring machine

12. Surface grinding machine

13. Cylindrical grinding machine

The following operations can be performed on the above listed machines.

1. Turning

2. Facing

3. Threading external cylindrical surfaces

4. Threading internal axial holes

5. Drilling axial holes

6. Drilling non-axial holes

7. Boring axial holes

8. Boring non-axial holes

9. Drilling and reaming axial holes

10. Drilling and reaming non-axial holes

11. Drilling and tapping axial holes

12. Drilling and tapping non-axial holes

13. Milling

14. Grinding

The cutting tools fall within the range specified below. Several grades are considered within these ranges.

1. Single point high speed steel tools.
2. Single point uncoated, indexable carbide tools.
3. Single point ceramic and diamond tools.
4. High speed steel milling cutters.
5. Carbide milling cutters.
6. High speed steel twist drills, reamers, and taps.
7. Carbide twist drills, reamers, and taps.
8. Grinding wheels.

The general categories of cutting fluids listed below are considered in this research.

1. Straight cutting oils.
2. Water soluble oils.
3. Synthetic oils.

These cutting fluids are further categorized as light, medium, or heavy duty.

4.2 EXPERT SYSTEM FOR THE ANALYSIS OF PROCESS PLANS

One of the many functions of a process plan is to specify the operations to be performed on a component, and their sequence. An expert process planner would realize the compatibilities that exist between the operation to be performed and the work-material of the component. This is important because some machining operations may be infeasible on some materials. Even if the material was subject to that particular machining operation, the extent of disbenefits would be enormous to make the operation impractical. In this research this aspect was thoroughly analyzed to generate rules which approve or reject machining operations on all types of work-materials.

4.2.1 Process Analysis for Materials

The first step was to find the most important factors which influenced the process. Excessive tool failure, machine breakdown due to excessive forces generated in cutting, insatisfactory surface finish due to the nature of the machining operation, metallurgical transformation of work-material, were identified as the major reasons for incompatibility between the operation and the work-material. The research then concentrated on the variables which contribute most to these factors.

Tool failure is a phenomenon that is caused mainly when machining hard or difficult to machine materials. It actually depends much on the tool characteristics too. Generally materials with hardness above 275 Brinell or below 60 Rockwell are difficult to machine. These materials have to be subject to heat treatment to lower the surface hardness, and to make machining easier. Some of these heat treatment methods include normalizing, annealing, quenching and tempering etc. Excessive tool failure and wear of machine parts leading to dimensional inaccuracy of component parts are generally caused when machining very hard materials, unless they have been heat treated suitably. This is true for all the operations except grinding. Since grinding is an extremely abrasive machining process, hard materials are easy to machine. It should be noted that grinding is an operation well suited for materials with hardness over 60 Rockwell, as other operations become infeasible for these materials, even with heat treating.

Generally there is no lower limit for material hardness that makes any operation infeasible. Exceptions are threading and grinding. Threading on a lathe is a complex operation wherein very soft materials do not form quality threads. So, for materials with hardness less than 40 Brinell, threading is not suitable. Grinding is a machining process where high contact pressures between the wheel and the workpiece are normally experienced. Very soft materials tend to penetrate the grinding wheel in the form of small particles and lead to very poor surface finish. All the other operations except the two mentioned above are suitable for materials with hardness less than 275 Brinell.

There are some materials for which hardness cannot be readily measured. In these cases it is necessary to consider the metallurgical structure as well as the physical properties of these materials. Materials whose structure is either plated, high or low elastic, or fibrous are especially difficult to machine. Materials with properties of high abrasiveness, yield strength, and toughness, pose some problems in all operations except grinding. Materials with low melting points cannot be easily machined using abrasive machining processes, as the extreme heat generation tends to distort the their metallurgical structure.

Plated materials usually have a small layer or coating of metal over a base material. This restricts metal removal to a very small depth. Since the coating material is likely to be brittle, the metal removal is best done by an abrasive process. This is why all operations apart from grinding are unsuitable for these materials.

Materials which are non-metallic and low elastic in nature are suitable for machining by most operations apart from threading and boring. The elasticity in the materials do not give rise to quality threads, and the nature of the boring operation is unsuitable for any elastic non-metallic material. On the other hand non-metallic materials with high elasticity are difficult to machine by all operations except grinding.

Some non-metallic materials like plastics possess a fibrous structure and are extremely hard and abrasive in nature. A hardness value cannot be assigned to them by the conventional methods. Threading is unsuitable for these materials, as the process tends to generate very unsatisfactory threads due to the fibrous nature of the material. Similarly materials with high yield strengths are difficult to cut and form threads by the nature of the process. These concepts have been incorporated as rules, and can be found in the computer code included in the appendix.

4.2.2 Data Requirements for the Analysis of Process Plans

First of all, the operation that is to be performed on the component has to be known. The type of operations considered in this research have been outlined before. The name, type, property, and hardness of the work-material are then required. Many types of work-material may be considered, namely non-metallic, ferrous, non-ferrous, non-austenitic ferrous, austenitic ferrous, hard-ferrous, and non free-machining ferrous.

These choices indicate the range in material types pertaining to ease of machining. Special material properties, such as high abrasiveness, high yield strength, and toughness are required. The type and property of the work-material may assume multiple values of data, as this is often the case in reality. The hardness of the work-material is one of the most important data requirements. This is required in the Brinell or the Rockwell scale.

The metallurgical structure of the the work-material is required only if the material type had been declared as non-ferrous. This is to specify those materials which have an unique metallurgical structure, namely high and low elasticity, fibrous or plated structure. The condition of the work-material is required only if the material type had been declared as ferrous or non-ferrous. The material condition could be normalized, annealed, aged, quenched and tempered, as cast, as forged, sintered, or hot rolled. The melting point of the work-material is required only if the operation had been declared as grinding.

The data may be input by the user or retrieved from data base files. Some types of data are to be input by the user only, as opposed to some other types which have to be read in from data base files. Personal preferences and subjective values are best input by the user while specific characteristics of the entities may be read from data base files. Figure 9 shows the flow of data within the expert system.

4.2.3 Inference Engine for the Analysis of Process Plans

When the expert system is executed, data acquisition for purpose of consultation is done first. The main goal variables are the operations which are to be determined as suitable

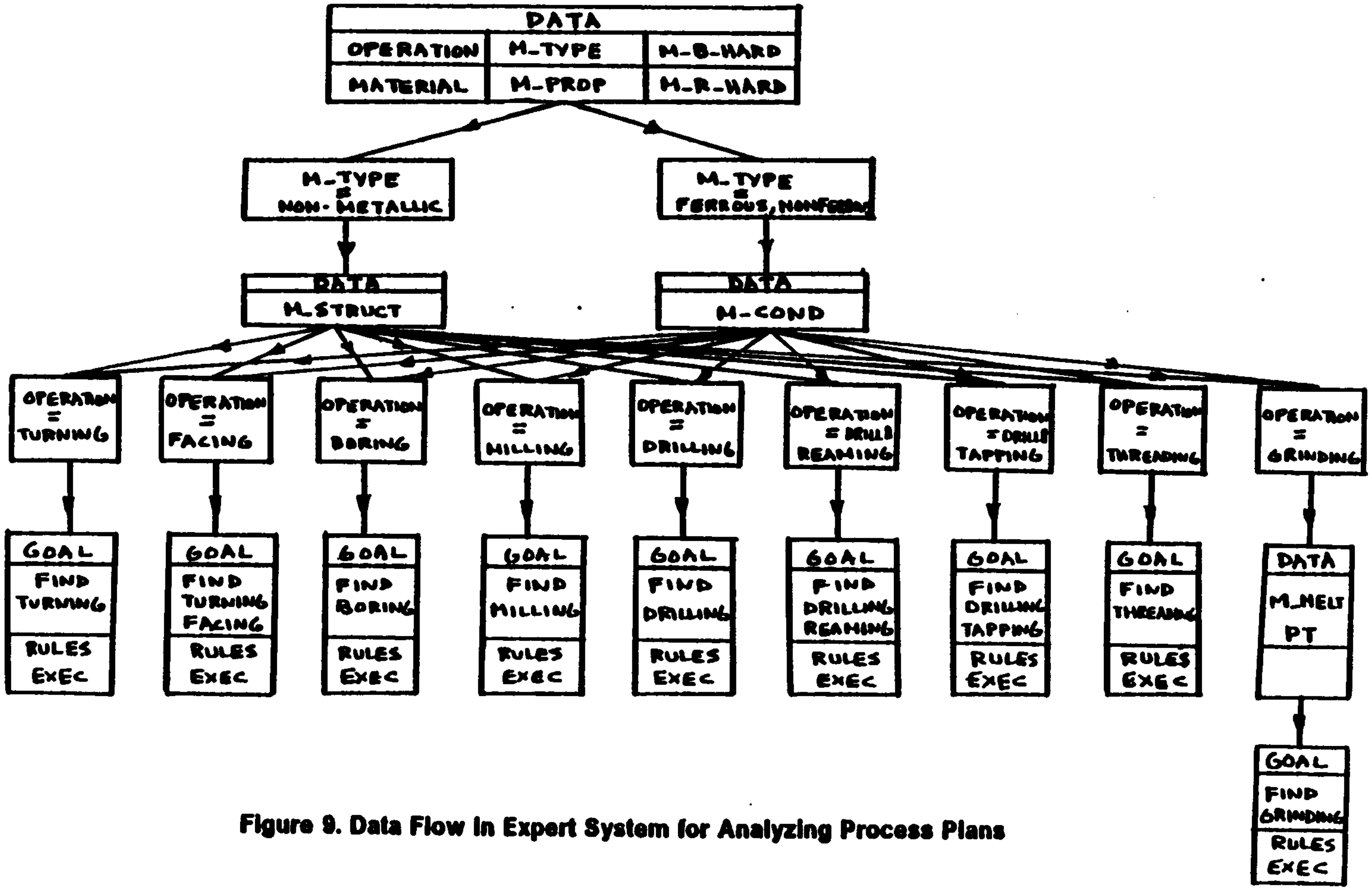


Figure 9. Data Flow In Expert System for Analyzing Process Plans

or not. Pseudo variables are sought to direct the inference engine along desired paths, both for data retrieval and for finding the desired main goal variables. The pseudo variables should be able to take on multiple values of data, as they would be used in many rules. The main goal variable to be pursued depends on the operation, as these are actually the same. The path of the inference engine then depends on the sequential process of finding the goal variables. For each operation to be declared as suitable, a set of rules have to be executed.

The operations to be analyzed by the expert system are in the following order : turning, threading, milling, drilling, boring, and grinding. When each operation has to declared as suitable or unsuitable, the expert system searches for the first rule which has the status of that operation in its conclusion. Then it begins to analyze the conditions. If all the conditions are true, then the operation is selected, otherwise it is declared as unknown. This process is continued for that operation till all the rules which have it in their conclusion have been analyzed. At this point in time, the operation would have been declared suitable, or unknown. If the value for the operation as the goal variable is unknown at this time, it will be declared as unsuitable. The inference tree for determining the suitability of the turning operation is shown in figure 10.

Because of the nature of execution of the rules as described above, for any particular operation, it is advantageous to place those rules in the order of decreasing range of materials that would make it possible to approve it. For example, let us consider the turning operation. The rule stating that all materials whose hardness value is less than 275 Brinell, would be placed first. This pattern in the placement of rules leads to savings in execution time. In some cases when the probability of attaining the goal is equal for all rules, the arrangement of rules may not contribute much to savings in execution time.

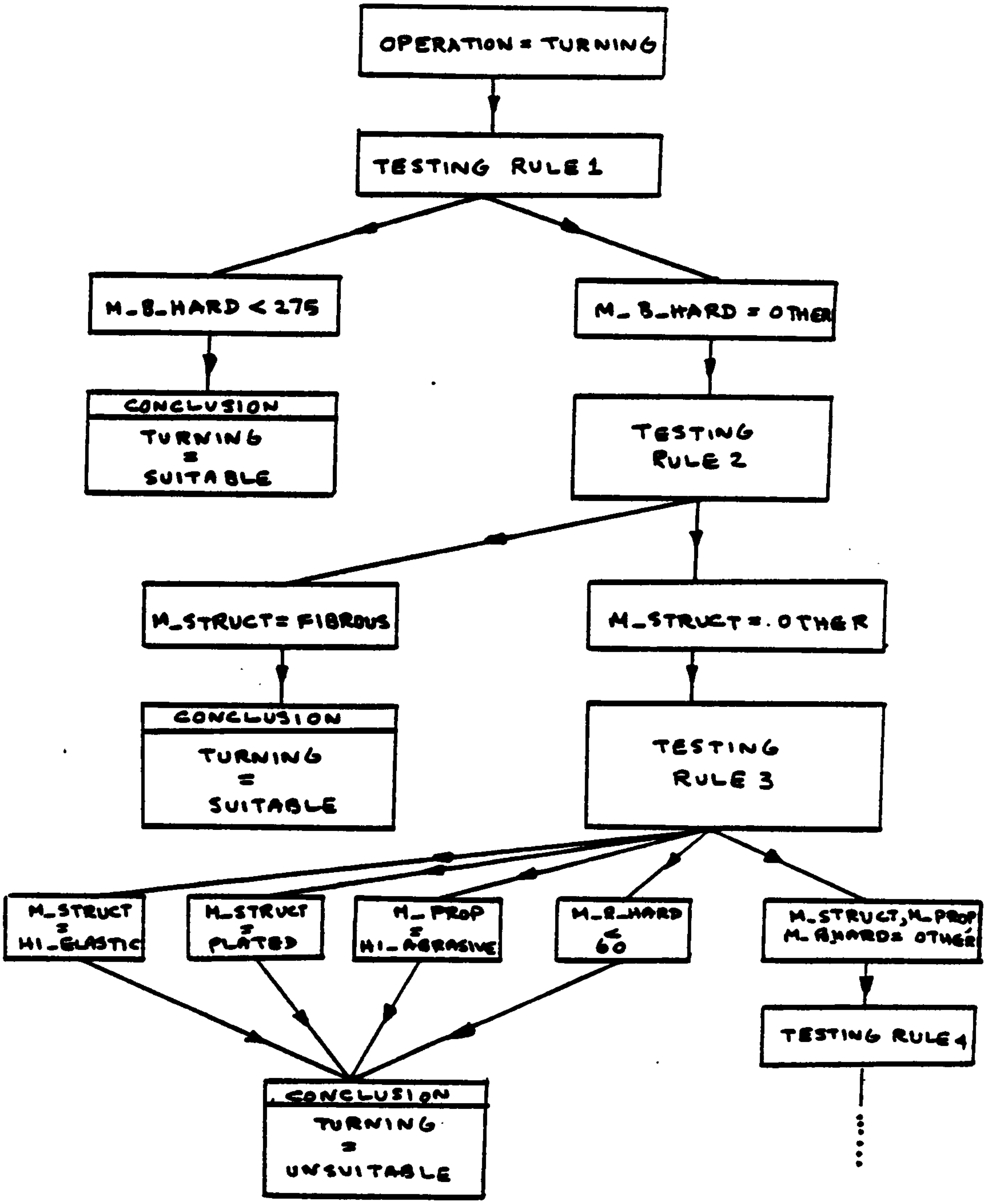


Figure 10. Inference Tree for the Turning Operation

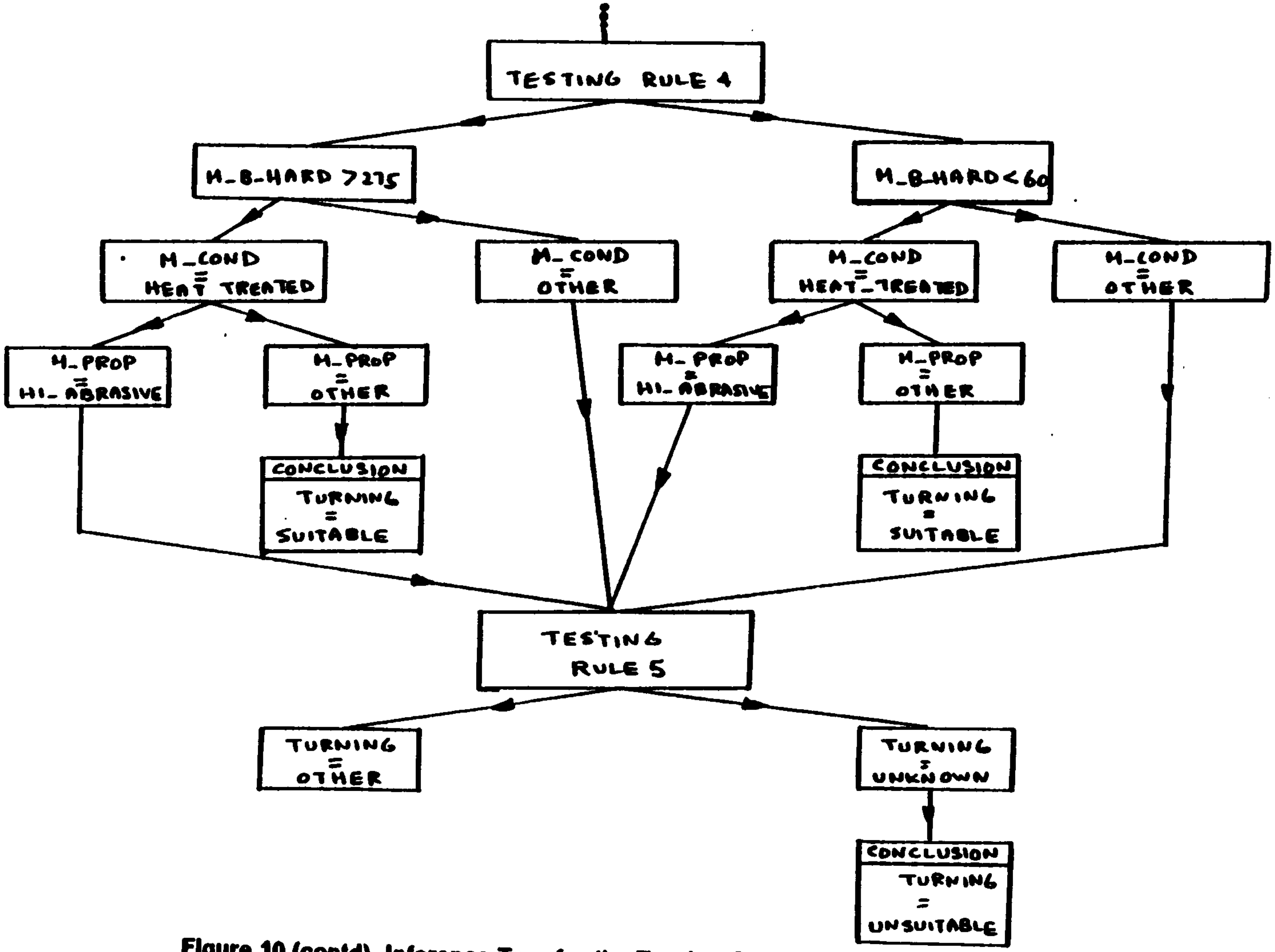


Figure 10 (contd). Inference Tree for the Turning Operation

The above described expert system is the first step in the selection of machining parameters. If any of the operations are declared unsuitable by this expert system, then one needs to modify the process plan before proceeding to the selection of machines, tools etc. The ramifications of the usefulness of this expert system for product designers and shop floor personnel will be investigated in chapter 6.

4.3 EXPERT SYSTEM FOR THE SELECTION OF MACHINES

This section deals with machine selection for each operation to be done on the component. The factors which contribute to the selection of a machine are the accommodation of the component on the machine tool, the deliverance of the required surface finish and tolerance on the component, type of surface to be generated, operational parameters, and the cost of operation.

4.3.1 Process Analysis for Machine Selection

The accommodation of the component on the machine tool depends largely on its physical characteristics. For engine lathes, machine swing dictates the maximum diameter of a component that can loaded on to the machine. The distance between centers dictates the maximum length of the component that can be loaded. The minimum distance between centers would restrict a job of length lesser than the specified value from being loaded on to the machine. All other kinds of lathes have a limit on the maximum diameter of job that can be loaded, and an upper and lower limit on the length of the job that can be accommodated. Milling, drilling, boring, and surface grinding machines have their table area and table height influencing the size of the component that can be loaded. Cylindrical grinding machines have physical characteristics similar to that of the lathe. Table 1 lists the physical characteristics of the machines considered in this research.

Each machine has a lower limit on the surface finish and tolerance that it can accomplish, depending on the operation it performs. The surface finish and tolerance required for any operation must be greater than what the machine being considered is capable of delivering. Table 2 shows the capabilities of various machine tools in this regard.

The milling operation is performed on the horizontal milling machine, vertical milling machine, or the numerical control milling machine. The vertical milling machine uses a small diameter end-mill to machine the surfaces. It is suited well for operations where the width of cut is lesser than 2.5 inches. If the width of cut is greater than 2.5 inches the horizontal milling machine can remove large volumes of metal owing to the use of face milling and side milling cutters. For practical reasons, a width of cut of 2.5 inches has been considered as the limit for using the vertical milling machine. This can be changed to suit the machine tool capabilities. The vertical milling machine is well suited for machining dovetails within the limit of the width of cut specified. If the surface to be generated is contoured, convex, concave, or flat, then the horizontal milling machine is a better choice. The numerical control milling machine is chosen if the job can be accommodated on the machine.

Drilling, reaming, and tapping operations can be performed on drilling machines or on some kinds of lathes like the turret lathe, single spindle automat, and the numerical control lathe. The restrictions for the use of these machines, apart from the physical accommodation of the component on them and the surface finish, tolerance require-

Table 1. Dimensional Characteristics of Machine Tools

MACHINE	MAX DIA COMP	MAX LENGTH COMP	MIN LENGTH COMP	TBL AREA	HEIGHT	MAX HOLE DIA	MIN HOLE DIA	MAX L/D
ENGINE LATHE	20	75	6	–	–	–	–	–
TURRET LATHE	4	56	3	–	–	3	0·25	0·4
SINGLE SP AUTO	8	40	0.05	–	–	2·5	0·05	0·41
NC LATHE	10	35	1	–	–	3·2	0·10	0·56
HOR MILL M/C	–	–	–	90	55	–	–	–
VER MILL M/C	–	–	–	75	45	–	–	–
NC MILL M/C	–	–	–	80	50	–	–	–
VER DRILL PRESS	–	–	–	40	36	1·5	0·25	0·24
RAD DRILL M/C	–	–	–	60	67	3·5	0·50	0·45
TURR DRILL M/C	–	–	–	67	57	3·5	0·25	0·60
HOR BOR M/C	–	–	89	–	–	–	–	–
CYL GRIND M/C	10	54	2	–	–	–	–	–
SUR GRIND M/C	–	–	–	79	50	–	–	–

Table 2. Surface Finish and Tolerance Capabilities of Machine Tools

MACHINE	TURNING	FACING	BORING	DRILLING	DRILL AND REAM	DRILL AND TAP	MILLING	GRINDING	THREADING
ENGINE LATHE	25 0·008	25 0·008	—	—	—	—	—	—	75 0·006
TURRET LATHE	9 0·003	9 0·003	63 0·001	63 0·004	33 0·001	63 0·006	—	—	64 0·005
SINGLE SP AUTO	16 0·004	16 0·004	63 0·0015	63 0·003	32 0·0013	63 0·0055	—	—	62 0·006
NC LATHE	3 0·008	3 0·0008	5 0·0008	10 0·001	4 0·0009	15 0·002	—	—	20 0·003
HOR MILL M/C	—	—	—	—	—	—	70 0·01	—	—
VER MILL M/C	—	—	—	—	—	—	65 0·006	—	—
NC MILL M/C	—	—	—	—	—	—	20 0·001	—	—
VER DRILL PRESS	—	—	—	78 0·009	30 0·003	80 0·009	—	—	—
RAD DRILL M/C	—	—	—	54 0·006	20 0·002	66 0·008	—	—	—
TURR DRILL M/C	—	—	—	45 0·009	20 0·002	45 0·008	—	—	—
HOR BOR M/C	—	—	3 0·0001	—	—	—	—	—	—
CYL GRIND M/C	—	—		—	—	—	—	0·01 0·0001	—
SUR GRIND M/C	—	—		—	—	—	—	0·02 0·0001	—

ments, are the maximum and minimum diameter of the hole that the machine can handle, and the length-to-diameter ratio of the hole. The hole diameter and its length-to-diameter ratio must be less than that which the machine is capable of producing. The type of surface required, namely flat or cylindrical, along with the other aspects outlined above, influences the selection of the cylindrical and the surface grinding machines. The rules developed, based on the above concepts, have been included in the appendix.

4.3.2 Data Requirement

The main types of data required for the selection of machines are the characteristics of the machines and the dimensions, quality requirements of the component. The feasibility of loading the component on lathes, and cylindrical grinding machines, is based on the maximum outer diameter of the component and the length of the component. For milling, drilling, boring, and surface grinding machines, it is based on the base area and the height of the component, assuming that the component has been set up for a particular operation on the machines. For milling and grinding machines, it is based on the type of surface to be generated.

Finally, data is required on the characteristics of the machine tools. Data bases are best suited to store information on the machines. Each machine type has its data base, whose fields are its characteristics. Since a finite set of machines can be considered for any operation, the relevant data on these machines only, are retrieved by the expert system. Figure 11 shows the data flow within the expert system for machine selection.

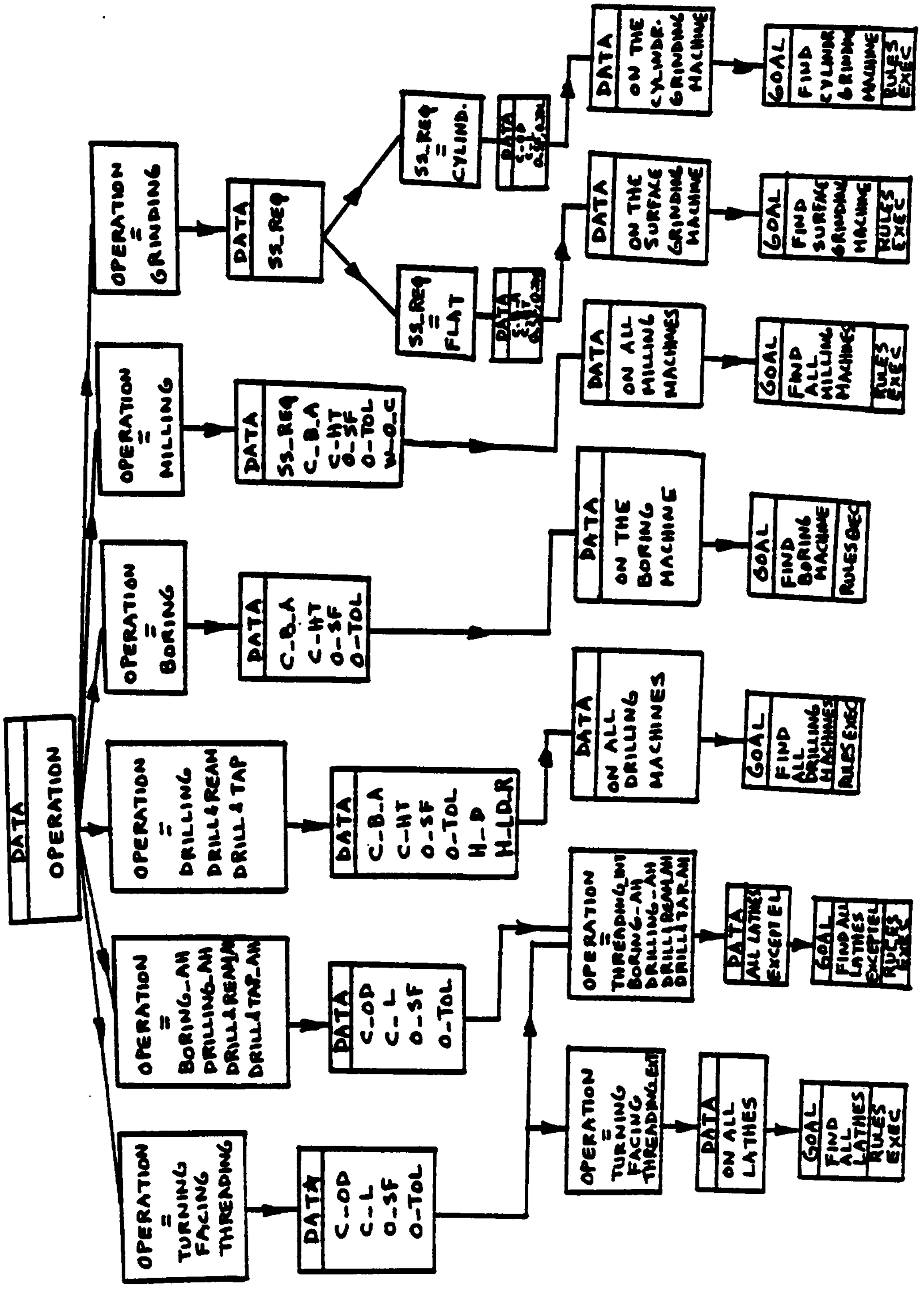


Figure 11. Data Flow in Expert System for Machine Selection

4.3.3 Inference Engine for Machine Selection

When the expert system is executed, the data requirements described above are acquired by the expert system. The main goal variables are the machines to be selected. As in the case of the previous expert system, pseudo sub-goals are required to facilitate the data flow and inference path in the desired direction. Forward chaining has been successfully employed for efficient data retrieval and to find the suitability of only those machines which are applicable for the operation under consideration.

The rules are formulated in such a way that there are two stages in the selection of each machine. The machine is considered feasible for the operation if it can accommodate the component on it. If the machine meets this requirement, then it is selected if it meets the surface finish, tolerance, and other requirements specific to the operation under consideration. This methodology has been observed to reduce the execution time as well as to make the selection process clear and understandable.

The goal variables can assume multiple values. This way the output would clearly list the machines that were considered suitable, and those which were both suitable and finally selected. The inference tree is similar in structure to that shown on figure 10, for the turning operation.

4.4 EXPERT SYSTEM FOR THE SELECTION OF CUTTING TOOLS

4.4.1 Process Analysis for Tool Selection

The expert system for the selection of cutting tools is divided into two sections. The first section deals with the process of selecting the cutting tool material, based on several factors which affect cutting efficiency. The final section deals with the selection of the cutting tool type and grade, based on the selection made in the earlier section.

The selection of cutting tool materials is dependent largely upon the factors which influence the efficiency of the cutting process. These can be identified broadly as the tool failure rate and the required surface finish. The tool failure rate is influenced considerably by the hardness of the work-material. Generally, high speed steel and carbides are suitable for machining materials with hardness lesser than 425 Brinell or 52 Rockwell. If the material hardness is greater than 275 Brinell or any value in the Rockwell scale, the material requires to be heat treated. High speed steel and carbide tools are used for producing medium to high surface finish on the components. High speed steel tools can be selected if the material is not abrasive, as this property of the material tends to reduce the tool life considerably. Carbides are superior to high speed steel tools in the sense that they can be used to machine materials with hardness up to 60 Rockwell or greater than 425 Brinell, and can work on abrasive materials too. Carbides can be used to produce better surface finishes on components, compared to high speed steel tools.

Ceramic tools are very brittle in nature, but their toughness enables them to be used to machine difficult to machine materials and very hard and abrasive materials. These tools produce very fine surface finishes when required. They are principally used to machine ferrous materials which are non-austenitic in nature. The use of ceramic tools on non ferrous materials like aluminium has been found to lead to the formation of built up edges which causes poor surface finish. The metallurgical structure of the material makes the material extremely tough and difficult to machine and generates shocks that are detrimental to the ceramic tool.

Diamond tools are principally used to machine non-ferrous material. The carbon in ferrous materials tends to react with the diamond under the extreme heat in the contact region and leads to the tool being burnt or the edge being chipped. Diamond is mainly used only when extremely fine surface finishes are required on the work-material. It is well suited for machining abrasive materials, and it is the only tool material suited for machining elastic and fibrous non-metallics. The rules, based on the concepts discussed in this section are shown in the appendix.

The final section of the expert system is for determining the type and grade of the cutting tool, based on the selection of the tool materials done earlier. High speed steel tools can be either single point tools, multi point milling cutters, drills, reamers, and taps. There are essentially three grades of high speed steel tools. These are the tungsten high speed steels, molybdenum high speed steels, and high speed steels containing cobalt. Carbide tools range from C1 through C8.

4.4.1.1 Turning, Facing, and Boring Operations

Turning, facing, and boring operations require the use of single point tools made of high speed steel, carbides, ceramics, or diamond. The entire tool may be made of the tool material, or an insert could be used on the tool holder made of some other material. M2 and M3 grades are widely used for machining materials whose hardness is below 275 Brinell. This is because M2 and M3 grades are general purpose tool grades containing molybdenum. Molybdenum high speed steels are tough and can be hardened upto 66 Rockwell, and are recommended for machining easy to machine materials. For materials with hardness greater than 275 Brinell but lesser than 52 Rockwell, T15, M42 grades are used. These are high speed steels containing cobalt, and are extremely abrasion resistant and are capable of machining very hard materials. Cobalt provides wear resistance to these tool materials. Grey cast iron is a material whose metallurgical structure makes it difficult to machine when the hardness is greater than 200 Brinell. In this case T15, M42 grades of high speed steel have to be used. In general abrasive materials require the use of T15, M42 grades of high speed steel.

Carbide tools are widely used for turning, facing and boring operations. The main grades of this material used are C7, C6, C8, C3, and C2. As we proceed from C1 to C8, which encompasses the entire spectrum of carbide grades, the toughness decreases and the hardness increases. C6 and C7 grades contain various combinations of tungsten carbide, tantalum carbide, and titanium carbide, bonded with cobalt. These materials are quite hard and less tough than previous grades, and are used for machining materials with hardness upto 50 Rockwell. If the material hardness is greater than 50 Rockwell, C8 grade can be used. Austenitic steels, grey cast irons, non-ferrous materials, non-metallics, and other abrasive materials need to be machined using tougher grades of carbides. Nickel and its alloys are an exception to this rule, as they are relatively easy to machine. C2 and C3 grades are very suitable for these operations. This is because they are straight tungsten carbides bonded just with cobalt, which provides considerable abrasion resistance to the tool material.

Ceramics are also extensively used for turning, facing and boring operations, but mostly for producing fine surface finishes and to machine difficult to machine materials. Ceramics are extremely brittle materials which are not capable of taking excessive thermal or other kinds of shock. There are two grades in ceramics, namely the cold pressed alumina (CPA) and the hot pressed cermet (HPC). Cermet tools are basically composed of aluminium oxide crystals alloyed with titanium carbide and other elements. Generally, for materials with hardness lesser than 275 Brinell, CPA is used. For materials with hardness in the Rockwell scale or hardness greater than 275 Brinell, HPC is used. Grey cast irons require the use of CPA for materials with hardness lesser than 200 Brinell and HPC otherwise. The above reasoning is based on the fact that HPC is more tough and abrasion resistant than CPC grades of ceramic.

4.4.1.2 Milling Operations

Milling operations require multi-point cutters which are either made entirely from the tool material, or made in the form of inserts. If a face milling, slab milling, or side and slot milling operation is performed on a horizontal milling machine, both high speed steel and carbides are suitable tool materials. Ceramics are used infrequently, and both HPC and CPA grades are used to machine difficult to machine materials, and when thermal, loading shock are likely to be minimal.

