Selection of cutting tools and conditions of machining operations using an expert system

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Abstract

This paper presents the development of a knowledge-based system for selection of cutting tools and conditions of turning operations. The system developed can be used to select the toolholder, insert and cutting conditions feed, speed and depth of cut. It is able to analyse and optimise cutting tools and condition selection. In addition, the user or tool supplier is able to modify and enhance the system to meet their individual requirements. This system is constructed and implemented using Prolog. It contains an inference engine, a user interface and explanation facility, a complete shell, a knowledge base, and an optimisation model for machining conditions. The inputs to the system developed are the part and tool files, which include the representation of the part features and cutting tools. This paper describes the application of the system developed using a typical example. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: CAD/CAM; Process planning; Cutting tools; Machining conditions; CIM

1. Introduction

There is no doubt that modern computing technologies have made a significant impact on manufacturing systems. These technologies have been used for developing many methods, techniques and tools to support the design and manufacturing functions [2,6]. This includes such developments as Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Aided Process Planning (CAPP), Flexible Manufacturing Systems (FMS), Integrated CAD/CAM and Computer Integrated Manufacturing (CIM).

The first step and one of the main objectives of a CIM system is to integrate the CAD and CAM components. The total integration of these two components into a common environment (CAD/CAM) is still under development. Many of the major developments have been uncoordinated and there is a great deal of overlap in terms of their intended functions. For example, the present CAD/CAM systems have their strength in geometrical definition, i.e., CAD component and CAM is mostly limited to NC/CNC programming. Other important intermediate elements such as process planning are not included. This is due to the fact that the numerical
information generated by a CAD system is not sufficient for process planning. The CAPP systems available in the market are incomplete and limited when compared to the number of CAD and CAM systems available.

In automated batch production, on-line process planning is desirable. The conflicting demands of increasing flexibility and efficiency on the shop floor require the rapid transfer of manufacturing information. Hence, there is a need for CAPP systems, which cover the whole process of decision making, from the integration of the product model through to the generation of CNC programs. These systems must be capable of taking routine decisions automatically to ensure that the user is not an essential bottleneck in the information flow and only required to act as supervisor dealing with exceptions. In this way, process planning can be carried out quickly and accurately to meet the demand of the automated machine shop.

The process planning function involves a number of activities [18]:
- Analysis of part requirements.
- Selection of raw workpiece.
- Selection of manufacturing processes.
- Selection of machine tools.
- Selection of cutting tools.
- Determination of machining conditions.

Despite the rapid development of system components in process planning, there has been little progress in the area of tool selection. The development of systems for the automatic selection of cutting tools for machining operations is in its infancy, and the tool selection process is still carried out manually through extensive searching of catalogues and manuals.

The optimum selection of cutting tools and conditions cannot be simply based upon the familiarity, experience and the memory of individuals. A system is required to identify and specify various tools and to verify their suitability and availability. The current manual-based tool selection system equipped with a suitable methodology to handle the difficulties mentioned earlier must be developed. This system should include the following features:
- a cutting tool database containing details of toolholders and inserts;
- a method of defining component geometry;
- a system to relate the component geometry to the tools in the database and select the optimum tool;
- a set of tool selection criteria;
- a method of formulating the optimising cutting conditions;
- an interface with the end user.

The system should also have the facility to interface with any tool manufacture and enable them to place their tooling system in the package. In addition, the system should be flexible enough to enable the user to feed his own shop floor experience into the system and adapt it to specific requirements.

Using the above characteristics, an Expert Computer Aided Tool Selection System (EXCATS) comprising a knowledge base, inference engine, user interface, working database and an explanation facility has been developed using the Prolog language.

2. Review of previous work

Cutting tools and conditions selection, as a sub-function of process planning, is a complex task which requires considerable experience and knowledge. The objectives of any tool selection exercise are to select the best toolholder(s) and insert(s) from available cutting tool stock, and to determine the optimum cutting conditions. Generative tool selection systems have been developed to different levels of automation and sophistication.

The early tool selection modules employed graphics and presented the user with a catalogue of available cutting tools [16,20]. The user then selected the tools from this catalogue. These systems represent the first level of automation in cutting tool selection.

