SELECTION OF ALTERNATIVE CUTTING TOOLS FOR PART FEATURES OF PRISMATIC COMPONENTS AND THEIR EFFECTS ON OPERATION SEQUENCE

T Dereci and I H Filiz
University of Gaziantep, Turkey
A Baykasoglu
University of Nottingham, UK

ABSTRACT

This paper outlines an integrated system called optTOOL, which is capable of selecting the best tool among many alternatives that can work with optimum parameters, while minimising the number of tool changes and/or tool travelling distance within a set-up, as well. Tool selection procedures are directly interacted with the optimisation procedures in order to control fitness of optimised cutting parameters to the selected cutting tools simultaneously. The outstanding characteristics, stages and rules in each of the basic modules of the developed system are also discussed.

INTRODUCTION

Recent research and development in manufacturing has the objective of increasing productivity and cost effectiveness by integrating many activities in a global CIM (Computer Integrated Manufacturing) system. For this purpose, an advanced production system called IMS (Intelligent Manufacturing System) is oriented towards the needs of the 21st Century and designed to maintain and improve the vitality of the manufacturing sector, the cornerstone of all economic activities. Ensuring that manufacturing remains an attractive industrial area, IMS is described by Bell (1) as a system which takes intellectual activities in manufacturing and improves productivity by systematising, optimising and flexibly integrating those corporate activities. CAD (Computer Aided Design) and CAM (Computer Aided Manufacturing) are two of the important activities to be amalgamated in a typical CIM environment. It has been recognised that this integration requires the development of an intelligent process planning system. Dereci (2) has defined CAPP (Computer Aided Process Planning) as an interface in a typical CAD/CAM integration which consists of the determination of processes, tools and parameters required to convert a blank into a finished part and declared Tool Selection as one of the basic modules of any process planning activity. Maropoulos (3) has recently pointed out the importance of tooling technology in process planning. Tooling has become the heart of manufacturing processes and one of the key steps in the process planning to increase productivity and to decrease the cost of machining while offering a superior quality in the highly competitive manufacturing area. So, effective selection of proper and productive tools for machining operations is vital to realise the objective of the IMS.

Many variables exist in a typical milling operation which is influenced considerably by the condition of all machines, tools, workpieces and requires awareness of various limitations such as: size, shape and strength of workpiece, rigidity, metal removal rate, chucking and fixturing, spindle speed and feed rate limitations, available power, holder overhang and cutting tool. One should take all of these limitations into consideration in order to perform a safe milling operation. Note that each of these parameters is interrelated with the other. For example, the size of a cutting tool is directly effective on the power required for cutting. It is worth emphasising that the cutting tool is one of the most effective and dynamic variables in milling process since it is the most flexible one (i.e., for a certain milling operation there are many alternative cutting tools to be employed). Figure 1 shows the three basic elements of a milling operation milling operation. Although it can be recognised that this flexibility makes cutting tool selection easy, unfortunately vice versa is also true. It is actually very difficult to select an optimum cutting tool for a particular milling operation that provides required surface quality, works well with the productive cutting speed, feed rate and depth of cut, and at the same time offers a long tool life and low total cost.

Choosing a cutting tool for a certain milling operation is a quite complicated task. There are actually three predominant parameters to be considered in any cutting tool selection procedure. They are: cost of cutter, productivity of cutter and quality of machined component. Each of these factors has its own impact on
the total cost of a milling operation. There may be often a need to make a compromise between these three factors. Apart from these which can be simultaneously controlled using some limitations with a selected objective function in an optimisation problem, there is another criterion: sequence of operations to cut the workpiece. Sometimes, a complicated milling work can even be accomplished with a single tool but machining time would be increased dramatically. However, selecting the most appropriate cutter for each of features on the component will result in a large tool set leading to higher number of tool changes in a machining session. There should also be a compromise between these two aspects by using different optimisation strategies like minimisation of number of tool changes and tool travelling distance. In order to make such optimisations, alternative tools should be assigned for each of machining operations.

