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A flexible tool selection decision support system for milling operations

I.D. Carpenter*, P.G. Maropoulos

School of Engineering, University of Durham, South Road, Durham DH1 3LE, UK

Abstract

Competitive cutting tool manufacturers are now facing increasing demands to supply a comprehensive advice service with relation to selection of appropriate tools and cutting data for a wide variety of workpiece materials and component geometries. This paper describes the development of methods and a computer based system for automated machinability assessment and tool selection for milling. The system is called OPTIMUM (Optimised Planning of Tooling and Intelligent Machinability evalUation for Milling) and is designed to provide reliable tool selection and cutting data for a range of milling operations. The machinability assessment method employs rule based decision logic and multiple regression techniques to produce feasible initial cutting conditions for a wide range of workpiece materials. A novel feature is that a wide variety of input data is permitted, including imprecise or incomplete workpiece descriptions. The tool selection process features the selection of tools based upon optimised machining performance. A new optimisation criterion related to initial average chip thickness, called *harshness*, is proposed. Unlike most CAPP systems, a large variety of workpiece materials (more than 750 ferrous alloys) and a comprehensive selection of tools (potentially 35 988 cutter/insert combinations) are considered. A tool variety reduction post processor facilitates the rationalisation of sets of selected tools to produce optimised tool sets for a limited number of available tool positions on a machining centre. The combination of knowledge based logic and statistical methods provide a powerful and flexible support tool for the process planning of milling operations.

Keywords: Milling; Process planning; Tool selection

1. Introduction

Over the last few decades, the range of engineering materials encountered in machine shops has increased greatly, as has the variety of cutting tools that are capable of machining these materials. Unfortunately, even as the demands placed upon the metal machining industry have broadened, the level of experience amongst process planners and machine operators has been falling due to natural wastage, the decline of apprenticeship schemes and increasing levels of automation. Therefore, it has become increasingly important for cutting tool manufacturers to provide a complete range of technical support for their products, including machinability information, tool selection and specification of cutting conditions.

Recent advances in computer hardware and software technology have led to research in calculation of efficient cutting parameters and selection of a tool or combination of tools for a specific operation or set of operations [1]. Most systems require that some form of applied mathematical model is used to simulate the milling process [2]. In the last decade, much attention has been paid to the possibility of using indeterminate and artificial intelligence techniques to select process parameters in intelligent machining environments [3].

The ongoing globalisation of many engineering markets has also introduced a particular problem in the recognition of a wide range of material standards. A machining jobbing shop may have to cut materials from a great variety of source countries. Some form of computer based assistance for the technical support of tooling manufacturers customers is required.

This paper describes the methods developed for the OPTIMUM decision support system [4]. The data intensive nature of the tooling support problem necessitated the development of the system as a series of integrated software modules written in Microsoft FoxPro and running under Microsoft Windows on a PC. The following sections describe the overall structure of the system and detailed information about each of the main functions available.

2. Overall system description

The OPTIMUM decision support system is designed to provide several functions to assist a process planner,

* Corresponding author.

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Nomenclature

a_a	axial depth of cut (mm)
B	radial width of cut (mm)
C_1	a constant in the tool life equation for any combination of material and insert grade
c_{total}	total cost of machining operation (£)
h_{max}	maximum average chip thickness for a cutter (mm)
h_{min}	minimum average chip thickness for a cutter (mm)
h_{zm}	average chip thickness (mm)
L	length of cut (mm)
m	metal removal rate (mm^3/min)
n_i	number of inserts on a cutter
ϕ_s	engagement angle of cutter (°)
q	level of harshness for initial average chip thickness
s_{eq}	equivalent feed rate (mm/min)
s_z	Feed per tooth (mm)
t_3	insert change time (min)
T	nominal tool life (min)
T_{exp}	expected tool life (min)
v	tangential cutting velocity (m/min)
w_c	weighting factor applied to total operation cost in tool sorting
w_m	weighting factor applied to metal removal rate in tool sorting
w_{rank}	total ranking weight applied to a tool and associated cutting parameters
w_T	weighting factor applied to tool life in tool sorting
w_{time}	weighting factor applied to total operation time in tool sorting
x	constant rate of machine tool (£/min)
y	cost per set of cutting edges (£)
Greeks	
α	exponent affecting the cutting velocity in the tool life equation
β	exponent affecting the feed per tooth in the tool life equation

production engineer or tooling support engineer. These functions include:

1. Straightforward geometry input for machining operations.
2. A flexible workpiece material description method including automatic material classification from incomplete data.
3. Machinability assessment to produce initial cutting data for a wide range of input data.
4. Optimised calculation of cutting data.
5. Rapid tool selection by applying user-defined criteria.
6. Tool variety reduction to produce tool sets of limited size.