The next step offered the user all combinations of tool sets, which could completely machine the component [15]. The user would select the best tool set according to his experience. The systems represent the second level of automation. The above two levels consider the geometric aspects of the component during machining and consider no cutting technology.

A further step is represented by systems, which incorporate some “tool preference criteria” into tool selection [8,19]. These systems do not only find all combinations of tool sets geometrically capable of machining the component, but also automatically
select the best set in terms of cost. These systems represent the third level of automation.

The fourth level of automation [3] is a more flexible system, which not only seeks the cheapest way of machining a component, but also takes the experience of the end user into account. This level of automation has the advantages of the third level systems while avoiding their rigid system design.

Several CAPP systems have been developed for both variant and generative methods of process planning. These systems have been reviewed and evaluated in the literature, e.g., Refs. [1,3,14,18,21].

Most tool selection modules use “minimum operational cost” criteria for tool selection. This criteria does not necessarily consider the technological constraints involved in modern machining practice. Existing systems cannot easily adapt to include the experience of machinists within the company as these systems always impose the “minimum cost” criteria. This problem makes these systems too rigid and inflexible. No general solution for tool selection is acceptable or feasible for all workshops in the metal cutting industry.

The research reviewed has demonstrated that the application of conventional computer systems, which use decision tables and decision trees, has proved to be inflexible and inadequate for this purpose. The user requirements must be completely specified prior to the design of the system, otherwise the design will be incomplete or prone to error. A further limitation of conventional programs is the mixing of data and logic in one program such as knowledge, which is an inextricable part of the program. This renders such knowledge inaccessible, hard to understand and extremely difficult to modify without making major alterations to the program. Hence, they are difficult to adapt to the specific needs of a company.

The field of process planning and in particular tool selection depends upon the experience of experts, which cannot be converted into logic or algorithmic rules. Generally, in process planning, the information required is not always explicitly available and heuristics determine the method of planning. This situation is more suitable for the application of Artificial Intelligence (AI).

Expert system techniques have been used in a number of process planning systems for the selection operation sequence [12,20]. The selection modules in these systems are either at the first level of automation or similar to conventional systems, which use the minimum cost criteria. The expert system developed by Mathieu et al. [12] for tools and conditions selection for turning operations aimed to define a general methodology for the selection of the optimum tool for every turning operation (first level of automation). Giusti et al. [7] developed an expert module for automatic tool selection of turning operations — Computer Aided Tool Selection System (COATS) — which is a part of PICAP (a process planning package). In this system, the analysis is too detailed and complicated. In addition, the process planners are skilled at judging the suitability of cutting tools (holder and insert) for specific tasks rather than judging the individual parameters concerned with different toolholder styles and geometry, insert materials and chip-breaker geometries. A further drawback of these systems is that they provide a range of cutting conditions and no attempt is made to optimise the conditions.

3. Development of an expert cutting tool selection system

An EXpert Computer Aided Cutting Tool Selection (EXCATS) system, which can select cutting tools and conditions for major turning operations is developed based upon several procedures. Fig. 1 illustrates the general configuration of the EXCATS system.

In the design of EXCATS, the following procedures were considered.

- The system is based upon a generative cutting tool selection approach.
- It is developed in a modular basis to accommodate different machining operations and tool manufacturers. Apart from higher efficiency and ease of development, updating and maintenance, this enables users to acquire only those modules, which are relevant to their own particular requirements.
- It permits the user to define a core file consisting of cutting tools suitable for the machining applications within their own company. Initial tool selection is made from the tools available in the core file.
- For a given set of components, the system can select the minimum number of cutting tools from
any cutting tool manufacturer’s tooling system to machine specified components.

- It can select cutting tools from any manufacturer’s tooling system included in the knowledge base.
- It permits the user to override the decisions made and carry on repeated consultations with the user.
- Cutting tool selection for a particular machining operation is based upon the suitability of the tool as determined by the cutting tool manufacturer and not on the composition and properties of the cutting tool.
- It selects optimised cutting parameters according to the criteria used in manufacturing industry: minimum cost per piece and maximum production rate.
- It has the facility to advise the user on the selection of coolants.
- It is available for trouble shooting (e.g., advise action in case of excessive wear).