As can be seen from the preceding paragraphs it can be stated that tool selection itself is not so efficient when it is considered as a separate block (i.e., when a tool selection module can not interact with the optimisation block simultaneously in each stage of the decision mechanism in a typical process planning system in which only a single cutting tool is assigned for each of operations and then cutting conditions are optimised accordingly). It should be effectively integrated and fed back with the optimisation block in order to satisfy a consensus between the limitations and optimisation strategies mentioned in above paragraphs. Therefore, an intelligent cutting tool system can select the optimum tool for a particular operation among alternatives which works with the optimum cutting conditions. The number of tool changes and tool travelling distance within a set-up should also be minimised. This can only be achieved using an integrated approach in which tool selection procedures are supported with the optimisation procedures. Such systems should be also able to select alternative tools for the operations.

Many works have been reported on the cutting tool selection in the literature such as the works performed by Giusti et al. (4) and Domazet (5). However, no one has considered a parallel approach in which optimisation procedures were directly amalgamated with the tool selection and operation sequencing, while some of them have attempted to optimise the cutting conditions after selecting a tool for each operation. Moreover, only a few of them have considered the optimisation of sequence of operations in relation with the cutting tools. A detailed discussion is given by Kayacan et al. (6). Another conclusion which can be drawn from the literature survey is that although milling is one of the most common metal removal processes, there have not been so many studies on the tool selection and optimisation of cutting conditions for prismatic components as compared with those for the rotational parts. This is mainly due to problems in geometrical representation of the prismatic parts which are often of complex shapes and also complex nature of cutting mechanism in milling and wide spectrum of candidate cutting tools as with the lack of standardisation of tool holders. It has been also recognised from the literature that the developed systems on the selection of cutting tools are not able to suggest alternative tools for the part features (machining operations) which is one of the basic requirements for suggesting alternative process plans.

This work in the first place attempts to fill those gaps with an integrated system called OPITOOL which is composed of three basic modules: CTSS (Cutting Tool Selection System) which has a simultaneous feedback from CPOS (Cutting Parameter Optimisation System), and RTSS (Right Tool Selection System). The system has been developed in UGCMICEN (University of Gaziantep Computer Integrated Manufacture Centre). A simplified block diagram of the OPITOOL is shown in Figure 2.

On top of those three significant modules, there is a definition block in which the frame of selection and optimisation strategies as well as behaviour of the system are defined (Level 1 to 4 in Figure 2). Input to the system is a list of machining features extracted from a feature recognition system called FRS-PP which is extensively discussed in the article of Filiz et al (7). This list also provides some geometrical hints to the system like characteristic dimensions, datums and approach directions related to part features. Candidate tools are assigned from the selected tooling data base for each of the part features using the rules in the knowledge base of the system, while dynamically optimising cutting parameters. A single cutting tool is then selected for each of the features to optimise the sequence of operations by minimising the number of tool changes as well as the tool travelling distance.

The system is currently adopted to milling process and able to handle a wide spectrum of finished part geometries and cutters. Present system can select cutting tools from a general tooling data base which includes extensive ranges of cutters or from tooling libraries of machine tools, for more than forty simple part features, and also for combined features and arbitrary-shaped pockets with islands. However, it is open any further modification because of its modular structure. It can work either as a stand-alone system or as an integrated module in the process planning system called OPPS-PRI (An optimum Process Planning System for Prismatic Parts) which is currently under development in the University of Gaziantep.

**OPITOOL - OPTIMUM TOOLING SYSTEM**

This section is to give a brief introduction on levels, in which the strategies, families, machines and tools to be considered for the CTSS, CPOS and RTSS, are selected by the user as shown in Figure 2.
machining features that are input to the system, by using the rules structured within the system. However, if the mode interactive is selected, the decision on each parameter that affects the selection process can be changed or modified in each step of each level of the system. For example, CTSS normally assigns equal-pitch face mills for face milling operations. However, if the user know that the target machine (available machine) has poor axial bearings, he/she can assign an unequal-pitch (differential) type of cutter for the operation. It is worth here pointing that actually the optimisation block of the system eliminates these type of manual interventions as possible as, since it takes more than seven limitations into account.

Next level (Level 2) is for the selection of machining family. Integrated system is currently capable of selecting milling tools, but it has been designed such that it will easily be extended to cover other machining processes.