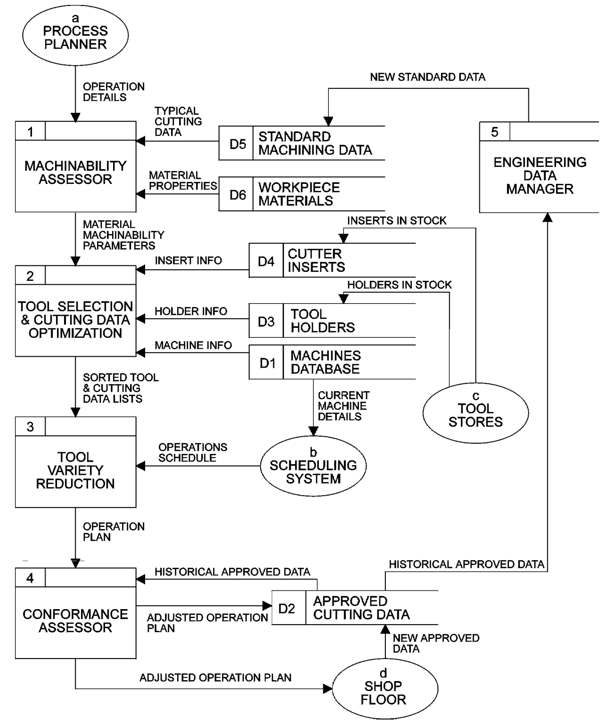

Fig. 1. Functional layout of the OPTIMUM system.

7. Feedback of approved data from shop floor into the system to enhance data accuracy in the future.
8. Robust data driven software design to facilitate maximum flexibility of operation.

Many of these functions are implemented in separate software modules that can be executed individually. However, the best results can be obtained when running the whole set of modules as many of the modules produce data that can be acted upon by other modules. The overall functional layout is shown in Fig. 1.

Many modern CAM and CAPP systems have been built up from CAD origins and feature complex geometry based functionality. However, the rate of development of tool selection and cutting data optimisation functions has been rather slower. This is possibly partly due to the complexity of maintaining an efficient tool management information system with which any automated tool selection and cutting data generation systems can interface.

The combination of a decline in personal machining knowledge and the relative paucity of quality tool selection functions in modern CAD/CAM software has led to an increased requirement for expert advice about finding efficient tooling solutions. This customer need is most often satisfied by tooling manufacturers who can use this form of after sales service to leverage further tool sales and establish market presence. It is no longer enough just to provide a set of tools: customers are increasingly likely to demand a complete package of high performance tools and expert advice on usage and maintenance. Many tool manufacturers are also now providing free user friendly software packages which can provide cutting data solutions such as the SecoCut package provided by Seco Tools (http://www.secotools.se). However, these tools tend not to provide tool selection advice and cutting data calculations are often based upon a small and conservative selection of proven speeds and feeds. Tool manufacturers possess substantial amounts of cutting test data and it is such a database (from Seco Tools (UK) Ltd.) that is used by the OPTIMUM system.

It is interesting to note that, as concurrent engineering methods for rapid product development gain acceptance, there may be a need for simple machining data much earlier in the development cycle [5]. The ability of the OPTIMUM system to provide tool selection and cutting data advice even with approximate or incomplete input data makes it well suited to assisting in '*what-if*' analyses at these early stages when exact product materials and geometries are not yet finalised.

3. Operation definition

One of the main input data requirements of the OPTIMUM system is a description of the geometry of the milling operations to be considered. Currently a simple icon based interface is used to input these data records. Individual milling operations within a component may be added or edited using the interface shown in Fig. 2. It is worth noting that, unlike traditional CAPP systems, this method of operation definition allows two levels of detail requirement. To execute the machinability assessment method, a complete operation definition is not required. The minimum data required is an operation type and an indication of the type of operation, such as roughing, semi-roughing or finishing. Typical values of axial depth of cut for these three operation subtypes are 8, 4 and 1 mm, respectively. This method of flexible operation definition allows rapid evaluation of the likely machinability characteristics of an operation even when a complete description of the operation geometry is not available, such as during the conceptual design stage. The ability to produce feasible cutting data at the earliest stages of the product development cycle is useful when attempting to implement concurrent engineering methods, as process planning information is required much earlier in the product cycle than in a more traditional engineering development environment.

For effective tool selection and cutting data optimisation, exact operation dimensions are required to facilitate comprehensive geometric suitability checking of tools.