The milling process generates much more cutting forces than turning. This is why harder, tougher, and more abrasion resistant grades are required in milling operations. M7 replaces M3 and C5 replaces C7, when compared with machining similar materials by the turning operation. M7 is more abrasion resistant than M3, and C5 is much tougher than C7. The use of T15 and M42 for machining hard, abrasive materials is the same as in turning.

End-milling operations performed on vertical milling machines can be classified as peripheral or slotting. For both these operations the end milling cutter is used. These operations are generally done with low depths of cut, and so the same grades used earlier for the milling operations described above can be used to machine harder materials. The 275 Brinell hardness limit can be moved upto 375 Brinell.

4.4.1.3 Drilling, Reaming, and Tapping Operations

Drilling operations require the use of a cutting tool in the form of a twist drill, made of high speed steel or carbide. Generally, if the material hardness were to be less than 375 Brinell then M10, M7, or M1 would be selected as the high speed steel grade. If the hardness is greater than 375 Brinell, then T15, M42 would be a good choice. Grey cast iron and ductile cast iron are two kinds of materials which are an exception to this rule. For these materials the limit on the Brinell hardness is lowered to 200 as opposed to 375 earlier. This is because of the poor machinability characteristics of these materials. C2 grade of carbide is suitable for drilling most materials, as this grade is very tough. Toughness of the tool material is an important property in drilling mainly because of the nature of the machining process wherein cutting forces are high.

The reaming operation is much lighter in terms of the cutting forces as compared with drilling. It is for this reason that lower grades of high speed steel, namely M1, M2, and M7 are selected for the operation. These grades are not as resistant to wear as the latter grades of high speed steel. It is for the same reason that the limit on the Brinell hardness value for reaming cast irons (all kinds) are raised to 250. For reaming non-ferrous materials, the limit on the hardness for use of M1, M2, or M7 is 275. Otherwise T15, M42 is recommended, as for turning and milling operations. Since reaming is a light metal removal process, all non ferrous materials including nickel alloys are included in this rule.

Tapping is a severe cutting operation, and shows a sharp contrast to reaming in this regard. It is rather similar to drilling in cutting pressures generated. So it uses M10, M7, or M1 grades of high speed steel for most materials, irrespective of their hardness. High temperature alloys require high speeds containing cobalt, and M44, M41 can provide the required hardness to tap these materials. Carbide grade C2 is suitable for tapping.

4.4.1.4 Threading Operation

Threading is an operation that is similar to tapping by way of the cutting pressures generated. The tool edges are flanked by the work material when the thread is being cut, and so the possibility of tool wear is very high. This means that the tool material should be very tough for machining easy to machine materials and very abrasion resistant for other materials. For materials other than stainless steels, grey cast iron, ductile cast iron, malleable cast iron, titanium alloy, and high temperature alloy, M2 is a suitable grade of high speed steel to use, provided the work material hardness is less than 225. In the same situation, if the hardness is greater than 225 Brinell or less than 50 Rockwell, T15, M42 is a better choice. T15 and M42 grades of high speed steel are well suited for the materials listed above, due to their poor machinability characteristics.

The most common grades of carbide used for threading operations are C6 and C2. C6 is used for general purposes, while C2 is suited for the difficult to machine materials. Grey cast irons and non ferrous materials except nickel alloys require C2 grade of carbide.

4.4.1.5 Grinding Operations

Grinding is different from all other operations considered before, and the selection of the grinding wheel involves the specification of the abrasive, grain size, grade, and the structure. For non-metallic materials, silicon carbide is widely used, and is denoted as C. For ferrous materials, aluminium oxide, denoted by A, is used. This is because non-ferrous materials tend to penetrate into aluminium oxide wheels, and cause poor surface finish on the component. The grain size depends on the surface finish required, as well as the extent of stock that is to be removed. Low grain sizes are suitable for heavy stock removal and medium surface finishes, while high grain sizes are required for low surface finishes and light stock removal. The structure depends on the type of machining operation. For surface grinding, sparse structures are used as opposed to cylindrical grinding. The rules developed, based on the concepts discussed in this section can be found in the appendix.

4.4.2 Data Requirement for Cutting Tool Selection

The data requirements are basically the same as that for the expert system on the analysis of process plans. Additional data is required on the type of surface finish required on the component. This should be specified as low, medium, or high. Some data from the execution of the expert system on machine selection is required, as some types of tools like the end mill, face mill, and side mill are loaded on different kinds of milling machines. The selection or rejection of the horizontal milling machine, vertical milling machine, and the numerical control milling machine has to be specified. For the grinding operation, the type of wheel selected depends largely on the type of grinding machine that has been selected previously. Hence, the selection or rejection of surface and cylindrical grinding machines is required. It is also necessary to specify the selection or rejection of high speed steel, carbide, or diamond as tool materials, for the purpose of selecting tool grades for operations other than grinding.

Data on the characteristics of the tool materials is not required at this stage, because the tool materials are selected on the basis of the cutting condition brought about by the influence of various product and operational parameters. The situation is not the same as the selection of machines, which were selected based entirely on their individual physical characteristics. Figure 12 shows the data flow within this expert system.

4.4.3 Control Structure within the Inference Engine

The main goal variables used in this expert system are the tool materials and tool grades to be selected. The use of pseudo goal variables are sought to influence the data acquisition process and the path of the inference engine, as described before. Here again, forward chaining has been employed for data retrieval and reduction of execution time. Combinations of tool material types are used as a single goal variable if the conditions for their selection are the same. The goal variables assume multiple values, thus permit-

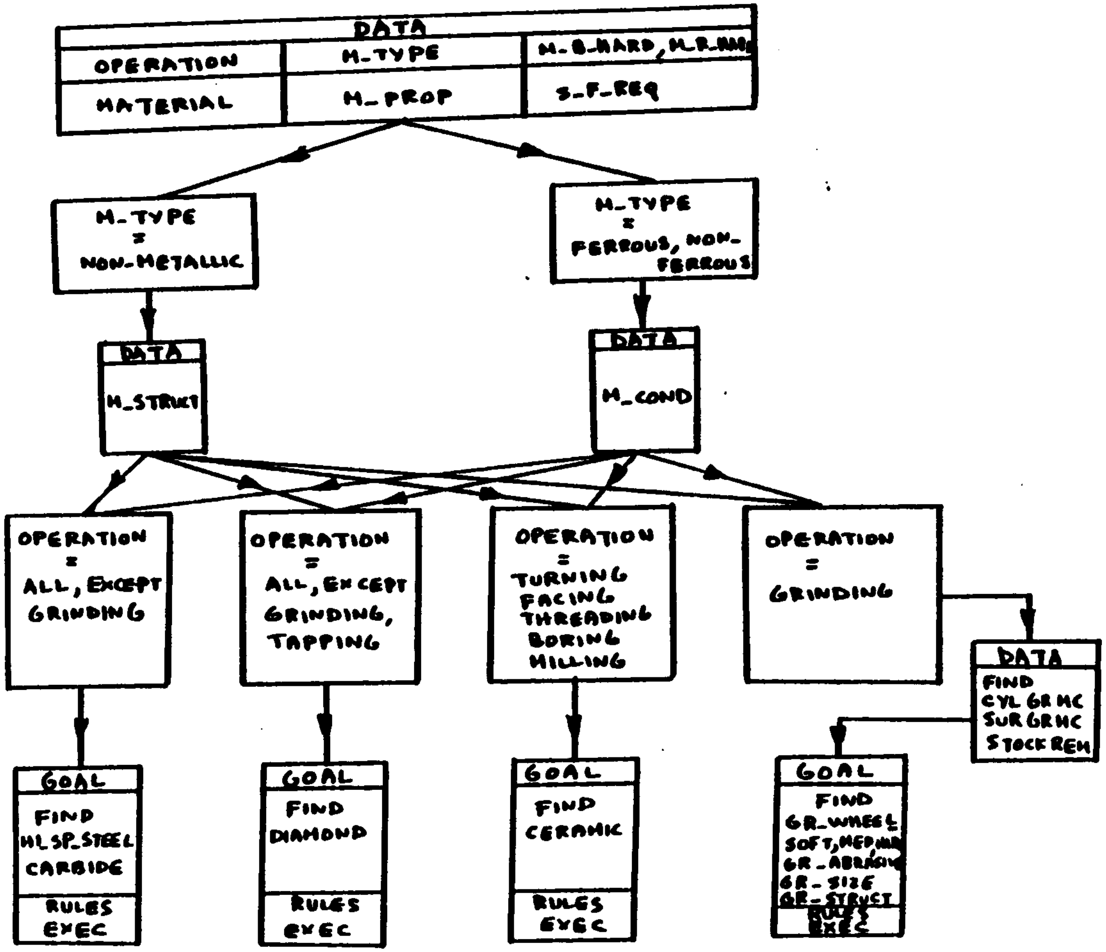


Figure 12. Data Flow in Expert System for Tool Selection

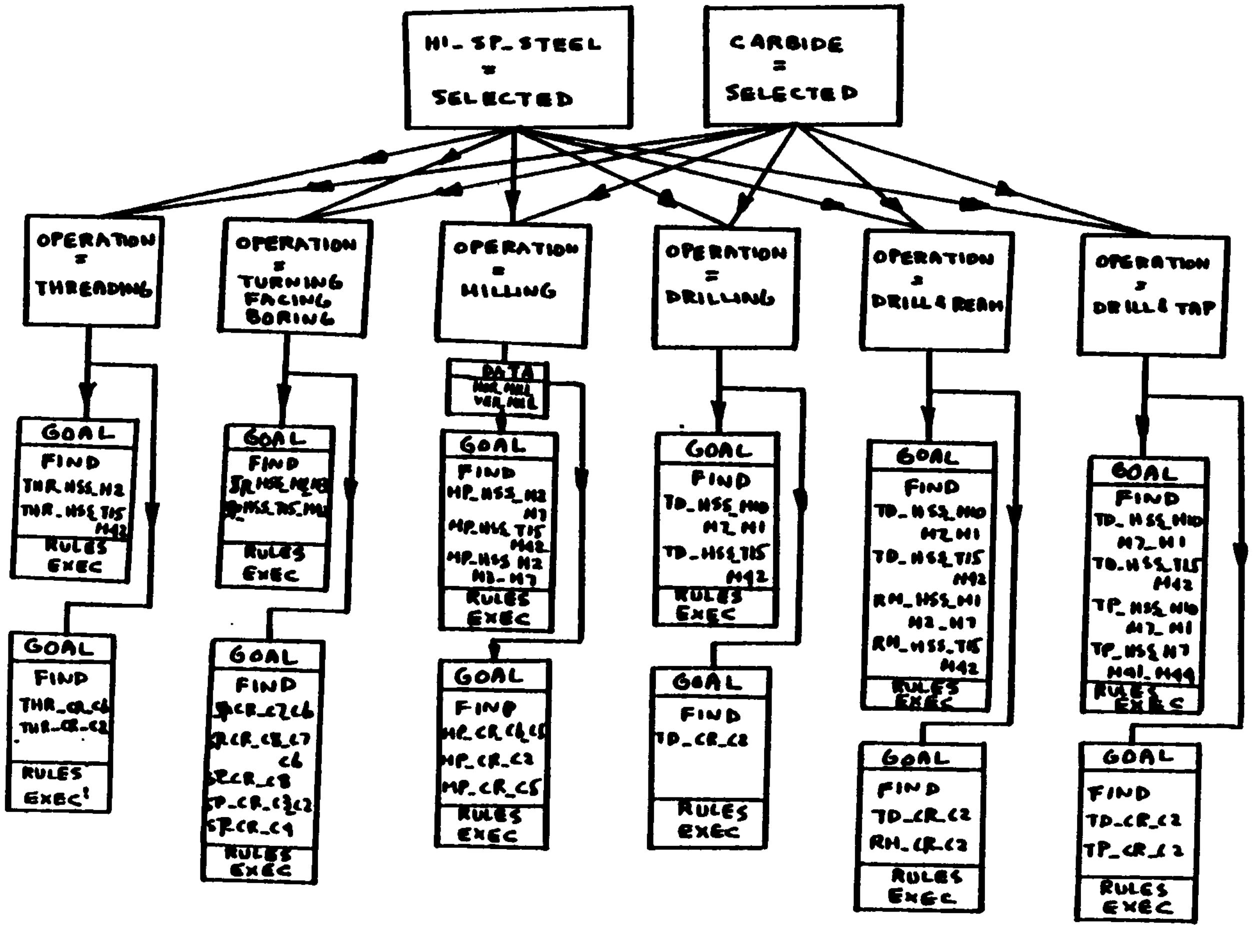


Figure 12 (contd). Data Flow in Expert System for Tool Selection

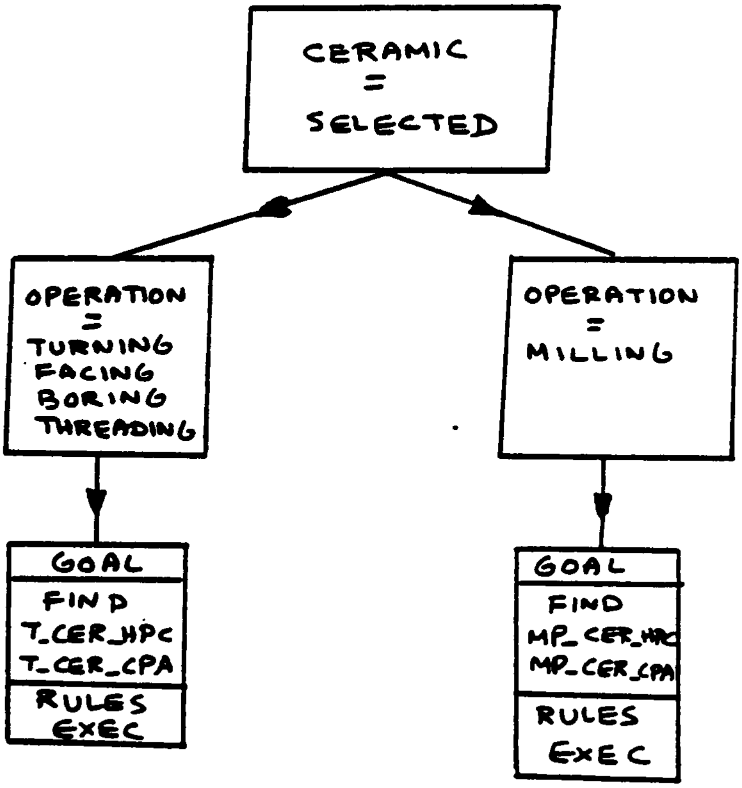


Figure 12 (contd). Data Flow in Expert System for Tool Selection ting the tool materials to be declared first as suitable and then selected. High speed steel and carbide are combined in one goal variable to investigate their suitability. The other tool materials, namely ceramic and diamond are pursued individually as goal variables.

4.5 EXPERT SYSTEM FOR THE SELECTION OF CUTTING FLUIDS

4.5.1 Process Analysis for the Selection of Cutting Fluids

The selection of cutting fluids is dependent mainly on the operation and the kind of cutting tools that have been selected. When high speed steel has been selected for operations like turning, facing, threading, boring, or milling, the cutting speeds can be generally expected to be low or medium. In this case the tool-chip friction will be high. When the tool-chip friction is high, and the hardness of the work material is lesser than 275 Brinell, straight cutting oils provide an excellent means of lubrication at the tool-work interface. In the same situation, if the material hardness is greater than 275 Brinell or less than 65 Rockwell, cutting oils can no longer provide good lubrication on account of the high friction. Synthetic oils are necessary to provide adequate lubrication in this case.

Carbide tools fail often due to thermal shock occurring during the cutting process. Thermal shock occurs when uneven temperatures are generated at the cutting zone due to the difference of thermal conductivity between the carbide insert and the tool holder. Thermal shock also occurs due to the incapability of the cutting fluid to absorb the heat in the cutting zone effectively. This problem can be solved by using synthetic and water soluble cutting fluids, as these have good thermal absorption capabilities. Milling hard ferrous materials using carbide tools can be effectively done without the use of a cutting fluid. Heat conduction by the chips may be a reason for this. Generally water soluble oils and synthetic fluids of varying degrees of strength are applicable for machining using carbides. However, some materials like aluminium alloys, zinc alloys, and copper alloys are stained by using water soluble oils and synthetic oils with sulphur in the active form. Machining of these materials requires the cutting fluids without sulphur.

Drilling, reaming, and tapping are operations which cause severe cutting forces when machining with carbides or high speed steel tools. Generally non-ferrous materials and abrasive non-metallics are machined dry in these circumstances. Otherwise water soluble oils or synthetic fluids are used with varying degrees of strength, subject to work material compatibility.

Machining with ceramic tools does not need any cutting fluid. This is because of the poor thermal conductivity of ceramic, which causes all the heat to be conducted away by the chips. Machining using diamond tools leads to a high level of heat generation which can burn the tool and may even chip the edges. Water soluble oils are most widely used to conduct the heat away, unless the material requires an alternate cutting fluid. The rules developed for this expert system can be found in the appendix.

4.5.2 Data Requirement for the Selection of Cutting Fluids

The data requirements for the work-material are the material, type, property, and hardness. The type of tool material selected for the operation is required for operations other than grinding. For the grinding operation, the type of wheel selected is required. The organization of the data retrieval and flow is shown in figure 13.

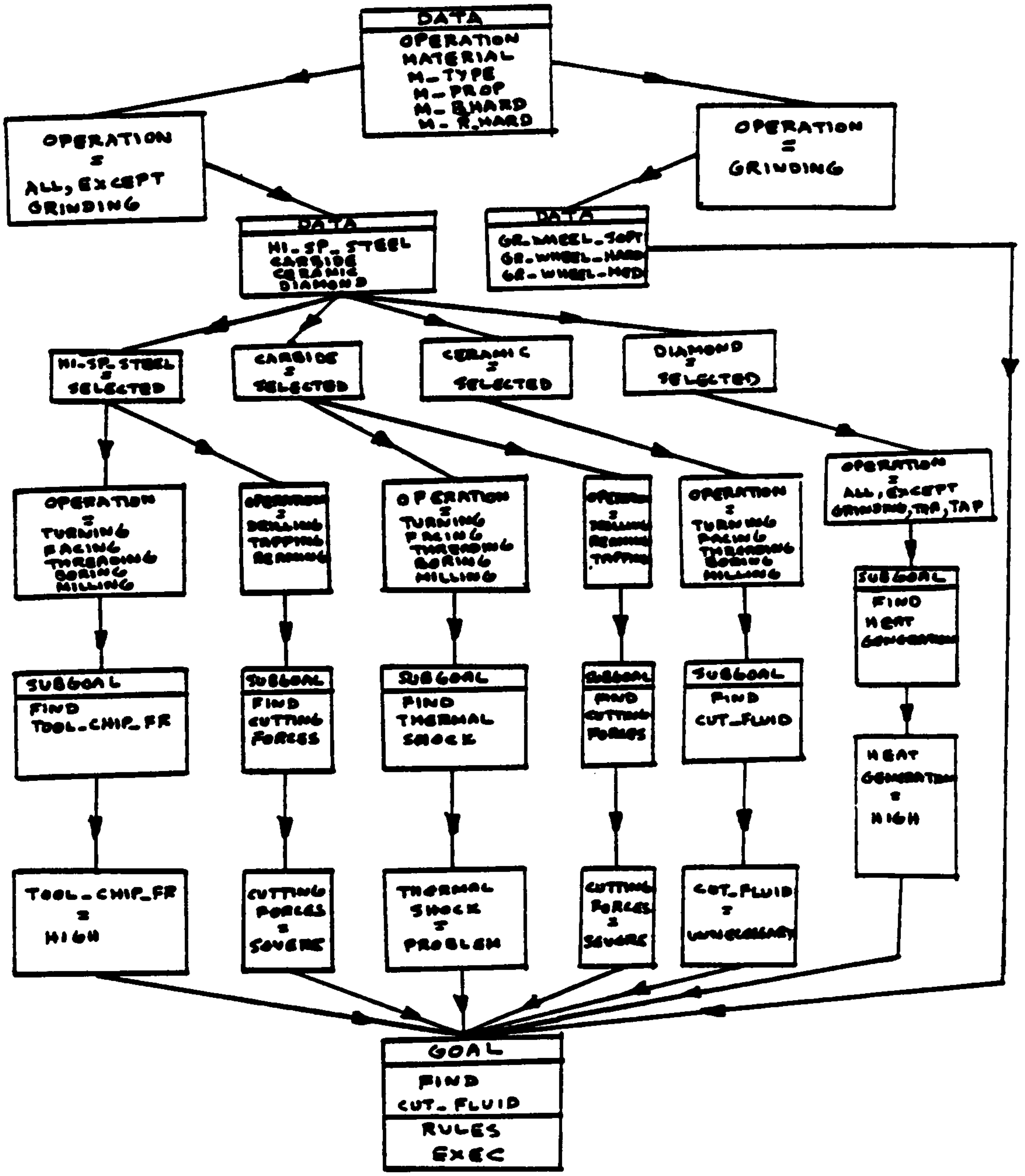


Figure 13. Data Flow in Expert System for Cutting Fluid Selection

4.5.3 Control Structure within the Inference Engine

Once the data values have been acquired by the expert system, the goal variables are pursued. The main goal variables are the cutting conditions and the types of cutting fluids to be selected, and the pseudo goal variables are used as usual to direct the data retrieval process. The goal variables pertaining to the cutting conditions are pursued initially. Once the cutting condition has been identified based on the operation and the tool material, the goal variables pertaining to the cutting fluid types are pursued. The goal variables assume multiple data values, as it is necessary to select as many cutting fluids as possible for an operation. The inference mechanism is similar to that shown on figure 10, for the turning operation.

4.6 EXPERT SYSTEM FOR THE SPECIFICATION OF TOOL ANGLES

4.6.1 Process Analysis for the Specification of Tool Angles

The specification of cutting tool angles, or the orientation of the cutting tool with respect to the work piece and the machine, can be theoretically determined to some extent. For example, for the turning operation, positive rake angles lead to good thermal efficiency but weaken the tool. Negative rake angles strengthen the tool, but can be only used when operating at high cutting speeds. This way a qualitative analysis can be conducted on the nature of the cutting tool angles, but the specification of the exact numerical values for these angles can be done only after experimentation. The Machining

Data Handbook [72] lists the values of these tool angles for cutting tools with respect to operations and work materials. In this research, the entire data on the tool angles was studied in detail in order to determine patterns that could be used to specify the angle ranges with fewer rules than would otherwise be the case. High speed steel and carbide tools were considered, due to the limited availability of data for ceramic and diamond tools.

For the turning and boring operations, the importance of tool life, necessity of thermal efficiency, and the extent of weakening of the cutting edge are determined, based on theoretical results reported in the literature. These factors are used to determine the tool angle to a limited extent. For example, machining aluminium or magnesium alloys requires thermal efficiency to be high. If not, the heat generated by the cutting process would be absorbed mostly by the materials. This would then lead to the distortion of the metallurgical configuration of the work-material. In this case high positive rake angles can direct the heat away to the chips in the cutting process, and so these values are specified as 15-20 degrees.

Generally, the specification of tool angles depend on the operation, material, material hardness, material type, tool material. For reaming and end milling, the tool angles depend on the cutter diameter also. The strategy for the development of rules was to find the conditions to be satisfied for particular types of tool angles to be within a range for most types of work-materials. This way the number of rules are kept to a minimum. Then the rules are developed for materials which were exceptions to the general rules.

4.6.1.1 Turning, Facing, and Boring Operations

For turning, facing, and boring operations using high speed steel tools, back rake, side rake, end relief, and side relief angles are to be specified. Thermal efficiency, surface finish, tool edge strength, and tool life are the most important factors which can be controlled by tool angles, irrespective of whether high speed steel or carbide is chosen as the tool material. Generally, machining materials whose hardness is less than 325 Brinell or 40 Rockwell using high speed steel tools or carbide tools causes stress on the tools to some extent. This may be relieved by using low positive values of back rake and side rake angles. The rake angles are reduced with increasing hardness of the materials. Aluminium alloys, magnesium alloys, and similar materials require the heat to be conducted away in the chips, so as to not develop any undesirable metallurgical transformations. Refractory alloys, titanium alloys, plastic and similar difficult to machine materials can cause excessive tool failure. Hence these require low positive rake angles.

The side rake angles and end relief angles influence the strength of the cutting edges and the surface finish. High positive angles are generally required for enhancing the edge strength. Materials like zinc alloy, aluminium alloy and nickel alloy need the surface finish to be controlled, and so the necessity for high values of relief angles.

4.6.1.2 Threading, Milling, Drilling, Reaming, Tapping, and Boring Operations

Similar to the research methodology for turning operations, an attempt was made to discern the pattern that exists in the tool angle data for various types of materials for other operations. End milling and reaming operations have their tool angles dependent upon the diameter of the cutting tools. Carbide tools for boring require tool angles different from those specified for turning, mainly when the horizontal boring machine is being used.

The orientation of grinding wheels was not considered because of lack of information on it. The rules are detailed in the appendix.

4.7 Data Requirement for the Specification of Tool Angles

Material, property, hardness, tool materials, type of tool chosen, and tool dimensions are required as data for this expert system. The data acquisition process is the same as that done for previous expert systems. The data flow is shown in figure 14.

4.8 Inference Engine for the Specification of Tool Angles

The main goal variables are the cutting conditions and the tool angles being sought. Pseudo variables are used too. Since there are many types of tool angles, it would not be wise to find all of them. This is because the tool angles correspond to specific operations and tool materials. The inference engine, after reading in the relevant data, proceeds to check the conditions involving operations and tool materials. If these conditions are true, a specific set of cutting conditions and tool angles are pursued as goal variables. The goal variables assume multiple data values.

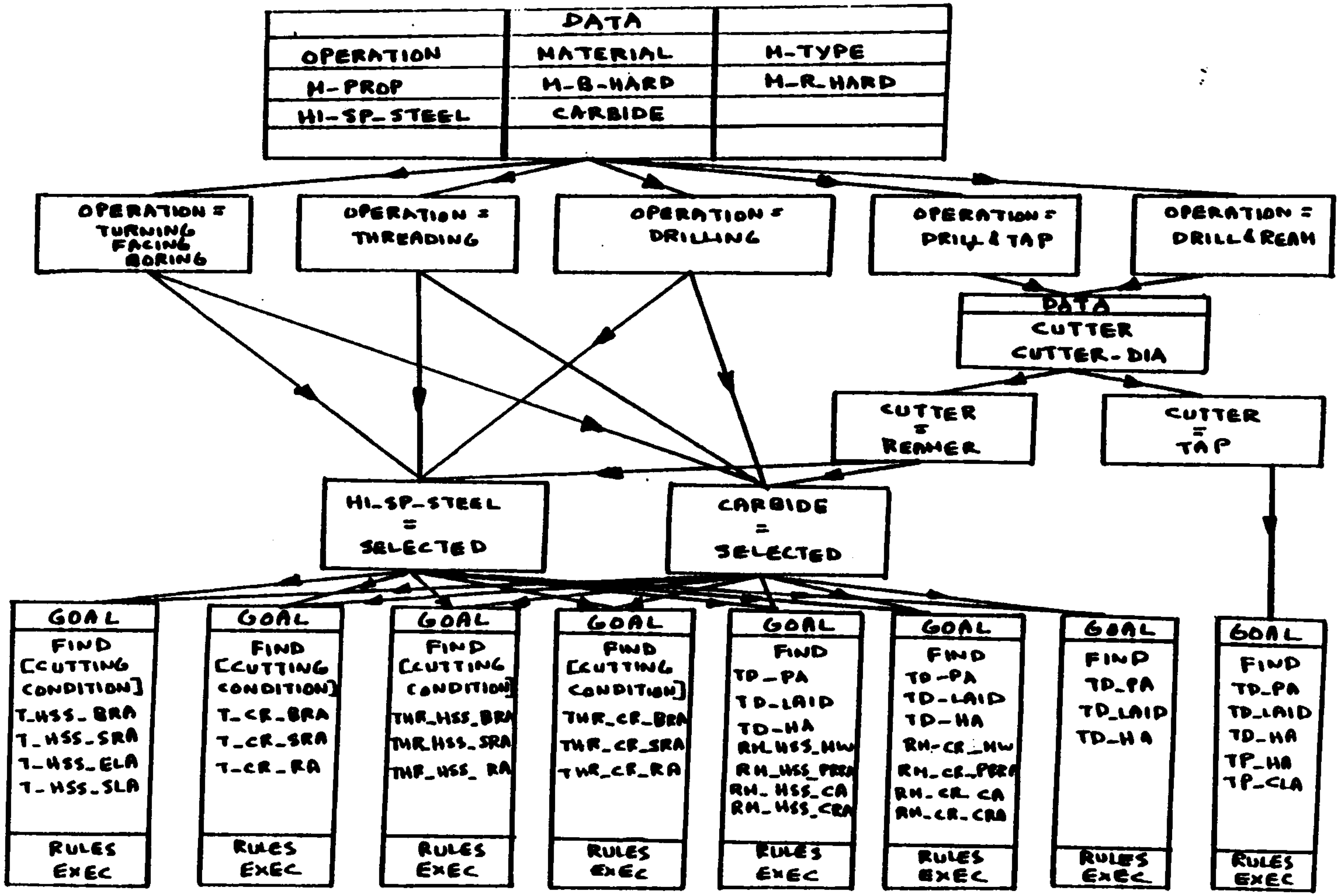


Figure 14. Data Flow In Expert System for Tool Angle Specification

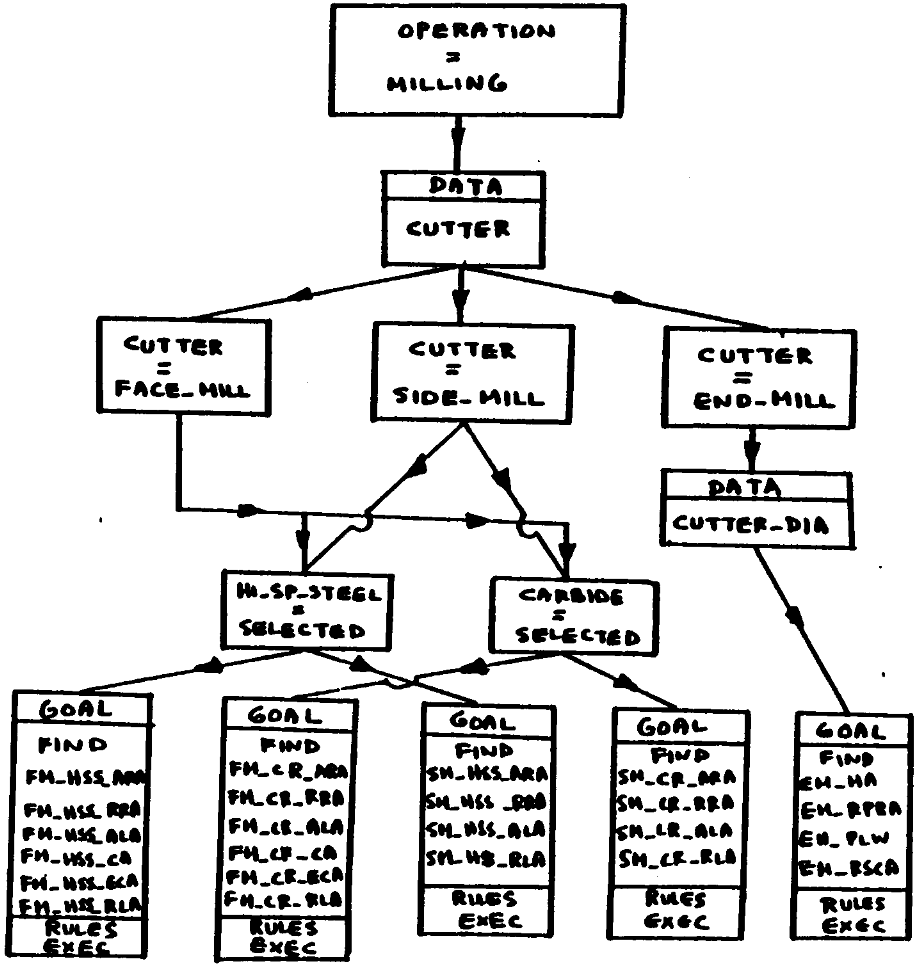


Figure 14 (contd). Data Flow in Expert System for Tool Angle Specification

4.9 CONCLUSION

This chapter has outlined the specific research approach to the design of expert systems for the selection of machining parameters. The formulation of the rules and the analysis of the manufacturing process to develop the rules have been described in detail. The specification of the type of data required for executing the expert systems have been outlined. Data flow has been shown for each expert system, along with the forward chaining procedures. The next chapter will describe the use of algorithms to provide cost attributes to the machines and tools that have been selected by the expert systems.

CHAPTER 5 : ALGORITHMS FOR MACHINE AND TOOL EVALUATION

5.1 INTRODUCTION

Algorithms use a sequential procedure for handling deterministic knowledge and output data that has to be analyzed before any decision can be made. The output from expert systems would indicate the suitability or unsuitability of machines and tools for the respective operations that are to be performed on the component. There would be a number of machines and tools that would comprise the feasible set at this stage.

Apart from the factors considered for selecting machines by expert systems, there are some others that can be considered only by the use of algorithms. The machines have different capacities in power and operating conditions. The cutting speed and feed at which an operation is being done influences the cost of manufacturing indirectly, as it affects the operating time. The operating conditions are restricted by the machine power and the surface finish required. Owing to these complex relationships, it is necessary to use algorithms to minimize the cost of manufacturing by optimizing the operating conditions of the machine tool. Expert systems are not very suitable for performing this kind of optimization.

Cutting tools have been selected by expert systems based on several factors which pertain subjectively to the reduction of the failure rate of the tool, suitability of the tool etc. It is important to know exactly how many times a tool may fail in the course of an operation, as this translates into cost. This cost comprises of the tool changing cost every time it fails, and the cost of the tool itself. The life of the tool depends mostly on the operating conditions of the machine tool and the work material. For the turning operation in particular, tool life equations can be formulated as a function of the machine operating conditions, for a type of work material. For other operations, this cannot be readily done, and so empirical equations can be used estimate the cost of tool usage. In effect, the total cost, which includes the cost of machining and the cost of tool usage, needs to be minimized, subject to constraints on the machine power, surface finish etc.

The set up costs associated with machines and jobs have to be considered in the selection process, as they contribute to the unit cost of machining. Machine set up costs vary with the operation, and job set up costs vary with the machine on which they are being loaded, and the machining operation. The sequence of the operations can lead to lower or higher costs of job set up. Labor costs vary depending on the machine.

Based on these costs, and the number of units to be manufactured, the costs associated with each machine is likely to vary a great deal. The consolidated cost information is required for the final selection of machines.

5.2 COST MODELS FOR TURNING OPERATIONS

The cutting conditions for the turning operation have been optimized in the literature by different methods. Differential calculus and geometric programming have been the most popular of these methods. It is possible to apply all these methods mainly because of the fact that tool life equations can be developed for the tool and work material combinations in turning.