Level 3 actually stands for the selection of cutting strategy. Following options exist in this level:

1. only roughing with a roughing tool
2. only finishing with a finishing tool
3. both roughing and finishing with a single tool
4. both roughing and finishing with a roughing tool and a finishing tool, respectively

Level 4 deals with the identification of tooling and machine tool family. This stage is extremely important for determination of frame of selection mechanism and branching of algorithm. There are two alternatives:

1. available tools on existing machines
2. available or purchasable tools for possible machines

If the first option is selected, the system asks user to assign machine tool available on the shop floor. Since each machine has its own tooling library, the selection process is performed by scanning corresponding tooling libraries. In this case, machine tool selection facility within the system can be skipped over.

On the other hand, the second case is different. For example, emphasis is given here to the use of right tool at the productive cutting conditions by using a proper machine tool. Which machine tool is suitable to use the right tool for performing a particular milling operation is in question. Hence, in this case, machine tool selection activity plays a critical role in the system. There is no limitation for the number of tools to be used.

Level 5 consists of two modules: CTSS and CPOS which work interactively with each other. Level 6 stands for RTSS. The detailed information on these three basic components of the system is given in next sections.
CTSS - CUTTING TOOL SELECTION SYSTEM

- Specification of workpiece material
- Determination of cutter-type domain of features
- Determination of cutting tool material
- Determination of characteristic angles
- Determination of diameter of cutting tool
- Determination of length of cutting tool
- Determination of number of inserts

Specifications of tools

Search tooling data base to find the tools that satisfy specifications

○ Candidate cutting tools best satisfying
○ the required specifications

Figure 3: Block diagram of CTSS

CTSS - CUTTING TOOL SELECTION SYSTEM

Basic specifications of a typical cutting tool are: material type, rake angles, approach angle, diameter, number of inserts, length, insert information, coding number, etc. CTSS checks geometry of the component and determines basic tool specifications which are the basic characteristics of candidate tools to be selected from the tooling libraries of machine tools or from the general cutting tool data base that has been prepared by using catalogues of several tool manufacturers based on ISO coding scheme. After determining those basic characteristics, the tooling data base in use is searched to find candidate tools which fulfil the determined characteristics. The simplified block diagram of CTSS is given in Figure 3.

Stages in the determination of the tool specifications are explained below.

Specification of workpiece material. The first stage of the CTSS is the specification of workpiece material. The selection in this stage will affect the forthcoming decisions like tool material selection. The user has four alternative domains for the specification type of workpiece material:

1. ISO grades (P, M, K)
2. Designation in international standards
3. Designations of tool manufacturers
4. Direct specification of workpiece hardness or breaking strength

Whatever the type of domain is, selected grade can be expressed or converted into other domains except the last option. For instance, if the third option is used to enter the workpiece material with a special material group number, the corresponding designation in other domains can be found. The last option is somewhat different and can be used, if the user is not aware of the type of material, but knows breaking strength or hardness of the workpiece. In this case those values might also be converted in the other domains. However, this may be just an assumption and it is actually impossible to make such conversions exactly. This option is useful for small-scale shop floor applications in which just the tooling library of a single machine tool is employed for cutting processes.

Determination of cutter-type domain for features.

The cutters are usually designed for performing certain cutting operations. For example, a thread milling operation can not be accomplished with an end mill. However, some of the operations can use a few types of cutters. For example, a shoulder can be machined either using a shoulder mill or end mill depending upon the size and geometry. A slitting tool may also be used if the geometry is suitable. On one hand, there are a lot of factors to be considered in the determination of a proper tool type. The geometry of the features on the part has a considerable effect on the type of cutter. Figure 4 shows three different orientations of a step feature on a component. If the height and width of the step are of a relatively medium size and they are more or less equal as shown in Figure 4a, a shoulder mill and an end mill, etc., can be placed in the cutter-type domain of step feature. If the width of the step is small as compared with its height as shown in Figure 4b, an end mill is sufficient. But, if the height of the step increases, it is better to add a long-edge end mill to the cutter-type domain of step feature. If the width of step is large as compared with its height as illustrated in Figure 4c, in this case a slitting mill may also be added to the type domain of step. Therefore, it is not so reasonable to select the cutter types using some simple rules based on the type of features like: "if feature is a shoulder then cutter is a shoulder mill".
CTSS allows user to select the strategy in the determination of type of cutting. This is very important because it is directly related to optimisation of cutting conditions with the selected tool and reflected to all other sub-stages of the program. The following options are presented to the user:

1. select always a single tool for each feature
2. assign candidate tools from the tooling domain of feature

If the first option is selected, the system will always select a single cutter type for each of machining operation. (i.e., a face mill for a face milling process.) If the second option is selected, it assigns candidate type of tools from the tooling domain of the machining feature which is mainly related to the geometry of volume to be removed. For example, for a rectangular slot, this domain may have a slotting mill, a long-edge mill, shoulder mill and roughing mill, etc.

**Determination of cutter material.** This stage is closely related to the type of workpiece material selected.

The system enable the user to select three alternatives for the strategy to be used in the determination of cutting tool material:

1. ISO coding
2. Cutting materials of tool manufacturers suggested for different workpiece materials
3. Heuristics using hardness or breaking strength values of workpiece materials

Note that again, as in the specification of workpiece materials, whatever the type of selection made in this stage is, selected grades may be converted into other domains. ISO coding is used when the workpiece material was expressed in terms of ISO grades of P, M, K, etc. The second option is especially preferred when the workpiece material is specified in terms of designations of tool manufacturers. Cutting tool material selection within the system can also be based on the workpiece material hardness or breaking strength like: "if hardness is greater than 1500 N/mm² then cutter material is carbide" and "if hardness is smaller than or equal to 1500 N/mm² then cutter material is HSS".

High Speed Steel (HSS) and carbides are stated as the two most common cutting tool materials for milling operations in Machining Data Handbook (8). HSS is used generally for soft and ductile materials whereas carbides are used for harder materials. However, for extremely-hard workpiece materials, ceramic inserts should be the first choice. Coated inserts are also available to allow increased speeds and extended tool life in specific materials.

One question arising from above heuristic (rule) is about whether if a HSS tool can be used or not when the workpiece has a hardness of, say 1501 N/mm². According to heuristic, it can not be used. However, in practice it can also be used, since there is actually only a small difference between the threshold value and actual hardness. On the other hand, if the workpiece has a hardness of 2500 N/mm², it is certainly decided that a HSS tool can never be used for that operation. So, here the important parameter is the degree of hardness membership of the workpiece material. In order to solve this problem, a fuzzy logic should be applied. A proper cutting tool material can be selected depending upon the degree of hardness membership of workpiece material. A fuzzy system for cutting tool material selection is under development and the results of that system will be reported elsewhere.

**Determination of characteristic angles.** rake is the angle between the base and face of the measured in a plane perpendicular to the base. Rake angles have considerable effects on the cutting forces and power required to accomplish the operation. Larger rake angle leads to the lower the cutting forces and power consumption and better surface finish. Smaller rake angles are generally used for harder materials whereas
larger rakes are used for soft-ductile materials (8). Positive axial-rake and negative radial-rake combination can cut all materials well. Double positive geometry (positive axial-rake and positive radial-rake) is used for soft materials like aluminium. Double negative geometry (negative axial-rake and negative radial-rake) is most suitable for hard materials like cast iron. Rake angles are sometimes automatically assigned according to special rules structured in the algorithm. For example, if the workpiece is fragile, positive angles are used for both of the rake angles. If the type of tool is end mill, and length of cut is too long, then it is better to use positive and negative values for axial and radial rake angles, respectively.

The approach angle (entering angle) is one of the most characteristics parameters that affects the cutting forces produced on the machine, cutter and component. If the smaller approach angle is used, the smaller radial forces are generated. A 75 degree approach angle is the most universal as it can be used economically for roughing and finishing and also power efficient. On one hand, a 45 degree approach angle presents a stronger cutting edge for heavy duty machining. In this case, the axial cutting force will be more or less equal to the radial cutting force. Therefore, if a long spindle overhang is expected, 45 degree should be preferred. 45 degree approach angle is also suitable when milling cast irons in which edge frttering of the workpiece is a problem. The determination of approach angle also depends on the geometry of the part features. For example, is obvious that approach angle is directly taken as 90 degree when selecting a cutter for a square shoulder on the part.