As illustrated in Fig. 1, the EXCATS system has a user inference, knowledge base, working database, inference engine and explanation facility. These were designed and developed by using Prolog. The knowledge base comprises two kinds of information: data files which hold different material properties, information of tool holders, inserts, etc., and mixture of factual, heuristic, and algorithmic knowledge of tool holder capabilities, tool selection guide lines, etc., held in rule-based form. The rules are designed in a form, which can be changed and adapted to different machine shop environment. For example:

- If the ‘machining operation’ is ‘external turning’ and
  - the component is ‘clamped in a chuck’ and
  - the ‘stability of the operation’ is fair then
  - ‘round inserts’ are not selected.
- If the ‘machining operation’ is ‘internal turning’ then
  - ‘solid boring bars’ are selected unless
  - the ‘overhang ratio’ is more than 4.

The working database also holds two forms of information. The first comprises knowledge, which represents the part. The second is the information, which is inferred by the system.

The system developed concentrates on the analysis and optimisation of cutting tools and conditions selection. It is assumed that the blank type and size, sequence of operations and work-holding methods are already known or found by the user.

The cutting tools considered consist of two main components, the toolholder and indexible insert. Both are internationally coded to indicate the character-
The turning operation is usually divided into roughing and finishing operations. The majority of the material to be machined is removed during the roughing operation, which requires maximum power. During the finishing operation a fine cut is used to provide the required surface finish and detailed profile. The selection of toolholder, insert, cutting conditions and coolant is based upon a number of factors such as the type of operation, workpiece material, geometry, accuracy, finish and power and rigidity of the machine tool. These can be considered as purely technical factors. A further aspect to cutting tool selection is concerned with cutting tool rationalisation. This is often the key to major economic benefits due to a reduction in cutting tool inventories and reduced tool set-up and change over times.

3.1. Part representation

All parts are represented in an English like syntax. To demonstrate the operation of the EXCATS system, a typical component is shown in Section 4. The part is represented separately for roughing and finishing operations. The roughing geometries are determined according to the operation sequence already known to the user. The finishing geometries represent the exact profile of the finished part. The circular elements are divided into quadrants and represented separately. The co-ordinates of the centre of each quadrant are represented in the fifth and sixth term of their predicates. These co-ordinates are used to calculate the angle between the component centre line and tangent at the circle to the start of each quadrant.

The part representation file can be created directly or interactively by the user [10,17]. A section of a typical part representation file for roughing and finishing operations is shown below:

```
component_001 has ext_rough_geom_1 to ext_rough_geom_7,
ex_rough_geom_1 is a long_turn,
ex_rough_geom_3 is a in_copy(95,5,93,15),
ex_rough_geom_4 is a long_turn(93,15,67,15),
ex_rough_geom_5 is a out_copy(67,15,65,5),
ex_rough_geom_6 is a in_arc(55,5,40,15,40,0),
ex_rough_geom_7 is a out_arc(40,15,25,5,40,0).
```

```
component_001 has ex_fin_geom_1 to ex_fin_geom_19,
ex_fin_geom_1 is a face in(155,5,93,15,67,15,ra is 3,2),
ex_fin_geom_2 is a out_chamfer(155,27,153,25),
ex_fin_geom is a long_turn(137,25,137,25).
```

3.2. Representation of toolholder

To match the capabilities of the toolholders with each element of the component, the toolholders are represented in similar manner to the workpiece as demonstrated below:

```
PSSN can_ext_turn long_turn
and face_in
and out_copy(max_angle, 45).
PCLN can_ext_turn long_turn
and face_in
and face_out
and out_copy(max_angle, 90).
MTEN can_ext_turn long_turn (See Fig. 2)
and out_copy(max_angle, 55)
and in_copy(max_angle, 55).
```

As the components are always described assuming the machining operations are against the chuck,
then any left hand toolholder has complementary capabilities to the corresponding right hand toolholder. For example, for MTJNR the maximum out_copy angle is 90° and the maximum in_copy angle is 22°, and the facing is clockwise. For MTJNL, the out_copy angle is 22° and the in_copy angle is 22°, and the facing is anti-clockwise.