5.2.1 Tool Life Equation for Turning

Developed by F.W. Taylor, the tool life equation has the tool life as a function of the operating conditions of the machine tool, for a type of work material. The relationship is non linear in nature, and can be obtained by experimental research.

The expanded form of the tool life equation is shown below.

$$TV^{(\frac{1}{n})}f^{(\frac{1}{m})}d^{\frac{p}{n}} = C^{\frac{1}{n}}$$

In the above equation [36], T is the tool life, V is the cutting speed, f is the cutting feed, d is the depth of cut, and n,m,p,C are constants based on the tool and work material combination. The tool life equation would play an important role in determining the tool cost and the tool changing cost, as it can be used to estimate the rate of failure of the tool.

5.2.2 Machine and Job Setup Costs

The set up costs on the machine and the job can be determined by the product of the respective set up times and the labor rate. These costs are fixed since machine and job set up can be assumed to be performed once per operation. The total set up costs would be as below.

$$\text{Total setup costs} = [\text{MSET}]\text{LR} + [\text{JSET}][\text{UN}]\text{LR}$$

In the above expression, MSET, JSET, UN, and LR represent the machine setup time, job setup time, number of units, and the labor rate. It is assumed that machine setup is done once for the same operations, and job set up is done once per operation per unit.

5.2.3 Machining Costs

The machining cost is the product of the machining time per operation and the labor rate. The machining time for turning can be expressed as below.

$$M_t = \frac{\pi L D}{12 V f}$$

This can also be expressed as $K_1 V^{-1} f^{-1}$, where $K_1 = \frac{\pi L D}{12}$. In this expression, L is the length of axial cut, and D is the diameter of the job [114]. Hence the total cost for the operation can be determined by the product of the machining time, the number of units that are to be made, and the labor rate, as shown below.

$$M_c = [C_1][UN] V^{-1} f^{-1}$$

In the above expression, $C_1 = [K_1][LR]$.

5.2.4 Tool costs

The tool changing time cost can be determined by the product of the total tool changing time and the labor rate. The total tool changing time can be obtained by the product of the tool changing time per cutting edge and the number of times the tool fails. Hence the total tool changing time cost can be expressed as below.

$$T_{c1} = [LR][UN][T_d][\frac{M_t}{T}]$$

In the above expression, T_d is the tool changing time per cutting edge, and M_t is the machining time.

The cost of the tool actually used for the operation on the units of the component can be determined by the product of the tool cost per cutting edge and the number of times the tool fails. The total cost of the tool usage is as below.

$$T_{c2} = [TCE][UN][\frac{M_t}{T}]$$

In the above expression, TCE is the cost of the tool per cutting edge. If the tool is brazed, solid, or insert type, the tool cost per cutting edge is $TCE = \frac{TC}{TSR}$. T_c is the total cost of the tool, and TSR is one greater than the number of times the tool can be re-sharpened if solid or brazed. It is equal to the number of cutting edges for the insert type of cutting tool.

Combining T_{e1} and T_{e2}, we can arrive at the total cost associated with tools for the turning operation. After substituting for T from the tool life equation, we get,

$$T_c = C_2 V^{(\frac{1}{n}-1)} f^{(\frac{1}{m}-1)}$$

In the above expression, C_2 is a function of all the constant terms. This is shown below.

$$C_2 = [\frac{K_1}{C^{\frac{1}{n}}}][d^{\frac{p}{n}}][[LR][T_d] + [\frac{TC}{TSR}]]$$

The depth of cut has been assumed to be a constant, as it has to be specified prior to the commencement of the turning operation.

5.2.5 Total Costs

Hence the total cost function, without the material cost and the setup costs, for the turning operation can be expressed as below as seen in [36].

$$CU = C_1 V^{-1} f^{-1} + C_2 V^{(\frac{1}{n}-1)} f^{(\frac{1}{m}-1)}$$

The production rate function can be derived in the same manner as the total cost function. In this research, minimization of the cost of manufacturing has been adopted as the criteria, as opposed to maximizing the production rate. These two factors are inversely proportional.

5.3 MACHINING CONSTRAINTS

Unconstrained optimization using differential calculus would yield optimum values for V and f. However, the optimization process is complicated by the presence of a number of constraints like the machine power, surface finish, machine speed, machine feed etc.

5.3.1 Machine-tool Maximum Power Restriction

The cutting power may be expressed by,

$$P = WVF^{\alpha}d^{\beta}$$

where P is the cutting power, and W, α, β are constants for the given tool-work combination [114]. The values of speed and feed selected are such that the available cutting power is exceeded, then one or both must be reduced. The form of this constraint is as below.

$$C_x V^b f^c d^e \leq HP_{\max}$$

In the above expression, C_x, b,c,e are constants and $HP_{\max}$ is the maximum available power of the machine tool [36]. This constraint means that the machine tool has limitations in the feeds and speeds under which it can operate. The combination of feed, speed and the depth of cut must be according to the above function. Otherwise, the machine tool will not be able to provide the necessary power for the cutting process and excessive vibration and damage may occur to the machine parts.

5.3.2 Maximum Force Restriction

This restriction is required for some machine tools for which the combination of feed and depth of cut may result in excessive tool-work deflections and result in dimensional component errors. This constraint may be expressed as below.

$$C_y f^{\gamma} d^{\delta} \leq F_{\max}$$

In the above expression C_y, γ, δ are constants and $F_{\max}$ is the maximum permissible cutting force on the machine [114].

5.3.3 Surface Finish Restriction

Surface finish is the maximum permissible surface roughness of the component in order to function in a specific engineering environment. For example, the surface finish requirement of the piston in the engine of an automobile needs to be at least 8 microinches. If the surface finish is more than this value, the could be problems when the piston operates on the wall of the cylinder. The surface finish value is usually measured as the average deviation expressed in microinches from the mean surface. When observed under the microscope, the mean surface of component is located in such a way that the volume of peaks above the surface cross-section exactly equals the volume of valleys below it.

Surface finish can usually be expressed as a function of the cutting speed, feed and the depth of cut. The following surface finish expression in the form of a constraint represents the approximate center line average (CLA) of the surface of the work piece.

$$C_z V^g f^h d^i \leq SF_{\max}$$

The exponents and C_z are constants for a particular machining operation and $SF_{\max}$ is the maximum permissible surface finish value [36].

5.3.4 Maximum Allowable Speed, Feed and Depth of Cut

Machine tools are designed to operate within a range of speeds, feeds and depths of cut. At times, the machine tools may not operate at these specified values but at values much different from these. For example, due to repair, a lathe may be able to operate only at 300 surface feet per minute cutting speed as opposed to the manufacturer's specification of 450 sfpm. When this lathe is used for machining operations the following constraint must be used in the machining model.

$$V \leq 300$$

The same principle holds for f and d as well. Hence, these constraints depend upon the machining operation and the state of the machine. These can be expressed as,

$$V \leq V_{\max}$$

$$f \leq f_{\max}$$

$$d \leq d_{\max}$$

Above are the most common forms of constraints associated with the machining problem.

5.3.5 Choice of Constraints

The machine power constraint and the surface finish constraint are two powerful constraints which influence the machining process the most. The machine power constraint includes the machine operational constraints in most cases. It sets limits to the machine cutting speed and feed for the machine power not to be exceeded in operation. The cutting force constraint and machine power constraints are related, and in most cases it is possible to assume that the machine power constraint includes it. In this research, the machine power and the surface finish are the only constraints being considered.

5.4 FORMULATION OF THE MACHINING ECONOMICS PROBLEM

Based on the description of the evaluation criteria and the machining constraints, the formulation may be stated as below.

$$Minimize CU = C_1 V^{-1} f^{-1} + C_2 V^{\frac{1}{n}-1} f^{\frac{1}{m}-1}$$

Subject to,

$$C_3 V^b f^c d^e \leq HP_{\max}$$

$$C_4 V^g f^h d^i \le SF_{\max}$$

Several approaches were considered to solve this problem. Differential calculus approach works well for unconstrained problems of this nature, but as the constraints are incorporated, the solution procedure does not yield satisfactory results. The traditional non-linear programming techniques are not well suited for this problem due to computational complexity. Geometric programming is very simple to use and is quite quick to implement as compared with other non-linear programming methods. It is for these reasons that geometric programming was adopted as the basic method to solve the machining optimization problem.

The advantages of a mathematical programming technique called Geometric Programming were instrumental in my decision to choose the technique for application to the optimization of machine operating parameters for turning operations.

GEOMETRIC PROGRAMMING APPROACH

The arithmetic-geometric mean inequality gave birth to the method of Geometric Programming, conceptually developed by Zener [112], and then refined by Duffin and Peterson [28]. Passy and Wilde made further improvements in this approach to include reversed inequalities and negative constraints. found by simple calculations, and then the values of the controllable variables for the optimal cost can be determined. This is one of the main advantages of GP over traditional NLP techniques.

Considering a posynomial, the optimal value for the variables can be found by the partial derivative approach. However, by defining weights as the ratio of the optimal value of the posynomial terms to the optimal value of the objective function, the tedious task of solving non-linear equations can be avoided. In fact, since these weights sum to unity, and are linear in nature, they are relatively easy to solve. Since these linear equations are independent of the cost coefficients, one can find the optimal values for these weights without determining the optimal values for the design variables.

The separation of the economic effects from the technological factors is the major advantage afforded by the geometric programming approach. The computational complexity is very low when compared with other non-linear programming methods, and the adaptability of the method for the machining problem is very good. However, as the "degree of difficulty" or the difference between the number of variables and the number of independent linear equations increases, the complexity of the geometric programming approach increases. optimal values of the decision variables.

5.6 OPTIMIZATION ALGORITHM FOR THE TURNING OPERATION

The formulation of the machining economics model as a function of the machine speed and feed was presented in the previous section. This formulation will now be converted into an equivalent geometric programming model.

The following quantities should be defined prior to the formulation.

$$C'_3 = \frac{C_3 d^e}{HP_{\max}}$$

$$C'_4 = \frac{C_4 d^i}{SF_{\max}}$$

The above transformation is necessary for the formulation of the dual problem.

The equivalent Geometric Programming problem can be stated as,

$$Maximize Q^{x} = \left(\frac{C_1}{DU_1}\right)^{DU_1}\left(\frac{C_2}{DU_2}\right)^{DU_2}(C'_3)^{DU_3}(C'_4)^{DU_4}$$

Subject to,

$$DU_1 + DU_2 = 1$$

$$-DU_1 + (\frac{1}{n} - 1)DU_2 + bDU_3 + gDU_4 = 0$$

$$-DU_1 + (\frac{1}{m} - 1)DU_2 + cDU_3 + hDU_4 = 0$$

$$DU_1, DU_2, DU_3, DU_4 \geq 0$$

5.6.1 Approach

The geometric programming dual problem formulated above is of one degree in difficulty. In the literature, these types of problems have been solved by expressing all the dual variables in terms of one dual variable, substituting these values in the objective function, thus rendering it in terms of one dual variable. The problem then becomes modified into an unconstrained problem, which then can be solved using differential calculus. Ermer and Kromordihardjo [36] have attempted successfully to solve this problem using a grid refinement technique along with the simplex approach, after linearizing the problem using logarithmic transformations. Tsai [106] has proposed a heuristic based on the interpretation of dual variables and unconstrained optimization, using differential calculus. The proposed algorithm takes advantage of the underlying structure of the problem and obtains the optimal solution without the use of formal optimization techniques.

5.6.2 Principle

In the dual constraint set, DU_1 can be substituted in terms of DU_2 in the remaining constraints, to make them a function of DU_2,DU_3 and DU_4. This would render the constraint set in terms of two dual constraint equations and three unknown dual variables.

It is reasonable to anticipate that the optimal solution for the primal problem would not have all the constraints being tight. Either the machine power constraint or the surface finish constraint are likely to be loose in the optimal solution. Based on this heuristic, one dual variable can be arbitrarily forced to zero, thus implying that the corresponding primal constraint is loose, from conditions of complementary slackness between primal constraints and dual variables. This also makes the dual constraints into a set of two simultaneous linear equations with two unknowns. The duals can be solved directly without any optimization procedure. The unit cost can also be obtained from the dual objective function. The primal variables can be solved by using the relationship between DU_1, DU_2, the unit cost and the corresponding terms in the primal objective function.

If any of the solved dual variables are negative, then the solution is infeasible. In this case, another dual can be forced to zero in isolation, and the same procedure repeated. It is likely that none of these procedures give rise to feasible duals. It is also possible that even if the dual solution is feasible, the primal solutions may not be feasible. In these cases, the primal constraints can both be made tight, and the primal variables can be solved.

5.6.3 Derivations

Based on the principles outlined above, the expressions for the dual and primal variables would be derived.

5.6.3.1 Case 1 -

$DU_3 = 0$

When DU_3 is made zero, and DU_1 has been substituted in terms of DU_2 in the dual constraint set, it becomes a function of DU_2 and DU_4 . There would be two linear equations and two unknowns. Solving for DU_2, we get the expression below.

$$DU_2 = \frac{[\frac{1}{g} - \frac{1}{h}]}{[\frac{1}{ng} - \frac{1}{mh}]}$$

Solving for DU_4, based on the value for DU_2,

$$DU_4 = [\frac{1}{g}] - [\frac{1}{ng}][DU_2]$$

5.6.3.2 Case 2 -

$DU_4 = 0$

If, on the other hand, DU_4 was forced to zero, the following expressions would result for DU_2 and DU_3.

$$DU_2 = \frac{[\frac{1}{b} - \frac{1}{c}]}{[\frac{1}{nb} - \frac{1}{mc}]}$$

$$DU_3 = [\frac{1}{b}] - [\frac{1}{nb}][DU_2]$$

In both cases, the unit cost, CU, may be determined from the dual objective function.

5.6.3.3 Primal Solutions

If the dual solutions obtained above in both cases are feasible, the primal solutions can be computed from the relationship between the terms in the primal objective function and dual variables DU_1, DU_2. The relationships are outlined below.

$$\frac{C_1 V^{-1} f^{-1}}{CU} = DU_1$$

$$\frac{C_2 V^{\frac{1}{n}} f^{\frac{1}{m}}}{CU} = DU_2$$

If both the primal constraints are made tight, they can be solved for V and f, as they would be two non-linear equations in two unknowns.

5.6.4 Steps of the Algorithm

1. Force DU_3 to be zero. Go to step 2.
2. Solve for DU_2, DU_1, DU_4. Go to step 3.
3. If the duals are either positive or zero, go to step 7. Else go to step 4.
4. If at least one dual is negative, the solution is infeasible. Force DU_4 to be zero. Solve for DU_1, DU_2, DU_3. Go to step 5.

5. If at least one dual is negative, the solution is infeasible, go to step 6. If all duals are greater than or equal to zero, go to step 7.

6. Force both primal constraints to be tight and solve for primal variables directly, go to step 9.

7. Determine the primal variables using the duals, unit cost, and terms in the primal objective function. Go to step 8.

8. Check for primal constraint feasibility. If any primal constraint is infeasible go to step 6. Else, go to step 9.

9. Stop, solution is optimal.

For multi-pass operations involving both roughing and finishing cuts, it is necessary to follow the steps of the algorithms for each cut taken. The flow chart for the algorithm is shown on figure 15.

5.7 TESTING THE ALGORITHM

The algorithm for optimizing the cutting conditions for turning was tested using two example problems.

5.7.1 Example #1

This problem was taken from Ermer and Kromordihardjo [36]. A job with a diameter of 6 inches, and a length of 8 inches, has to be turned. The required surface finish for

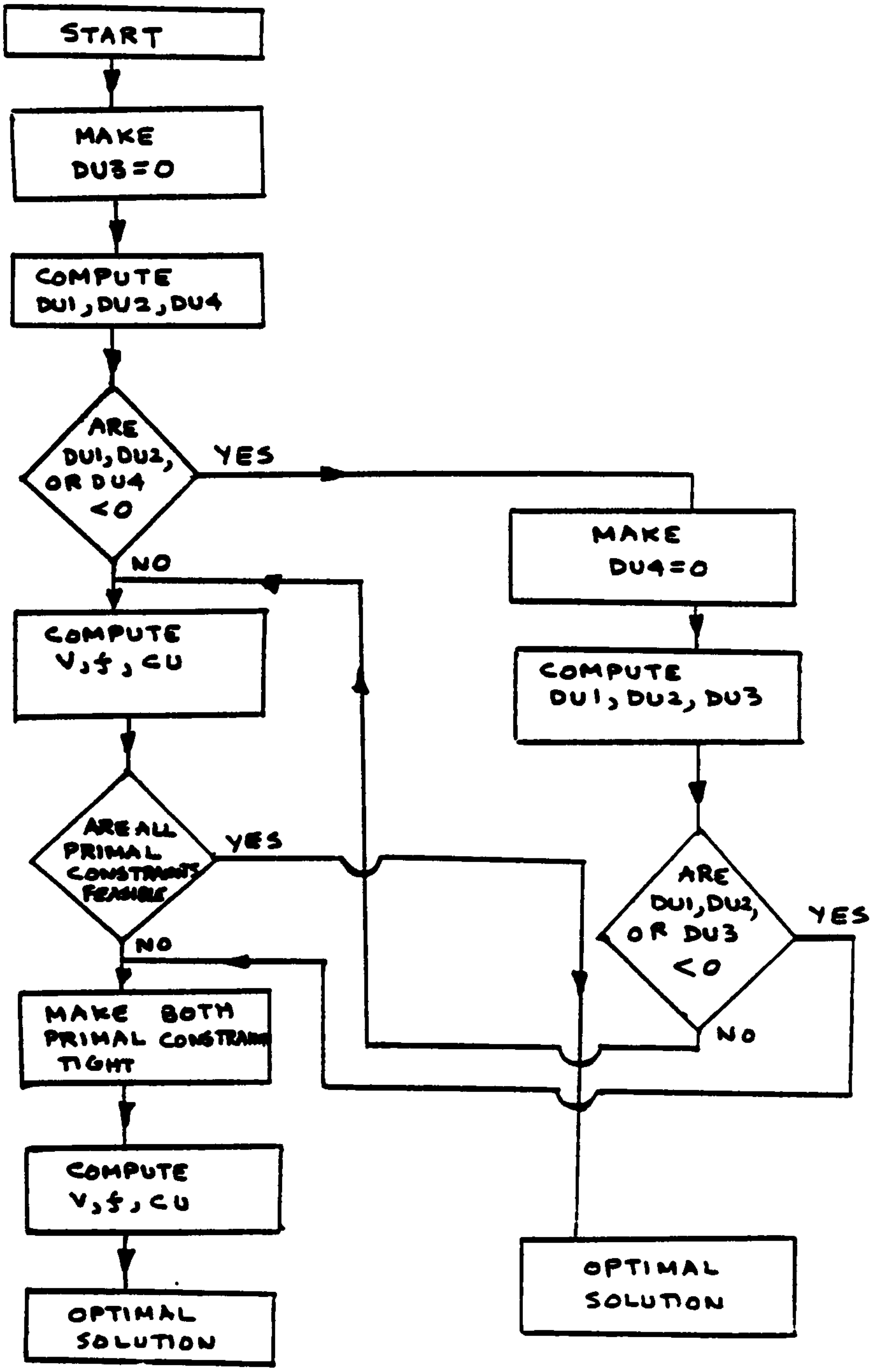


Figure 15. Flow Chart for the Optimizing Algorithm on Turning Operations

the operation is 50 microinches. A depth of cut of 0.2 inches is specified. The machine power is restricted to 4 HP. The labor rate is $ 0.10 per minute. The tool cost is $ 0.5 per cutting edge and the tool changing time is 0.5 minute per tool. The tool life equation is given as below.

$$TV^{4.0}f^{1.16}d^{1.4} = 40960000$$

The values for C_3,C_4 are 2.394 and 204620000 respectively.

For the above problem, the algorithm gave V = 433.23, f = 0.0038042, and CU = 1.35. These results are the same as that obtained by Ermer and Kromordihardjo [36] and Tsai [106]. The machine power constraint was forced to be loose, in order to obtain this optimal solution quickly.

5.7.2 Example #2

A job of diameter 11 inches has to be turned to a length of 5 inches. The surface finish required is 19 microinches, and the machine power is restricted to 2.98 HP. A depth of cut of .099 inches is specified. The labor rate is $ 0.45 per minute. The cost of the cutting tool is $0.49 per cutting edge, and the tool changing time is 1.98 minute per tool. The tool life equation is given below.

$$TV^{1.98}f^{0.45}d^{0.28} = 939276$$

The values for C_3,C_4 are 0.78 and 1100000 respectively.

In this case both the machine power and the surface finish constraints were tight. This indicates that either the dual solutions were infeasible, or the primal solutions were infeasible for feasible dual solutions. The results were, $V = 243.87$, $f = 0.1351$, and $CU = 0.203$.

5.8 OPERATION TIMES IN THE ABSENCE OF TOOL LIFE EQUATION

For operations like facing, boring, milling, drilling, reaming, tapping, and grinding, there are no formulations for the tool life equations reported in the literature. This is due to the complexity of these operations, where experimental results cannot easily yield an expression for the life of the tool in terms of the operational parameters of the machine tool. Even in the case of the turning operation, the tool life equation may not be available to use for a particular tool, work-material combination. In these cases, the tool life has to be estimated from past experience. Optimization of the cutting speed and feed are no longer possible, and the best that can be done is to compute the machining and tool changing times based upon the given value of tool life, cutting speed, feed etc. Once these are known, the respective costs can be determined as a function of the labor rate and the number of units to be machined.

5.8.1 Machining Time, Tool Changing Time, and Tool Failure Rate

The machining time (MT), tool changing time (TT) for various operations are as follows [72].

5.8.1.1 Turning and Boring Operations

$$MT = \frac{\pi DL}{12Vf}$$

$$TT = \frac{[MT][T_d]}{T}$$

5.8.1.2 Facing Operations

$$MT = \frac{FCCUT}{FCFD}$$

$$TT = [\frac{MT}{FCLIFE}][T_d]$$

In the above expressions, FCCUT is the length of cut, FCFD is the feed, and FCLIFE is the tool life for facing operations.

5.8.1.3 Milling Operations

$$MT = \frac{\pi[MLDIA][MLCUT]}{[12Vf][MLTEE]}$$

$$TT = \frac{[MLCUT]T_d}{[MLTEE][MLIFE]}$$

In the above expressions, MLDIA is the diameter of the milling cutter, MLCUT is the length of cut in milling, MLTEE is the number of teeth on periphery of the milling cutter, and MLIFE is the life of the milling cutter expressed in inches of travel.

5.8.1.4 Drilling and Reaming Operations

$$MT = \frac{\pi[DLDIA][DLCUT]}{12Vf}$$

$$TT = \frac{[DLCUT][T_d]}{DLIFE}$$

In the above expressions, DLDIA is the diameter of the drill, DLCUT is the length of cut in drilling, and DLIFE is the life of the drill measured in inches of travel.

5.8.1.5 Tapping Operations

$$MT = \frac{\pi[TPI][TAPDIA][TAPCUT]}{12V}$$

$$TT = \frac{[TAPCUT][T_d]}{TPLIFE}$$

In the above expressions, TAPDIA is the diameter of the tap being used, TAPCUT is the length of cut in tapping, and TPLIFE is the life of the tap expressed in inches of tool travel.

5.8.1.6 Threading Operations

$$MT = \frac{\pi[D][THRCUT]}{12Vf}$$

$$TT = \frac{[MT][T_d]}{[THRLIFE]}$$

In the above expressions, THRCUT is the length of cut in threading, and THRLIFE is the life of the threading tool.

5.8.1.7 Grinding Operations

$$MT = \frac{GRCUT}{GRFD}$$

$$TT = [\frac{MT}{GRLIFE}][T_d]$$

In the above expressions, GRCUT is the length of cut in grinding, GRFD is the feed for grinding, and GRLIFE is the life of the grinding wheel.

5.9 MACHINE AND TOOL EVALUATOR

The algorithm and formulae reported in the previous section form part of a larger framework used to evaluate machines and tools for all operations to be done on several components. Let us assume that we have a number of different components of varying quantities to be manufactured in a job shop. Process plans indicate the operations and their sequence for each of these components. It is necessary to select machines, tools, fluids, and tool angles for each of these operations.

The expert systems described in chapter 4 can be used to select a set of machines, tools, fluids, and tool angles for each of these operations. There would not be one, but a number of different kinds of machines and tools chosen at this point. To evaluate the different kinds of machines and tools selected by the expert systems, the machine and tool evaluator (MTE) is used. Using the required data, the evaluator is capable of determining the machine, tool, and setup costs for all the operations done on each component.

5.9.1 Data Requirement for the Machine and Tool Evaluator

The data for MTE should be in the matrix or vector form. Input files are used to read the data into the system. Each component to be manufactured has an identifying number. Each operation is identified by means of an identification number. The nature of data requirement is outlined below.

- The number of machines, number of operations on each component, number of tools, and the number of components, are required.
- The identification number of each operation on each component is then required. This enables the system to determine the specific nature of the machining operation.
- The identification number of the components and the lot size of each is required.
- The surface finish for each operation is required.
- The machine power information is required.
- The suitability of each machine for each operation is required. This is a matrix of 0,1. This data is generated by the expert systems.
- The suitability of each tool for each operation is required. This is also a matrix of 0,1. This data is generated by the expert systems.

- The exponents and coefficients for Taylor's tool life equation are required whenever possible, for tools selected for turning operations. The coefficients and exponents for machine power and surface finish functions are also required.

- The component setup times on each machine, for each operation is required.

- The machine setup times for each operation is required.

- The tool setup times for each tool on each machine is required.

- The characteristics of tools, namely the size parameters and estimated tool life are required for each tool and each operation.

- The tool costs and the number of times they can be resharpened are required for solid or brazed tools. For insert type tools, the number of cutting edges are required.

- The profile of each job an each machine as identified by a number, is required.

- The labor rate for operating each machine, with respect to each operation is required.

- The process parameters are required for each operation. This includes the depth of cut, length of cut, threads per inch required etc.

5.9.2 System Execution

Once the data described above has been read into the system, the first component in the list is considered. The identification number of the first operation would enable the system to go to the proper operation segment. If this operation is turning, then the system would check the suitability of all the machines. If at least one machine is found suitable, the suitability of tools for the operation is analyzed. If at least one tool is suitable and the tool life equation exists for the tool and work material combination, the optimization algorithm for turning is executed, and the cutting speed, feed, and the unit cost for the operation are determined. The output also includes the costs for machining, tool usage, and setup. If on the other hand, the tool considered suitable does not have a tool life equation defined for the work material, optimization is not performed. Instead, the various costs are computed using the data on the speed, feed, tool life etc. This principle is adopted for operations other than turning. Figure 16 shows the flow chart for the entire machine and tool evaluation system.

5.9.3 Sequence Dependent Setup Times

The setup time for a job on a machine is used to determine part of the setup costs for an operation. These set up costs would be negligible if an operation had been performed on it just previously on the same machine, provided the orientation of the job with respect to the machine is the same in both cases. In order to implement this concept, job profiles were identified by numbers.

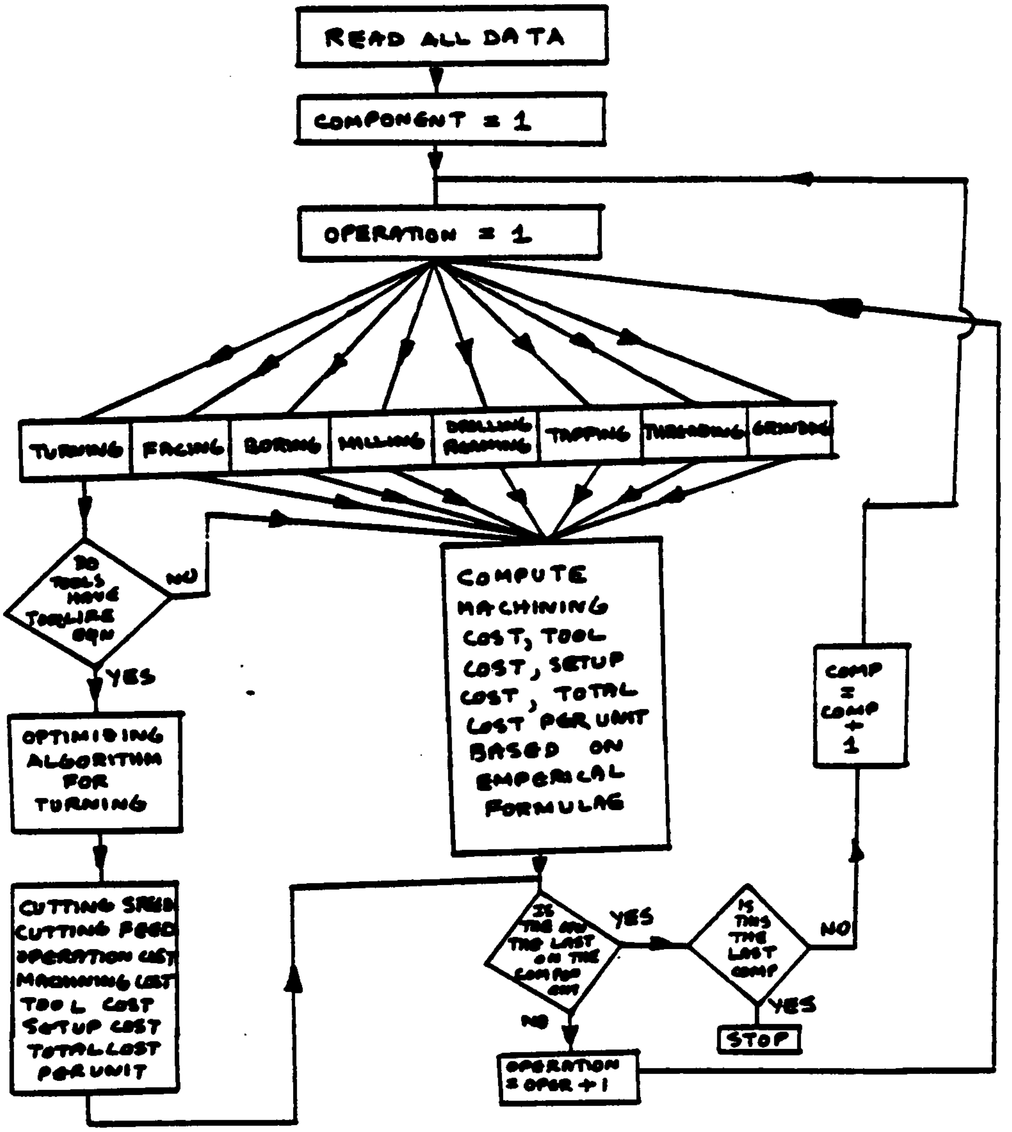


Figure 16. Flow Chart for the Machine and Tool Evaluator

For any particular operation to be performed on a machine, the process of determining the setup costs leads the system to search for information on whether the previous operation was performed on the same machine. If so, the job profile numbers are checked for the job on both the machines. If these profile numbers are the same, the job setup time for the operation under consideration is made zero. This concept would make some machines have lower total overall costs due to their use for the the previous operation. The reduction of costs in this situation makes the selection of the machine more attractive than otherwise.

5.9.4 System Output

The output includes the name of the operation, the component number, machine number, operation number, tool number, machining cost, tool cost, setup cost, and total cost per unit. For turning operations with the tool life equations being defined, the output would indicate the constraint status; whether the machine power and surface finish constraints are tight or loose. In addition, the optimized values for the cutting speed, feed, machining costs, tool costs, setup costs, and cost per operation on one component are indicated.

For operations other than turning, apart from the machine number, operation number, component number, and tool number, the individual costs are shown. When the output is analyzed, it would be clear that for each operation done on each component, as many machine, tool combinations that were feasible have been considered by the system and the costs determined. The user will thus have information on sets of optimal selections, and the final selection can be done easily, based on this information. The program listing and the output can be found in the appendix.

5.10 CONCLUSION

This chapter has shown the necessity of using algorithms for selection of machines and tools. The development of an optimization algorithm for the turning operation has been detailed. The development of the Machine and Tool Evaluator (MTE) has been described, along with data requirements and execution procedures. The next chapter will outline the implementation of the developed systems in this research along with suitable examples.

CHAPTER 6 : SYSTEM IMPLEMENTATION AND ANALYSIS

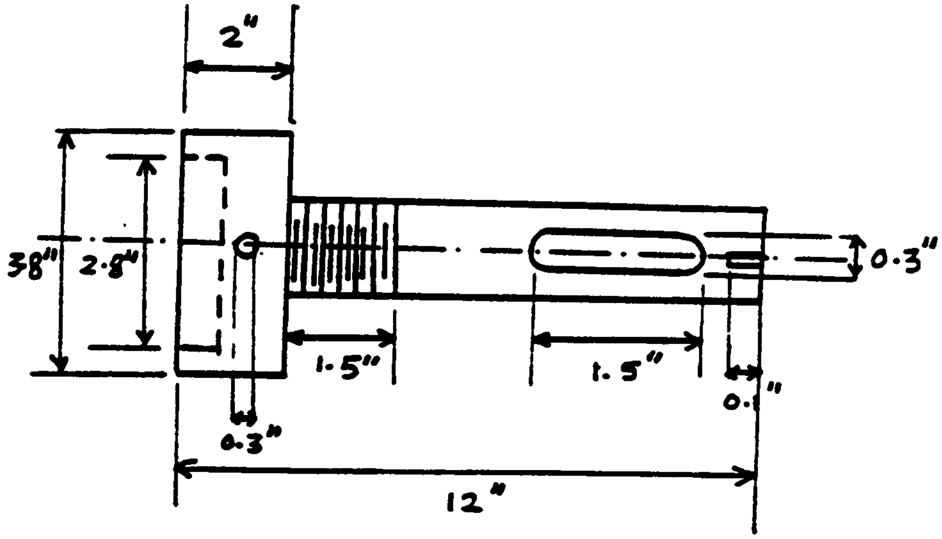
In this chapter we will consider the implementation of the expert system and the algorithms developed in chapters 4 and 5. Examples will be considered for illustrating the concepts. The expert systems were developed using VP-EXPERT, a commercially available expert system shell, on the IBM PC. The algorithms were designed in FORTRAN 77 and implemented on IBM mainframe.

6.1. EXAMPLE SCENARIO

A complex example of a part to be manufactured will be developed and tested using the expert systems and algorithms. The component drawing with details are shown on figure 17.

The following operations are to be done on it in sequence.

1. Turning.



NOT TO SCALE

Figure 17. Component Drawing

2. Threading.
3. Drilling and tapping axial hole.
4. Facing.
5. Milling a slot.
6. Drilling non-axial hole.
7. Boring axial hole.
8. Grinding flat surface.

Grey cast iron or high silicon cast iron are recommended as work-materials for this component. The cylindrical component has an outer diameter of 3.8 inches and a length of 12 inches.

6.1.1 Turning

The component has to be turned for a length of 10 inches. The depth of cut is 0.2 inches. The surface finish and tolerance requirements are 15 microinches and 0.004 inches respectively.

6.1.2 Threading

The threading operation then has to be performed for a length of 1.5 inches. The speed and feed estimated for this operation are 172 sfpm and .017 ipr respectively. The surface finish and tolerance required are 78 microinches and 0.007 inches respectively. The orientation for this component on a lathe is the same as that for turning.