4. Machinability assessment

This section describes the rationale, algorithm and implementation of the machinability assessment module of the OPTIMUM system. The module produces initial cutting conditions for a wide range of material and tools. The method is data driven and highly flexible and tolerant, enabling it to function effectively with a large variety of input data including incomplete or imprecise data. The

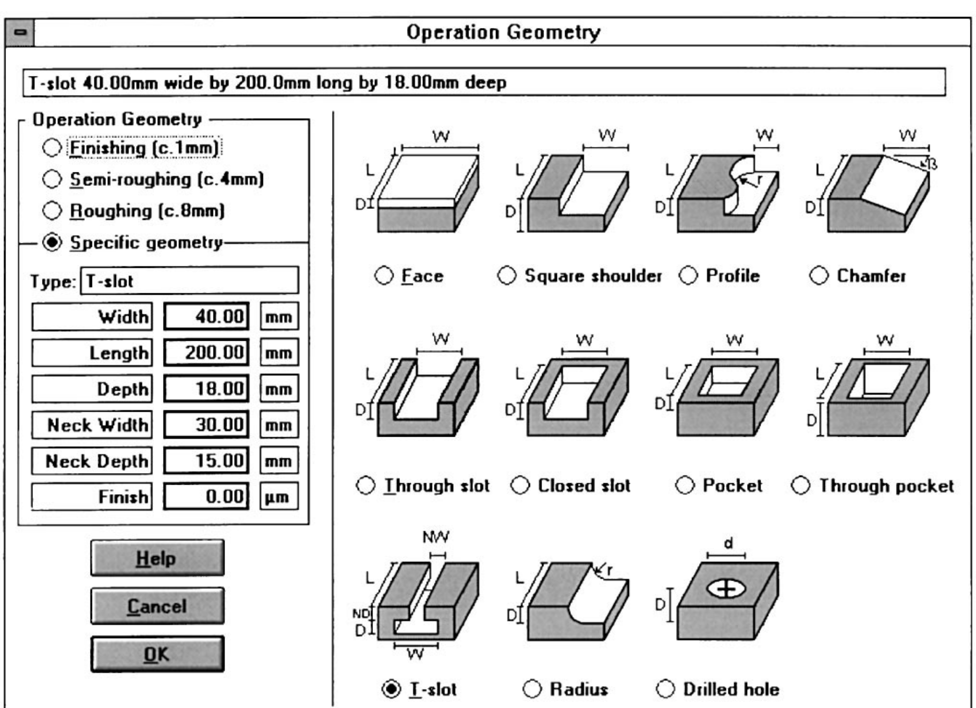

Fig. 2. Operation definition interface.

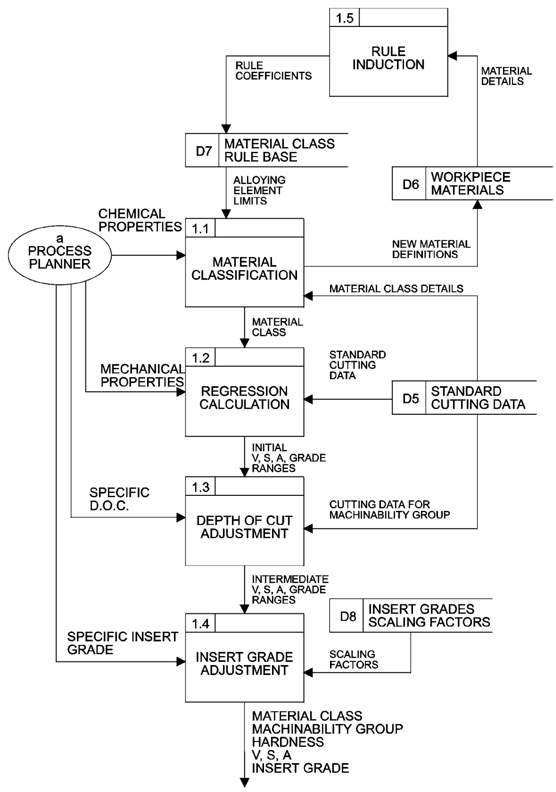

Fig. 3. Machinability assessment module.

workpiece material can be specified in one of the three ways: by standard designation, by general material type or by partial or complete chemical composition. In the latter case, a rule based system is used to classify the material within a group of similar materials. Cutting data is then calculated using multiple regression techniques on a database of cutting conditions relating to the selected material group. Finally the user may specify adjustments to the cutting data to accommodate specific insert grades and exact values of depth of cut. The overall structure of the algorithm is shown in Fig. 3.

The system is implemented in a completely data driven fashion. For instance, a new type of milling operation may be implemented by adding a record to the operations table. The system maintains all its databases in the dBase-compatible FoxPro file format, so data can be easily prepared or edited using a wide range of available database management tools. The main material composition table contains an initial range of over 1500 engineering alloys divided into 56 main classes of material. These groups are further divided into 198 machinability groups, each of which is related to a set of typical cutting data for roughing, semi-roughing (medium roughing) and finishing. Data is provided for various values of surface hardness and types of surface conditioning, such as cold drawn, annealed or quenched and tempered.