3.3. Machining design assumptions

The following are examples of the machining guidelines, which have been used for cutting tool and conditions selection:

- EXCATS selects the minimum number of tools which can completely machine the workpiece.
- EXCATS selects a toolholder which accommodates the insert with strongest (largest point angle) shape to give maximum productivity and lowest edge cost.
- EXCATS selects the largest shank size which the machine will allow to give maximum rigidity, minimum tool deflection and reduced tool overhang ration.
- EXCATS selects the largest nose radius which the workpiece or machining condition will permit, to give high feed rate, nose strength and heat dissipation.
- EXCATS selects the smallest insert size that cutting condition will allow to give lowest edge cost and tool cost per piece.
- EXCATS selects the greatest depth of cut which the workpiece or machine will permit to maximise productivity.
- EXCATS selects single sided inserts for roughing operations and double sided inserts for finishing operations unless otherwise stated by the user.
- Right hand tools are preferred to left hand tools and left hand tools are in turn preferred to neutral tools.

3.4. Cutting tool selection procedure

The cutting tools are initially selected for the finishing operations before selecting for roughing operations. The workpiece is first matched with available toolholders represented in the knowledge base. The system selects the toolholder(s), which can completely finish turn the workpiece and lists them in priority order in accordance with the guidelines incorporated in the system. Following this, the geometry of each element is compared with neighbouring elements to identify the presence of any complex geometries such as recesses or wide grooves. The optimum cutting conditions are calculated, the insert type, size, grade and chip breaking geometry are selected to meet the cutting conditions and toolholder requirements. Tools for rough turning operations are selected in a similar manner.

3.5. Selection of cutting conditions

The EXCATS system first calculates the optimised cutting conditions for the finishing operations. The finishing depth of cut is then subtracted from the maximum depth of cut to determine the amount of material to be removed during the roughing operation. The system uses either the minimum cost or minimum machining time criteria as specified by the user. The maximum rate of profit criteria is not included but can be added if required. The tool life equation used is the expanded Taylor equation [4], which considers the feed rate and depth of cut in addition to cutting speed. Fig. 3 shows the flow diagram of cutting conditions selection.

The procedure for determining optimum machining conditions is taken from [9]:

\[ V = CT f y d z. \]  \hspace{1cm} (1)

The total machining cost is represented by:

\[ C_{pc} = M(t_i + t_m + N_i t_{ci}) + N_i C_i. \]  \hspace{1cm} (2)
The machining time \( t_m \) and the number of tools \( N_t \) used for each component are found from Eqs. (3) and (4) where the number of cuts \( n \) is represented by Eq. (5):

\[
t_m = \frac{\pi DL \cdot d_c}{Vf \cdot d}, \quad D \in [D, D - d] \tag{3}
\]

\[
N_t = \frac{t_m}{T} \tag{4}
\]

\[
n = \frac{d_c}{d} \tag{5}
\]

Using Eqs. (3) and (4) in Eq. (2) gives:

\[
C_{pc} = Mt_1 + \left( \pi DL \cdot \frac{d_c}{Vf \cdot d} \right) \left( M + \frac{Mt_{cl}}{T} + \frac{C_t}{T} \right). \tag{6}
\]

Substituting Eq. (1) in Eq. (8) gives:

\[
C_{pc} = Mt_1 + \left( \pi DL \cdot \frac{d_c}{C} \right) \times \left( \frac{MT + Mt_{cl}}{T^{x+1}} + \frac{1}{f^{y+1}} \right). \tag{7}
\]