6.1.3 Drilling and tapping axial hole

The next operation is to drill and tap an axial hole of diameter 0.3 inches, with the l/d ratio being 0.33. The final surface finish and tolerance required are 67 microinches and 0.007 inches respectively. The orientation of the component on the lathe is the same as that for turning. If the component were to be loaded on a drilling machine, its base area and height would be 12 square inches and 12 inches respectively. The length of cut in drilling is 0.09 inch. The cutting speed and feed for drilling are 300 sfpm and 0.013 ipr respectively. The cutting speed and feed for tapping are 123 sfpm and 0.015 ipr respectively.

6.1.4 Facing

The end of the component has to be faced. The feed for this operation is 0.2 inches per minute. The feed has been expressed in this manner to facilitate the computation of the cutting time, taking advantage of the fact that the facing tool travels perpendicular to the axis of the job. The length of cut is 2 inches. The surface finish and tolerance required are 13 microinches and 0.004 inch respectively. The orientation of the component on a lathe is the same as that for turning.

6.1.5 Milling

A slot has to be milled on the component surface. The base area and height of the component as loaded for the operation on to a milling machine table are 46 square inches and 4 inches respectively. The surface finish and tolerance required are 70 micro-inches and 0.009 inch respectively. The cutting speed and feed for this operation are 334 sfpm and 0.018 ipr respectively. The length of cut is 1.5 inches, and the width of cut is 0.3 inches.

6.1.6 Drilling non axial hole

A non axial hole of diameter 0.3 inches, l/d ratio of 0.33, and length 0.09 inch has to be drilled on the head of the component. The surface finish and tolerance required are 47 microinches and 0.01 respectively. The cutting speed and feed are 300 sfpm and 0.013 ipr respectively. The orientation of the component on a drilling is the same as that for drilling and tapping axial hole, as indicated earlier.

6.1.7 Boring Axial Hole

It is assumed that one end of the component has a recess drilled into it. The diameter of the hole to be bored is 2.8 inches and the length of cut is 0.3 inches. The orientation of the component requires a base area of 46 square inches, and a height of 4 inches. The surface finish and tolerance required are 4 microinches and 0.001 inch respectively. The cutting speed and feed are 445 sfpm and 0.0023 ipr respectively.

6.1.8 Grinding a Flat Surface

The head of the component has to be ground. The length of cut is 3.8 inches and the feed is 0.12 inches per minute. The orientation of the component requires a machine table area of at least 12 square inches and a height of at least 12 inches.

6.2 EXPERT SYSTEM CONSULTATION

The data described above for the product and operations were input into the expert systems for the selection of machining parameters.

6.2.1 Expert System : Operation, Work-material Compatibility Analysis

The expert system rejected high silicon cast iron as a suitable work-material for the prescribed process plan. This is because of the highly abrasive nature of the material. In fact all the operations except grinding were found to be unsuitable for this material. The non free-machining nature, along with a hardness of about 52 Rockwell, made this material unsuitable for most operations.

Grey cast iron was found suitable on all counts, for all the operations. The hardness of grey cast iron is about 234 Brinell. This means that the material need not be heat-treated for improving the surface machinability. The material does not possess any extremely adverse machinability deteriorating properties. This is why grey cast iron was found to be suitable for the prescribed operations.

6.2.2 Expert System : Machine Selection

For the turning operation, the turret lathe and the numerical control lathe were selected. The output shows that the engine lathe and single spindle automat were found suitable for accommodating the component on the machine, but fell short of delivering the surface finish and tolerance requirements.

All classes of lathes were found suitable for the threading operation. This was because the surface finish and tolerance requirements were not very stringent as before. For the drilling and tapping operations, the turret lathe, single spindle automat, numerical control lathe, radial drilling machine, and turret drilling machine were found suitable. The engine lathe was not selected because it would not have been able to deliver the required surface finish and tolerance for the operation. The vertical drill press was not selected because of the incapability of the machine to operate at the l/d ratio of the hole.

Turret lathe and numerical control lathe were selected for the facing operation. The low surface finish and tolerance required did not permit the other lathes to be selected. Both the vertical and numerical control milling machines were selected for the milling operation. The rejection of the horizontal milling machine was due to the fact that a very small slot was required to be milled. A larger width of cut might have caused the horizontal milling machine to be selected.

The turret drilling machine was the only one selected for drilling the non-axial hole on the component, because it was the only one that could provide the medium surface finish required. The lathes were not applicable because of the orientation of the hole on the component. The horizontal boring machine was selected for the boring operation. This was mainly due to the extremely low surface finish, tolerance, and precision required for the operation. The surface grinding machine was selected because it was the only machine which could grind the profile that was required.

6.2.3 Expert System : Selection of Cutting Tools

High speed steel and carbide were found suitable for all applicable machining operations. Ceramic were not selected because the surface finishes required were either medium or high. The requirement of extremely low surface finishes on ferrous non-austenitic materials usually makes ceramic tools an attractive alternative for selection. Diamond tools were not selected because of the medium to high nature of the surface finish specified. Diamond tools are extremely suitable for machining non-ferrous and abrasive non-metallics.

T15 and M42 grades of high speed steel were selected for the turning operation. C3 and C2 grades of carbide were also selected. The tougher grades were chosen because the machinability of grey cast is not very acceptable for hardness values greater than 200 Brinell. The same tools were selected for the facing and boring operations, since the rules observe the similarities between two operations.

For both the drilling operations, T15, M42 grades of high speed steel, and C2 grade of carbide were selected. For the tapping operation, M10, M7, M1 grades of high speed steel was selected. For the grinding operation, a soft grade of wheel made of aluminium oxide was selected. The grain size and grain structure selected were 220-600, and 9-16 respectively. The larger values for the grain sizes indicate that the surface finish required and stock removal were very low. The numbers for the grain structure indicate an open structure typically used with surface grinding machines.

6.2.4 Expert System : Selection of Cutting Fluids

The friction between the tool and the chip was found to be high for the turning operation using high speed steel tools. Hence a straight cutting oil with low to medium duty was specified as the cutting fluid. Turning with the carbide tool causes thermal shock, which made the selection of low to medium duty water soluble oil suitable. The same cutting fluids were chosen for the threading, facing, boring, and milling operations. This can be attributed to the relative ease in machining associated with grey cast iron. If the material had possesed any undesirable properties or was of special nature, the system would have selected varying cutting fluids for these operations.

Drilling and tapping, being high pressure metal removal operations, required the use of low to medium duty water soluble oils for use with the high speed steel and carbide tool materials. Severe cutting forces were the reason behind this selection. The grinding operation required the use of a heavy duty water soluble oil. This is due to the inherent severity associated with the abrasive machining process.

6.2.5 Expert System : Selection of Tool Angles

The back rake, side rake, end relief, and side relief angles were specified for the turning, facing, and boring operations, for both high speed steel and carbide tool materials. The point angle, lip angle, and the hook angle were specified for the twist drills. The hook angle, radial primary relief angle, primary land width, and radial secondary clearance angle were specified for the end-milling operation. The back rake, side rake, and relief angle were specified for the threading operation. Table 3 shows the selection of machining parameters using expert systems.

6.3 IMPLEMENTATION OF ALGORITHMS

The algorithm is primarily used to evaluate machines and tools based on cost factors. The data used for the algorithms can be found in the appendix.

For the turning operation, two cutting tools were assumed to have the tool life equations defined. This permitted the use of the optimization algorithm developed for turning. In general, the machining costs were much lower with the numerical control lathe, as opposed to the turret lathe. This is because of the lower labor rates associated with the numerical control lathe. Since the machine is automatic, it requires very little supervision, and hence the machining costs are lower. The turret lathe, on the other hand, requires much more skilled labor. The setup costs were higher for the numerical control lathe, mainly because of the extensive setup operations required prior to the commencement of machining. The tool cost was higher with the high speed steel tool when compared with the carbide tool. This can be attributed to the higher failure rates for the high speed steel tool. In all occasions but one, the machine power constraint was loose at optimality. In an isolated case, both constraints were found to be tight. On the whole, using the numerical control lathe with a ceramic tool gave the lowest unit cost. If the lot size were reduced from the present amount of 50, the choice is likely to change to using

Table 3. Results of the Expert System Consultations

OPERATION	MACHINES	TOOLS	FLUIDS	ANGLES
TURNING	TURRET LATHE NC LATHE	SP_HSS_TIS_M42 SP_CR_C2_C2	ST_CUTTING_OIL -LMD WATERSOL-OIL LMD	HSS_BRA = 5-10 HSS_SRA = 8-12 HSS-ELA = 5-8 HSS_SLA = 5-8 CR-BRA = 0-5 CR-SRA = 5-10 CR-RA = 5-7
THREADING	ENGINE LATHE TURRET LATHE SINGLE SP AUTO NC LATHE	— do —	— do —	HSS_BRA = 5-15 HSS_SRA = 5-15 CR_BRA = 0 CR_RRA = 5-8 CR_RA = 5-15
DRILLING & TAPPING	TURRET LATHE SINGLE SP AUTO NC LATHE RADIAL DRILL M/C TURR DRILL M/C	DRILL HSS_TIS_M42 CR_C2 TAP HSS_M10_M7_M1 CR_C2	WATER SOL OIL LMD	TD_PA = 118 TD_LAID = 8-16 TD_HA = STD LOW TCHA = 0-10 TP_CLA = 8-10
FACING	TURRET LATHE NC LATHE	HSS_TIS_M42 CR_C2	SAME AS FOR TURNING	SAME AS FOR TURNING
MILLING	NC MILL M/C VER MILL M/C	MP_HSS_M2_M3_M10 MP_CR_C2	— do —	EM_HA = 30-35 EM_RPRA = 10-20 EM_PLW = 0.007-0.025
DRILLING	TURRET DRILLING MACHINE	HSS_TIS_M42 CR_C2	WATER SOL OIL LMD	SAME AS IN DRILL & TAP
BORING	HORIZONTAL BORING MACHINE	HSS_TIS_M42 CR_C2	SAME AS FOR TURNING	HSS SAME AS TURNING CARBIDE CT_ARA = 0-15 CV_RRA = 3-10 CV_ELA = 5-10
GRINDING	SURFACE GRINDING MACHINE	GR_WHEEL_SOFT GR_ABRASIVE = A GR_SIZE = 220 - 600 GR_STRUCTURE = 9-16	WATER SOL OIL HD	—

the turret lathe, because the high set up costs would then offset the advantage of lower machining costs with the numerical control lathe.

The use of the single spindle automat with the carbide tool resulted in the lowest cost for threading. This is due to the low labor cost for the automatic machine. The other machine and tool combinations were not far behind in the unit cost incurred. At this point, it is important to understand that the setup costs have been computed on the basis of the selection of the same machine for the previous operation. If the machine was not selected for the previous operation, the set up costs, particularly the job setup cost would have to be included as many times as the number of units to be made. Since this is a sequencing problem, it has to be addressed when the final operating schedules and cost estimates are determined by the master scheduling system within the shop.

The minimum cost for drilling the axial hole are associated with the use of lathes, because they have been considered suitable for earlier operations. Drilling machines are expensive to use because of this reason. Tapping costs are quite low, due to the machining costs are low. The low values for the length of cut leads to low machine operational times.

Facing operations lead to almost same costs on the turret and numerical control lathe, since both of them had been selected for the previous operation. Milling with carbide tools show much lower costs than with high speed steel tools. The setup costs form the bulk of the costs in these operations. Similarly, drilling the non-axial hole, boring the axial hole on a horizontal boring machine, and grinding lead to high setup costs. The program output showing the detailed costs for machine and cutting tool combinations can be found in the appendix.

6.4 EXPERT SYSTEMS APPLICATION IN PRODUCT DESIGN AND SHOP FLOOR CONTROL

It is interesting to perform sensitivity analysis using the "WHATIF" option in VP-EXPERT. This option permits the variation in one or more of the component or operation parameters, depending on the structure of the decision tree that is being used in the expert system. A series of questions will be asked to the user, depending on the node of the decision tree that is being changed. This option is very important from the viewpoint of machining parameter selection, as it allows the product designer to come up with an effective design, based on the consultations of the expert system. It emphasizes the fact that proper material selection at an early stage of product design simplifies the manufacturing processes on the component, and leads to cost savings.

Sensitivity analysis can be performed by changing the data on the component parameters, or the operation parameters. By changing the physical dimensions of the component, the product designer can design the component such that it can be accommodated easily on most number of applicable machines on the shop floor. This gives the engineer in the shop greater flexibility to choose from many machines that would then have been selected for the operation, by the expert system.

The alteration of the surface finish and the quality requirements influences the set of machines that are selected for the operations. The expert system would be a very useful aid to the product designer to specify quality requirements that are a trade-off between the functional requirements of the component and the ease of manufacturing in the shop.

Product design can lead to reduction in the costs of tool usage by the choice of proper work materials which can be easily machined using most of the tools available in the shop. The choice of the surface finish required for the operation also influences the selection of tool materials. Unnecessary specification of very low surface finishes would require using tools like single crystal and polycrystalline diamonds, which are expensive.

The section of the expert system on the selection of tool grades is more useful to the shop floor engineer than the product designer, since the engineer can alter the component parameters to find the ranges in which the tool grades are selected. If some tool grades are applicable only to a very small family of components normally machined in the shop, these may not be stocked in the inventory again. This can lead to substantial reduction of procurement and inventory costs for specific tool grades.

The expert system for the selection of cutting fluids can be used effectively by shop floor personnel to analyze the applicability of each type of cutting fluid for specific cutting conditions. Based on the type of components normally manufactured in the shop, and the results of the expert system consultation, substantial inventory reductions can be made in some type of cutting fluids. The expert system can also identify critical situations in manufacturing and recommend suitable cutting fluids. This is because the use of certain types of cutting fluids can be disastrous to product quality in some cases. For example, cutting fluids with sulphur in the active form can stain the component, and this can lead to delays and costs in order to bring the component surface to specified quality standards. The system also identifies situations where cutting fluids are not necessary, thus reducing costs.

The expert system for the specification of tool angles is very useful to the operator of the machine tool for setting up the cutting tool on the machine. For single point cutting tools and multi point cutters, the operator can use the tool angle ranges specified by the expert system, conduct test runs, and try to add more specific conditions to the rules of the expert system. Since this expert system is based on the experience of a multitude of operators, it would be beneficial for the shop to use the expert system and build on it, thus making it more customized to the general operating conditions in the shop.

Milling operations, can be done on many types of milling machines with different physical configurations. The type of cutter used in the operation dictates the specification of the tool angles to some extent. The operator, given the liberty of milling on the horizontal milling machine, vertical milling machine, or the numerical control milling machine, can choose the cutter, which in his opinion is the easiest to setup on the machine tool, with respect to the tool angles specified. Consultation with the expert system would enable the operator to have rapid access to information on tool angle specification.

6.5 ROLE OF THE ALGORITHM IN PRODUCT DESIGN AND SHOP FLOOR CONTROL

The costs associated with each machine and cutting tool combination, can be effectively used both by the product designer and the shop floor engineer. For the product designer, it is a way of showing the overall cost effectiveness of his/her product design. The cost is based on several system parameters, some within the control of the product designer, and some not. Although these parameters can be identified, the influence of one parameter on the other, and their relationships which contribute to the efficiency of the manufacturing process, makes it necessary to provide a tool for the product designer with a system which "rates" the designs from the manufacturing viewpoint. The algorithm can be used as such a system. When the expert systems, and the algorithms are linked to form a total system, the product designer can alter his designs and find the cost effectiveness associated with each of the designs. In fact, he/she is being offered optimized alternatives of product designs to choose from.

The algorithm can also be very important on the shop floor, for the selection of machines and tools, based on their capacities which have already been committed, and which are available. As seen in an earlier chapter, the algorithm would contribute to the role of the machining parameter selection model within the manufacturing system. The manufacturing engineer can thus choose from among the optimized set of machines and tools, for overal reduction of the cost of manufacturing.

The algorithm is also useful at the level of the operator, as he/she can choose from a given set of machines which are equally cost effective and available, depending on their personal preferences. The algorithm has been designed to evaluate machines and tools in the shop, for any number of components and their operations.

6.6 CONCLUSION

This chapter has described the implementation of the expert systems and the algorithm. An example was formulated and the results from the consultations with the expert systems and algorithms have been analyzed. The role of the overall system in producing effective product designs and providing efficient shop floor control, has been described.

CHAPTER 7 : CONCLUSIONS AND AREAS OF FUTURE RESEARCH

Machining parameter selection will continue to be an area of great interest to researchers in the future, mainly because of the substantial benefits that can be realized from the process. In today's competitive manufacturing environment, it can lead to reduction in costs, improvement in quality and other factors that play a large role in the success or failure of a manufacturing industry. "Doing it right the first time" is the answer to today's manufacturing problems. Whether in preliminary product design, or detailed product design, it is important to look at the effect the decision taken at each stage has on producibility or manufacturability. Selection of one entity or the other to service the product to be manufactured is frequently done in a manufacturing industry, be it men, materials, or machines. Arbitrary selection of these may prevent savings to occur, which otherwise may have been possible. This is why future research in this area is so exciting and rewarding.

7.1 CONCLUSIONS

The research for this dissertation falls into place in the schema of the entire manufacturing system, as seen in chapter 1. The research has shown that expert systems and algorithms in an integrated fashion can be very useful in the selection of entities to service a product to be manufactured. The design and development of the data requirements and the rules that go into the knowledge bases have also been outlined in detail. The application of this system for the specific case of the selection of machining parameters has been described. The technical underpinnings of the selection of machining parameters have been analyzed in depth. An algorithm for the evaluation of machines and tools based on cost has been developed. An optimization algorithm using geometric programming has been developed for the turning operation. This algorithm is simple to implement and exploits the realistic situation that occurs in turning operations for purpose of simplifying the approach to optimization.

This research has shown that expert systems and algorithms are quite powerful tools for solving manufacturing problems. The design of data bases and knowledge bases for this environment are quite unique. It has been shown that it is advantageous to understand the manufacturing processes in depth prior to designing the expert systems. It is also important to disseminate the information used for decision making in order to determine patterns in the domain dependent knowledge. The interface between the inference engine and data bases was accomplished using forward chaining procedures. However, research advances in this area can go a long way in improving the effectiveness of large scale expert systems for manufacturing applications.

This research has shown that a combination of expert systems and algorithms can be used to solve manufacturing problems efficiently. Expert systems and algorithms are excellent tools which function their best under environments which sometimes overlap, and sometimes are disjoint. It is to the advantage of the industrial community to exploit this for great increases in productivity and quality. A research issue here is to address the types of problems that can be effectively solved using both tools, and to develop methods for accomplishing this. Operations Research is a very powerful tool for manufacturing applications, and the interface between expert systems and such quantitative techniques promises a bright future in industrial applications.

The optimizing algorithm for turning operations developed in this dissertation has shown that heuristics based on the fundamental reasoning pertaining to manufacturing processes tends to yield quick and efficient solution procedures. It is thus important to modify existent solution techniques as required for the process at hand, rather than trying to just improve the efficiency of the solution technique without proper understanding of its application.

The human interface has been shown to be necessary, however sophisticated the technology might be. The emphasis of this research has been to provide as refined information as possible to the human decision maker without forcing a decision on him/her. It is necessary to automate the refinement of information for decision making, as this is a waste of human energy. If this is achieved, great increases in productivity can be expected, similar to those realized by automated functions like CAD, CAM etc.

7.2 AREAS OF FUTURE RESEARCH

The underlying assumptions in this research make room for future research. In this research, a finite set of operations, machines, tools, and cutting fluids were selected, and a methodology for their selection was formulated. There is the need to develop a framework which can include all types of machining operations. Optimization algorithm was developed only for the turning operation, based on the assumption that tool-life equations are known only for these operations. Also, this research assumes that the general process plan is already present, and the sequence of operations are already known. Single tool operations are assumed in all cases. Based on these assumptions, the research defines its boundaries. The areas outside this boundary and within the manufacturing system form the bases for future research.

The areas of future research may be outlined as below.

- The development of a totally integrated manufacturing system which includes the selection of machining parameters for optimizing the operating schedules for the job shop.
- The development of expert systems for the selection of parameters for other forms of manufacturing, such as welding, casting, foundry etc.
- The inclusion of jigs and fixtures as parameters in the selection process.
- The development of expert systems for product design.
- The development of learning processes within the expert system framework.

- The development of data driven expert systems for manufacturing applications.

- The development of optimization algorithms for operations other than turning.

- Integration of sensor-based information systems with the expert system for machining parameter selection, to afford a real time decision making environment.

- The development of computer integrated systems to provide the product design function with information on all aspects along the product/system life cycle.

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APPENDIX A

EXPERT SYSTEM FOR ANALYZING OPERATION-WORK MATERIAL COMPATIBILITY

```
ENDOFF;

ACTIONS

        find operation
        DISPLAY "Input the name of the material without any blank
        spaces."
        DISPLAY "Use _ to connect words, and use singular form."
        find material
        find m_type
        find m_prop
        DISPLAY "Input EITHER the Brinell or Rockwell hardness values.
        If one is known, type a ? for the other"
        find m_b_hard
        find m_r_hard
        find search1;

RULE 1

IF     m_type = non_metallic
THEN      search1 = in_process
       find m_struct;

RULE 2

IF     m_type = ferrous OR
       m_type = non_ferrous
THEN      search1 = in_process
       find m_cond;

RULE 3

IF     operation = turning
THEN      search1 = in_process
```

```
        find turning;

RULE 4

IF      operation = facing
THEN    search1 = in_process
        find turning
        find facing;

RULE 5

IF      operation = threading_ext OR
        operation = threading_int_ah
THEN    search1 = in_process
        find threading;

RULE 6

IF      operation = milling
THEN    search1 = in_process
        find milling;

RULE 7

IF      operation = drilling_ah OR
        operation = drilling_nah
THEN    search1 = in_process
        find drilling;

RULE 8

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah
THEN    search1 = in_process
        find drilling
        find reaming;

RULE 9

IF      operation = drill&tap_ah OR
        operation = drill&tap_nah
THEN    search1 = in_process
        find drilling
        find tapping;

RULE 10

IF      operation = boring_ah OR
        operation = boring_nah
THEN    search1 = in_process
        find boring;
```

RULE 11

```
IF     operation = grinding
THEN    search1 = in_process
       find m_melt_pt
       find grinding;
```

RULE 12

```
IF     operation = turning OR
       operation = facing AND
       m_b_hard < 275
THEN    turning = suitable;
```

RULE 13

```
IF     operation = turning AND
       m_struct = fibrous
THEN    turning = suitable;
```

RULE 14

```
IF     operation = turning AND
       m_struct = hi_elastic OR
       m_struct = plated OR
       m_prop = highly_abrasive OR
       m_r_hard > 60
THEN    turning = unsuitable;
```

RULE 15

```
IF     operation = turning AND
       m_b_hard > 275 OR
       m_r_hard < 60 AND
       m_cond = normalized OR
       m_cond = as_forged OR
       m_cond = annealed OR
       m_cond = q&temp OR
       m_cond = sintered OR
       m_cond = hot_rolled OR
       m_cond = as_cast OR
       m_cond = aged AND
       m_prop < > highly_abrasive
THEN    turning = suitable;
```

RULE 16

```
IF     turning = unknown
THEN    turning = unsuitable;
```

RULE 17

```
IF     operation = facing AND
       turning = suitable
THEN   facing = suitable;
```

RULE 18

```
IF     operation = facing AND
       turning = unsuitable
THEN   facing = unsuitable;
```

RULE 19

```
IF     operation = threading_ext OR
       operation = threading_int_ah AND
       m_b_hard < 40 OR
       m_r_hard > 60 OR
       m_prop = hi_yield_str OR
       m_prop = highly_abrasive OR
       m_struct = plated OR
       m_struct = fibrous OR
       m_struct = hi_elastic OR
       m_struct = lo_elastic
THEN   threading = unsuitable;
```

RULE 20

```
IF     operation = threading_ext OR
       operation = threading_int_ah AND
       m_b_hard < 275 AND
       m_b_hard > 40
THEN   threading = suitable;
```

RULE 21

```
IF     operation = threading_ext OR
       operation = threading_int_ah AND
       m_b_hard > 275 OR
       m_r_hard < 60 AND
       m_cond = normalized OR
       m_cond = annealed OR
       m_cond = as_cast OR
       m_cond = hot_rolled OR
       m_cond = sintered OR
       m_cond = as_forged OR
       m_cond = q&temp OR
       m_cond = aged AND
```

```
        m_prop < > tough
THEN    threading = suitable;

RULE 22

IF      threading = unknown
THEN    threading = unsuitable;

RULE 23

IF      operation = milling AND
        m_b_hard < 275_Bhn
THEN    milling = suitable;



RULE 24

IF      operation = milling AND
        m_b_hard > 275 OR
        m_r_hard < 60 AND
        m_cond = normalized OR
        m_cond = sintered OR
        m_cond = hot_rolled OR
        m_cond = as_forged OR
        m_cond = aged OR
        m_cond = as_cast OR
        m_cond = annealed OR
        m_cond = q&temp AND
        m_prop < > highly_abrasive
THEN    milling = suitable;

RULE 25

IF      operation = milling AND
        m_r_hard > 60 OR
        m_struct = hi_elastic OR
        m_prop = highly_abrasive OR
        m_struct = plated
THEN    milling = unsuitable;

RULE 26

IF      operation = milling AND
        m_struct = fibrous
THEN    milling = suitable;

RULE 27

IF      milling = unknown
THEN    milling = unsuitable;
```

RULE 28

```
IF      operation = drilling_ah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
        operation = drilling_nah AND
        m_b_hard < 275
THEN    drilling = suitable;
```

RULE 29

```
IF      operation = drilling_ah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
        operation = drilling_nah AND
        m_b_hard > 275 OR
        m_r_hard < 60 AND
        m_cond = normalized OR
        m_cond = as_cast OR
        m_cond = aged OR
        m_cond = hot_rolled OR
        m_cond = as_forged OR
        m_cond = sintered OR
        m_cond = annealed OR
        m_cond = q&temp AND
        m_prop < > highly_abrasive
THEN    drilling = suitable;
```

RULE 30

```
IF      operation = drilling_ah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
        operation = drilling_nah AND
        m_r_hard > 60 OR
        m_prop = highly_abrasive OR
        m_struct = plated OR
        m_struct = hi_elastic
THEN    drilling = unsuitable;
```

RULE 31

```
IF      operation = drilling_ah OR
        operation = drill&ream_ah OR
```

```
         operation = drill&ream_nah OR
         operation = drill&tap_ah OR
         operation = drill&tap_nah OR
         operation = drilling_nah AND
         m_struct = fibrous
THEN     drilling = suitable;

RULE 32

IF       drilling = unknown
THEN     drilling = unsuitable;

RULE 33

IF       operation = drill&ream_ah OR
         operation = drill&ream_nah AND
         drilling = suitable
THEN     reaming = suitable;

RULE 34

IF       operation = drill&ream_ah OR
         operation = drill&ream_nah AND
         drilling = unsuitable
THEN     reaming = unsuitable;

RULE 35

IF       operation = drill&tap_ah OR
         operation = drill&tap_nah AND
         drilling = suitable
THEN     tapping = suitable;

RULE 36

IF       operation = drill&tap_ah OR
         operation = drill&tap_nah AND
         drilling = unsuitable
THEN     tapping = unsuitable;

RULE 37

IF       operation = boring_ah OR
         operation = boring_nah AND
         m_b_hard < 275
THEN     boring = suitable;

RULE 38

IF       operation = boring_ah OR
         operation = boring_nah AND
```

```
        m_b_hard > 275 OR
        m_r_hard < 60 AND
        m_cond = annealed OR
        m_cond = as_cast OR
        m_cond = hot_rolled OR
        m_cond = sintered OR
        m_cond = as_forged OR
        m_cond = aged OR
        m_cond = normalized OR
        m_cond = q&temp
THEN    boring = suitable;

RULE 39

IF      operation = boring_ah OR
        operation = boring_nah AND
        m_r_hard > 60 OR
        m_struct = plated OR
        m_struct = lo_elastic OR
        m_struct = hi_elastic
THEN    boring = unsuitable;

RULE 40

IF      operation = boring_ah OR
        operation = boring_nah AND
        m_struct = fibrous
THEN    boring = suitable;

RULE 41

IF      operation = boring_ah OR
        operation = boring_nah
THEN    boring = unsuitable;

RULE 42

IF      operation = grinding AND
        m_b_hard < 100 OR
        m_melt_pt < 500
THEN    grinding = unsuitable;

RULE 43

IF      operation = grinding AND
        m_b_hard > 100 OR
        m_r_hard > 20
THEN    grinding = suitable;

RULE 44
```

```
IF      operation = grinding AND
      m_struct = fibrous
THEN    grinding = suitable;

RULE 45

IF      grinding = unknown
THEN    grinding = unsuitable;

ASK operation : "Name the operation to be performed";

CHOICES operation : turning,facing,boring_ah,boring_nah,
threading_ext, threading_int_ah, milling,
drilling_ah,drilling_nah,drill&ream_ah,
drill&ream_nah, drill&tap_ah,drill&tap_nah,
grinding;

ASK m_b_hard : "What is the brinell hardness of the work-material?";

ASK m_r_hard : "What is the rockwell hardness of the work-material?";

ASK material : "What is the work-material?";

ASK m_type : "Name the work-material type";

CHOICES m_type : non_metallic,ferrous,non_ferrous,
non_aus_ferrous,aus_ferrous,hard_ferrous,
n_fr_mach_ferrous;

ASK m_prop : "Name any of the properties below, which the work-material
may have.";

CHOICES m_prop : hi_yield_str,highly_abrasive,tough;

ASK m_cond : "What is the heat treated condition of the material?";

CHOICES m_cond : normalized,as_forged,annealed,q&temp,sintered,
hot_rolled,as_cast,aged;

ASK m_struct : "Describe the metallurgical structure of the material";

CHOICES m_struct : hi_elastic,lo_elastic,plated,fibrous;

ASK m_melt_pt : "What is the melting point of the work-material in F?";

PLURAL : search1, m_type,m_prop,m_struct;
```

APPENDIX B

EXPERT SYSTEM FOR THE SELECTION OF MACHINES

```
ENDOFF;

ACTIONS
        find operation
        find search1
        find search2;

RULE 1

IF       operation = turning OR
        operation = facing OR
        operation = threading_ext OR
        operation = threading_int_ah
THEN     search1 = in_process
        find c_od
        find c_l
        find o_sf
        find o_tol;

RULE 2

IF       operation = boring_ah OR
        operation = drilling_ah OR
        operation = drill&ream_ah OR
        operation = drill&tap_ah
THEN     search1 = in_process
        find c_od
        find c_l
        find o_sf
        find o_tol;

RULE 3

IF      operation = grinding
THEN     search1 = in_process
```

```
        find ss_req;

RULE 4

IF      operation = milling
THEN      search1 = in_process
        find ss_req
        find c_b_a
        find c_ht
        find o_sf
        find o_tol
        find w_o_c;

RULE 5

IF      operation = grinding AND
        ss_req = flat
THEN      search1 = in_process
        find c_b_a
        find c_ht
        find o_sf
        find o_tol;

RULE 6

IF      operation = grinding AND
        ss_req = cylindrical
THEN      search1 = in_process
        find c_od
        find c_l
        find o_sf
        find o_tol;

RULE 7

IF      operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah
THEN      search1 = in_process
        find c_b_a
        find c_ht
        find o_sf
        find o_tol
        find h_d
        find h_ld_r;

RULE 8
```

```
IF      operation = boring_ah OR
       operation = boring_nah
THEN    search1 = in_process
       find c_b_a
       find c_ht
       find o_sf
       find o_tol;

RULE 9

IF        operation = turning OR
         operation = facing OR
         operation = threading_ext
THEN         search2 = in_process
         get all, b:eng_lathe,all
         close b:eng_lathe
         get all, b:turr_lathe, all
         close b:turr_lathe
          get all, b:sp_auto, all
         close b:sp_auto
          get all, b:nc_lathe, all
         close b:nc_lathe
          find engine_lathe
          find turret_lathe
         find single_sp_auto
         find nc_lathe;

RULE 10

IF        operation = threading_int_ah OR
         operation = boring_ah OR
         operation = drilling_ah OR
         operation = drill&ream_ah OR
         operation = drill&tap_ah
THEN         search2 = in_process
         get all, b:turr_lathe, all
         close b:turr_lathe
          get all, b:sp_auto, all
         close b:sp_auto
          get all, b:nc_lathe, all
         close b:nc_lathe
          find turret_lathe
         find single_sp_auto
         find nc_lathe;

RULE 11

IF        operation = milling
THEN         search2 = in_process
         get all, b:ver_mill, all
         close b:ver_mill
```

```
          get all, b:hor_mill, all
          close b:hor_mill
          get all, b:nc_mill, all
          close b:nc_mill
          find ver_mill_mc
          find hor_mill_mc
          find hor&ver_mill_mc
          find nc_mill_mc;

RULE 12

IF        operation = drilling_ah OR
          operation = drilling_nah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah OR
          operation = drill&tap_ah OR
          operation = drill&tap_nah
THEN         search2 = in_process
          get all, b:ver_drmc, all
          close b:ver_drmc
          get all, b:rad_drmc, all
          close b:rad_drmc
          get all, b:turr_drmc, all
          close b:turr_drmc
          find ver_dr_pr
          find rad_dr_mc
          find turr_dr_mc;

RULE 13

IF        operation = boring_ah OR
          operation = boring_nah
THEN         search2 = in_process
          get all, b:hor_bmc, all
          close b:hor_bmc
          find hor_bor_mc;

RULE 14

IF        operation = grinding AND
          ss_req = flat
THEN         search2 = in_process
          get all, b:sur_grmc, all
          close b:sur_grmc
          find sur_gr_mc;

RULE 15

IF        operation = grinding AND
          ss_req = cylindrical
THEN         search2 = in_process
```

```
          get all, b:cyl_grmc, all
         close b:cyl_grmc;
         find cyl_gr_mc;


RULE 16

IF        operation = turning OR
         operation = threading_ext OR
         operation = facing AND
         el_swing > (c_od) AND
         el_max_dc > (c_l) AND
         el_min_dc < (c_l)
THEN         engine_lathe = suitable;

RULE 17

IF        operation = turning OR
         operation = threading_ext OR
         operation = threading_int_ah OR
         operation = drill&tap_ah OR
         operation = facing OR
         operation = boring_ah OR
         operation = drilling_ah OR
         operation = drill&ream_ah AND
         tl_max_d > (c_od) AND
         tl_max_l > (c_l) AND
         tl_min_l < (c_l)
THEN         turret_lathe = suitable;

RULE 18

IF        operation = turning OR
         operation = threading_ext OR
         operation = threading_int_ah OR
         operation = drill&tap_ah OR
         operation = drilling_ah OR
         operation = boring_ah OR
         operation = facing OR
         operation = drill&ream_ah AND
         sp_max_d > (c_od) AND
         sp_max_l > (c_l) AND
         sp_min_l < (c_l)
THEN         single_sp_auto = suitable;

RULE 19

IF        operation = turning OR
         operation = threading_ext OR
         operation = threading_int_ah OR
         operation = boring_ah OR
```

```
          operation = drill&tap_ah OR
          operation = drilling_ah OR
          operation = facing OR
          operation = drill&ream_ah AND
          nc_max_d > (c_od) AND
          nc_max_l > (c_l) AND
          nc_min_l < (c_l)
THEN          nc_lathe = suitable;

RULE 20

IF         operation = turning AND
          engine_lathe = suitable AND
          el_trn_sf < (o_sf) AND
          el_trn_tol < (o_tol)
THEN          engine_lathe = selected;

RULE 21

IF         operation = threading_ext AND
          engine_lathe = suitable AND
          el_thr_sf < (o_sf) AND
          el_thr_tol < (o_tol)
THEN          engine_lathe = selected;

RULE 22

IF         operation = facing AND
          engine_lathe = suitable AND
          el_fc_sf < (o_sf) AND
          el_fc_tol < (o_tol)
THEN          engine_lathe = selected;

RULE 23

IF         operation = turning AND
          turret_lathe = suitable AND
          tl_trn_sf < (o_sf) AND
          tl_trn_tol < (o_tol)
THEN          turret_lathe = selected;

RULE 24

IF         operation = facing AND
          turret_lathe = suitable AND
          tl_fc_sf < (o_sf) AND
          tl_fc_tol < (o_tol)
THEN          turret_lathe = selected;

RULE 25
```

```
IF       operation = threading_ext AND
         turret_lathe = suitable AND
         tl_thre_sf < (o_sf) AND
         tl_thre_to < (o_tol)
THEN        turret_lathe = selected;

RULE 26

IF       operation = threading_int_ah AND
         turret_lathe = suitable AND
         tl_thri_sf < (o_sf) AND
         tl_thri_to < (o_tol)
THEN        turret_lathe = selected;

RULE 27

IF       operation = boring_ah AND
         turret_lathe = suitable AND
         tl_bor_sf < (o_sf) AND
         tl_bor_tol < (o_tol)
THEN        turret_lathe = selected;

RULE 28

IF       operation = drilling_ah AND
         turret_lathe = suitable AND
         tl_max_hd > (h_d) AND
         tl_min_hd < (h_d) AND
         tl_ld_r > (h_ld_r) AND
         tl_drl_sf < (o_sf) AND
         tl_drl_tol < (o_tol)
THEN        turret_lathe = selected;

RULE 29

IF       operation = drill&tap_ah AND
         turret_lathe = suitable AND
         tl_max_hd > (h_d) AND
         tl_min_hd < (h_d) AND
         tl_ld_r > (h_ld_r) AND
         tl_dtpg_sf < (o_sf) AND
         tl_dtpg_to < (o_tol)
THEN        turret_lathe = selected;

RULE 30

IF       operation = drill&ream_ah AND
         turret_lathe = suitable AND
         tl_max_hd > (h_d) AND
         tl_min_hd < (h_d) AND
         tl_ld_r > (h_ld_r) AND
```

```
         tl_drmg_sf < (o_sf) AND
         tl_drmg_to < (o_tol)
THEN        turret_lathe = selected;

RULE 31

IF        operation = turning AND
         single_sp_auto = suitable AND
         sp_trn_sf < (o_sf) AND
         sp_trn_tol < (o_tol)
THEN        single_sp_auto = selected;

RULE 32

IF        operation = facing AND
         single_sp_auto = suitable AND
         sp_fc_sf < (o_sf) AND
         sp_fc_tol < (o_tol)
THEN        single_sp_auto = selected;



RULE 33

IF        operation = boring_ah AND
         single_sp_auto = suitable ANd
         sp_bor_sf < (o_sf) AND
         sp_bor_tol < (o_tol)
THEN        single_sp_auto = selected;

RULE 34

IF        operation = drilling_ah AND
         single_sp_auto = suitable AND
         sp_max_hd > (h_d) AND
         sp_min_hd < (h_d) AND
         sp_ld_r > (h_ld_r) AND
         sp_drl_sf < (o_sf) AND
         sp_drl_tol < (o_tol)
THEN        single_sp_auto = selected;

RULE 35

IF        operation = drill&tap_ah AND
         single_sp_auto = suitable AND
         sp_max_hd > (h_d) AND
         sp_min_hd < (h_d) AND
         sp_ld_r > (h_ld_r) AND
         sp_dtpg_sf < (o_sf) AND
         sp_dtpg_to < (o_tol)
THEN        single_sp_auto = selected;
```