**Determination of cutter diameter.** This stage is the most critical step in the determination of cutting tool specification. The diameter of the cutting tool is basically determined by the size of the feature to be machined. For hole features, the diameter is the diameter of the hole to be machined.

The determination of cutter diameter for face milling is the most complicated among the all milling operations. There is a wide range of diameters to be used and recommendations on this range vary from source to source or from manufacturer to manufacturer. For example, in order to get best result for face milling, Gileslin and Jones (9) have recommended that the cutter diameter should be 1.6 times the width of the region machined. Instead of 1.6, Ref. (10) gives 1.25, whereas in Ref. (11), a range (1.20-1.50) is given. Therefore, determination of the diameter of the face mill for a given width of cut is a fuzzy task. It is especially important for the power requirement of cutting. This problem is solved in such a manner that tool diameter is calculated by using the multiplication factor specified in the corresponding manufacturer's catalogue. If the diameter found is bigger than the biggest tool available in the tooling data base, biggest tool diameter available is selected.

![Figure 5: Dynamic tool selection technique for pockets](image)

A new approach for the determination of diameter of cutter(s) for pocket milling (roughing plus finishing - fourth option in Level 3) is developed. As shown in Figure 5, fillet radius of pocket (CR) has a critical effect on dynamic cutter size selection. The selection is performed by using following rules:

**Rule 1:** \[ |x| \leq \text{width of pocket} \] and,

**Rule 2:** \[ |y| \leq |\text{AD}| \text{ or } |\text{AE}| \]

The biggest tool which satisfy both rules is assigned as candidate roughing tool. Note that if the cutter diameter is equal to the width of cutter, this leads to a single cut, then a finishing operation. A smaller one completes the roughing in more than one cut (expectedly two) before the finishing operation. A single cutting tool which has a radius equal to fillet radius of pocket can also be selected for the pocket if the third option is selected in Level 3. So, selection strategy of tools for pockets depends mainly on option selected in the Level 3 as depicted in Figure 2.

When selecting an end mill for a milling operation, the workpiece material to be cut is an extremely important consideration. However, part (feature) configuration plays the most important role when determining the tool size. On one hand, since deflection is another important parameter to be kept in control when selecting an end mill, the most desirable tool size is assumed as the one which has the largest diameter with the shortest length.

CTSS can also select a single cutter for arbitrary-shaped pockets. Those pockets are described by borders like lines, circles with one or more islands inside the
boundary. The input data for pocket and islands are based on entity types like lines and circles, and starting and end coordinates of those entities. The entities of islands are also given numbers to recognise the different islands separately. The coordinates of the pocket boundary are given in counter-clockwise direction whereas coordinates of island(s) are given in the clockwise direction. After receiving the geometrical data which include the vertex coordinates of outer and inner entities, the system calculates the minimum distance in between islands, and between islands and pocket contours. The mathematical formulations have been available in various books on trigonometry in the form of minimum distance between a line and a point, between a line and an arc, and between arcs, etc. The minimum distance found is then used for the determination of maximal allowable cutter size for continuous milling. A new tool path generation scheme for this type of pockets have been also developed but due to space limitations it would not be discussed here. Machining an arbitrary-shaped pocket with multiple tools has not been addressed at this stage of the work.

**Determination of cutter length.** The effective length is determined by the depth of feature to be machined.

**Determination of number of inserts on the tool.** It is usually recommended to use a cutter with the smaller number of teeth that will keep at least two insert in contact with the work piece (9). Milling cutters classified into coarse, close or extra close pitch cutters. They are selected according to the rules structured in the knowledge base. There are some special cases for some milling applications or milling tools. For example, when performing a heavy cut like slotting with an end mill (or slot mill), the removal of chip is essential in order to quality. For these applications, it is always better to select an end mill which provides sufficient room for making the chip removal easy (i.e., a 2-teeth end mill).