Initial cutting data of this type has been collected from various machining handbooks and tool manufacturers' documentation for all the main types of milling operations such as facing, slotting and end milling. Supplementary databases contain more unusual materials such as high alloy aerospace steels. As new data is gathered and added to the databases the initial standard data can be purged to enhance the accuracy of the cutting parameters generated.

4.1. Rule based material classification

An important operation to be performed is the classification of the material by its chemical composition. Researchers have determined simple relationships between the amounts of alloying elements and typical machining parameters [6]. However, most attempts to relate the 20 or more critical alloying elements to cutting data inevitably leads to failure as the range of chemical compounds and structures that affect machinability is found to be too wide for any consistent mathematical relationship to emerge. Therefore a method of categorising a material into a small group which exhibits consistent machining characteristics is required.

The material is classified by applying a set of rules relating chemical composition to machinability group. These rules are automatically generated from the main materials data table using a rule induction system that forms a part of the Crystal expert system shell. The output of the rule induction system is a text file containing rules of the form shown below.

```
Machinability_Group_No is 4 (free
machining carbon steels, wrought —
medium carbon resulfurised)
IF Si is less than 0.275
  AND NOT P is less than 0.025
  AND C is less than 0.575
  AND NOT C is less than 0.295
  AND Fe is less than 98.515
OR Si is less than 0.275
  AND NOT P is less than 0.025
  AND Fe is less than 98.620
  AND NOT Fe is less than 98.515
  AND S is less than 0.075
```

This text based rule file is to produce a summary data table, as shown in Table 1. This lists the minimum and maximum values for each alloying element within each machinability group.

Table 1
Machinability group rules in table form

Machinability group	Fe minimum (%)	Fe maximum (%)	C minimum (%)	C maximum (%)	etc.
4	0.000	98.515	0.295	0.575	....
4	98.515	98.620	0.295	0.455	....

As can be seen in Table 1, there may be several different rules all relating to the same machinability group. The default minimum and maximum values are 0 and 100% to allow any material to fulfil a rule which does not specify limits for all the alloying elements. The chemical composition given by the user is used to search the rules table for all the machinability groups that the material might lie within. Generally only one rule will be fulfilled but on the rare occasion that several machinability groups are possible the user is prompted with details of each group and asked to select which he believes to be more suitable.

As new materials are added to the main materials database it is possible to automatically regenerate all the rules to further refine the accuracy of the material categorisation process.

4.2. Cutting data calculation using regression techniques

After a material has been categorised into a machinability group it is possible, using details of hardness or conditioning, to suggest initial cutting data for standard depths of cut (corresponding to finishing, semi-roughing or roughing) and standard tool materials by extracting the information from the cutting data database. However, the cutting data database is generally only a conservative guide and some further modification of the cutting data is usually required to customise it for specific operation details.

As cutting data is only stored for certain discrete values of hardness multiple regression is applied to the stored cutting data to generate a mathematical relationship between material hardness and the critical cutting parameters, such as cutting velocity, feed rate and the corresponding metal removal rate. This regression equation is then used to generate a more precise value of the cutting parameter with regard to an exact value of hardness, as can be seen in Fig. 4. A similar technique is used to interpolate a value for feed and for cutting velocity for non-standard depths of cut.

The cutting data database holds information for generic ISO standard carbide grades. The user may want to use a particular more efficient grade and in this case the cutting data is converted using a table of scaling factors derived from statistical analysis of manufacturers' data.

5. Performance based tool selection

OPTIMUM features a performance based tool selection module [7,8]. The tool selection procedure within OPTIMUM operates by calculating optimised cutting data for all the available cutting tools and then sorting them by a set of user-defined criteria to give the preferred tool as shown in Fig. 5.

The process constraints implemented in the OPTIMUM cutting data optimisation procedure are as follows:

1. Tool class suitability;
2. Geometric tool suitability (tool diameter, approach angle, etc.);
3. Insert grade suitability;
4. Chip evacuation suitability (cutter rake angles);
5. Tool height;
6. Tool life;
7. Harshness of chip thickness;
8. Axial and radial depth of cut usage;
9. Surface finish;
10. Available spindle power;
11. Available spindle speeds;
12. Available range of table feed rates.