RULE 36

```
IF       operation = drill&ream_ah AND
         single_sp_auto = suitable AND
         sp_max_hd > (h_d) AND
         sp_min_hd < (h_d) AND
         sp_ld_r > (h_ld_r) AND
         sp_drmg_sf < (o_sf) AND
         sp_drmg_to < (o_tol)
THEN       single_sp_auto = selected;
```

RULE 37

```
IF       operation = threading_ext AND
         single_sp_auto = suitable AND
         sp_thre_sf < (o_sf) AND
         sp_thre_to < (o_tol)
THEN       single_sp_auto = selected;
```

RULE 38

```
IF       operation = threading_int_ah AND
         single_sp_auto = suitable AND
         sp_thri_sf < (o_sf) AND
         sp_thri_to < (o_tol)
THEN       single_sp_auto = selected;
```

RULE 39

```
IF       operation = turning AND
         nc_lathe = suitable AND
         nc_trn_sf < (o_sf) AND
         nc_trn_tol < (o_tol)
THEN       nc_lathe = selected;
```

RULE 40

```
IF       operation = facing AND
         nc_lathe = suitable AND
         nc_fc_sf < (o_sf) AND
         nc_fc_tol < (o_tol)
THEN       nc_lathe = selected;
```

RULE 41

```
IF       operation = boring_ah AND
         nc_lathe = suitable AND
         nc_bor_sf < (o_sf) AND
         nc_bor_tol < (o_tol)
THEN       nc_lathe = selected;
```

RULE 42

```
IF       operation = drilling_ah AND
        nc_lathe = suitable AND
        nc_max_hd > (h_d) AND
        nc_min_hd < (h_d) AND
        nc_ld_r > (h_ld_r) AND
        nc_drl_sf < (o_sf) AND
        nc_drl_tol < (o_tol)
THEN       nc_lathe = selected;
```

RULE 43

```
IF       operation = drill&tap_ah AND
        nc_lathe = suitable AND
        nc_max_hd > (h_d) AND
        nc_min_hd < (h_d) AND
        nc_ld_r > (h_ld_r) AND
        nc_dtpg_sf < (o_sf) AND
        nc_dtpg_to < (o_tol)
THEN       nc_lathe = selected;
```

RULE 44

```
IF       operation = drill&ream_ah AND
        nc_lathe = suitable AND
        nc_max_hd > (h_d) AND
        nc_min_hd < (h_d) AND
        nc_ld_r > (h_ld_r) AND
        nc_drmg_sf < (o_sf) AND
        nc_drmg_to < (o_tol)
THEN       nc_lathe = selected;
```

RULE 45

```
IF       operation = threading_ext AND
        nc_lathe = suitable AND
        nc_thre_sf < (o_sf) AND
        nc_thre_to < (o_tol)
THEN       nc_lathe = selected;
```

RULE 46

```
IF       operation = threading_int_ah AND
        nc_lathe = suitable AND
        nc_thri_sf < (o_sf) AND
        nc_thri_to < (o_tol)
THEN       nc_lathe = selected;
```

RULE 47

```
IF        operation = milling AND
          vm_tbl_a > (c_b_a) AND
          vm_ht > (c_ht) AND
          vm_sf < (o_sf) AND
          vm_tol < (o_tol)
THEN          ver_mill_mc = suitable;
```

RULE 48

```
IF        operation = milling AND
          hm_tbl_a > (c_b_a) AND
          hm_ht > (c_ht) AND
          hm_sf < (o_sf) AND
          hm_tol < (o_tol)
THEN          hor_mill_mc = suitable;
```

RULE 49

```
IF        operation = milling AND
          ncm_tbl_a > (c_b_a) AND
          ncm_ht > (c_ht) AND
          ncm_sf < (o_sf) AND
          ncm_tol < (o_tol)
THEN          nc_mill_mc = suitable;
```

RULE 50

```
IF        operation = milling AND
          ver_mill_mc = suitable AND
          w_o_c < 2.5 AND
          ss_req < > concave OR
          ss_req < > convex
THEN          ver_mill_mc = selected;
```

RULE 51

```
IF        operation = milling AND
          ver_mill_mc = suitable AND
          ss_req = t_slot
THEN          ver_mill_mc = selected;
```

RULE 52

```
IF        operation = milling AND
          hor_mill_mc = suitable AND
          ss_req < > dovetail AND
          ss_req = contoured OR
          ss_req = convex OR
          ss_req = concave OR
          ss_req = flat AND
```

```
         w_o_c > 2.5
THEN        hor_mill_mc = selected;

RULE 53

IF        operation = milling AND
         hor_mill_mc = suitable AND
         ver_mill_mc = suitable AND
         w_o_c > 2.5 AND
         ss_req = dovetail
THEN        hor&ver_mill_mc = selected;

RULE 54

IF        operation = milling AND
         nc_mill_mc = suitable
THEN        nc_mill_mc = selected;

RULE 55

IF        operation = drilling_ah OR
         operation = drilling_nah OR
         operation = drill&tap_ah OR
         operation = drill&tap_nah OR
         operation = drill&ream_ah OR
         operation = drill&ream_nah AND
         vdp_max_d > (h_d) AND
         vdp_min_d < (h_d) AND
         vdp_ld_r > (h_ld_r) AND
         vdp_tbl_a > (c_b_a) AND
         vdp_ht > (c_ht)
THEN        ver_dr_pr = suitable;

RULE 56

IF        operation = drilling_ah OR
         operation = drilling_nah OR
         operation = drill&tap_ah OR
         operation = drill&tap_nah OR
         operation = drill&ream_ah OR
         operation = drill&ream_nah AND
         rdm_max_d > (h_d) AND
         rdm_min_d < (h_d) AND
         rdm_ld_r > (h_ld_r) AND
         rdm_tbl_a > (c_b_a) AND
         rdm_ht > (c_ht)
THEN        rad_dr_mc = suitable;

RULE 57

IF       operation = drilling_ah OR
```

```
          operation = drilling_nah OR
          operation = drill&tap_ah OR
          operation = drill&tap_nah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah AND
          tdm_max_d > (h_d) AND
          tdm_min_d < (h_d) AND
          tdm_ld_r > (h_ld_r) AND
          tdm_tbl_a > (c_b_a) AND
          tdm_ht > (c_ht)
THEN          turr_dr_mc = suitable;

RULE 58

IF         operation = drilling_ah OR
          operation = drilling_nah AND
          ver_dr_pr = suitable AND
          vdp_dr_sf < (o_sf) AND
          vdp_dr_tol < (o_tol)
THEN          ver_dr_pr = selected;

RULE 59

IF         operation = drill&tap_ah OR
          operation = drill&tap_nah AND
          ver_dr_pr = suitable AND
          vdp_drt_sf < (o_sf) AND
          vdp_drt_to < (o_tol)
THEN          ver_dr_pr = selected;

RULE 60

IF         operation = drill&ream_ah OR
          operation = drill&ream_nah AND
          ver_dr_pr = suitable AND
          vdp_drr_sf < (o_sf) AND
          vdp_drr_to < (o_tol)
THEN          ver_dr_pr = selected;

RULE 61

IF         operation = drilling_ah OR
          operation = drilling_nah AND
          rad_dr_mc = suitable AND
          rdm_dr_sf < (o_sf) AND
          rdm_dr_tol < (o_tol)
THEN          rad_dr_mc = selected;

RULE 62

IF         operation = drill&tap_ah OR
```

```
          operation = drill&tap_nah AND
          rad_dr_mc = suitable AND
          rdm_drt_sf < (o_sf) AND
          rdm_drt_to < (o_tol)
THEN          rad_dr_mc = selected;
```

RULE 63

```
IF         operation = drill&ream_ah OR
          operation = drill&ream_nah AND
          rad_dr_mc = suitable AND
          rdm_drr_sf < (o_sf) AND
          rdm_drr_to < (o_tol)
THEN          rad_dr_mc = selected;
```

RULE 64

```
IF         operation = drilling_ah OR
          operation = drilling_nah AND
          turr_dr_mc = suitable AND
          tdm_dr_sf < (o_sf) AND
          tdm_dr_tol < (o_tol)
THEN          turr_dr_mc = selected;
```

RULE 65

```
IF         operation = drill&tap_ah OR
          operation = drill&tap_nah AND
          turr_dr_mc = suitable AND
          tdm_drt_sf < (o_sf) AND
          tdm_drt_to < (o_tol)
THEN          turr_dr_mc = selected;
```

RULE 66

```
IF         operation = drill&ream_ah OR
          operation = drill&ream_nah AND
          turr_dr_mc = suitable AND
          tdm_drr_sf < (o_sf) AND
          tdm_drr_to < (o_tol)
THEN          turr_dr_mc = selected;
```

RULE 67

```
IF         operation = boring_ah OR
          operation = boring_nah AND
          hbm_tbl_a > (c_b_a) AND
          hbm_sf < (o_sf) AND
          hbm_tol < (o_tol)
THEN          hor_bor_mc = selected;
```

```
RULE 68

IF        operation = grinding AND
          ss_req = flat AND
          sgm_sf < (o_sf) AND
          sgm_tol < (o_tol) AND
          sgm_tbl_a > (c_b_a) AND
          sgm_ht > (c_ht)
THEN          sur_gr_mc = selected;

RULE 69

IF        operation = grinding AND
          ss_req = cylindrical AND
          cgm_sf < (o_sf) AND
          cgm_tol < (o_tol) AND
          cgm_max_dc > (c_l) AND
          cgm_min_dc < (c_l) AND
          cgm_max_d > (c_od)
THEN          cyl_gr_mc = selected;

PLURAL : search1, search2;

PLURAL : engine_lathe, turret_lathe, single_sp_auto;

PLURAL : nc_lathe, ver_mill_mc, hor_mill_mc, ver_dr_pr;

PLURAL : rad_dr_mc, turr_dr_mc, hor_bor_mc, sur_gr_mc;

PLURAL : cyl_gr_mc, hor&ver_mill_mc, nc_mill_mc;


ASK operation : "Name the operation to be performed";

CHOICES operation : turning,facing,boring_ah,boring_nah,
threading_ext, threading_int_ah, milling,
drilling_ah,drilling_nah,drill&ream_ah,
drill&ream_nah, drill&tap_ah,drill&tap_nah,
grinding;

ASK c_od : "What is the maximum outer diameter of the component for
loading on to a lathe or a cylindrical grinding machine, for this
operation?";

ASK c_l : "What is the length of the component for loading on to a
lathe or a cylindrical grinding machine, for this operation?";

ASK c_b_a : "What is the base area of the component for loading on
to a milling, drilling, boring, or a surface grinding machine,
for this operation?";
```

```
ASK c_ht : "What is the height of the component as placed for
operation on a milling, drilling, boring, or a surface grinding
machine?";

ASK o_sf : "What is the surface finish required for the operation?";

ASK o_tol : "What is the tolerance requirement for the operation?";

ASK w_o_c : "What is the width of cut for milling?";

ASK h_d : "What is the diameter of the hole to be drilled?";

ASK h_ld_r : "What is the length to diameter ratio of the hole?";
```

APPENDIX C

EXPERT SYSTEM FOR THE SELECTION OF CUTTING TOOL MATERIALS

```
ENDOFF;

ACTIONS
        find operation
        DISPLAY "Input the name of the material without any blank
        spaces."
        DISPLAY "Use _ to connect words, and use singular form."
        find material
        find m_type
        find m_prop
        DISPLAY "Input EITHER the Brinell or Rockwell hardness values.
        If one is known, type a ? for the other"
        find m_b_hard
        find m_r_hard
        find s_f_req
        find search1
        find search4
        find hss_carbide
        find hi_sp_steel
        find carbide
        find ceramic
        find diamond;

RULE 1

IF      m_type = non_metallic
THEN      search1 = in_process
        find m_struct;

RULE 2

IF      m_type = ferrous OR
        m_type = non_ferrous
THEN      search1 = in_process
```

```
        find m_cond;

    RULE 3

    IF       operation = turning OR
            operation = threading_int_ah OR
            operation = threading_ext OR
            operation = facing AND
            s_f_req = medium OR
            s_f_req = high AND
            m_b_hard < 275 OR
            m_r_hard < 52
    THEN        hss_carbide = suitable;

    RULE 2

    IF       operation = drilling_ah OR
            operation = drilling_nah OR
            operation = drill&tap_ah OR
            operation = drill&tap_nah OR
            operation = drill&ream_ah AND
            s_f_req = medium OR
            s_f_req = high AND
            m_b_hard < 275 OR
            m_r_hard < 52
    THEN        hss_carbide = suitable;

    RULE 3

    IF       operation = milling OR
            operation = drill&ream_nah OR
            operation = boring_ah OR
            operation = boring_nah AND
            s_f_req = medium OR
            s_f_req = high AND
            m_b_hard < 275 OR
            m_r_hard < 52
    THEN        hss_carbide = suitable;

    RULE 4

    IF       operation = turning OR
            operation = threading_int_ah OR
            operation = threading_ext OR
            operation = drilling_ah AND
            m_b_hard > 275 AND
            m_b_hard < 425 OR
            m_r_hard < 52 AND
            s_f_req = medium OR
            s_f_req = high AND
            m_cond = annealed OR
```

```
        m_cond = normalized OR
        m_cond = as_forged OR
        m_cond = q&temp OR
        m_cond = sintered OR
        m_cond = hot_rolled OR
        m_cond = as_cast OR
        m_cond = aged
THEN        hss_carbide = suitable;
```

RULE 5

```
IF       operation = drilling_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        m_b_hard > 275 AND
        m_b_hard < 425 OR
        m_r_hard < 52 AND
        s_f_req = medium OR
        s_f_req = high AND
        m_cond = annealed OR
        m_cond = normalized OR
        m_cond = as_forged OR
        m_cond = q&temp OR
        m_cond = sintered OR
        m_cond = hot_rolled OR
        m_cond = as_cast OR
        m_cond = aged
THEN        hss_carbide = suitable;
```

RULE 6

```
IF       operation = milling OR
        operation = facing OR
        operation = boring_ah OR
        operation = boring_nah AND
        m_b_hard > 275 AND
        m_b_hard < 425 OR
        m_r_hard < 52 AND
        s_f_req = medium OR
        s_f_req = high AND
        m_cond = annealed OR
        m_cond = normalized OR
        m_cond = as_forged OR
        m_cond = q&temp OR
        m_cond = sintered OR
        m_cond = hot_rolled OR
        m_cond = as_cast OR
        m_cond = aged
THEN        hss_carbide = suitable;
```

RULE 7

```
IF      hss_carbide = suitable AND
        m_prop < > abrasive AND
        s_f_req < > low
THEN        hi_sp_steel = selected;
```

RULE 8

```
IF      carbide = unknown AND
        m_r_hard > = 52 AND
        operation < > grinding AND
        m_r_hard < = 60 OR
        s_f_req < > low OR
        m_prop = abrasive
THEN        carbide = selected;
```

RULE 9

```
IF      carbide = unknown AND
        operation < > grinding AND
        m_b_hard > 425
THEN        carbide = selected;
```

RULE 10

```
IF      hss_carbide = suitable AND
        operation < > grinding AND
        s_f_req < > low
THEN        carbide = selected;
```

RULE 11

```
IF      operation = turning OR
        operation = threading_int_ah OR
        operation = threading_ext AND
        m_prop = abrasive OR
        m_r_hard > 52 OR
        m_b_hard > 425 OR
        s_f_req = low  AND
        operation < > grinding AND
        m_type = non_aus_ferrous AND
        material < > refractory_alloy AND
        material < > aluminium_alloy
THEN        ceramic = selected;
```

RULE 12

```
IF      operation = boring_ah OR
        operation = boring_nah OR
```

```
          operation = facing OR
          operation = milling AND
          m_prop = abrasive OR
          m_r_hard > 52 OR
          m_b_hard > 425 OR
          s_f_req = low  AND
          m_type = non_aus_ferrous AND
          material < > refractory_alloy AND
          material < > aluminium_alloy
THEN         ceramic = selected;

RULE 13

IF         m_type = non_ferrous AND
          operation = turning OR
          operation = facing OR
          operation = boring_ah OR
          operation = boring_nah OR
          operation = drilling_ah OR
          operation = drilling_nah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah OR
          operation = milling AND
          s_f_req = low
THEN         diamond = selected;

RULE 14

IF         operation = turning OR
          operation = facing OR
          operation = boring_ah OR
          operation = boring_nah OR
          operation = drilling_ah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah OR
          operation = drilling_nah OR
          operation = milling AND
          diamond = unknown AND
          m_type = non_ferrous AND
          m_prop = abrasive OR
          m_struct = fibrous OR
          m_struct = lo_elastic
THEN         diamond = selected;

RULE 15

IF         diamond = unknown AND
          operation < > drill&tap_ah OR
          operation < > drill&tap_nah AND
          m_type = non_ferrous AND
          m_b_hard > 425 OR
```

```
          m_r_hard >  52 AND
          s_f_req = high OR
          s_f_req = medium
THEN          diamond = selected;

RULE 16

IF       operation = milling
THEN       search1 = in_process
        find hor_mill_mc
        find ver_mill_mc
        find nc_mill_mc;

RULE 17

IF           operation = turning OR
          operation = facing OR
          operation = boring_ah OR
          operation = boring_nah AND
          hi_sp_steel = selected
THEN           search4 = in_process
          find sp_hss_m2_m3
          find sp_hss_t15_m42;

RULE 18

IF           operation = turning OR
          operation = facing OR
          operation = boring_ah OR
          operation = boring_nah AND
          carbide = selected
THEN           search4 = in_process
          find sp_cr_c7_c6
          find sp_cr_c8_c7_c6
          find sp_cr_c8
          find sp_cr_c3_c2
          find sp_cr_c4;

RULE 19

IF           operation = turning OR
          operation = facing OR
          operation = boring_ah OR
          operation = boring_nah AND
          ceramic = selected
THEN           search4 = in_process
          find sp_cer_cpa
          find sp_cer_hpc;

RULE 20
```

```
IF        operation = milling AND
        hi_sp_steel = selected
THEN        search4 = in_process
        find mp_hss_m2_m7
        find mp_hss_t15_m42
        find mp_hss_m2_m3_m7;

RULE 21

IF        operation = milling AND
        carbide = selected
THEN        search4 = in_process
        find mp_cr_c6_c5
        find mp_cr_c2
        find mp_cr_c5;

RULE 22

IF        operation = milling AND
        ceramic = selected
THEN        search4 = in_process
        find mp_cer_cpa_hpc;

RULE 23

IF        operation = drilling_ah OR
        operation = drilling_nah AND
        hi_sp_steel = selected
THEN        search4 = in_process
        find td_hss_m10_m7_m1
        find td_hss_t15_m42;

RULE 24

IF        operation = drilling_ah OR
        operation = drilling_nah AND
        carbide = selected
THEN        search4 = in_process
        find td_cr_c2;

RULE 25

IF        operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected
THEN        search4 = in_process
        find td_hss_m10_m7_m1
        find td_hss_t15_m42
        find rm_hss_m1_m2_m7
        find rm_hss_t15_m42;
```

RULE 26

```
IF        operation = drill&ream_ah OR
         operation = drill&ream_nah AND
         carbide = selected
THEN        search4 = in_process
         find td_cr_c2
         find rm_cr_c2;
```

RULE 27

```
IF        operation = drill&tap_ah OR
         operation = drill&tap_nah AND
         hi_sp_steel = selected
THEN        search4 = in_process
         find td_hss_m10_m7_m1
         find td_hss_t15_m42
         find tp_hss_m10_m7_m1
         find tp_hss_m7_m41_m44;
```

RULE 28

```
IF        operation = drill&tap_ah OR
         operation = drill&tap_nah AND
         carbide = selected
THEN        search4 = in_process
         find td_cr_c2
         find tp_cr_c2;
```

RULE 29

```
IF        operation = grinding
THEN        search4 = in_process
         find op_gr_wheel_hard
         find op_gr_wheel_soft
         find gr_wheel_hard
         find gr_wheel_soft
         find gr_wheel_med
         find gr_abrasive
         find gr_grain_size
         find gr_structure;
```

RULE 30

```
IF        operation = threading_ext OR
         operation = threading_int_ah AND
         hi_sp_steel = selected
THEN        search4 = in_process
         find thr_sp_hss_m2
         find thr_sp_hss_t15_m42;
```

```
RULE 31

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        carbide = selected
THEN        search4 = in_process
        find thr_sp_cr_c6
        find thr_sp_cr_c2;

RULE 32

IF       operation=turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        m_b_hard < 275 AND
        material < > grey_cast_iron AND
        material < > ductile_cast_iron AND
        material < > malleable_cast_iron
THEN       SP_HSS_M2_M3 = selected;

RULE 33

IF       operation=turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        m_b_hard > 275 OR
        m_r_hard < 52 AND
        material < > grey_cast_iron AND
        material < > ductile_cast_iron AND
        material < > malleable_cast_iron
THEN       SP_HSS_T15_M42 = selected;

RULE 34

IF       operation=turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        material = grey_cast_iron OR
        material = ductile_cast_iron OR
        material = malleable_cast_iron AND
        m_b_hard < 200
THEN       SP_HSS_M2_M3 = selected;

RULE 35
```

```
IF       operation = turning OR
         operation = boring_ah OR
         operation = facing OR
         operation = boring_nah AND
          hi_sp_steel = selected AND
         material = grey_cast_iron OR
         material = ductile_cast_iron OR
         material = malleable_cast_iron AND
         m_b_hard > 200
THEN         SP_HSS_T15_M42 = selected;

RULE 36

IF       operation = turning OR
         operation = boring_ah OR
         operation = facing OR
         operation = boring_nah AND
         carbide = selected AND
         material < > ductile_cast_iron AND
         material < > malleable_cast_iron AND
         material < > grey_cast_iron AND
         material < > refractory_alloy AND
         m_prop < > abrasive AND
         m_type < > non_ferrous AND
         m_type < > aus_ferrous AND
         m_b_hard < 275
THEN         SP_CR_C7_C6 = selected;

RULE 37

IF       operation = turning OR
         operation = boring_ah OR
         operation = facing OR
         operation = boring_nah AND
          carbide = selected AND
         material < > ductile_cast_iron AND
         material < > malleable_cast_iron AND
         material < > grey_cast_iron AND
         material < > refractory_alloy AND
         m_prop < > abrasive AND
         m_type < > non_ferrous AND
         m_type < > aus_ferrous AND
         m_b_hard > 275 OR
         m_r_hard < 50
THEN         SP_CR_C8_C7_C6 = selected;

RULE 38

IF       operation = turning OR
         operation = boring_ah OR
         operation = facing OR
```

```
        operation = boring_nah AND
         carbide = selected AND
        material < > refractory_alloy AND
        m_prop < > abrasive AND
        m_type < > non_ferrous AND
        m_type < > aus_ferrous AND
        m_r_hard > 50
THEN        SP_CR_C8 = selected;

RULE 39

IF       operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         carbide = selected AND
        material =  ductile_cast_iron OR
        material = malleable_cast_iron
THEN        SP_CR_C7_C6 = selected;

RULE 40


IF       operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         carbide = selected AND
        material = grey_cast_iron
THEN        SP_CR_C3_C2 = selected;

RULE 41

IF       operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         carbide = selected AND
        m_prop = abrasive OR
        m_type = non_ferrous OR
        m_type = aus_ferrous AND
        material < > nickel_alloy
THEN        SP_CR_C3_C2 = selected;

RULE 42

IF       operation = turning OR
        operation = boring_ah OR
        operation = boring_nah AND
         carbide = selected AND
```

```
        material =  refractory_alloy
THEN        SP_CR_C4 = selected;

RULE 43

IF        operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         carbide = selected AND
        material =  nickel_alloy AND
        m_b_hard < 275
THEN        SP_CR_C7_C6 = selected;

RULE 44

IF        operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         carbide = selected AND
        material = nickel_alloy AND
        m_b_hard > 275
THEN        SP_CR_C8_C7_C6 = selected;


RULE 45

IF        operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         ceramic = selected AND
        material < > grey_cast_iron AND
        m_b_hard < 275
THEN        SP_CER_CPA = selected;

RULE 46

IF        operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         ceramic = selected AND
        material < > grey_cast_iron AND
        m_b_hard > 275
THEN        SP_CER_HPC = selected;

RULE 47

IF        operation = turning OR
```

```
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         ceramic = selected AND
        material = grey_cast_iron AND
        m_b_hard < 200
THEN       SP_CER_CPA = selected;

RULE 48

IF       operation = turning OR
        operation = boring_ah OR
        operation = facing OR
        operation = boring_nah AND
         ceramic = selected AND
        material = grey_cast_iron AND
        m_b_hard > 200
THEN       SP_CER_HPC = selected;

RULE 49

IF       operation = milling AND
        hi_sp_steel = selected  AND
        hor_mill_mc = selected AND
        m_b_hard < 275
THEN       MP_HSS_M2_M7 = selected;

RULE 50

IF       operation = milling AND
        hi_sp_steel = selected  AND
        hor_mill_mc = selected AND
        m_b_hard > 275 OR
        m_r_hard < 52
THEN       MP_HSS_T15_M42 = selected;

RULE 51

IF       operation = milling AND
        carbide = selected  AND
        hor_mill_mc = selected AND
        material < > grey_cast_iron AND
        m_type < > non_ferrous AND
        m_type < > aus_ferrous AND
        m_prop < > abrasive AND
        m_b_hard < 275 OR
        m_b_hard > 275 OR
        m_r_hard < 50
THEN       MP_CR_C6_C5 = selected;

RULE 52
```

```
IF       operation = milling AND
         carbide = selected  AND
         hor_mill_mc = selected AND
         material = grey_cast_iron OR
         m_type =  non_ferrous OR
         m_type = aus_ferrous OR
         m_prop = abrasive OR
         m_r_hard > 50 AND
         material < > nickel_alloy
THEN         MP_CR_C2 = selected;

RULE 53

IF       operation = milling AND
         carbide = selected AND
         hor_mill_mc = selected AND
         material = nickel_alloy
THEN         MP_CR_C6_C5 = selected;

RULE 54

IF       operation = milling AND
         hi_sp_steel = selected  AND
         ver_mill_mc = selected OR
         nc_mill_mc = selected AND
         material < > grey_cast_iron AND
         m_b_hard < 375
THEN         MP_HSS_M2_M3_M7 = selected;

RULE 55

IF       operation = milling AND
         hi_sp_steel = selected  AND
         ver_mill_mc = selected OR
         nc_mill_mc = selected AND
         material < > grey_cast_iron AND
         m_b_hard > 375 OR
         m_r_hard < 50
THEN         MP_HSS_T15_M42 = selected;

RULE 56

IF       operation = milling AND
         hi_sp_steel = selected  AND
         ver_mill_mc = selected OR
         nc_mill_mc = selected AND
         material = grey_cast_iron AND
         m_b_hard < 250
THEN         MP_HSS_M2_M3_M7 = selected;
```

```
RULE 57

IF      operation = milling AND
        hi_sp_steel = selected  AND
        ver_mill_mc = selected OR
        nc_mill_mc = selected AND
        material = grey_cast_iron AND
        m_b_hard > 250
THEN        MP_HSS_T15_M42 = selected;

RULE 58

IF      operation = milling AND
        carbide = selected  AND
        ver_mill_mc = selected OR
        nc_mill_mc = selected AND
        material < > grey_cast_iron AND
        m_type < >  non_ferrous AND
        m_type < > aus_ferrous AND
        m_prop < > abrasive
THEN        MP_CR_C5 = selected;

RULE 59

IF      operation = milling AND
        carbide = selected  AND
        ver_mill_mc = selected OR
        nc_mill_mc = selected AND
        material = grey_cast_iron OR
        m_type = non_ferrous OR
        m_type = aus_ferrous OR
        m_prop = abrasive
THEN        MP_CR_C2 = selected;

RULE 60

IF      operation = milling AND
        ceramic = selected
THEN        MP_CER_CPA_HPC = selected;

RULE 61

IF      operation = drill&ream_ah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
        operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material < > grey_cast_iron AND
        material < > ductile_cast_iron AND
```

```
        m_b_hard < 375
THEN    TD_HSS_M10_M7_M1 = selected;

RULE 62

IF       operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material < > grey_cast_iron AND
        material < > ductile_cast_iron AND
        m_type < > non_ferrous AND
        material < > malleable_cast_iron AND
        m_b_hard < 375
THEN    RM_HSS_M1_M2_M7 = selected;

RULE 63


IF       operation = drill&ream_ah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
         operation = drilling_ah OR
        operation = drilling_nah OR
         operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material < > grey_cast_iron AND
        material < > ductile_cast_iron AND
        m_b_hard > 375
THEN    TD_HSS_T15_M42 = selected;

RULE 64


IF       operation = drill&ream_ah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
         operation = drilling_ah OR
        operation = drilling_nah OR
         operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material < > grey_cast_iron AND
        m_type < > non_ferrous AND
        material < > malleable_cast_iron AND
        material < > ductile_cast_iron AND
        m_b_hard > 375
THEN    RM_HSS_T15_M42 = selected;

RULE 65

IF       operation = drill&ream_ah OR
        operation = drill&tap_ah OR
```

```
        operation = drill&tap_nah OR
         operation = drilling_ah OR
        operation = drilling_nah OR
         operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material = grey_cast_iron OR
        material = ductile_cast_iron AND
        m_b_hard < 200
THEN       TD_HSS_M10_M7_M1 = selected;

RULE 66

IF       operation = drill&ream_ah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
         operation = drilling_ah OR
        operation = drilling_nah OR
         operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material = grey_cast_iron AND
        material = ductile_cast_iron AND
        m_b_hard > 200
THEN       TD_HSS_T15_M42 = selected;

RULE 67

IF       operation = drill&ream_ah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah OR
         operation = drilling_ah OR
        operation = drilling_nah OR
         operation = drill&ream_nah AND
        carbide = selected
THEN       TD_CR_C2 = selected;

RULE 68

IF      operation = grinding
THEN      search1 = in_process
       find sur_gr_mc
       find cyl_gr_mc
       find stock_rem;

RULE 69

IF       operation = drill&ream_ah OR
         operation = drill&ream_nah AND
        carbide = selected
THEN       RM_CR_C2 = selected;

RULE 70
```

```
IF      operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        carbide = selected
THEN    TP_CR_C2 = selected;

RULE 71

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material = grey_cast_iron OR
        material = ductile_cast_iron OR
        material = malleable_cast_iron AND
        m_type < > non_ferrous AND
        m_prop < > abrasive AND
        m_b_hard < 250
THEN    RM_HSS_M1_M2_M7 = selected;

RULE 72

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        material = grey_cast_iron OR
        material = ductile_cast_iron OR
        material = malleable_cast_iron AND
        m_type < > non_ferrous AND
        m_prop < > abrasive AND
        m_b_hard > 250
THEN    RM_HSS_T15_M42 = selected;

RULE 73

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        m_type = non_ferrous AND
        m_b_hard < 275
THEN    RM_HSS_M1_M2_M7 = selected;

RULE 74

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        m_type = non_ferrous AND
        m_b_hard > 275 OR
        m_r_hard < 52  OR
        m_prop = abrasive
THEN    RM_HSS_T15_M42 = selected;
```

```
RULE 75

IF      operation = drill&tap_ah OR
       operation = drill&tap_nah AND
       hi_sp_steel = selected AND
       material < > high_temp_alloy
THEN      TP_HSS_M10_M7_M1 = selected;

RULE 76

IF      operation = drill&tap_ah OR
       operation = drill&tap_nah AND
       hi_sp_steel = selected AND
       material = high_temp_alloy
THEN      TP_HSS_M7_M41_M44 = selected;

RULE 77

IF      operation = grinding AND
       sur_gr_mc = selected AND
       stock_rem = heavy
THEN      op_gr_wheel_hard = suitable;

RULE 78

IF      operation = grinding AND
       sur_gr_mc = selected AND
       stock_rem = light
THEN      op_gr_wheel_soft = suitable;

RULE 79

IF      operation = grinding AND
       cyl_gr_mc = selected AND
       stock_rem = heavy
THEN      op_gr_wheel_hard = suitable;

RULE 80

IF      operation = grinding AND
       cyl_gr_mc = selected AND
       stock_rem = light
THEN      op_gr_wheel_soft = suitable;

RULE 81

IF      operation = grinding AND
       op_gr_wheel_hard = suitable AND
       m_b_hard < 100
THEN      gr_wheel_hard = selected;
```

```
RULE 82

IF      operation = grinding AND
        op_gr_wheel_hard = suitable AND
        m_b_hard > 100 OR
        m_r_hard > 40
THEN    gr_wheel_med = selected;

RULE 83

IF      operation = grinding AND
        op_gr_wheel_soft = suitable AND
        m_b_hard < 100
THEN    gr_wheel_med = selected;

RULE 84

IF      operation = grinding AND
        op_gr_wheel_soft = suitable AND
        m_b_hard > 100 OR
        m_r_hard > 40
THEN    gr_wheel_soft = selected;

RULE 85

IF      operation = grinding AND
        m_type = non_ferrous
THEN    GR_abrasive = C;

RULE 86

IF      operation = grinding AND
        m_type  = ferrous
THEN    GR_abrasive = A;

RULE 87

IF      operation = grinding AND
        s_f_req = medium AND
        stock_rem = heavy
THEN    GR_grain_size = 8-24;

RULE 88

IF      operation = grinding AND
        s_f_req = medium AND
        stock_rem = light
THEN    GR_grain_size = 60-180;

RULE 89
```

```
IF      operation = grinding AND
        s_f_req = medium AND
        stock_rem = medium
THEN    GR_grain_size = 30-60;

RULE 90

IF      operation = grinding AND
        s_f_req = low AND
        stock_rem = heavy
THEN    GR_grain_size = 30-60;

RULE 91

IF      operation = grinding AND
        s_f_req = low AND
        stock_rem = medium
THEN    GR_grain_size = 70-180;

RULE 92

IF      operation = grinding AND
        s_f_req = low AND
        stock_rem = light
THEN    GR_grain_size = 220-600;

RULE 93

IF      operation = grinding AND
        sur_gr_mc = selected
THEN    GR_structure = 9-16;

RULE 94

IF      operation = grinding AND
        cyl_gr_mc = selected
THEN    GR_structure = 1-8;

RULE 95

IF      operation = threading_ext OR
        operation = threading_int_ah AND
        hi_sp_steel = selected AND
        material < > stainless_steel AND
        material < > grey_cast_iron AND
        material < > ductile_cast_iron AND
        material < > malleable_cast_iron AND
        material < > titanium_alloy AND
        material < > nickel_alloy AND
        material < > hi_temp_alloy AND
```

```
       m_b_hard < 225
THEN      thr_sp_hss_m2 = selected;

RULE 96

IF      operation = threading_ext OR
       operation = threading_int_ah AND
       hi_sp_steel = selected AND
       material < > stainless_steel AND
       material < > grey_cast_iron AND
       material < > ductile_cast_iron AND
       material < > malleable_cast_iron AND
       material < > titanium_alloy AND
       material < > nickel_alloy AND
       material < > hi_temp_alloy AND
       m_b_hard > 225 OR
       m_r_hard < 50
THEN      thr_sp_hss_t15_m42 = selected;

RULE 97

IF      operation = threading_ext OR
       operation = threading_int_ah AND
       hi_sp_steel = selected AND
       material = stainless_steel OR
       material = grey_cast_iron OR
       material = ductile_cast_iron OR
       material = malleable_cast_iron OR
       material = titanium_alloy OR
       material = nickel_alloy OR
       material = hi_temp_alloy
THEN      thr_sp_hss_t15_m42 = selected;

RULE 98

IF      operation = threading_ext OR
       operation = threading_int_ah AND
       carbide = selected AND
       material < > grey_cast_iron AND
       m_type < > non_ferrous AND
       m_b_hard < 375
THEN      thr_sp_cr_c6 = selected;

RULE 99

IF      operation = threading_ext OR
       operation = threading_int_ah AND
       carbide = selected AND
       material < > grey_cast_iron AND
       m_type < > non_ferrous AND
       m_b_hard > 375 OR
```

```
       m_r_hard < 60
THEN     thr_sp_cr_c2 = selected;

RULE 100

IF       operation = threading_ext OR
       operation = threading_int_ah AND
       carbide = selected AND
       material = grey_cast_iron OR
       m_type = non_ferrous AND
       material < > nickel_alloy
THEN     thr_sp_cr_c2 = selected;

RULE 101

IF       operation = threading_ext OR
       operation = threading_int_ah AND
       carbide = selected AND
       material = nickel_alloy
THEN     thr_sp_cr_c6 = selected;

PLURAL : hss_carbide, hi_sp_steel, carbide;

PLURAL : ceramic, diamond;

PLURAL : engine_lathe, turret_lathe, single_sp_auto;

PLURAL : nc_lathe, ver_mill_mc, hor_mill_mc, ver_dr_pr;

PLURAL : rad_dr_mc, turr_dr_mc, hor_bor_mc, sur_gr_mc;

PLURAL : cyl_gr_mc, hor&ver_mill_mc, nc_mill_mc,search3;

PLURAL : search1, m_type,m_prop,m_struct;

        PLURAL :    search4;
        PLURAL :    search5;
        PLURAL :    sp_hss_m2_m3;
        PLURAL :    sp_hss_t15_m42;
        PLURAL :    sp_cr_c7_c6;
        PLURAL :    sp_cr_c8_c7_c6;
        PLURAL :    sp_cr_c8;
        PLURAL :    sp_cr_c3_c2;
        PLURAL :    sp_cr_c4;
        PLURAL :    sp_cer_cpa;
        PLURAL :    sp_cer_hpc;
        PLURAL :    mp_hss_m2_m7;
        PLURAL :    mp_hss_t15_m42;
        PLURAL :    mp_hss_m2_m3_m7;
        PLURAL :    mp_cr_c6_c5;
        PLURAL :    mp_cr_c2;
```

```
          PLURAL :   mp_cr_c5;
          PLURAL :   mp_cer_cpa_hpc;
          PLURAL :   td_hss_m10_m7_m1;
          PLURAL :   td_hss_t15_m42;
          PLURAL :   td_cr_c2;
          PLURAL :   td_hss_m10_m7_m1;
          PLURAL :   td_hss_t15_m42;
          PLURAL :   rm_hss_m1_m2_m7;
          PLURAL :   rm_hss_t15_m42;
          PLURAL :   td_cr_c2;
          PLURAL :   rm_cr_c2;
          PLURAL :   td_hss_m10_m7_m1;
          PLURAL :   td_hss_t15_m42;
          PLURAL :   tp_hss_m10_m7_m1;
          PLURAL :   tp_hss_m7_m41_m44;
          PLURAL :   td_cr_c2;
          PLURAL :   tp_cr_c2;
          PLURAL :   op_gr_wheel_hard;
          PLURAL :   op_gr_wheel_soft;
          PLURAL :   gr_wheel_hard;
          PLURAL :   gr_wheel_soft;
          PLURAL :   gr_wheel_med;
          PLURAL :   gr_abrasive;
          PLURAL :   gr_grain_size;
          PLURAL :   gr_structure;
          PLURAL :   thr_sp_hss_m2;
          PLURAL :   thr_sp_hss_t15_m42;
          PLURAL :   thr_sp_cr_c6;
          PLURAL :   thr_sp_cr_c2;
          PLURAL :   ver_mill_mc, nc_mill_mc, hor_mill_mc;

ASK operation : "Name the operation to be performed";

CHOICES operation : turning,facing,boring_ah,boring_nah,
threading_ext, threading_int_ah, milling,
drilling_ah,drilling_nah,drill&ream_ah,
drill&ream_nah, drill&tap_ah,drill&tap_nah,
grinding;

ASK m_b_hard : "What is the brinell hardness of the work-material?";

ASK m_r_hard : "What is the rockwell hardness of the work-material?";

ASK material : "What is the work-material?";

ASK m_type : "Name the work-material type";

CHOICES m_type : non_metallic,ferrous,non_ferrous,
non_aus_ferrous,aus_ferrous,hard_ferrous,
n_fr_mach_ferrous;
```

```
ASK m_prop : "Name any of the properties below, which the work-material
may have ";

CHOICES m_prop : hi_yield_str,highly_abrasive,tough;

ASK s_f_req : "Describe the nature of the surface finish required";

CHOICES s_f_req : low,high,medium;

ASK m_cond : "What is the heat treated condition of the material?";

CHOICES m_cond : normalized,as_forged,annealed,q&temp,sintered,
hot_rolled,as_cast,aged;

ASK m_struct : "Describe the metallurgical structure of the material
surface";

CHOICES m_struct : hi_elastic,lo_elastic,plated,fibrous;

ASK ver_mill_mc : "Was the vertical milling machine selected for this
operation?";

ASK hor_mill_mc : "Was the horizontal milling machine selected for this
operation?";

ASK nc_mill_mc : "Was the numerical control milling machine selected for
this operation?";

CHOICES ver_mill_mc,hor_mill_mc,nc_mill_mc : selected, not_selected;

ASK stock_rem : "What is the nature of stock removal for the grinding
operation?";

CHOICES stock_rem : light,medium,heavy;

ASK sur_gr_mc : "Was the surface grinding machine selected for the
operation?";

ASK cyl_gr_mc : "Was the cylindrical grinding machine selected for
the opration?";

CHOICES sur_gr_mc,cyl_gr_mc : selected, not_selected;
```