Similarly the total machining time is represented by:

\[
T_t = t_1 + \frac{\pi DL d_c}{C} \left( \frac{T + t_{cl}}{T^{x+1}} \right) \left( \frac{1}{f^{y+1}} \right) \left( \frac{1}{d^{z+1}} \right). \tag{8}
\]
To obtain the minimum cost and minimum machining time Eqs. (7) and (8) must be minimised. Let $K_1$ and $K_2$ be the objective functions:

$$
K_1 = \left( \frac{MT + M_{t+1} + C}{T_{x+1}} \right) \left( \frac{1}{x^{t+1}} \right) \left( \frac{1}{d^{t+1}} \right) 
$$

$$
K_2 = \left( \frac{T + l_{t+1}}{T_{x+1}} \right) \left( \frac{1}{x^{t+1}} \right) \left( \frac{1}{d^{t+1}} \right) 
$$

where:

$-1 < x, y, z < 0.$ (11)

The objective functions can be generalised as:

$$
K = F_1 F_2 F_3. 
$$

(12)

Considering the objective functions above, it can be seen that apart from the tool life $T$, only the upper limit restrictions for feed rate and depth of cut need to be considered as these are strictly decreasing functions of both feed rate and depth of cut. Dynamic programming [5,13] is applied to this problem with the explicit optimisation rationale applied at one or two stages depending on whether the tool life is predefined by the user or not. Fig. 4 illustrates flow diagrams of selection procedure of the cutting conditions for roughing and finishing operations.

For simplicity, the roughing operations are described first. The procedures for calculating the optimised cutting conditions for roughing operations are as follows:

• If the tool life $T$ is predefined by the user, then $F_1$ in Eq. (12) is consistent and the procedure is:

• The maximum depth of cut is set equal to $d_e$, i.e., rough turning in one pass.

Fig. 4. Flow diagrams of cutting conditions selection for roughing and finishing operations.
The maximum feed rate is selected.

The cutting speed is calculated using Eq. (1). If the selected conditions do not comply with the constraints, the feed rate is first reduced incrementally to its lower limit and then the depth of cut is reduced to \( d_{c}/2, \ d_{c}/3, \ etc. \), until the constraints are satisfied.

If the tool life is not defined by the user, it is optimised within the range 6–30 min. This achieved by minimising \( F_t \) while selecting the feed and depth as above and testing against the constraints until the optimised cutting conditions are obtained.

The surface finish predefines the feed rate in finishing operations as it acts as a constraint. Often the depth of cut is predefined by the user and hence the tool life and cutting speed are optimised. If this is not the case, the system optimises the depth of cut in the range 0.25–1.5 mm or as defined by the user.

Several machining constraints are considered by the EXCATS system [3], including:

- Limits on the operating parameters.
  \[ V_{\text{min}} < V < V_{\text{max}} \]
  \[ f_{\text{min}} < f < f_{\text{max}} \]
  \[ d_{\text{min}} < d < d_{\text{max}} \]

- Limits on the feasible tool life.
  \[ T_{\text{min}} < T < T_{\text{max}} \]

- Limit on available power. The power required by in kiloWatts for a turning operation can be calculated using the following formula [11]:
  \[ p = \frac{d f^m c k V}{60000 \times E_{\text{ff}}} \]  
  \[ (13) \]

- Limit on tool thrust [9].
  \[ \text{Th} = C_t f^m d^n < \text{Th}_{\text{max}} \]

- Limit on spindle torque [9].
  \[ M_t = C_2 f^n d \cdot D < M_{\text{max}} \]

- Limit on the surface finish [4].
  \[ r_s = \frac{0.0321 f^2}{r_c} \]

4. Exemplary application of EXCATS system

To demonstrate the EXCATS system, cutting tools and conditions are selected to machine the part shown in Fig. 5.

This component is a steel component manufactured to DIN standard C15, which is equivalent to 040A15 in British standard, and the hardness is 120 Brinel. It is designed to demonstrate the full range of features presented by EXCATS. In this example, it is assumed that more than one set-up is required. This part contains a number of internal and external geometries. The first step is to represent the part in accordance with procedure specified in Section 3.1. Fig. 6 illustrates the complete representation of the part.