Whilst it is quite possible to implement this algorithm by hand, the large number of possible cutter and insert combinations combine with the iterative optimisation procedure to make this an impractical task. However, it is ideally suited to realisation in software form. The cutting data algorithm is of an iterative form and is applied to each of the available and

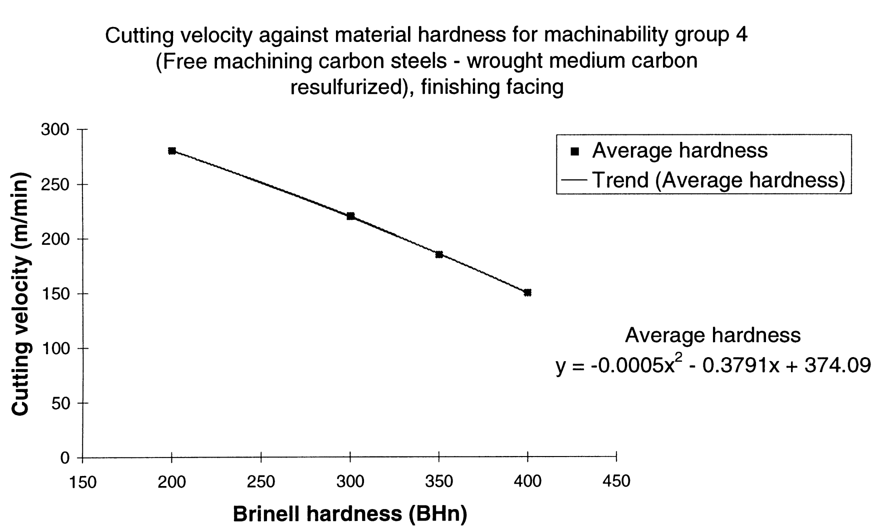

Fig. 4. Using regression curves to calculate cutting velocity for a given material hardness.

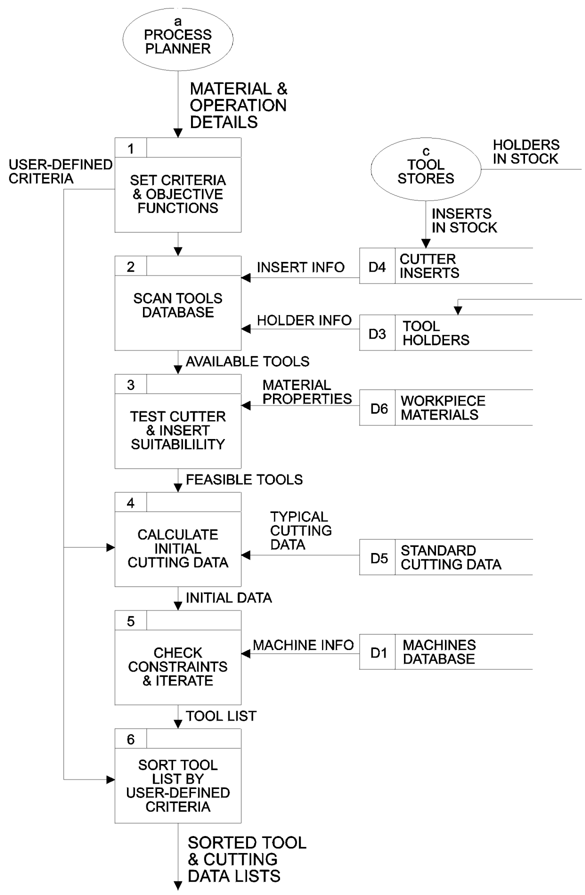

Fig. 5. Layout of the cutting data optimisation and tool selection algorithm.

feasible tools to produce a list of possible tools and associated cutting data. The algorithm contains four main procedures:

1. Cutter and insert suitability checking;
2. Evaluation of the initial cutting parameters;
3. Optimisation of the cutting parameters;
4. User-defined tool sorting.

The following four sections briefly describe these procedures.

5.1. Cutter and insert suitability checking

It is important to only consider tool holders and inserts which are suitable for the milling operation under consideration. The first check is that the tool holder is of a suitable overall type (e.g. facing cutter, end mill). Certain critical dimensions of the cutter must also be checked against the shape of the operation, such as effective cutter radius and gauge length. The overall size of the tool must also be suitable to fit into the machine tool. The rake angles of the holder are checked for suitability with respect to the workpiece material. For example, face milling aluminium requires a positive geometry of cutter with an axial rake of about +15° and a radial rake of about +15°. A set of sample rules derived from Sandvik [9] is shown in Table 2.

Table 2
Cutter geometry selection guidelines

Area of application	Axial rake	Radial rake
General face milling (not for very hard materials)	+7°	+2°
Heavy duty face milling (not cost efficient for light machining)	+12°	−8°
Face milling of hard materials (increased power and tool loading)	−6°	−7°
Face milling aluminium alloys	+15°	+15°

The insert grade is tested by comparing the ISO carbide application designation of the workpiece material with the range for which the insert is suitable. One of the last checks is to calculate the ratio between the overall effective cutting area of the cutter and the overall area of the operation. This ratio is compared with user-defined minimum and maximum values in order to eliminate tools that are either very small or very large compared to the operation dimensions.