APPENDIX D

EXPERT SYSTEM FOR THE SELECTION OF CUTTING FLUIDS

```
ENDOFF;

ACTIONS
        find operation
        DISPLAY "Input the name of the material without any blank
        spaces."
        DISPLAY "Use _ to connect words, and use singular form."
        find material
        find m_type
        find m_prop
        DISPLAY "Input EITHER the Brinell or Rockwell hardness values.
        If one is known, type a ? for the other"
        find m_b_hard
        find m_r_hard
        find tool_chip_fr
        find thermal_shock
        find cutting_fluid
        find heat_generation
        find cutting_forces
        find cut_fluid
        find search1;

RULE 1

IF      operation < > grinding
THEN       search1 = in_process
        find hi_sp_steel
        find carbide
        find ceramic;

RULE 2

IF      operation = grinding
THEN       search1 = in_process
        find gr_wheel_soft
```

```
        find gr_wheel_med
        find gr_wheel_hard;

RULE 3

IF       operation = turning OR
         operation = facing OR
         operation = threading_int_ah OR
         operation = threading_ext OR
         operation = boring_ah OR
         operation = boring_nah OR
         operation = milling AND
         hi_sp_steel = selected
THEN        tool_chip_fr = high;

RULE 4

IF       operation = turning OR
         operation = facing OR
         operation = threading_int_ah OR
         operation = threading_ext OR
         operation = boring_ah OR
         operation = boring_nah OR
         operation = milling AND
         carbide = selected
THEN        thermal_shock = problem;

RULE 5

IF       operation = turning OR
         operation = facing OR
         operation = threading_int_ah OR
         operation = threading_ext OR
         operation = boring_ah OR
         operation = boring_nah OR
         operation = milling AND
         ceramic = selected
THEN        cutting_fluid = unnecessary;

RULE 6

IF       operation = turning OR
         operation = facing OR
         operation = drilling_ah OR
         operation = drilling_nah OR
         operation = drill&ream_ah OR
         operation = drill&ream_nah OR
         operation = boring_ah OR
         operation = boring_nah OR
         operation = milling AND
```

```
        diamond = selected
THEN    heat_generation = high;

RULE 7

IF      operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        hi_sp_steel = selected OR
        carbide = selected
THEN    cutting_forces = severe;

RULE 8

IF      operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        ceramic = selected
THEN    cutting_fluid = unnecessary;

RULE 9

IF      cutting_fluid = unnecessary
THEN    cut_fluid = dry_cutting;

RULE 10

IF      heat_generation = high AND
        material = magnesium_alloy
THEN    cut_fluid = synthetic_fluid_LD;

RULE 11

IF      operation = grinding AND
        gr_wheel_soft = selected
THEN    cut_fluid = w_sol_oil_HD;

RULE 12

IF      operation = grinding AND
        gr_wheel_hard = selected
THEN    cut_fluid = w_sol_oil_LMD;

RULE 13
```

```
IF      operation = grinding AND
        gr_wheel_med = selected
THEN       cut_fluid = water_sol_oil_HD;

RULE 14

IF      tool_chip_fr = high AND
        m_b_hard < 275
THEN       cut_fluid = st_cutting_oil_LMD;

RULE 15

IF      tool_chip_fr = high AND
        m_r_hard < 65 OR
        m_b_hard > 275
THEN       cut_fluid = synthetic_fluid_HD;

RULE 16

IF      thermal_shock = problem AND
        material = magnesium_alloy
THEN       cut_fluid = synthetic_fluid_LD;

RULE 17

IF      thermal_shock = problem AND
        operation = milling AND
        m_type = hard_ferrous
THEN       cut_fluid = dry_cutting;

RULE 18

IF      thermal_shock = problem AND
        material = copper_alloy OR
        material = aluminium_alloy OR
        material = zinc_alloy
THEN       cut_fluid = synthetic_oil_L_NS
        cut_fluid = w_sol_oil_LD_NS;

RULE 19

IF      thermal_shock = problem AND
        operation < > milling AND
        material < > magnesium_alloy AND
        material < > aluminium_alloy AND
        material < > zinc_alloy AND
        material < > copper_alloy AND
        m_b_hard < 275
THEN       cut_fluid = w_sol_oil_LMD;

RULE 20
```

```
IF      thermal_shock = problem AND
        operation < > milling AND
        m_r_hard < 65 OR
        m_b_hard > 275
THEN    cut_fluid = w_sol_oil_HD;

RULE 21

IF      cutting_forces = severe AND
        material = copper_alloy OR
        material = aluminium_alloy OR
        material = zinc_alloy
THEN    cut_fluid = synthetic_fluid_L_NS
        cut_fluid = w_sol_oil_NS;

RULE 22

IF      cutting_forces = severe AND
        operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        m_type = non_ferrous AND
        m_prop = abrasive
THEN    cut_fluid = air_blast;

RULE 23

IF      cutting_forces = severe AND
        material < > plastic AND
        material < > copper_alloy AND
        material < > aluminium_alloy AND
        material < > zinc_alloy AND
        material < > magnesium_alloy AND
        m_prop < > abrasive AND
        m_b_hard < 275
THEN    cut_fluid = w_sol_oil_LMD;

RULE 24

IF      cutting_forces = severe AND
        material < > plastic AND
        m_prop < > abrasive AND
        m_r_hard < 65 OR
        m_b_hard > 275
THEN    cut_fluid = w_sol_oil_HD;

RULE 25
```

```
IF      heat_generation = high AND
        material < > copper_alloy AND
        material < > aluminium_alloy AND
        material < > zinc_alloy AND
        material < > magnesium_alloy
THEN    cut_fluid = w_sol_oil_LD;

RULE 26

IF      heat_generation = high AND
        material = copper_alloy OR
        material = aluminium_alloy OR
        material = zinc_alloy
THEN    cut_fluid = synthetic_fluid_L_NS
        cut_fluid = w_sol_oil_LD_NS;

PLURAL : search1, m_type,m_prop,m_struct;

PLURAL : cut_fluid;

PLURAL : hss_carbide, hi_sp_steel, carbide;

PLURAL : ceramic, diamond;

ASK operation : "Name the operation to be performed";

CHOICES operation : turning,facing,boring_ah,boring_nah,
threading_ext, threading_int_ah, milling,
drilling_ah,drilling_nah,drill&ream_ah,
drill&ream_nah, drill&tap_ah,drill&tap_nah,
grinding;

ASK m_b_hard : "What is the brinell hardness of the work-material?";

ASK m_r_hard : "What is the rockwell hardness of the work-material?";

ASK material : "What is the work-material?";

ASK m_type : "Name the work-material type";

CHOICES m_type : non_metallic,ferrous,non_ferrous,
non_aus_ferrous,aus_ferrous,hard_ferrous,
n_fr_mach_ferrous;

ASK m_prop : "Name any of the properties below, which the work-material
may have ";

CHOICES m_prop : hi_yield_str,highly_abrasive,tough;
```

```
ASK hi_sp_steel : "Was high speed steel chosen as the tool material
for the operation?";

ASK carbide : "Was carbide chosen as the tool material
for the operation?";

ASK ceramic : "Was ceramic chosen as the tool material
for the operation?";

ASK gr_wheel_soft : "Was a soft grinding wheel selected?";

ASK gr_wheel_med : "Was a medium grinding wheel selected?";

ASK gr_wheel_hard : "Was a hard grinding wheel selected?";

CHOICES hi_sp_steel,carbide,ceramic,gr_wheel_med,gr_wheel_hard,
gr_wheel_soft : selected, not_selected;
```

APPENDIX E

EXPERT SYSTEM FOR THE SPECIFICATION OF TOOL ANGLES

```
ENDOFF;

ACTIONS
        find operation
        DISPLAY "Input the name of the material without any blank
        spaces."
        DISPLAY "Use _ to connect words, and use singular form."
        find material
        find m_type
        find m_prop
        DISPLAY "Input EITHER the Brinell or Rockwell hardness values.
        If one is known, type a ? for the other"
        find m_b_hard
        find m_r_hard
        find hi_sp_steel
        find carbide
        find search6;

RULE 1

IF        operation = turning OR
         operation = facing OR
         operation = boring_ah AND
         hi_sp_steel = selected
THEN        search6 = in_process
         find t_hss_tool_life
         find t_hss_ther_eff
         find t_hss_cutting_edge
         find t_hss_surface_finish;

RULE 2

IF        operation = turning OR
         operation = facing OR
         operation = boring_ah AND
```

```
        hi_sp_steel = selected
THEN        search6 = in_process
        find t_hss_bra
        find t_hss_sra
        find t_hss_ela
        find t_hss_sla;

RULE 3

IF       operation = turning OR
        operation = facing OR
        operation = boring_ah AND
        carbide = selected
THEN        search6 = in_process
        find t_cr_tool_life
        find t_cr_cutting_edge
        find t_cr_surface_finish;

RULE 4

IF       operation = turning OR
        operation = facing OR
        operation = boring_ah AND
        carbide = selected
THEN        search6 = in_process
        find t_cr_bra
        find t_cr_sra
        find t_cr_ra;

RULE 5

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        hi_sp_steel = selected
THEN        search6 = in_process
        find thr_hss_tool_life
        find thr_hss_ther_eff
        find thr_hss_cutting_edge;

RULE 6

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        hi_sp_steel = selected
THEN        search6 = in_process
        find thr_hss_bra
        find thr_hss_sra
        find thr_hss_ra;

RULE 7
```

```
IF       operation = threading_ext OR
        operation = threading_int_ah AND
        carbide = selected
THEN        search6 = in_process
        find thr_cr_tool_life
        find thr_cr_cutting_edge;

RULE 8

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        carbide = selected
THEN        search6 = in_process
        find thr_cr_bra
        find thr_cr_sra;

RULE 9

IF       operation = milling AND
        cutter = face_mill AND
        hi_sp_steel = selected
THEN        search6 = in_process
        find fm_hss_ara
        find fm_hss_rra
        find fm_hss_ala
        find fm_hss_ca
        find fm_hss_eca
        find fm_hss_rla;

RULE 10

IF       operation = milling AND
        cutter = face_mill AND
        carbide = selected
THEN        search6 = in_process
        find fm_cr_ara
        find fm_cr_rra
        find fm_cr_ala
        find fm_cr_ca
        find fm_cr_eca
        find fm_cr_rla;

RULE 11

IF       operation = milling AND
        cutter = side_mill AND
        hi_sp_steel = selected
THEN        search6 = in_process
        find sm_hss_ara
        find sm_hss_rra
        find sm_hss_ala
```

```
        find sm_hss_rla;

RULE 12

IF       operation = milling AND
         cutter = side_mill AND
         carbide = selected
THEN       search6 = in_process
         find sm_cr_ara
         find sm_cr_rra
         find sm_cr_ala
         find sm_cr_rla;

RULE 13

IF       operation = milling AND
         cutter = end_mill
THEN       search6 = in_process
         find em_ha
         find em_rpra
         find em_plw
         find em_rsca;

RULE 14

IF       operation = drilling_ah OR
         operation = drilling_nah
THEN       search6 = in_process
         find td_pa
         find td_laid
         find td_ha;

RULE 15

IF       operation = drill&ream_ah OR
         operation = drill&ream_nah AND
         cutter = reamer AND
         hi_sp_steel = selected
THEN       search6 = in_process
         find rm_hss_mw
         find rm_hss_prra
         find rm_hss_ca
         find rm_hss_cra
         find td_pa
         find td_laid
         find td_ha;

RULE 16

IF       operation = drill&ream_ah OR
         operation = drill&ream_nah AND
```

```
        cutter = reamer AND
        carbide = selected
THEN       search6 = in_process
        find rm_cr_m
        find rm_cr_prra
        find rm_cr_sca
        find rm_cr_loc
        find rm_cr_cpra
        find rm_cr_csca
        find td_pa
        find td_laid
        find td_ha;


RULE 17

IF       operation = boring_ah OR
        operation = boring_nah AND
        ceramic = selected
THEN       search6 = in_process
        find br_cer_ara
        find br_cer_rra
        find br_cer_ela
        find br_cer_sla;

RULE 18

IF       operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        cutter = tap
THEN       search6 = in_process
        find tp_ha
        find tp_cla
        find td_pa
        find td_laid
        find td_ha;

RULE 19

IF       operation = turning OR
        operation = facing OR
        operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        m_b_hard < 325 OR
        m_r_hard < 40 AND
        m_type < > n_fr_mach_ferrous AND
        material < > hi_temp_alloy AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > refractory_alloy AND
```

```
        material < > titanium_alloy AND
        material < > plastic
THEN        t_hss_bra = low_positive
        t_hss_sra = low_positive
        t_hss_bra = 5-10
        t_hss_sra = 8-12;

RULE 20

IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy
THEN        t_hss_ther_eff = important;

RULE 21

IF       t_hss_ther_eff = important
THEN        t_hss_bra = high_positive
        t_hss_sra = high_positive
        t_hss_bra = 15-20
        t_hss_sra = 10-15;

RULE 22

IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        m_type = n_fr_mach_ferrous OR
        material = high_temp_alloy OR
        material = titanium_alloy OR
        material = refractory_alloy OR
        material = plastic
THEN        t_hss_tool_life = very_important;

RULE 23

IF       t_hss_tool_life = very_important
THEN        t_hss_bra = very_low_positive
        t_hss_bra = zero
        t_hss_sra = low_positive
        t_hss_bra = 0
        t_hss_sra = 5-10;

RULE 24
```

```
IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        m_b_hard < 325 OR
        m_r_hard < 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > nickel_alloy AND
        material < > zinc_alloy AND
        material < > zirconium_alloy AND
        material < > plastic
THEN       t_hss_cutting_edge = weakened
        t_hss_ela = 10-13
        t_hss_sla = 10-13;

RULE 25

IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        m_b_hard > 325 OR
        m_r_hard > 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > nickel_alloy AND
        material < > zinc_alloy AND
        material < > zirconium_alloy AND
        material < > plastic
THEN       t_hss_cutting_edge = weakened;

RULE 26

IF       t_hss_cutting_edge = weakened
THEN       t_hss_ela = low_positive
        t_hss_sla = low_positive
        t_hss_ela = 5-8
        t_hss_sla = 5-8;

RULE 27

IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        material = zinc_alloy
THEN       t_hss_cutting_edge = weakened
```

```
        t_hss_sla = low_positive
        t_hss_sla = 4-6;
```

RULE 28

```
IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy OR
        material = nickel_alloy OR
        material = zinc_alloy OR
        material = zirconium_alloy
THEN       t_hss_surface_finish = to_be_controlled
        t_hss_ela = high_positive
        t_hss_sla = high_positive
        t_hss_ela = 10-14
        t_hss_sla = 10-14;
```

RULE 29

```
IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        hi_sp_steel = selected AND
        material = plastic
THEN       t_hss_surface_finish = to_be_controlled
        t_hss_ela = very_high_positive
        t_hss_sla = very_high_positive
        t_hss_ela = 20-30
        t_hss_sla = 15-20;
```

RULE 30

```
IF       operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        carbide = selected AND
        m_b_hard < 325 OR
        m_r_hard < 40 OR
        material = plastic
THEN       t_cr_tool_life = important;
```

RULE 31

```
IF      t_cr_tool_life = important AND
```

```
        material < > plastic
THEN       t_cr_bra = low_positive
        t_cr_sra = low_positive
        t_cr_bra = 0-5
        t_cr_sra = 5-10;

RULE 32

IF        t_cr_tool_life = important AND
        material = plastic
THEN       t_cr_bra = zero
        t_cr_sra = high_positive
        t_cr_bra = 0
        t_cr_sra = 10-15;

RULE 33

IF        operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        carbide = selected AND
        m_b_hard > 325 OR
        m_r_hard > 40 AND
        material < > plastic
THEN       t_cr_tool_life = very_important;

RULE 34

IF        t_cr_tool_life = very_important
THEN       t_cr_bra = low_positive
        t_cr_bra = negative
        t_cr_sra = low_positive
        t_cr_bra = -5-0
        t_cr_sra = 0-5;

RULE 35

IF        operation = turning OR
        operation = facing OR
         operation = boring_ah OR
        operation = boring_nah AND
        carbide = selected AND
        material < > plastic
THEN       t_cr_cutting_edge = weakened
        t_cr_ra = 5-7;

RULE 36

IF        operation = turning OR
        operation = facing OR
```

```
         operation = boring_ah OR
        operation = boring_nah AND
        carbide = selected AND
        material = plastic
THEN     t_cr_surface_finish = to_be_controlled
        t_cr_ra = 20-30;

RULE 37

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        hi_sp_steel = selected AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        m_b_hard < 325 OR
        m_r_hard < 40
THEN     thr_hss_tool_life = important;

RULE 38

IF       thr_hss_tool_life = important AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy
THEN     thr_hss_bra = low_positive
        thr_hss_sra = low_positive
        thr_hss_bra = 5-15
        thr_hss_sra = 5-15;

RULE 39

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        hi_sp_steel = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy
THEN     thr_hss_ther_eff = important
        thr_hss_bra = high_positive
        thr_hss_sra = low_positive
        thr_hss_bra = 20-30
        thr_hss_sra = 10-15;

RULE 40

IF       operation = threading_ext OR
        operation = threading_int_ah AND
        hi_sp_steel = selected
THEN     thr_hss_cutting_edge = weakened
        thr_hss_ra = 5-15;

RULE 41
```

```
IF      operation = milling AND
        cutter = face_mill AND
        hi_sp_steel = selected AND
        m_b_hard < 325 OR
        m_r_hard < 40 AND
        material < > cast_iron AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > nickel_alloy AND
        material < > refractory_alloy
THEN    fm_hss_ara = 10-15
        fm_hss_rra = 10-15;

RULE 42

IF      operation = milling AND
        cutter = face_mill AND
        hi_sp_steel = selected AND
        m_b_hard > 325 OR
        m_r_hard > 40 AND
        material < > cast_iron OR
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > nickel_alloy AND
        material < > refractory_alloy
THEN    fm_hss_ara = 5-10
        fm_hss_rra = 5-10;

RULE 43

IF      operation = milling AND
        cutter = face_mill AND
        hi_sp_steel = selected AND
        material = nickel_alloy
THEN    fm_hss_ara = 7-10
        fm_hss_rra = 15-17;

RULE 44

IF      operation = milling AND
        cutter = face_mill AND
        hi_sp_steel = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy
THEN    fm_hss_ara = 20-35
        fm_hss_rra = 20-35;

RULE 45

IF      operation = milling AND
        cutter = face_mill AND
```

```
        hi_sp_steel = selected AND
        material = refractory_alloy
THEN        fm_hss_ara = 0-2
        fm_hss_rra = 20-22;

RULE 46

IF          operation = milling AND
        cutter = face_mill AND
        hi_sp_steel = selected AND
        material = cast_iron
THEN        fm_hss_ara = 20-30
        fm_hss_rra = -5to-10;

RULE 47

IF          operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        m_b_hard < 325 OR
        m_r_hard < 40 AND
        m_type < > ferrous AND
        material < > titanium_alloy OR
        material < > hi_temp_alloy OR
        material < > tungsten_alloy
THEN        fm_cr_ara = 5-11;

RULE 48

IF          operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        m_b_hard > 325 OR
        m_r_hard > 40 AND
        m_type < > ferrous AND
        material < > titanium_alloy OR
        material < > hi_temp_alloy OR
        material < > tungsten_alloy
THEN        fm_cr_ara = 3-7;


RULE 49

IF          operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = titanium_alloy
THEN        fm_cr_ara = 0to-5;

RULE 50
```

```
IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = hi_temp_alloy
THEN     fm_cr_ara = 0-5;


RULE 51

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = tungsten_alloy
THEN     fm_cr_ara = -4to-8;

RULE 52

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        m_b_hard < 325 OR
        m_r_hard < 40 AND
        material < > aluminium_alloy AND
        material < > titanium_alloy AND
        material < > magnesium_alloy AND
        material < > copper_alloy AND
        material < > zinc_alloy AND
        material < > tungsten_alloy
THEN     fm_cr_rra = -5to-14;

RULE 53

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        m_b_hard > 325 OR
        m_r_hard > 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > copper_alloy AND
        material < > titanium_alloy AND
        material < > zinc_alloy AND
        material < > tungsten_alloy
THEN     fm_cr_rra = -3to-11;

RULE 54

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = aluminium_alloy OR
```

```
        material = zinc_alloy OR
        material = magnesium_alloy
THEN      fm_cr_rra = 0-5;


RULE 55

IF        operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = titanium_alloy
THEN      fm_cr_rra = 0to-5;

RULE 56

IF        operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = copper_alloy
THEN      fm_cr_rra = 0-5;

RULE 57

IF        operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = hi_temp_alloy
THEN      fm_cr_rra = 0to-5;


RULE 58

IF        operation = milling AND
        cutter = face_mill AND
        carbide = selected AND
        material = tungsten_alloy
THEN      fm_cr_rra = -3to-11;


RULE 59

IF        operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected
THEN      fm_cr_ca = 30-45
        fm_hss_ca = 30-45;

RULE 60

IF        operation = milling AND
```

```
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        m_b_hardness < 325 OR
        m_r_hardness < 40 AND
        material < > aluminium_alloy AND
        material < > titanium_alloy AND
        material < > zinc_alloy AND
        material < > magnesium_alloy AND
        material < > copper_alloy
THEN        fm_hss_eca = 5-10
        fm_cr_eca = 5-10;

RULE 61

IF          operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        m_b_hardness > 325 OR
        m_r_hardness < 60 AND
        material < > aluminium_alloy AND
        material < > titanium_alloy AND
        material < > zinc_alloy AND
        material < > magnesium_alloy AND
        material < > copper_alloy
THEN        fm_cr_eca = 4-7
        fm_hss_eca = 4-7;

RULE 62

IF          operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material =  aluminium_alloy OR
        material =  titanium_alloy OR
        material =  zinc_alloy OR
        material =  magnesium_alloy OR
        material =  copper_alloy
THEN        fm_cr_eca = 7-12
        fm_hss_eca = 7-12;

RULE 63

IF          operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material < > aluminium_alloy AND
        material < > copper_alloy AND
```

```
        material < > magnesium_alloy AND
        material < > tungsten_alloy
THEN    fm_cr_ala = 5-11
        fm_hss_ala = 5-11;

RULE 64

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material = aluminium_alloy OR
        material = copper_alloy OR
        material = magnesium_alloy
THEN    fm_cr_ala = 3-5
        fm_hss_ala = 3-5;

RULE 65

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material = tungsten_alloy
THEN    fm_cr_ala = 15-17
        fm_hss_ala = 15-17;


RULE 66

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material < > aluminium_alloy AND
        material < > titanium_alloy  AND
        material < > magnesium_alloy
THEN    fm_cr_rla = 3-9
        fm_hss_rla = 3-9;

RULE 67

IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy OR
        material = titanium_alloy
THEN    fm_cr_rla = 10-12
        fm_hss_rla = 10-12;
```

RULE 68

```
IF      operation = milling AND
        cutter = face_mill AND
        carbide = selected OR
        hi_sp_steel = selected AND
        material = tungsten_alloy
THEN      fm_cr_rla = 15-17
        fm_hss_rla = 15-17;
```

RULE 69

```
IF      operation = milling AND
        cutter = side_mill AND
        hi_sp_steel = selected AND
        m_b_hardness < 325 OR
        m_r_hardness < 40 AND
        material < > aluminium_alloy AND
        material < > refractory_alloy AND
        material < > magnesium_alloy AND
        material < > zinc_alloy
THEN      sm_hss_ara = 10-15
        sm_hss_rra = 10-15
        sm_hss_ala = 3-5
        sm_hss_rla = 4-8;
```

RULE 70

```
IF      operation = milling AND
        cutter = side_mill AND
        hi_sp_steel = selected AND
        m_b_hardness > 325 OR
        m_r_hardness > 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > refractory_alloy AND
        material < > zinc_alloy
THEN      sm_hss_ara = 8-13
        sm_hss_rra = 5-10
        sm_hss_ala = 1-4
        sm_hss_rla = 3-7;
```

RULE 71

```
IF      operation = milling AND
        cutter = side_mill AND
        carbide = selected AND
        m_b_hardness < 325 OR
```

```
        m_r_hardness < 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > refractory_alloy AND
        material < > zinc_alloy
THEN       sm_cr_ara = 0to-5
        sm_cr_rra = -5to5
        sm_cr_ala = 2-4
        sm_cr_rla = 5-8;

RULE 72

IF        operation = milling AND
        cutter = side_mill AND
        carbide = selected AND
        m_b_hardness > 325 OR
        m_r_hardness > 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > refractory_alloy AND
        material < > zinc_alloy
THEN       sm_cr_ara = -5to-10
        sm_cr_rra = 0to-10
        sm_cr_ala = -3to4
        sm_cr_rla = 0-5;


RULE 73

IF        operation = milling AND
        cutter = side_mill AND
        carbide = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy OR
        material = zinc_alloy
THEN       sm_cr_ara = 10-20
        sm_cr_rra = 5-15
        sm_cr_ala = 5-7
        sm_cr_rla = 7-10;

RULE 74

IF        operation = milling AND
        cutter = side_mill AND
        carbide = selected AND
        material = refractory_alloy
THEN       sm_cr_ara = 0-2
        sm_cr_rra = 5-15
        sm_cr_ala = 7-10
        sm_cr_rla = 7-10;
```