This representation is the only input to the EXCATS concerning the part. All other representations related to the component preparation are generated automatically by the system. Different stages of system consultation are carried out using different Prolog files to complete the tool and conditions selection. When the EXCATS starts the consultation, the kind of job (tool selection) is determined. Then the tool manufacturer, type of machining operation and number of the machine tools are determined. The result of this stage is:

: Your job is Tooling system selection.
: the tool manufacturing company is Sandvik.
: the machining operation is turning.
: the Machine tool is CNC Machine no. 1.
: the Machine power in kW is 25.
: the Machine Max shank capacity is 32 by 25.
: the Machine Turret capacity is 10.
: the Machine eff. is 0.7.
: the Machine feed range in mm is 0.1 to 1.4.
: the Machine spindle speed range is 20 to 2000.
: the Machine depth of cut range in mm is 0.1 to 15.
: the Machine and operator rate in P is 30.
: the machine “tool changing time” for “finishing operations” in (min) is 15.
: the Machine “tool changing time” for “roughing operations” in (min) is 5.

The next five questions relate to the stability conditions of the turning operation. For example:

Is the turning operation:

a: continuous turning
b: interrupted turning
Enter (a...b): a
Is the component:
a: held in the chuck
b: held in the chuck and tailstock
c: held in the chuck and steady rest
Enter (a...c): a
...

EXCATS determines this using a set of rules. The results obtained from these questions are:
: the turning operation is continuous turning.
: the component is held in the chuck.

: the surface condition of the blank is bright bar.
: the surface structure is light skin.
: the component Length to Diameter is \( \frac{L}{D} \leq 5 \).
: the component is cylinder type component.
: the stability of machine tool is fair.
: the stability of cutting operation is reasonable.

The stability of cutting conditions is established as being “reasonable”. If the answers to questions of the above step were different, then the stability conditions would have changed. For example, if the following question was (b: interrupted turning):
Is the turning operation:
a: continuous turning

b: interrupted turning
b: interrupted turning

Enter (a . . . b): b

Then this condition would make the stability condition “unfavourable”. If the answers of the user to the next four questions were different, this would invoke the following rule:

if the component is held in the chuck and tailstock and the surface structure is light scale skin and the component is cylinder type component and the stability of machine tool is good then the stability of cutting operation is favorable.

The stability condition of the turning operation effects the insert grade and chip breaker geometry selection. The complete rules for stability conditions are constructed in Prolog. These rules can be changed, added to or deleted from the knowledge base as required.

The EXCATS system then determines the component material and hardness from which the merchantability group number and chip type of material will be retrieved using the following questions:

Is the material code:

a: DIN code
b: BS code
c: AISI code

Enter (a . . . c): a

: the material code is DIN code.

Write the material code number: C15

: the material code number is C15.

Write the material hardness in BHN: 120

: the material hardness in BHN is 120.

: the material group number is 1.

: the material is long_chipping.

: the material group is steel or cast steel group.

EXCATS has established that the material is steel, its group number is 1, and it is long_chipping. The next stage involves retrieving the tool life exponents for all available inserts grades regardless of which grade will be selected later by the EXCATS system.

In the “tool_life_exp” predicates above, the first element (1) represents the material group number, the second element (P . . . ) denotes the application area of the carbide grade, the four remaining elements represent the Taylor tool life exponents (C, X, Y and Z). The complete listing of available materials, their merchantability group number and the exponents for different materials are represented in Prolog files. In the following stage, the system will require the part file name: : the component name is component1.
Table 1
The recommendation of the system

### RECOMMENDATION

#### EXTERNAL FINISHING OPERATION

<table>
<thead>
<tr>
<th>HOLDER</th>
<th>INSERT</th>
<th>TOOL</th>
<th>GEOMETRIES</th>
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<tbody>
<tr>
<td>MTJNL 20 20 K 16</td>
<td>MTJNL ext. fin_turns geometries no [6,7,2 of 9°]</td>
<td>TNMG</td>
<td>1,2,3,4,5,6,8,10,1 of 9°</td>
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<tr>
<td>MTJNR 20 20 K 16</td>
<td>MTJNR ext. fin_turns geometries no [6,7,2 of 9°]</td>
<td>TNMG</td>
<td>1,2,3,4,5,6,8,10,1 of 9°</td>
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</table>