5.2. Evaluation of the initial cutting parameters

Having selected which of the available holder and insert combinations are broadly suitable for the milling operation, it is necessary to calculate an initial set of cutting parameters, consisting of a radial depth of cut, axial depth of cut, feed per tooth, and cutting velocity.

The depths of cut are calculated by evenly dividing the operation dimensions by the maximum axial and radial depth of cut of the cutter and rounding to the next higher number of passes. Feed per tooth is derived from an initial value of chip thickness, h_{zm}, which is specified by the user as a harshness percentage, q.

$$h_{zm} = h_{\min} + \frac{(h_{\max} - h_{\min})q}{100} \tag{1}$$

A value of tool life is required in order to calculate cutting velocity. The expected tool life for minimum cost is given by the following equation:

$$T_{\exp} = (\alpha - 1)\left(\frac{n_{\mathrm{i}} x t_3 + y}{x}\right) \tag{2}$$

For maximum production rate, the expected tool life is given by the following equation:

$$T_{\exp} = (\alpha - 1) n_{\mathrm{i}} t_3 \tag{3}$$

Alternatively, the tool life may be set to a user-defined value. Having defined the tool life, cutting velocity can be calculated from the Extended Taylor's Equation, as shown in the following equation:

$$v = \left(\frac{C_1 \pi}{T_{\exp} \phi_s s_{\mathrm{eq}}{}^{\beta}}\right)^{1/\alpha} \tag{4}$$

5.3. Optimisation of the cutting parameters

The cutting data optimisation procedure in OPTIMUM is based upon the approach of initially generating data that is as aggressive as possible and then gradually reducing the severity of this data until all the active constraints have been satisfied.

In order for initial cutting data to be generated for a given cutter/insert combination, many geometric and material constraints must be satisfied. The most common process constraint that can be exceeded is the power requirement. If any process constraint was not satisfied in the previous sections it is necessary to reduce the severity of the cutting process. The three major parameters that can be changed to effect this reduction are average chip thickness, radial width of cut and axial depth of cut.

It is most economical to reduce these parameters in ascending order of impact on tool life and cost, i.e. chip thickness first, radial depth of cut second and lastly, axial depth of cut. Chip thickness is reduced by small increments through the useful chip thickness range of the cutter and cutting data is recalculated for each new value until all constraints are satisfied. If the constraints cannot be satisfied then the chip thickness is reset, the number of radial passes is increased by one and the process is repeated, as shown in Fig. 6.

When the optimisation recalculations are complete, the tool is either stored along with its associated cutting data or, if the constraints could not be satisfied, the tool is discarded.

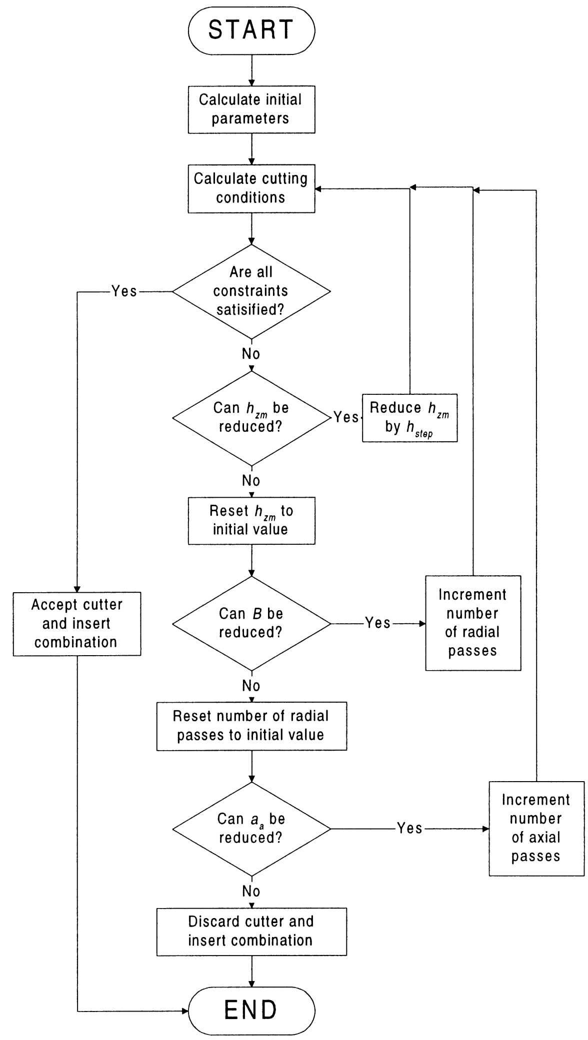

Fig. 6. Cutting data optimisation routine.