RULE 75

```
IF      operation = milling AND
        cutter = end_mill AND
        cutter_dia > .0625 AND
        cutter_dia < .3125 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy
THEN    em_ha = 30-35
        em_rpra = 10-20
        em_plw = .007-.025
        em_rsca = 20-32;
```

RULE 76

```
IF      operation = milling AND
        cutter = end_mill AND
        cutter_dia > .3125 AND
        cutter_dia < .75   AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy
THEN    em_ha = 30-35
        em_rpra = 8-11
        em_plw = .025-.04
        em_rsca = 15-20;
```

RULE 77

```
IF      operation = milling AND
        cutter = end_mill AND
        cutter_dia > .75 AND
        cutter_dia < 2 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy
THEN    em_ha = 30-35
        em_rpra = 6-9
        em_plw = .04-.06
        em_rsca = 9-15;
```

RULE 78

```
IF      operation = milling AND
        cutter = end_mill AND
        cutter_dia > .0625 AND
        cutter_dia < .3125 AND
        material = aluminium_alloy OR
        material = magnesium_alloy
THEN    em_ha = 35-45
        em_rpra = 12-20
        em_plw = .007-.025
        em_rsca = 19-30;
```

RULE 79

```
IF      operation = milling AND
        cutter = end_mill AND
        cutter_dia > .3125 AND
        cutter_dia < .75   AND
        material = aluminium_alloy OR
        material = magnesium_alloy
THEN    em_ha = 30-35
        em_rpra = 10-12
        em_plw = .025-.04
        em_rsca = 17-25;
```

RULE 80

```
IF      operation = milling AND
        cutter = end_mill AND
        cutter_dia > .75 AND
        cutter_dia < 2 AND
        material = aluminium_alloy OR
        material = magnesium_alloy
THEN    em_ha = 30-35
        em_rpra = 8-12
        em_plw = .025-.04
        em_rsca = 12-24;
```

RULE 81

```
IF      operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        m_b_hard < 325 OR
        m_r_hard < 40 AND
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > plastic
THEN    td_pa = 118
        td_laid = 8-16
        td_ha = std_low;
```

RULE 82

```
IF      operation = drilling_ah OR
        operation = drilling_nah OR
        operation = drill&ream_ah OR
        operation = drill&ream_nah OR
        operation = drill&tap_ah OR
```

```
          operation = drill&tap_nah AND
           m_b_hard > 325 OR
          m_r_hard > 40 AND
          material < > aluminium_alloy AND
          material < > magnesium_alloy AND
          material < > plastic
THEN      td_pa = 118-135
          td_laid = 8-16
          td_ha = std_low;

RULE 83

IF         operation = drilling_ah OR
          operation = drilling_nah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah OR
          operation = drill&tap_ah OR
          operation = drill&tap_nah AND
           material = aluminium_alloy AND
          material = magnesium_alloy
THEN      td_pa = 70-118
          td_laid = 12-20
          td_ha = high;

RULE 84
IF         operation = drilling_ah OR
          operation = drilling_nah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah OR
          operation = drill&tap_ah OR
          operation = drill&tap_nah AND
           material = aluminium_alloy AND
          material = magnesium_alloy
THEN      td_pa = 70-118
          td_laid = 12-20
          td_ha = high;

RULE 85

IF         operation = drilling_ah OR
          operation = drill&ream_ah OR
          operation = drill&ream_nah OR
          operation = drill&tap_ah OR
          operation = drill&tap_nah OR
           operation = drilling_nah AND
          material = plastic
THEN      td_pa = 60-90
          td_laid = 12-20
          td_ha = low;

RULE 86
```

```
IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        cutter = reamer AND
        hi_sp_steel = selected AND
        cutter_dia < .5
THEN        rm_hss_mw = .004-.015
        rm_hss_prra = 8-20
        rm_hss_ca = 45
        rm_hss_cla = 7-12;

RULE 87

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        hi_sp_steel = selected AND
        cutter = reamer AND
        cutter_dia > .5
THEN        rm_hss_mw = .012-.017
        rm_hss_prra = 5-10
        rm_hss_ca = 45
        rm_hss_cla = 7-12;

RULE 88

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        carbide = selected AND
        cutter = reamer AND
        cutter_dia < .75
THEN        rm_cr_m = .005-.015
        rm_cr_prra = 9-15
        rm_cr_sca = 20-32
        rm_cr_loc = .02-.05
        rm_cr_prra = 7-12
        rm_cr_csca = 14-27;

RULE 89

IF      operation = drill&ream_ah OR
        operation = drill&ream_nah AND
        carbide = selected AND
        cutter = reamer AND
        cutter_dia > .75
THEN        rm_cr_m = .015-.023
        rm_cr_prra = 7-10
        rm_cr_sca = 16-22
        rm_cr_loc = .04-.06
        rm_cr_cpra = 6-10
        rm_cr_csca = 12-18;
```

```
RULE 90

IF      operation = boring_ah OR
        operation = boring_nah AND
        hor_bor_mc = selected AND
        m_b_hard < 325 AND
        m_r_hard < 40 AND
        material < > stainless_steel AND
        material < > cast_iron AND
        material < > aluminium_alloy AND
        material < > copper_alloy AND
        material < > hi_temp_alloy AND
        material < > nickel_alloy AND
        material < > zinc_alloy AND
        material < > refractory_alloy
THEN    br_cr_rra = -3to-10
        br_cr_ara = 0-15
        br_cr_era = 5-10
        br_cr_sla = 2-3;

RULE 91

IF      operation = boring_ah OR
        operation = boring_nah AND
        hor_bor_mc = selected AND
        m_b_hard > 325 AND
        m_r_hard > 40 AND
        material < > stainless_steel AND
        material < > cast_iron AND
        material < > aluminium_alloy AND
        material < > copper_alloy AND
        material < > hi_temp_alloy AND
        material < > nickel_alloy AND
        material < > zinc_alloy AND
        material < > refractory_alloy
THEN    br_cr_rra = 0to-6
        br_cr_ara = -5to10
        br_cr_ela = 5-10
        br_cr_sla = 2-3;

RULE 92

IF      operation = boring_ah OR
        operation = boring_nah AND
        hor_bor_mc = selected AND
        material = aluminium_alloy OR
        material = magnesium_alloy OR
        material = zinc_alloy
THEN    br_cr_rra = 0-15
        br_cr_ara = 5-15
        br_cr_ela = 8-15
```

```
       br_cr_sla = 5-8;

RULE 93


IF      operation = boring_ah OR
       operation = boring_nah AND
       hor_bor_mc = selected AND
       material = stainless_steel OR
       material = nickel_alloy OR
       material = hi_temp_alloy
THEN    br_cr_rra = 3-10
       br_cr_ara = 0-15
       br_cr_ela = 5-10
       br_cr_sla = 2-3;


RULE 94

IF      operation = boring_ah OR
       operation = boring_nah AND
       hor_bor_mc = selected AND
       material = refractory_alloy
THEN    br_cr_rra = 0-2
       br_cr_ara = 20-22
       br_cr_ela = 8-12
       br_cr_sla = 3-5;


RULE 95

IF      operation = drill&tap_ah OR
       operation = drill&tap_nah AND
       cutter = tap AND
       m_b_hard < 325 OR
       m_r_hard < 40 AND
       material < > aluminium_alloy ANd
       material < > magnesium_alloy AND
       material < > copper_alloy AND
       material < > zinc_alloy
THEN    tp_ha = 0-10
       tp_cla = 8-10;


RULE 96

IF      operation = drill&tap_ah OR
       operation = drill&tap_nah AND
       cutter = tap AND
       m_b_hard > 325 OR
       m_r_hard > 40 AND
```

```
        material < > aluminium_alloy AND
        material < > magnesium_alloy AND
        material < > copper_alloy AND
        material < > zinc_alloy
THEN      tp_ha = -5to5
        tp_cla = 4-6;

RULE 97

IF       operation = drill&tap_ah OR
        operation = drill&tap_nah AND
        cutter = tap AND
        material = aluminium_alloy OR
        material = magnesium_alloy OR
        material = copper_alloy OR
        material = zinc_alloy
THEN      tp_ha = 10-20
        tp_cla = 12-14;

PLURAL : search6, t_hss_tool_life, t_hss_ther_eff, t_hss_cutting_edge;

PLURAL : t_hss_surface_finish, t_hss_bra, t_hss_sra, t_hss_ela;

PLURAL : thr_hss_cutting_edge, thr_hss_bra, thr_hss_sra, thr_hss_ra;

PLURAL : thr_cr_tool_life, thr_cr_cutting_edge, thr_cr_bra, thr_cr_sra;

PLURAL : cutter, cutter_dia, fm_hss_ara, fm_hss_rra, fm_hss_ala;

PLURAL : fm_hss_ca, fm_hss_eca, fm_hss_rla, fm_cr_ara, fm_cr_rra;

PLURAL : fm_cr_ala, fm_cr_ca, fm_cr_eca, fm_cr_rla, sm_hss_ara;

PLURAL : sm_hss_rra, sm_hss_ala, sm_hss_rla, sm_cr_ara, sm_cr_rra;

PLURAL : sm_cr_ala, sm_cr_rla, em_ha, em_rpra, em_plw, em_rsca;

PLURAL : td_pa, td_laid, td_ha, rm_hss_mw, rm_hss_prra, rm_hss_ca;

PLURAL : rm_hss_cra, rm_cr_m, rm_cr_prra, rm_cr_sca, rm_cr_loc;

PLURAL : rm_cr_cpra, rm_cr_csca, br_cer_ara, br_cer_rra, br_cer_ela;

PLURAL : br_cer_sla, tp_ha, tp_cla;

PLURAL : hss_carbide, hi_sp_steel, carbide;

PLURAL : ceramic, diamond;

PLURAL : engine_lathe, turret_lathe, single_sp_auto;
```

```
PLURAL : nc_lathe, ver_mill_mc, hor_mill_mc, ver_dr_pr;

PLURAL : search1, m_type,m_prop,m_struct;

PLURAL : rad_dr_mc, turr_dr_mc, hor_bor_mc, sur_gr_mc;

PLURAL : cyl_gr_mc, hor&ver_mill_mc, nc_mill_mc,search3;

PLURAL : search1, m_type,m_prop,m_struct;


ASK operation : "Name the operation to be performed";

CHOICES operation : turning,facing,boring_ah,boring_nah,
threading_ext, threading_int_ah, milling,
drilling_ah,drilling_nah,drill&ream_ah,
drill&ream_nah, drill&tap_ah,drill&tap_nah,
grinding;

ASK m_b_hard : "What is the brinell hardness of the work-material?";

ASK m_r_hard : "What is the rockwell hardness of the work-material?";

ASK material : "What is the work-material?";

ASK m_type : "Name the work-material type";

CHOICES m_type : non_metallic,ferrous,non_ferrous,
non_aus_ferrous,aus_ferrous,hard_ferrous,
n_fr_mach_ferrous;

ASK m_prop : "Name any of the properties below, which the work-material
may have ";

CHOICES m_prop : hi_yield_str,highly_abrasive,tough;

ASK hi_sp_steel : "Was high speed steel selected as a tool material
for the operation?";

ASK carbide : "Was carbide selected as a tool material for the
operation?";

ASK ceramic : "Was ceramic selected as a tool material for the
operation?";

CHOICES hi_sp_steel,carbide,ceramic : selected, not_selected;

ASK cutter : "Indicate the type of cutter used";

CHOICES cutter : face_mill, end_mill, side_mill, reamer, tap;
```

```
ASK cutter_dia : "Give the diameter of the cutter in inches";
```

APPENDIX F

MACHINE AND TOOL EVALUATOR

```
C***********************************************************************
C     DECLARING VARIABLES
C***********************************************************************
      INTEGER MOS(20,20), TOS(40,40), JMPROF(20,20,20)
      INTEGER M,O(20),T,C,OI,UI,UNITS(20),FX,KS,LQ,OL,VB,OPID(20,20)
      INTEGER W,UY,AA,JJ,KK,TL,TO,YY,PO,LP,QW,ER,QS,DAI,POL,GOG,KG
      INTEGER JH,GB,GX,LM,LA,DS,WS,ZS,ZA,FV,CNUM(20),WER,TOH,QWT
      INTEGER DOH,TOY,ROR,ASE,K,SOS,FOR,YQ
      REAL C1,C2,DU2,DU1,DU3,DU4,CU,X,Y,Z,TV,V,F,TC
      REAL BRSPD(20),BRFD(20)
      REAL BRMTM,BRMCS,BRTTM,BLIFE(40),BRFAIL,BRTCS
      REAL BRSCS
      REAL TRTCS,TRSCS,TRMTM,TRTTM,TRFAIL,TLIFE(40),FSHP,FSSF
      REAL MLMTM,MLMCS,MLTEE(40),MLTTM,MLFAIL,TRMCS,PREC1
      REAL MLTCS,MLSCS,MLIFE(40),DRMTM,DRMCS,PREC2
      REAL DRTTM, DLIFE(40),DRFAIL,DRTCS,DRSCS,PREC3
      REAL FCMTM, FCCUT(20)
      REAL FCFD(20),FCMCS,FCTTM,FCFAIL,FCLIFE(40),FCTCS,FCSCS
      REAL A(40,40), N(40,40), MC(40,20), P(40,40)
      REAL TPI(20),TPMTM,TPTTM,TPFAIL,TPMCS,TPLIFE(40)
      REAL TPTCS,TPSCS,THMTM,THTTM,THLIFE(40),MHP(20),SFREQ(10,10)
      REAL THFAIL,THMCS,THTCS,THSCS,GRMTM,GRLIFE(40)
      REAL DE(40,40), C3(40,40), C4(40,40), B(40,40), D(40,40),CA
      REAL GRWTM, GRFAIL, GRMCS, GRWCS, GRSCS
      REAL E(40,40), G(40,40), H(40,40), I(40,40)
      REAL LR(20,20), JSETUP(20,20,20), MSETUP(20,20)
      REAL TSETUP(40,40), TCOST(40), TSHARP(40)
      REAL JDIA(20), TRLCUT(20), MLDIA(40), DLDIA(40), RMDIA(20)
      REAL TAPDIA(40), MLCUT(20), DLCUT(20), RMCUT(20), TAPCUT(20)
      REAL MLSPD(20), MLFD(20), DLSPD(20), DLFD(20), RMSPD(20)
      REAL TAPSPD(20),TAPFD(20),GRCUT(20),GRFD(20),THRSP(20)
      REAL THRFD(20), TRSPD(20), TRFD(20)
      REAL BRCUT(20),THRCUT(20)
C***********************************************************************
```

```
C     OPEN DATA FILES
C**************************************************************************
      OPEN(UNIT=12, FILE = 'MOS.DAT')
      OPEN(UNIT=13, FILE = 'TOS.DAT')
      OPEN(UNIT=14, FILE = 'TWK.DAT')
      OPEN(UNIT=15, FILE = 'JSET.DAT')
      OPEN(UNIT=16, FILE = 'MSET.DAT')
      OPEN(UNIT=17, FILE = 'TSET.DAT')
      OPEN(UNIT=18, FILE = 'OPER.DAT')
      OPEN(UNIT=19, FILE = 'TCOST.DAT')
      OPEN(UNIT=20, FILE = 'NUM.DAT')
      OPEN(UNIT=21, FILE = 'PROF.DAT')
      OPEN(UNIT=22, FILE = 'LABOR.DAT')
      OPEN(UNIT=23, FILE = 'WKPAR.DAT')
      OPEN(UNIT=24, FILE = 'OPID.DAT')
      OPEN(UNIT=25, FILE = 'COMP.DAT')
      OPEN(UNIT=26, FILE = 'SF.DAT')
      OPEN(UNIT=27, FILE = 'MHP.DAT')
      OPEN(UNIT=28, FILE = 'ONUM.DAT')
      OPEN(UNIT=29, FILE = 'ANS.OUT')
C**************************************************************************
C     READ DATA
C**************************************************************************
      READ(20,30)M,T,C
      READ (28,30) (O(DAI), DAI = 1,C)
      DO 81 KS=1,C
 81    READ(24,30) (OPID(KS,POL), POL = 1,O(KS))
      DO 33 LQ=1,C
 33    READ(25,30) CNUM(LQ), UNITS(LQ)
      DO 991 MOL=1,C
 991   READ(26,40) (SFREQ(MOL,GOG), GOG = 1,O(MOL))
      DO 712 KOL=1,M
 712   READ(27,40) MHP(KOL)
      DO 1 W=1,M
      DO 1 WER=1,C
      READ (12,30) (MOS(W,UY), UY=1,O(WER))
 1    CONTINUE
      DO 2 W=1,T
      DO 2 TOH=1,C
 2    READ (13,30) (TOS(W,UY), UY=1,O(TOH))
 30    FORMAT(20I2)
 40    FORMAT(9F8.2/9F8.2/9F8.2/9F8.2/9F8.2)
      DO 3 W=1,T
      DO 673 UY=1,C
      READ (14,41) A(W,UY),N(W,UY),MC(W,UY),P(W,UY),C3(W,UY),C4(W,UY),
     1 B(W,UY),D(W,UY),E(W,UY),G(W,UY),H(W,UY),I(W,UY),DE(W,UY)
 673   CONTINUE
 3    CONTINUE
      DO 4 W = 1, C
      DO 4 ASE = 1,O(W)
 4    READ (15,40) (JSETUP(W,ASE,UY), UY = 1,M)
```

```
      DO 5 W = 1, M
      DO 5 QWT=1,C
 5     READ (16,40) (MSETUP(W,UY), UY = 1,O(QWT))
      DO 6 W = 1, T
 6     READ (17,40) (TSETUP(W,UY), UY = 1,M)
 41    FORMAT(4F12.2/4F12.2/4F12.2/4F12.2/4F12.2/4F12.2/4F12.2/4F12.2
     1 /4F12.2/4F12.2/4F12.2/4F12.2/4F12.2/4F12.2)
      DO 7 YQ=1,T
 7     READ (18,40) MLDIA(YQ),DLDIA(YQ),TAPDIA(YQ),TLIFE(YQ),MLTEE(YQ),
     1 MLIFE(YQ),DLIFE(YQ),TPLIFE(YQ),THLIFE(YQ),GRLIFE(YQ),FCLIFE(YQ),
     1 BLIFE(YQ)
      DO 8 W = 1,T
 8     READ (19,40) TCOST(W), TSHARP(W)
      DO 9 W = 1,C
      DO 700 OI = 1,O(W)
      READ (21,30) (JMPROF(W,OI,UY), UY=1,M)
 700   CONTINUE
 9     CONTINUE
C*******************************************************************
      DO 10 W = 1,M
      DO 10 KG=1,C
 10    READ (22,40) (LR(W,UY), UY = 1,O(KG))
      DO 555 VB=1,C
      WRITE(29,*) 'COMPONENT NUMBER',VB
      WRITE(29,*)
      WRITE(29,*)
      DO.4555 W=1,O(VB)
      READ (23,40) JDIA(W),TRLCUT(W),TRSPD(W),TRFD(W),
     1 BRCUT(W),BRSPD(W),BRFD(W),
     1 FCCUT(W),FCFD(W),
     1 MLCUT(W),MLSPD(W),MLFD(W),
     1 DLCUT(W),DLSPD(W),DLFD(W),
     1 TAPCUT(W),TAPSPD(W),TAPFD(W),TPI(W),
     1 THRCUT(W),THRSP(W),THRFD(W),
     1 GRCUT(W),GRFD(W)
C*******************************************************************
 4555  CONTINUE
      DO 70 JJ = 1,O(VB)
      DO 80 AA = 1,M
      IF (OPID(VB,JJ).EQ.1.AND.MOS(AA,JJ).EQ.1) THEN
      GOTO 90
      ELSE
      GOTO 80
      ENDIF
C*******************************************************************
C     OPTIMIZING ALGORITHM FOR TURNING
C*******************************************************************
 90    DO 100 KK = 1,T
      IF (TOS(KK,JJ).EQ.1.AND.A(KK,CNUM(VB)).NE.0.)THEN
      GOTO 120
      ELSE
```

```
      GOTO 100
      ENDIF
C**********************************************************************
C     DETERMINE COST COEFFICIENTS AND FUNCTION PARAMETERS
C**********************************************************************
 120  C1 = (LR(AA,JJ))*((3.14*TRLCUT(JJ)*JDIA(JJ))/12.)
      CA = C1/LR(AA,JJ)
      C2 = (DE(KK,CNUM(VB))**
     1 (P(KK,CNUM(VB))/N(KK,CNUM(VB))))*(((LR(AA,JJ)*
     1 TSETUP(KK,AA)*CA)/
     1 (A(KK,CNUM(VB))**(1/N(KK,CNUM(VB))))) +
     1 (((TCOST(KK)/TSHARP(KK))*CA)/(A(KK,CNUM(VB))**
     1 (1/N(KK,CNUM(VB))))))
      C3(KK,CNUM(VB)) = (C3(KK,CNUM(VB))*(DE(KK,CNUM(VB))**
     1 E(KK,CNUM(VB)))))/MHP(AA)
      C4(KK,CNUM(VB)) = (C4(KK,CNUM(VB))*(DE(KK,CNUM(VB))**
     1 I(KK,CNUM(VB)))))/
     1 SFREQ(VB,JJ)
C**********************************************************************
C     DETERMINING DUAL VARIABLES : DU3 = 0
C**********************************************************************
      DU2 = ((1/G(KK,CNUM(VB)))-(1/H(KK,CNUM(VB)))))/
     1 ((1/(N(KK,CNUM(VB))*G(KK,CNUM(VB)))
     1 )-(1/(MC(KK,CNUM(VB))*H(KK,CNUM(VB)))))
      DU1 = 1.- DU2
      DU4 = (1/G(KK,CNUM(VB)))-(1/(N(KK,CNUM(VB))*G(KK,CNUM(VB)))))*DU2
C**********************************************************************
C     CHECK FOR DUAL INFEASIBILITY
C**********************************************************************
      IF (DU1.LT.0) THEN
      GO TO 190
      ENDIF
      IF (DU2.LT.0) THEN
      GO TO 190
      ENDIF
      IF (DU4.LT.0) THEN
      GO TO 190
      ELSE
      WRITE(29,*) 'HP CONSTRAINT IS LOOSE'
      ENDIF
C**********************************************************************
C     DETERMINE UNIT COSTS AND CUTTING SPEED, FEED
C**********************************************************************
      CU = ((C1/DU1)**DU1)*((C2/DU2)**DU2)*(C4(KK,CNUM(VB))**DU4)
 200  X = (DU2*CU)/C2
      Y = (C1/(DU1*CU))**(1-(1/MC(KK,CNUM(VB))))
      Z = X*Y
      TV = LOG(Z)/((1/N(KK,CNUM(VB)))-(1/MC(KK,CNUM(VB))))
      V = EXP(TV)
      F = C1/(V*DU1*CU)
C**********************************************************************
```

```
C     CHECK PRIMAL FEASIBILITY
C**********************************************************************
      FSHP = C3(KK,CNUM(VB))*(V**B(KK,CNUM(VB)))*(F**D(KK,CNUM(VB)))
      FSSF = C4(KK,CNUM(VB))*(V**G(KK,CNUM(VB)))*(F**H(KK,CNUM(VB)))
      IF (FSHP.GT.1.5.OR.FSSF.GT.1.5) THEN
      GOTO 923
      ELSE
      ENDIF
      GOTO 60
C**********************************************************************
C     DETERMINING DUAL VARIABLES : DU4 = 0
C**********************************************************************
 190  DU2 = ((1/B(KK,CNUM(VB)))-(1/D(KK,CNUM(VB))))/
     1 ((1/(B(KK,CNUM(VB))*N(KK,CNUM(VB))))
     1 -(1/(MC(KK,CNUM(VB))*D(KK,CNUM(VB)))))
      DU1 = 1.- DU2
      DU3 = (1/B(KK,CNUM(VB))) - (1/(B(KK,CNUM(VB))*N(KK,CNUM(VB))))*
     1 DU2
      IF(DU1.LT.0.OR.DU2.LT.0.OR.DU3.LT.0)THEN
      GOTO 923
      ELSE
      WRITE(29,*) 'SF CONSTRAINT IS LOOSE'
      CU = ((C1/DU1)**DU1)*((C2/DU2)**DU2)*(C3(KK,CNUM(VB))**DU3)
      GOTO 200
      ENDIF
C**********************************************************************
C     MAKE BOTH PRIMAL CONSTRAINTS TIGHT
C**********************************************************************
 923  WRITE(29,*) 'BOTH HP AND SF CONSTRAINTS ARE TIGHT'
      PREC1= (C3(KK,CNUM(VB))**(H(KK,CNUM(VB))/D(KK,CNUM(VB))))/
     1 C4(KK,CNUM(VB))
      PREC2 = LOG(PREC1)
      PREC3 = PREC2/(G(KK,CNUM(VB))-(B(KK,CNUM(VB))*H(KK,CNUM(VB))/
     1 D(KK,CNUM(VB))))
      V = EXP(PREC3)
      F = 1./((C3(KK,CNUM(VB))**(1./D(KK,CNUM(VB))))*(V**(B(KK,CNUM(VB)
     1 )/D(KK,CNUM(VB)))))
      CU = (C1/(V*F)) + (C2*(V**((1./N(KK,CNUM(VB)))-1))*(F**((1./
     1 MC(KK,CNUM(VB)))-1)))
C**********************************************************************
C     DETERMINING COSTS FOR TURNING
C**********************************************************************
 60   TRMCS = (C1/(V*F))*UNITS(VB)
      TRTCS = C2*(V**((1/N(KK,CNUM(VB)))-1))*
     1 (F**((1/MC(KK,CNUM(VB)))-1))*UNITS(VB)
      IF (JJ.EQ.1) THEN
      GOTO 61
      ELSE
      GOTO 63
      ENDIF
C**********************************************************************
```

```
C     INVESTIGATE JOB PROFILE
C**************************************************************************
 63   IF (MOS(AA,JJ-1).EQ.1.AND.JMPROF(CNUM(VB),JJ-1,AA).EQ.
    1 JMPROF(CNUM(VB),JJ,AA)) THEN
      JSETUP(CNUM(VB),JJ,AA) = 0
      ENDIF
 61   TRSCS = LR(AA,JJ)*JSETUP(CNUM(VB),JJ,AA)*
    1 UNITS(VB) + MSETUP(AA,JJ)*
    1 LR(AA,JJ)
      TC=(TRMCS+TRTCS+TRSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS TURNING'
      WRITE(29,*) 'MACHINE NUMBER',AA
      WRITE(29,*) 'OPERATION NUMBER',JJ
      WRITE(29,*) 'TOOL NUMBER',KK
      WRITE(29,*) 'CUTTING SPEED',V
      WRITE(29,*) 'CUTTING FEED',F
      WRITE(29,*) 'UNIT COST OF OPERATION',CU
      WRITE(29,*) 'MACHINING COST',TRMCS
      WRITE(29,*) 'TOOL COST',TRTCS
      WRITE(29,*) 'SETUP COST',TRSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 100  CONTINUE
 80   CONTINUE
 70   CONTINUE
      WRITE(29,*)
C***************************************************************************
C     TURNING OPERATION IN THE ABSENSE OF TOOL LIFE EQUATIONS
C**************************************************************************
 235  DO 230 TO= 1,O(VB)
      DO 240 TL= 1,M
      IF (OPID(VB,TO).EQ.1.AND.MOS(TL,TO).EQ.1) THEN
      GOTO 250
      ELSE
      GOTO 240
      ENDIF
C***********************************************************************
C     DETERMINING COSTS FOR TURNING
C***********************************************************************
 250  DO 270 YY = 1,T
      IF (TOS(YY,TO).EQ.1.AND.A(YY,CNUM(VB)).EQ.0) THEN
      TRMTM = (3.14*JDIA(TO)*TRLCUT(O))/(12.*TRSPD(TO)*TRFD(TO))
      TRMCS = TRMTM*LR(TL,TO)*UNITS(VB)
      TRTTM = (TRMTM*TSETUP(YY,TL))/TLIFE(YY)
      TRFAIL = TRTTM/TSETUP(YY,TL)
      TRTCS = TRTTM*LR(TL,TO)*UNITS(VB) + (TRFAIL*(TCOST(YY)/
    1 TSHARP(YY)))*UNITS(VB)
      ELSE
      GOTO 270
      ENDIF
      IF (TO.EQ.1) THEN
      GOTO 201
```

```
      ELSE
      GOTO 203
      ENDIF
 203  IF (MOS(TL,TO-1).EQ.1.AND.
     1 JMPROF(CNUM(VB),TO-1,TL).EQ.JMPROF(CNUM(VB),TO,TL)) THEN
      JSETUP(CNUM(VB),TO,TL) = 0
      ENDIF
 201  TRSCS = JSETUP(CNUM(VB),TO,TL)*UNITS(VB)*LR(TL,TO) +
     1 MSETUP(TL,TO)*LR(TL,TO)
      TC=(TRTCS+TRMCS+TRSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS TURNING'
      WRITE(29,*) 'OPERATION NUMBER',TO
      WRITE(29,*) 'MACHINE NUMBER',TL
      WRITE(29,*) 'TOOL NUMBER',YY
      WRITE(29,*) 'MACHINING COST',TRMCS
      WRITE(29,*) 'TOOL COST',TRTCS
      WRITE(29,*) 'SETUP COST',TRSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 270  CONTINUE
 240  CONTINUE
 230  CONTINUE
      WRITE(29,*)
C**********************************************************************
C     BORING OPERATION
C**********************************************************************
      DO 2875 SOS=1,O(VB)
      DO 3456 FOR=1,M
      IF (OPID(VB,SOS).EQ.2.AND.MOS(FOR,SOS).EQ.1) THEN
      GOTO 5677
      ELSE
      GOTO 3456
      ENDIF
C*******************************************************************
C     DETERMINING COSTS FOR BORING
C*******************************************************************
 5677 DO 8322 YY = 1,T
      IF (TOS(YY,SOS).EQ.1.AND.A(YY,CNUM(VB)).EQ.0) THEN
      BRMTM = (3.14*JDIA(SOS)*BRCUT(SOS))/(12.*BRSPD(SOS)*BRFD(SOS))
      BRMCS = BRMTM*LR(FOR,SOS)*UNITS(VB)
      BRTTM = (BRMTM*TSETUP(YY,FOR))/BLIFE(YY)
      BRFAIL = BRTTM/TSETUP(YY,FOR)
      BRTCS = BRTTM*LR(FOR,SOS)*UNITS(VB) + (BRFAIL*(TCOST(YY)/
     1 TSHARP(YY)))*UNITS(VB)
      ELSE
      GOTO 8322
      ENDIF
      IF (SOS.EQ.1) THEN
      GOTO 2010
      ELSE
      GOTO 2030
```

```
      ENDIF
C**********************************************************************
C     INVESTIGATE JOB PROFILE
C**********************************************************************
 2030 IF (MOS(FOR,SOS-1).EQ.1.AND.
     1 JMPROF(CNUM(VB),SOS-1,FOR).EQ.JMPROF(CNUM(VB),SOS,FOR)) THEN
      JSETUP(CNUM(VB),SOS,FOR) = 0
      ENDIF
 2010 BRSCS = JSETUP(CNUM(VB),SOS,FOR)*UNITS(VB)*LR(FOR,SOS) +
     1 MSETUP(FOR,SOS)*LR(FOR,SOS)
      TC=(BRTCS+BRMCS+BRSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS BORING'
      WRITE(29,*) 'OPERATION NUMBER',SOS
      WRITE(29,*) 'MACHINE NUMBER',FOR
      WRITE(29,*) 'TOOL NUMBER',YY
      WRITE(29,*) 'MACHINING COST',BRMCS
      WRITE(29,*) 'TOOL COST',BRTCS
      WRITE(29,*) 'SETUP COST',BRSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 8322 CONTINUE
 3456 CONTINUE
 2875 CONTINUE
      WRITE(29,*)
C*********************************************************************
C     FACING OPERATION
C*********************************************************************
      DO 1000 TOY= 1,O(VB)
      DO 1100 DOH= 1,M
      IF (OPID(VB,TOY).EQ.3.AND.MOS(DOH,TOY).EQ.1) THEN
      GO TO 1200
      ELSE
      GO TO 1100
      ENDIF
C********************************************************************
C     DETERMINING COSTS FOR FACING
C********************************************************************
 1200 DO 1300 ROR= 1,T
      IF(TOS(ROR,TOY).EQ.1) THEN
      FCMTM = FCCUT(TOY)/FCFD(TOY)
      FCMCS = FCMTM*LR(DOH,TOY)*UNITS(VB)
      FCTTM = (FCMTM/FCLIFE(ROR))*TSETUP(ROR,TOY)
      FCFAIL = FCMTM/FCLIFE(ROR)
      FCTCS = FCTTM*LR(DOH,TOY)*UNITS(VB) + (FCFAIL*(TCOST(ROR)/
     1 TSHARP(ROR)))*UNITS(VB)
      ELSE
      GO TO 1300
      ENDIF
      IF(TOY.EQ.1) THEN
      GO TO 1400
      ELSE
      GO TO 1500
```

```
      ENDIF
C************************************************************************
C     INVESTIGATE JOB PROFILE
C************************************************************************
 1500 IF(MOS(DOH,TOY-1).EQ.1.ANDJMPROF(CNUM(VB),TOY-1,DOH).EQ.
     1 JMPROF(CNUM(VB),TOY,DOH)) THEN
      JSETUP(CNUM(VB),TOY,DOH)= 0
      ENDIF
 1400 FCSCS = (JSETUP(CNUM(VB),TOY,DOH)*LR(DOH,TOY))*UNITS(VB) +
     1 MSETUP(DOH,TOY)*LR(DOH,TOY)
      TC=(FCMCS+FCTCS+FCSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS FACING'
      WRITE(29,*) 'OPERATION NUMBER',TOY
      WRITE(29,*) 'MACHINE NUMBER',DOH
      WRITE(29,*) 'TOOL NUMBER',ROR
      WRITE(29,*) 'MACHINING COST',FCMCS
      WRITE(29,*) 'TOOL COST',FCTCS
      WRITE(29,*) 'SETUP COST',FCSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 1300 CONTINUE
 1100 CONTINUE
 1000 CONTINUE
      WRITE(29,*)
C*******************************************************************
C     MILLING OPERATION
C*******************************************************************
 238  DO 300 LP = 1,O(VB)
      DO 310 PO = 1,M
      IF (OPID(VB,LP).EQ.4.AND.MOS(PO,LP).EQ.1) THEN
      GOTO 320
      ELSE
      GOTO 310
      ENDIF
C*********************************************************************
C     DETERMINING COSTS FOR MILLING
C*********************************************************************
 320  DO 340 QW = 1, T
      IF (TOS(QW,LP).EQ.1) THEN
      MLMTM = (3.14*MLDIA(QW)*MLCUT(LP))/(12.*MLFD(LP)*MLSPD(LP)*
     1 MLTEE(QW))
      MLMCS = MLMTM*LR(PO,LP)*UNITS(VB)
      MLTTM = (MLCUT(LP)*TSETUP(QW,PO))/(MLTEE(QW)*MLIFE(QW))
      MLFAIL = MLTTM/TSETUP(QW,PO)
      MLTCS = MLTTM*LR(PO,LP)*UNITS(VB) + (MLFAIL*(TCOST(QW)/
     1 TSHARP(QW)))*UNITS(VB)
      ELSE
      GOTO 340
      ENDIF
      IF (LP.EQ.1) THEN
      GOTO 635
      ELSE
```

```
      GOTO 636
      ENDIF
C*********************************************************************
C     INVESTIGATE JOB PROFILE
C*********************************************************************
 636  IF (MOS(PO,LP-1).EQ.1.AND.JMPROF(CNUM(VB),LP-1,PO).EQ.
    1 JMPROF(CNUM(VB),LP,PO)) THEN
      JSETUP(CNUM(VB),LP,PO) = 0
      ENDIF
 635  MLSCS = (JSETUP(CNUM(VB),LP,PO)*LR(PO,LP))*UNITS(VB) +
    1 MSETUP(PO,LP)*LR(PO,LP)
      TC=(MLMCS+MLTCS+MLSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS MILLING'
      WRITE(29,*) 'OPERATION NUMBER',LP
      WRITE(29,*) 'MACHINE NUMBER',PO
      WRITE(29,*) 'TOOL NUMBER',QW
      WRITE(29,*) 'MACHINING COST',MLMCS
      WRITE(29,*) 'TOOL COST',MLTCS
      WRITE(29,*) 'SETUP COST',MLSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 340  CONTINUE
 310  CONTINUE
 300  CONTINUE
      WRITE(29,*)
C*********************************************************************
C     DRILLING OPERATION
C*********************************************************************
 335  DO 350 QS = 1,O(VB)
      DO 360 ER = 1,M
      IF (OPID(VB,QS).GE.5.AND.OPID(VB,QS).LE.8.
    1 AND.MOS(ER,QS).EQ.1) THEN
      GOTO 370
      ELSE
      GOTO 360
      ENDIF
C******************************************************************
C     DETERMINING COSTS FOR DRILLING
C******************************************************************
 370  DO 391 JH = 1,T
      IF(TOS(JH,QS).EQ.1) THEN
      DRMTM = (3.14*DLDIA(JH)*DLCUT(QS))/(12.*DLFD(QS)*DLSPD(QS))
      DRMCS = DRMTM*LR(ER,QS)*UNITS(VB)
      DRTTM = (DLCUT(QS)*TSETUP(JH,ER))/DLIFE(JH)
      DRFAIL = DRTTM/TSETUP(JH,ER)
      DRTCS = DRTTM*LR(ER,QS)*UNITS(VB) + (DRFAIL*(TCOST(JH)/
    1 TSHARP(JH)))*UNITS(VB)
      ELSE
      GOTO 391
      ENDIF
      IF (QS.EQ.1) THEN
      GOTO 789
```

```
      ELSE
      GOTO 790
      ENDIF
C**********************************************************************
C     INVESTIGATE JOB PROFILE
C**********************************************************************
 790  IF (MOS(ER,QS-1).EQ.1.AND.JMPROF(CNUM(VB),QS-1,ER).EQ.
     1 JMPROF(CNUM(VB),QS,ER)) THEN
      JSETUP(CNUM(VB),QS,ER) = 0
      ENDIF
 789  DRSCS = JSETUP(CNUM(VB),QS,ER)*UNITS(VB) + MSETUP(ER,QS)*
     1 LR(ER,QS)
      TC=(DRMCS+DRTCS+DRSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS DRILLING OR REAMING'
      WRITE(29,*) 'OPERATION NUMBER',QS
      WRITE(29,*) 'MACHINE NUMBER',ER
      WRITE(29,*) 'TOOL NUMBER',JH
      WRITE(29,*) 'MACHINING COST',DRMCS
      WRITE(29,*) 'TOOL COST',DRTCS
      WRITE(29,*) 'SETUP COST',DRSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 391  CONTINUE
 360  CONTINUE
 350  CONTINUE
      WRITE(29,*)
C*******************************************************************
C     TAPPING OPERATION
C*******************************************************************
 375  DO 390 GX = 1, O(VB)
      DO 400 GB = 1, M
      IF (OPID(VB,GX).GE.9.AND.OPID(VB,GX).LE.10.
     1 AND.MOS(GB,GX).EQ.1) THEN
      GOTO 410
      ELSE
      GOTO 400
      ENDIF
C*******************************************************************
C     DETERMINING COSTS FOR TAPPING
C*******************************************************************
 410  DO 430 LM =1,T
      IF(TOS(LM,GX).EQ.1) THEN
      TPMTM = (TPI(GX)*3.14*TAPDIA(LM)*TAPCUT(GX))/(6.*TAPSPD(GX))
      TPTTM = (TAPCUT(GX)*TSETUP(LM,GB))/TPLIFE(LM)
      TPFAIL = TPTTM/TSETUP(LM,GB)
      TPMCS = TPMTM*LR(GB,GX)*UNITS(VB)
      TPTCS = TPTTM*LR(GB,GX)*UNITS(VB) + (TPFAIL*(TCOST(LM)/
     1 TSHARP(LM)))*UNITS(VB)
      ELSE
      GOTO 430
      ENDIF
      IF (GX.EQ.1) THEN
```

```
      GOTO 927
      ELSE
      GOTO 945
      ENDIF
C***********************************************************************
C     INVESTIGATE JOB PROFILE
C***********************************************************************
 945  IF (MOS(GB,GX-1).EQ.1.AND.JMPROF(CNUM(VB),GX-1,GB).EQ.
     1 JMPROF(CNUM(VB),GX,GB)) THEN
      JSETUP(CNUM(VB),GX,GB) = 0
      ENDIF
 927  TPSCS = JSETUP(CNUM(VB),GX,GB)*LR(GB,GX)*UNITS(VB) +
     1 MSETUP(GB,GX)*
     1 LR(GB,GX)
      TC=(TPMCS+TPTCS+TPSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS TAPPING'
      WRITE(29,*) 'OPERATION NUMBER',GX
      WRITE(29,*) 'MACHINE NUMBER',GB
      WRITE(29,*) 'TOOL NUMBER',LM
      WRITE(29,*) 'MACHINING COST',TPMCS
      WRITE(29,*) 'TOOL COST',TPTCS
      WRITE(29,*) 'SETUP COST',TPSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 430  CONTINUE
 400  CONTINUE
 390  CONTINUE
      WRITE(29,*)
C*******************************************************************
C     THREADING OPERATION
C*******************************************************************
 425  DO 450 DS = 1,O(VB)
      DO 470 LA = 1,M
      IF (OPID(VB,DS).GE.11.AND.OPID(VB,DS).LE.12.AND.
     1 MOS(LA,DS).EQ.1) THEN
      GOTO 480
      ELSE
      GOTO 470
      ENDIF
C*********************************************************************
C     DETERMINING COSTS FOR THREADING
C*********************************************************************
 480  DO 500 WS = 1,T
      IF(TOS(WS,DS).EQ.1) THEN
      THMTM =(3.14*JDIA(DS)*THRCUT(DS))/(12.*THRSP(DS)*THRFD(DS))
      THTTM = (THMTM*TSETUP(WS,LA))/(THLIFE(WS))
      THFAIL = THTTM/TSETUP(WS,LA)
      THMCS = THMTM*LR(LA,DS)*UNITS(VB)
      THTCS = THTTM*TSETUP(WS,LA)*UNITS(VB) + (THFAIL*(TCOST(WS)/
     1 TSHARP(WS)))*UNITS(VB)
      ELSE
      GOTO 500
```

```
      ENDIF
      IF (DS.EQ.1) THEN
      GOTO 122
      ELSE
      GOTO 124
      ENDIF
C***********************************************************************
C     INVESTIGATE JOB PROFILE
C***********************************************************************
 124  IF(MOS(LA,DS-1).EQ.1.AND.JMPROF(CNUM(VB),DS-1,LA).EQ.
     1 JMPROF(CNUM(VB),DS,LA)) THEN
      JSETUP(CNUM(VB),DS,LA) = 0
      ENDIF
 122  THSCS = JSETUP(CNUM(VB),DS,LA)*
     1 LR(LA,DS)*UNITS(VB) + MSETUP(LA,DS)*
     1 LR(LA,DS)
      TC=(THMCS+THTCS+THMCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS THREADING'
      WRITE(29,*) 'OPERATION NUMBER',DS
      WRITE(29,*) 'MACHINE NUMBER',LA
      WRITE(29,*) 'TOOL NUMBER',WS
      WRITE(29,*) 'MACHINING COST', THMCS
      WRITE(29,*) 'TOOL COST',THTCS
      WRITE(29,*) 'SETUP COST',THSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 500  CONTINUE
 470  CONTINUE
 450  CONTINUE
      WRITE(29,*)
C*******************************************************************
C     GRINDING OPERATION
C*******************************************************************
 495  DO 510 ZA = 1,O(VB)
      DO 520 ZS = 1,M
      IF (OPID(VB,ZA).EQ.13.AND.MOS(ZS,ZA).EQ.1) THEN
      GOTO 530
      ELSE
      GOTO 520
      ENDIF
C*******************************************************************
C     DETERMINING COSTS FOR GRINDING
C*******************************************************************
 530  DO 550 FV = 1,T
      IF(TOS(FV,ZA).EQ.1)THEN
      GRMTM = GRCUT(ZA)/GRFD(ZA)
      GRWTM = (GRMTM/GRLIFE(FV))*TSETUP(FV,ZS)
      GRFAIL = GRWTM/TSETUP(FV,ZS)
      GRMCS = GRMTM*LR(ZS,ZA)*UNITS(VB)
      GRWCS = GRWTM*LR(ZS,ZA)*UNITS(VB) + (GRFAIL*(TCOST(FV)/
     1 TSHARP(FV)))
      ELSE
```

```
      GOTO 550
      ENDIF
      IF(ZS.EQ.1) THEN
      GOTO 444
      ELSE
      GOTO 446
      ENDIF
C*************************************************************************
C     INVESTIGATE JOB PROFILE
C*************************************************************************
 446  IF (MOS(ZS,ZA-1).EQ.1.AND.JMPROF(CNUM(VB),ZA-1,ZS).EQ.
     1 JMPROF(CNUM(VB),ZA,ZS)) THEN
      JSETUP(CNUM(VB),ZA,ZS) = 0
      ENDIF
 444  GRSCS = JSETUP(CNUM(VB),ZA,ZS)*LR(ZS,ZA)*UNITS(VB) +
     1 (MSETUP(ZS,ZA)*
     1 LR(ZS,ZA))
      TC=(GRMCS+GRWCS+GRSCS)/UNITS(VB)
      WRITE(29,*) 'OPERATION IS GRINDING'
      WRITE(29,*) 'OPERATION NUMBER',ZA
      WRITE(29,*) 'MACHINE NUMBER',ZS
      WRITE(29,*) 'TOOL NUMBER',FV
      WRITE(29,*) 'MACHINING COST',GRMCS
      WRITE(29,*) 'TOOL COST',GRWCS
      WRITE(29,*) 'SETUP COST',GRSCS
      WRITE(29,*) 'TOTAL COST PER UNIT',TC
 550  CONTINUE
 520  CONTINUE
 510  CONTINUE
 555  CONTINUE
 600  STOP
      END
```