#### CUTTING DATA: (min_cost)

<table>
<thead>
<tr>
<th>Tool</th>
<th>INS</th>
<th>DEPTH</th>
<th>FEED</th>
<th>VEL</th>
<th>T/LIFE</th>
<th>POWER</th>
<th>FINISH</th>
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<tbody>
<tr>
<td>MTJNL TNMG 1.5</td>
<td>0.19</td>
<td>408</td>
<td>26.5</td>
<td>7.404</td>
<td>Ra = 1.0</td>
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<tr>
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<td>9.257</td>
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<td>408</td>
<td>26.5</td>
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<td>Ra = 1.0</td>
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#### EXTERNAL ROUGHING OPERATIONS

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<th>GEOMETRIES</th>
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<td>PCLNR 32 25 P 12</td>
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<td>PDJNR ext. rough_turns geometries no [1,3,4,5,8,1 of 7]</td>
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#### CUTTING DATA: (min_cost)

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<tr>
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<th>DEPTH</th>
<th>FEED</th>
<th>VEL</th>
<th>T/LIFE</th>
<th>POWER</th>
<th>PASS NO</th>
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<td>PCLNR CNMG 5.58</td>
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<td>15.4</td>
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<td>other pass(s)</td>
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</tbody>
</table>

#### INTERNAL FINISHING OPERATIONS

<table>
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<tr>
<th>HOLDER</th>
<th>INSERT</th>
<th>TOOL</th>
<th>GEOMETRIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDUCL 25 20 SDUCL</td>
<td>SDUCL fin_turns geometries no [3,4]</td>
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</tr>
<tr>
<td>SDUCR 25 20 SDUCR</td>
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#### CUTTING DATA: (min_cost)

<table>
<thead>
<tr>
<th>Tool</th>
<th>INS</th>
<th>DEPTH</th>
<th>FEED</th>
<th>VEL</th>
<th>T/LIFE</th>
<th>POWER</th>
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<td>26.5</td>
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<td>Ra = 3</td>
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<td>330</td>
<td>26.5</td>
<td>9.70</td>
<td>Ra = 6.0</td>
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<td>26.5</td>
<td>9.70</td>
<td>Ra = 3</td>
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#### INTERNAL ROUGHING OPERATIONS

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<tr>
<th>HOLDER</th>
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<th>TOOL</th>
<th>GEOMETRIES</th>
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</thead>
<tbody>
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<tr>
<td>SDUCR 20 S SDUCR</td>
<td>SDUCR rough_turns geometries no [1,2,4,5,6]</td>
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</table>

#### CUTTING DATA: (min_cost)
Table 1 continued

<table>
<thead>
<tr>
<th>RECOMMENDATION</th>
<th>INTERNAL ROUGHING OPERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool</td>
<td>INS</td>
</tr>
<tr>
<td>PTFNL</td>
<td>TNMG</td>
</tr>
<tr>
<td>PTFNR</td>
<td>TNMG</td>
</tr>
</tbody>
</table>

Two of nine and one of nine mean that the arc geometry number 9 resides on two quadrants, which are treated as two separate features 2 and 1 (an in_copy and an out_copy with an angle of 90°).

The system automatically prepares the part representation for the tool selection as follows:
- External finishing geometries.
- External roughing geometries.
- Internal finishing geometries.
- Internal roughing geometries.

Following this, EXCATS generates a complete list of each operation with geometries involved (total of four lists). These lists are called the component primary feature lists (the primary or basic machining operations in a turning operation can be divided into longitudinal turning, facing-in, facing-out, in-copying, and out-copying), which are used by EXCATS for the tool selection. The system generates a complete list for each set-up component set-up lists. Each list includes all the geometries, which are to be machined in that set-up. These lists will be also used to determine the existence of any recesses and their sizes. The system has recognised a total of six recesses of which two are external finishing, two are external roughing, one is internal finishing and the last one is internal roughing. At this stage, the part representation is completed and EXCATS now requires the tool file name, in which the available tools are stored. Tool preparation is the next stage of the operation. Initially, the system breaks the capabilities of each tool and registers them in a single operation: the Tool file name is tool1.