5.4. User-defined tool sorting

Having generated a list of possible tools along with associated optimised cutting conditions it is necessary to apply some form of user-defined sorting to the list in order to produce some best choice tools and to fulfil the function of tool selection as well as cutting data calculation.

There are four main criteria for the tool selection sort weighting:

1. Maximum metal removal rate;
2. Maximum tool life;
3. Minimum overall cost;
4. Minimum overall time.

Each weighting is applied to a normalised value of each appropriate parameter and summed to give an overall weighting. The overall weighting factor is given by the following equation:

$$w_{\text{rank}} = \left(\frac{m}{\bar{m}} w_{\text{m}}\right) + \left(\frac{T}{\bar{T}} w_{\text{T}}\right) - \left(\frac{c_{\text{total}}}{\bar{c}_{\text{total}}} w_{\text{c}}\right) - \left(\frac{t_{\text{total}}}{\bar{t}_{\text{total}}} w_{\text{time}}\right) \tag{5}$$

This compound weighting factor is calculated for each tool in the feasible tool list. The list is then sorted by this weighting to give the preferred tool at the top of the list, based upon machining performance.

5.5. Tool variety reduction

The tool selection procedure described in the previous section is highly effective for calculating optimised cutting data and selecting a tool for a single operation according to a variety of user-defined criteria. However, tool selection in an industrial environment should not be considered purely as a one stage operation. In reality there are two sets of constraints to be considered. Firstly there are the process constraints that dictate the cutting conditions for any given tool and secondly there is the need to make best use of a tool within the work scheduling framework of a multi-job environment. Research at UMIST has produced modules for the TECHTURN process planning system that perform tool variety reduction and wear balancing for turning tools [10,11]. Further work at UMIST has refined the calculation of the overall cost of various feasible sets of milling tools [12].

This section describes a post processor for the tool selection method of the OPTIMUM system that rationalises the selected tools for a given set of operations on one or more components so as to reduce tool setup times and more effectively derive the optimum tool set for a given batch of components.

There are several main reasons for the reduction of variety within a tool list.

1. Machining centres have a limited number of tool positions available for automatic tool changing and a component may require more unique tools than that number.
2. There may be a desire to reduce costs by controlling the level of tool inventory.
3. It is important to manage the tool life usage of individual tools to reduce the number of machine stoppages due to tool wear.
4. For tools with high tool life usage, it may be possible to add duplicate sister tools to the tool carousel to reduce the number of tool change stoppages.

As the tool selection process in OPTIMUM considers all the available tools, for any given operation optimised cutting data exists in the tool list for all feasible tools. The process of finding substitute tools is thus reduced to a searching problem across all the possible combinations of tools that could be selected from a set of tool lists.

All the tools in the stored tool lists have associated optimised cutting data and a weighting factor that was used to sort the list into an order of preference. As these weighting factors reflect the preferred performance characteristics of individual tools, they can be used to evaluate the performance penalty of substituting tools to reduce tool variety. The tool lists are scanned to generate each possible tool set. For each possible set of tools, the associated weighting factors are summed and stored with the tool combination. The reduced tool sets are then sorted by this combined weighting factor to give the rationalised tool set that gives the least reduction in overall performance, as defined by the user. If each tool is selected from all the available tools, this variety reduction approach is guaranteed to produce all the possible tool sets that satisfy the constraint of a limited number of available tool positions.

Table 3
Tool list with tool selection weighting values

Facing operation		Shoulder operation		Slot operation	
Tool	Weight	Tool	Weight	Tool	Weight
Tool A	2284	Tool G	2962	Tool E	1746
Tool B	1778	Tool H	2952	Tool A	686
Tool C	1768	Tool A	2402		
Tool D	1170	Tool J	2098		
Tool E	956				

Table 4
Sorted list of rationalised tool sets

Tool set	Combined weighting
AGA	5932
AHA	5922
EGE	5664
EHE	5654
AAA	5372
EAE	5104
AJA	5068
EJE	4800

As a simple example of this procedure, the tool lists for three different operations (facing, shouldering and slotting) are shown in Table 3 along with the associated weighting values generated in the tool selection procedure.

The rationalised tool sets to reduce the number of unique tools to two or less are the following combinations: AGA, AHA, AAA, AJA, EGE, EHE, EAE, EJE. For each of these tool sets, the weighting factors of the constituent tools are summed to give a combined weighting value for the tool set. Ordering the tool sets by combined weighting gives the list or rationalised tool sets shown in Table 4.