APPENDIX G

COST EVALUATION OF MACHINES AND TOOLS

```
COMPONENT NUMBER          1


HP CONSTRAINT IS LOOSE
OPERATION IS TURNING
MACHINE NUMBER          2
OPERATION NUMBER          1
TOOL NUMBER          2
CUTTING SPEED          303.5212402
CUTTING FEED           0.0066310
UNIT COST OF OPERATION          4.6932240
MACHINING COST          148.2129974
TOOL COST          86.4467010
SETUP COST         303.0000000
TOTAL COST PER UNIT          10.7531929
HP CONSTRAINT IS LOOSE
BOTH HP AND SF CONSTRAINTS ARE TIGHT
OPERATION IS TURNING
MACHINE NUMBER          2
OPERATION NUMBER          1
TOOL NUMBER          6
CUTTING SPEED          499.2094727
CUTTING FEED           0.0027324
UNIT COST OF OPERATION          4.8950233
MACHINING COST          218.6866150
TOOL COST          26.0645599
SETUP COST         303.0000000
TOTAL COST PER UNIT          10.9550190
HP CONSTRAINT IS LOOSE
OPERATION IS TURNING
MACHINE NUMBER          4
OPERATION NUMBER          1
TOOL NUMBER          2
CUTTING SPEED          164.4614716
CUTTING FEED           0.0580936
```

```
UNIT COST OF OPERATION          0.9062698
MACHINING COST          28.6201630
TOOL COST          16.6932068
SETUP COST          313.4997559
TOTAL COST PER UNIT          7.1762590
HP CONSTRAINT IS LOOSE
OPERATION IS TURNING
MACHINE NUMBER          4
OPERATION NUMBER          1
TOOL NUMBER          6
CUTTING SPEED          378.9638672
CUTTING FEED          0.0328986
UNIT COST OF OPERATION          0.8048776
MACHINING COST          21.9325867
TOOL COST          18.3112183
SETUP COST          313.4997559
TOTAL COST PER UNIT          7.0748672


OPERATION IS BORING
OPERATION NUMBER          8
MACHINE NUMBER          8
TOOL NUMBER          1
MACHINING COST          5.2614536
TOOL COST          18.3256073
SETUP COST          226.3799896
TOTAL COST PER UNIT          4.9993401
OPERATION IS BORING
OPERATION NUMBER          8
MACHINE NUMBER          8
TOOL NUMBER          7
MACHINING COST          5.2614536
TOOL COST          16.7476654
SETUP COST          226.3799896
TOTAL COST PER UNIT          4.9677811

OPERATION IS FACING
OPERATION NUMBER          5
MACHINE NUMBER          2
TOOL NUMBER          2
MACHINING COST          300.0000000
TOOL COST          52.2387390
SETUP COST          3.5999994
TOTAL COST PER UNIT          7.1167669
OPERATION IS FACING
OPERATION NUMBER          5
MACHINE NUMBER          2
TOOL NUMBER          6
MACHINING COST          300.0000000
TOOL COST          41.6666565
SETUP COST          3.5999994
```

```
TOTAL COST PER UNIT            6.9053268
OPERATION IS FACING
OPERATION NUMBER        5
MACHINE NUMBER        4
TOOL NUMBER        2
MACHINING COST          259.9997559
TOOL COST            52.2387390
SETUP COST            4.1599998
TOTAL COST PER UNIT            6.3279638
OPERATION IS FACING
OPERATION NUMBER        5
MACHINE NUMBER        4
TOOL NUMBER        6
MACHINING COST          259.9997559
TOOL COST            41.6666565
SETUP COST            4.1599998
TOTAL COST PER UNIT            6.1165228

OPERATION IS MILLING
OPERATION NUMBER        6
MACHINE NUMBER        6
TOOL NUMBER        12
MACHINING COST            0.3801552
TOOL COST            8.2552061
SETUP COST           527.1496582
TOTAL COST PER UNIT           10.7156982
OPERATION IS MILLING
OPERATION NUMBER        6
MACHINE NUMBER        6
TOOL NUMBER        14
MACHINING COST            1.2907600
TOOL COST            18.0468445
SETUP COST           527.1496582
TOTAL COST PER UNIT           10.9297409
OPERATION IS MILLING
OPERATION NUMBER        6
MACHINE NUMBER        7
TOOL NUMBER        12
MACHINING COST            0.3684582
TOOL COST            11.9427071
SETUP COST           555.6596680
TOTAL COST PER UNIT           11.3594131
OPERATION IS MILLING
OPERATION NUMBER        6
MACHINE NUMBER        7
TOOL NUMBER        14
MACHINING COST            1.2510443
TOOL COST            9.6718721
SETUP COST           555.6596680
TOTAL COST PER UNIT           11.3316498
```

```
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER        2
TOOL NUMBER       18
MACHINING COST          0.0350231
TOOL COST          2.9681797
SETUP COST          1.9999990
TOTAL COST PER UNIT          0.1000640
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER        2
TOOL NUMBER       19
MACHINING COST          0.0350231
TOOL COST         15.5999889
SETUP COST          1.9999990
TOTAL COST PER UNIT          0.3527002
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER        3
TOOL NUMBER       18
MACHINING COST          0.0455300
TOOL COST          7.5881777
SETUP COST          6.2399998
TOTAL COST PER UNIT          0.2774741
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER        3
TOOL NUMBER       19
MACHINING COST          0.0455300
TOOL COST         11.0099869
SETUP COST          6.2399998
TOTAL COST PER UNIT          0.3459100
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER        4
TOOL NUMBER       18
MACHINING COST          0.0481567
TOOL COST          7.9931755
SETUP COST         19.2500000
TOTAL COST PER UNIT          0.5458264
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER        4
TOOL NUMBER       19
MACHINING COST          0.0481567
TOOL COST         11.2124882
SETUP COST         19.2500000
TOTAL COST PER UNIT          0.6102127
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER        3
MACHINE NUMBER       12
```

```
TOOL NUMBER          18
MACHINING COST                  0.0525346
TOOL COST           10.4681749
SETUP COST          605.3999023
TOTAL COST PER UNIT                  12.3184080
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER           3
MACHINE NUMBER         12
TOOL NUMBER          19
MACHINING COST                  0.0525346
TOOL COST           26.3999634
SETUP COST          605.3999023
TOTAL COST PER UNIT                  12.6370459
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER           3
MACHINE NUMBER         13
TOOL NUMBER          18
MACHINING COST                  0.0437788
TOOL COST           9.5681725
SETUP COST          654.0000000
TOTAL COST PER UNIT                  13.2722359
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER           3
MACHINE NUMBER         13
TOOL NUMBER          19
MACHINING COST                  0.0437788
TOOL COST           15.3749905
SETUP COST          654.0000000
TOTAL COST PER UNIT                  13.3883734
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER           7
MACHINE NUMBER         13
TOOL NUMBER          18
MACHINING COST                  0.1031166
TOOL COST           9.9281693
SETUP COST          353.6398926
TOTAL COST PER UNIT                   7.2734222
OPERATION IS DRILLING OR REAMING
OPERATION NUMBER           7
MACHINE NUMBER         13
TOOL NUMBER          19
MACHINING COST                  0.1031166
TOOL COST           15.6899891
SETUP COST          353.6398926
TOTAL COST PER UNIT                   7.3886566

OPERATION IS TAPPING
OPERATION NUMBER           4
MACHINE NUMBER          2
TOOL NUMBER          23
MACHINING COST                  0.0194335
```

```
TOOL COST            2.4868393
SETUP COST            3.5000000
TOTAL COST PER UNIT              0.1201254
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER          2
TOOL NUMBER         25
MACHINING COST              0.0194335
TOOL COST            3.0599966
SETUP COST            3.5000000
TOTAL COST PER UNIT              0.1315886
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER          3
TOOL NUMBER         23
MACHINING COST              0.0202109
TOOL COST            4.2868385
SETUP COST            5.7199993
TOTAL COST PER UNIT              0.2005410
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER          3
TOOL NUMBER         25
MACHINING COST              0.0202109
TOOL COST            1.7639990
SETUP COST            5.7199993
TOTAL COST PER UNIT              0.1500841
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER          4
TOOL NUMBER         23
MACHINING COST              0.0213769
TOOL COST            2.5993395
SETUP COST           17.5999908
TOTAL COST PER UNIT              0.4044141
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER          4
TOOL NUMBER         25
MACHINING COST              0.0213769
TOOL COST            3.8249950
SETUP COST           17.5999908
TOTAL COST PER UNIT              0.4289269
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER         12
TOOL NUMBER         23
MACHINING COST              0.0233202
TOOL COST            4.7368364
SETUP COST           6.0000000
TOTAL COST PER UNIT              0.2152031
```

```
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER        12
TOOL NUMBER        25
MACHINING COST            0.0233202
TOOL COST            1.4399986
SETUP COST           6.0000000
TOTAL COST PER UNIT            0.1492664
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER        13
TOOL NUMBER        23
MACHINING COST            0.0194335
TOOL COST            3.6118393
SETUP COST           2.5000000
TOTAL COST PER UNIT            0.1226254
OPERATION IS TAPPING
OPERATION NUMBER          4
MACHINE NUMBER        13
TOOL NUMBER        25
MACHINING COST            0.0194335
TOOL COST            3.9599972
SETUP COST           2.5000000
TOTAL COST PER UNIT            0.1295886

OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER         1
TOOL NUMBER        30
MACHINING COST          20.4035492
TOOL COST           90.9001007
SETUP COST          363.9997559
TOTAL COST PER UNIT            2.6341438
OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER         1
TOOL NUMBER        32
MACHINING COST          20.4035492
TOOL COST          114.2527771
SETUP COST          363.9997559
TOTAL COST PER UNIT            3.1011972
OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER         2
TOOL NUMBER        30
MACHINING COST          12.7522192
TOOL COST           90.9001007
SETUP COST           3.0000000
TOTAL COST PER UNIT            2.3280897
OPERATION IS THREADING
OPERATION NUMBER          2
```

```
MACHINE NUMBER          2
TOOL NUMBER        32
MACHINING COST             12.7522192
TOOL COST          166.9618835
SETUP COST            3.0000000
TOTAL COST PER UNIT              3.8493261
OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER          3
TOOL NUMBER        30
MACHINING COST             13.2623072
TOOL COST          243.1765594
SETUP COST          265.1997070
TOTAL COST PER UNIT              5.3940182
OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER          3
TOOL NUMBER        32
MACHINING COST             13.2623072
TOOL COST           59.8432770
SETUP COST          265.1997070
TOTAL COST PER UNIT              1.7273569
OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER          4
TOOL NUMBER        30
MACHINING COST             14.0274401
TOOL COST          216.9219971
SETUP COST           16.5000000
TOTAL COST PER UNIT              4.8995371
OPERATION IS THREADING
OPERATION NUMBER          2
MACHINE NUMBER          4
TOOL NUMBER        32
MACHINING COST             14.0274401
TOOL COST           84.7809448
SETUP COST           16.5000000
TOTAL COST PER UNIT              2.2567158

OPERATION IS GRINDING
OPERATION NUMBER          9
MACHINE NUMBER         10
TOOL NUMBER        27
MACHINING COST            744.1662598
TOOL COST          111.7898254
SETUP COST            6.5799999
TOTAL COST PER UNIT             17.2507172
```

APPENDIX H

DATA FOR THE ALGORITHMS

NUM.DAT

```
1332 1
```

ONUM.DAT

```
9
```

COMP.DAT

```
1 50
```

MOS.DAT

```
0 1 0 0
1 1 1 1 1
0 1 1 1 0 0
1 1 1 1 1 0
0 0 0 0 0 0
0 0 0 0 0 1
0 0 0 0 0 1 0 0
0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 1
0 0 0 0
0 0 1 1 0 0 0
0 0 1 1 0 0 1
```

TOS.DAT

```
0 0 0 0 0 0 0 1
1 0 0 0 1 0 0 1


1 0 0 0 1 0 0 1
0 0 0 0 0 0 0 1



0 0 0 0 0 1

0 0 0 0 0 1


0 0 1 0 0 0 1
0 0 1 0 0 0 1


0 0 0 1

0 0 0 1

0 0 0 0 0 0 0 0 1


0 1

0 1
```

TWK.DAT

```
83.      .2         .83       .33
4.35     20460000.  .91        .78
0.75     -1.52      1.004      .25
0.2
```

```
120.      .29      .77       .31
5.67      208920000. .89       .72
0.76      -1.53     1.1       .28
0.2
```

JSET.DAT

```
0.    10.    0.    11.

9.    11.    10.    12.

0.    10.    9.    10.
            12.   13.
0.    10.    9.    10.
            12.   13.
      9.    8.

                             16.    17.


                  7.
                                         9.

13.
```

MSET.DAT

```
0.    5.

5.    6.    5.    7.     6.

      10.   12.    11.

20.   30.    35.    32.   8.



                             11.

                             32.

                                         12.


                                               14.
```

9. 10.

8. 5. 7.

TSET.DAT

8.

5. 8.

10. 7. 13.

13.

12. 18.

20. 10.

4. 9. 9.
11. 12.
9. 3. 3.
14. 7.

```
    2.   5.   2.
         5.   4.

    6.   3.   7.
         2.   8.

18.


11.  11.  18.  17.

14.  17.  10.  12.
```

OPER.DAT

```
         3.
              3.
    2.



              5.
    3.
         5.




4.3                  24.  3.

7.3                  12.  5.
```

```
0.29          3.

0.29          2.


    0.29          4.


    0.29          5.


120.


                        34.


                        45.
```

TCOST.DAT

```
12.   10.
14.   67.


2.    8.
10.   7.
```

```
10.    80.

5.75   4.


25.    66.
10.    3.


23.    19.

6.     15.

75.    120.


12.    67.

22.35  4.
```

PROF.DAT

```
0 1 0 2
5 1 4 2
5 1 4 2           6 7
5 1 4 2           6 7
0 1   2
        8 9
                  10
          11
             12
```

LABOR.DAT

```
      .8

0.6   .5    .4     .5    .6

      .52   .52    .52

0.55    .55   .55    .55   .52



                             .65

                             .63
```

```
                            .49

                                .47

        .6  .6

        .5  .5              .52
```

WKPAR.DAT

```
3.8  10.

3.8
    1.5  172.  .017
            .09  300.  .013

                        .09  123.  .015
7.
                            2.   .2

1.5  334.  .018

            .09  123.  .014
2.8             .3   445.  .0023


                .3.8  .12
```

OPID.DAT

```
1 115 9 3 4 6 2 13
```

SF.DAT

```
15.   78.   67.   69.   13.   70.   68.   4.   1.
```

MHP.DAT

```
3.
6.
9.
8.
8.
7.
10.
12.
15.
16.
7.
5.
6.
```

APPENDIX I

EXPERT SYSTEMS NOMENCLATURE

- M_TYPE = Material type
- M_COND = Material condition
- M_PROP = Material properties
- M_STRUCT = Material structure
- M_B_HARD = Brinell hardness
- M_R_HARD = Rockwell hardness
- S_F_REQ = Surface finish required
- SS_REQ = surface profile to be generated
- ...._AH = Axial hole
- ...._NAH = Non axial hole
- HI_SP_STEEL = High speed steel
- SINGLE_SP_AUTO = Single spindle automatic lathe
- HOR_MILL_MC = Horizontal milling machine
- VER_MILL_MC = Vertical milling machine
- VER_DR_PR = Vertical drill press
- RAD_DR_MC = Radial drilling machine
- TURR_DR_MC = Turret drilling machine
- NC_LATHE = Numerical control lathe
- NC_MILL_MC = Numerical control milling machine
- HOR_BOR_MC = horizontal boring machine

- CYL_GR_MC = Cylindrical grinding machine
- SUR_GR_MC = Surface grinding machine
- AUS_FERROUS = Austenitic ferrous
- NON_AUS_FERROUS = Non austenitic ferrous
- N_FR_MACH_FERROUS = Non free machining ferrous
- HI_ELASTIC = Highly elastic
- LO_ELASTIC = Low elasticity
- STOCK_REM = Amount of metal removed
- GR_WHEEL_HARD,SOFT,MED = Grinding wheel grades
- GR_ABRASIVE = Type of grinding abrasive
- GR_SIZE = Grain size for grinding wheel abrasives
- GR_STRUCTURE = Open or dense structure of grinding wheels
- TOOL_CHIP_FR = Friction between tool and chip
- CUT_FLUID = Cutting fluid
- HSS = High speed steel, as used in tool grades
- CR = carbide, as used in tool grades
- CER = Ceramic, as used in tool grades
- SP = Turning, facing, and boring single point tools, as used in tool grades
- THR = Threading, as used in tool grades
- TD = Twist drills, as used in tool grades
- RM = Reamers, as used in tool grades
- TP = Taps, as used in tool grades
- MSP = Multi point milling cutters, as used in tool grades
- C = Carbide tool grades
- M, T = High speed steel tool grades
- FM = Face milling cutter, as used in tool angle specs
- SM = Side milling cutter, as used in tool angle specs
- EM = End milling cutter, as used in tool angle specs
- CUTTER = Type of cutter used

- CUTTER_DIA = Diameter of cutter used
- HI_YIELD_STR = High yield strength
- M_MELT_PT = Melting point of material
- C_OD = Component outer diameter
- C_L = Component length
- C_B_A = Component base area
- C_HT = Component height
- O_SF = Surface finish for operation
- O_TOL = Tolerance for operation
- W_O_C = Width of cut for operation
- H_D = Hole diameter
- H_LD_R = Hole l/d ratio
- ST_CUTTING_OIL = Straight cutting oil
- WATER_SOL_OIL = Water soluble oil
- LMD = Low to medium duty, as in cutting fluid specs
- HD = Heavy duty, as in cutting fluid specs
- NS = Non sulphur, as used in cutting fluid specs

ALGORITHM NOMENCLATURE

- MOS.DAT = Machine suitability data base
- TOS.DAT = Tool suitability data base
- TWK.DAT = Tool life equation parameter data base
- OPER.DAT = Tool size and life data base
- WKPAR.DAT = Operational parameters (feed, speed, cut etc) data base
- MHP.DAT = Machine power data base
- SF.DAT = Surface finish data base
- NUM.DAT = Data base containing information on number of machines, tools, and components.
- ONUM.DAT = Data base containing the number of operations per component.
- OPID.DAT = Operation identification data base

- TCOST.DAT = Tool cost and regrinding data base
- LABOR.DAT = Labor rate data base
- PROF.DAT = Job profile data base
- JSET.DAT = Job setup data base
- TSET.DAT = Tool setup data base
- MSET.DAT = Machine setup data base
- COMP.DAT = Data base containing number of components and lot sizes.
- MOS = Machine suitability for each operation for all components
- TOS = Tool suitability for each operation for all components
- JMPROF = Profile of each job on each machine, for each operation
- M = Number of machines
- O = Number of operations per component, for all components
- T = Number of tools
- C = Number of components
- UNITS = Lot size
- OPID = Identification number of each operation
- CNUM = Identification number of component
- DU1,DU2,DU3,DU4 = Dual variables in optimizing algorithm for turning
- CU = unit cost per operation
- V = Cutting speed
- F = Cutting feed
- THRFD = Cutting feed for threading
- TRTCS = Tool costs for turning
- TRMTM = Machining time for turning
- TRTTM = Tool changing time for turning
- TRFAIL = Tool failure rate for turning
- TLIFE = Tool life for turning
- MLMTM = Machining time for milling
- MLMCS = Machining costs for milling
- MLTEE = Number of teeth on the milling cutter

- MLTTM = Tool changing time for milling
- MLFAIL = Tool failure rate for milling
- TRMCS = Machining costs for turning
- MLTCS = Tool costs for milling
- MLSCS = Setup costs for milling
- MLIFE = Tool life for milling
- DRMTM = Machining time for drilling
- DRMCS = Machining costs for milling
- THRCUT = Length of cut in threading
- DRTTM = Tool changing time for drilling
- DLIFE = Tool life for drilling
- DRFAIL = Tool failure rate for drilling
- DRTCS = Tool costs for drilling
- DRSCS = Setup costs for drilling
- FCMTM = Machining time for facing
- FCCUT = Length of cut for facing
- FCFD = Feed for facing
- FCMCS = Machining costs for facing
- FCTTM = Tool changing time for facing
- FCFAIL = Tool failure rate for facing
- FCLIFE = Tool life for facing
- FCTCS = Tool costs for facing
- FCSCS = Setup costs for facing
- TPI = Threads per inch
- A,N,MC,P,C3,C4,B,D,E,G,H,I = Parameters for tool life equations
- TPMTM = Machining time for tapping
- TPTTM = Tool changing time for tapping
- TPFAIL = Tool failure rate for tapping
- TPMCS = Machining costs for tapping
- TPLIFE = Tool life for tapping

- TPTCS = Tool costs for tapping
- TPSCS = Setup costs for tapping
- THMTM = Machining time for threading
- THTTM = Tool changing time for threading
- THLIFE = Tool life for threading
- MHP = Machine power
- SFREQ = Surface finish
- THFAIL = Tool failure rate for threading
- THMCS = Machining costs for threading
- THTCS = Tool costs for threading
- THSCS = Setup costs for threading
- GRMTM = Machining costs for grinding
- GRLIFE = Tool life for grinding
- DE = Depth of cut in turning
- GRWTM = Tool changing time for grinding
- GRFAIL = Tool failure rate in grinding
- GRMCS = Machining costs for grinding
- GRWCS = Tool costs for grinding
- GRSCS = Setup costs for grinding
- THRSP = Cutting speed for threading
- LR = Labor rate for each machine and each operation
- JSETUP = Job setup times for each operation on each machine
- MSETUP = Machine setup time for each operation
- TSETUP = Tool setup time for each tool on each machine
- TCOST = Cost of tool
- TSHARP = Number of resharpening + 1 for solid or brazed tools, Number of cutting edges for inserts.
- JDIA = Diameter of job
- TRLCUT = Length of cut for turning
- MLDIA = Diameter of milling cutter

- DLDIA = Diameter of drill
- TAPDIA = Diameter of tap
- MLCUT = Length of cut in milling
- DLCUT = Length of cut in drilling
- TAPCUT = Length of cut in tapping
- MLSPD = Cutting speed for milling
- MLFD = Cutting feed for milling
- DLSPD = Cutting speed for drilling
- DLFD = Cutting feed for drilling
- TAPSPD = Cutting speed for tapping
- TAPFD = Cutting speed for tapping
- GRCUT = Length of cut in grinding
- GRFD = Cutting feed for grinding
- TRSPD = Cutting speed for threading
- TRFD = Cutting feed for threading
- TC = Total cost per unit
- BRSPD = Cutting speed for boring
- BRFD = Cutting feed for boring
- BRCUT = Length of cut in boring
- BLIFE = Tool life for boring
- BFAIL = Tool failure rate in boring
- BRMTM = Machining time for boring
- BRMCS = Machining costs for boring
- BRTTM = Tool changing time for boring
- BRTCS = Tool costs for boring
- BRSCS = Setup costs for boring
- 1 = Engine lathe
- 2 = Turret lathe
- 3 = Single spindle automatic lathe
- 4 = Numerical control lathe

- 5 = Horizontal milling machine
- 6 = Vertical milling machine
- 7 = Numerical control milling machine
- 8 = Horizontal boring machine
- 9 = Cylindrical grinding machine
- 10 = Surface grinding machine
- 11 = Vertical drill press
- 12 = Radial drilling machine
- 13 = Turret drilling machine
- 1 = High speed steel boring tool, T15
- 2 = High speed steel turning tool, M42
- 6 = Carbide turning tool, C2
- 7 = Carbide boring tool, C3
- 12 = High speed steel milling cutter, M3
- 14 = Carbide milling cutter, C2
- 18 = High speed steel drill, T15
- 19 = Carbide drill, C2
- 23 = High speed steel tap, M10
- 25 = Carbide tap, C2
- 27 = Medium grade grinding wheel
- 30 = High speed steel threading tool, M42
- 32 = Carbide threading tool, C2