**CPOS - CUTTING PARAMETERS OPTIMISATION SYSTEM**

Determination of optimal cutting parameters like number of passes, depth of cut for each pass, speed, and feed applicable for selected cutting tools is a crucial module in the OPTTOOL and it is accomplished by CPOS module which continuously interacts with the tool selection module: CTSS. CPOS offers three alternative modes for optimisation:

1. using recommended values
2. using search methods
3. using constrained optimisation techniques

Machining data handbook values or catalogue recommendations specified for different cutting tool material and workpiece material combinations are used. If the first option is selected. To tell the truth, these values are actually are just starting values and can not be accepted as optimised values. If the second one is preferred, in that case optimum cutting parameters are determined by using search methods in conjunction with optimum cutting zones given for inserts in catalogues of tool manufacturers. Last option is based on mathematical models and can only be applicable if an empirical mathematical model can be established for the optimisation. A case study is performed for multipass face and plain milling operations in this work. The developed strategy is based on the maximum production rate criterion and incorporates eight technological constraints associated with such as the cutting, speed and feed limitations, etc. The developed strategy makes use of two mathematical methods, dynamic programming and geometric programming. The optimum number of passes and depth of cut for each pass are determined through the former, while the other cutting parameters are determined by using latter. Sönnmez et al (12) have presented a detailed information on the developed strategy. One of the important steps in executing the program is to select a proper number of sections for the problems, since higher precision, i.e., selecting a higher number for the number of sections, will increase the execution time dramatically, although more effective times can be calculated for the objective function. This value should be selected always according to the total depth of cut.

**RTSS - RIGHT TOOL SELECTION SYSTEM**

The effect of tool replacement and tool travelling could not be included in operation sequencing and initial tool assignment stage of a process planning since the cutters are not exactly assigned at that stages. However, they should also be considered to provide a global optimisation in a machining cycle of a component. The goal of this module is to find an optimum operation sequence which is characterised by a minimum number of tool changes and/or minimum distance of tool travelling within a set-up. When the specifications of candidate cutters are determined, they are placed in a matrix to express the relations between the features and the tools, along the horizontal axis the features and along the vertical axis the cutters by adapting the procedures given in the study of Rho et al (13). In this way, it is possible to express that different operations can use the same tool and that for one feature alternative tools exist.

Consider the example part in Figure 6. On this part, there are two features to be machined: a step and a side slot. Assume that the target machine is a vertical milling centre. The cutter-type domain of the step feature includes i.e., a shoulder mill, an end mill and a disc mill, while cutter-type domain of side-slot includes only a disc mill. To obtain an optimum operation sequence for the minimum number of tool changes, both features should be machined with the same tool. This is possible if the disc mill used for the side-slot feature can also be used for machining the step feature.
The following rules are used to select the right tool for a part feature between alternative tools:

1. select the tool which is used by the most successive part features
2. if there are alternatives, choose the tool which is used for one of the previous part features
3. if there are still alternatives, choose that tool can be used for the largest number of part features.

The sequence can also be optimised taking the minimum travelling distance and direction of machining into account for each cutting tool. The operations can be rearranged in such a way that machining directions are unified and the travelling distance between two successive operations is kept to minimum.

**DISCUSSION AND CONCLUSIONS**

**OPTTOOL** can select optimum cutting tools among many alternatives to machine a component which work with the optimum cutting parameters, while minimising the number of tool changes and tool travelling distance within a set-up. It uses an integrated approach in which a dynamic link is established between the tool selection module and cutting parameter optimisation module. Thus, a safe and efficient way is provided for finding the most suitable tool. For each of the machining feature on the component, a 'type of cutter' domain is determined, which allows alternative cutting tools to be selected and leads to alternative process plans. New cutting tool selection techniques are suggested for pocket-like features.

**OPTTOOL** has been made also modular to provide an opportunity for the users to add their additional requirements in any level and therefore, to make the system open to any modification which may be necessitated with the advancement in the tooling technology. In order to make a self-learning system, the implementation of the same strategy by using neural networks might be considered. Fuzzy logic can also be applied to some of the decision stages in the **OPTTOOL**.

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