It can be seen that, for this example, the rationalised tool sets that gives the least decrease in machining performance comprises tools A, G and A again. It is interesting to note that the over-rationalised tool set of just tool A for all three operations appears some way down this list as the performance decrease entailed with two tool substitutions is often greater than that found with only one tool substitution.

6. Results

An example of the use of the machinability assessor is presented in this section. Detailed examples for the performance based tool selection module [7] and the variety reduction module [8] are given in other papers.

6.1. Machinability assessor example

In order to test the ability of the machinability assessor to function using varying amounts and levels of detail of input data, the test operations are taken from real field test reports generated by engineers from Seco Tools, UK. These field tests are carried out at customers' premises and are often used to demonstrate the superior performance and lower cost of a Seco tool set over the standard tool set being used. Field tests are also a vital element of the process of introduction of a new tool into the marketplace. These field test reports feature a wide variety of recorded data. It is interesting to note that, even with a standard data collection form as used by Seco, the data obtained can vary considerably in accuracy and completeness.

It is also worth considering how these field tests are conducted. Generally, the tool engineer does not try to

Table 5
Machinability assessor output

	v (m/min)	s_z (mm)
Field test	170	0.20
Machinability assessment (135 BHN)	201	0.30
Machinability assessment (185 BHN)	185	0.28
Machinability assessment (235 BHN)	164	0.23

achieve OPTIMUM cutting conditions immediately but rather, a process of gradual adjustment is used to try to achieve cutting parameters that give a higher performance than the standard data in use at that particular facility. The main parameter that is varied is cutting velocity. Feed per tooth is generally set to a conservative value that is expected to be safe and then the cutting velocity is altered. One of the main advantages of a CAPP system is that it is possible to manipulate many independent variables to produce optimised data, a feat that is difficult to achieve manually.

The test operation setup is as follows:

Operation	Facing
Material	S/Steel 304
Hardness	
Seco Group	9
Machine	Giddings Lewis & Fraser
Power	Adequate
Condition	Average
Coolant	Dry
Cutter No.	R220.13.0125-12
Inserts	SEKN 1203 AFTN T25M

The critical operation dimensions were:

a_a (mm)	2
B (mm)	50
L (mm)	3650

The output of the machinability assessor, along with the actual field test figures are shown in Table 5.

The specified material, stainless steel 304, is classified as a wrought austenitic stainless steel. As no value for surface hardness is provided, the assessor provides a set of cutting data for the range of expected hardness values for this material group (135–235 BHN). The worst case scenario is the highest surface hardness and this presents cutting data that is comparable, although a little higher, to the final result of the field test. The other preliminary cutting data presented in the field test report is lower than the final cutting data so it seems likely that the eventual values were not arrived at by a process of reduction.

7. Summary and conclusions

A decision support system for process planning milling operations called OPTIMUM has been developed. The system is designed to be of use to process planners and, in particular, to the support functions of tool manufacturers. The system features a combination of rigorous mathematical modelling of the machining process and more flexible rule based and statistical methods.

In providing an continually increasing range of support services to their customers, tool manufacturers are often faced with poor descriptions of machining jobs and unusual workpiece materials. Unlike most traditional CAPP systems, the machinability assessor in OPTIMUM allows the generation of conservative initial cutting data from incomplete or fuzzy input data. As the system is implemented according to the theory of *data driven design*, the performance of the machinability assessor can be upgraded by adding more company specific historical cutting data to the main data tables.

If detailed information about the milling operation under consideration is known, the tool selection module of OPTIMUM can be used to select the best tool for the job relative to machining performance. Optimised cutting data is calculated for each feasible tool. It is worth noting that this optimisation algorithm is *not* designed to produce the most highly optimised cutting data possible. It is intended just to optimise cutting data for the tool selection process. Thus, a slightly relaxed cutting process model is used to enhance the performance of the implementation (cutting data may be calculated for many thousands of possible tools). Efficient machining performance can be measured in several ways (e.g. minimum cost, maximum tool life, maximum production rate) so the selection of the preferred tool is performed by sorting the list of feasible tools (with associated cutting data) by a compound objective function defined by the user. Industrial performance criteria may not be as simple as minimum cost all the time.

Although the OPTIMUM system is effective at selecting individual tools for specific machining operations, the efficient use of modern machining centres requires the selection of tools for a set of operations on a component. As automatic tool changing systems feature a limited number of tool positions, a post processor for the tool selection procedure has been developed to reduce the number of unique tools selected for a set of operations.

In conclusion, the provision of support information to by tooling manufacturers to their customers is a demanding task with large amounts of tool specific data and often incomplete or poor descriptions of the actual machining operations being considered. A decision support system like the one described in this paper can assist in providing good quality tooling advice to a wide range of customers.

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