EXCATS will then group the capabilities of each toolholder in one single list. At this stage, the tool preparation phase is completed and the tool selection for external finishing operation starts. The capabilities of each external finishing tool will be compared to the external finishing geometries of the component using the procedure of tool selection for external finishing operations. The component geometries, which can be machined by each tool will be registered for the tool, for example:

- (MTJN,R) can_ext_fin_turn face_in no 1
- (MTJN,R) can_ext_fin_turn long_turn no 2
- (MTJN,R) can_ext_fin_turn out_copy no 3
- (MTJN,R) can_ext_fin_turn long_turn no 4
- (MTJN,R) can_ext_fin_turn out_copy no 5
- (MTJN,R) can_ext_fin_turn long_turn no 6
- (MTJN,R) can_ext_fin_turn long_turn no 8
- (MTJN,R) can_ext_fin_turn out_copy no 1 of 9
- (MTJN,R) can_ext_fin_turn long_turn no 10
- (MTJN,R) can_ext_fin_turn face_out no 11

Following this, EXCATS groups the geometries in a single list for each tool. Automatic searching will be initiated to find a single tool to finish the external geometries of the component. If not successful, the system searches for a set of two tools, three tools, etc., until it finds a set of tools which can completely turn the external geometries of the component. The system determines which set is superior using the tool preference rules. For example:

- if (`MTJN`, `R`) can_ext_fin_machine `the component`
  and (`MTEN`, `R`) can_ext_fin_machine `the component`
  then (`MTJN`, `R`) has first_ext_fin_priority
  and (`MTEN`, `R`) has second_ext_fin_priority.

In this exemplary application, EXCATS has determined that “MTJNR” and “MTJNL” is the only tool set, which has a first priority and no second priority; hence, it has established that this set is superior to others. Consequently, this tool set is offered to the user for confirmation. It will also offer the user the possibility of an explanation or rejection of the superior tool set and search for the next best set using specific EXCATS menus. If the user con-
firms the EXCATS selection for external finishing geometries, the system will determine the toolholder size and examine the tool for possible collisions.

To ensure maximum stability of the turning operation, the EXCATS system always selects the maximum shank size available, which is compatible with the machine tool size. The compatible insert size is also selected for the toolholder. The toolholder selection for the external finishing operation is completed before EXCATS begins the tool selection for external roughing operations. Tool selection procedures for the remaining operations are identical to the selection procedure for finishing operations. The user confirms the selection of EXCATS and the system determines the size of toolholders.

In this example, EXCATS cannot find a suitable size for the ‘‘MTGNR’’ toolholder in the tool file, which does not collide with the component. When such condition arises, the system will reject the selected tool sets and redo the selection procedures as before assuming that ‘‘MTGNR’’ and ‘‘MTGNL’’ are removed from the tool file.

EXCATS finds a suitable toolholder size for this selection and the procedure for external roughing geometries is completed. The tool selection for internal finishing operations and internal roughing operations follows.

The tool selection for all types of operations are completed. At this stage, cutting conditions optimisation starts. EXCATS initially determines the objective function for cutting conditions selection as:

Is the optimisation criteria:
   a: Minimum production cost
   b: Minimum production time
   c: Fixed tool life

Enter [a . . . c]: a

The system defaults for ‘‘Workpiece and Machine tool’’ (WM) are presented to the user and confirmation is requested. The maximum and minimum external and internal workpiece diameters, from which EXCATS will calculate the maximum external and internal depth of cut to be removed, are determined. The system will select the insert and chip-breaking geometry using a set of rules, which are only valid for Sandvik turning inserts. Similar rules could be developed for other tool manufacturers.

EXCATS retrieves the tool life exponents for the finishing and roughing insert grades from the database. The finishing and roughing cutting conditions are calculated as presented in Section 3.5. The system has now determined all the required information and presents this as the recommendations of the system in tabular forms as illustrated in Table 1 (the coding of the selected toolholders and inserts is taken from the ISO standard for external and internal toolholder and inserts).

At the end of the consultation, EXCATS offers the possibility of optimising the cutting conditions according to a second objective function (e.g., fixed tool life), starting a new consultation problem or aborting the system. If EXCATS is used to optimise the cutting conditions according to minimum production time and fixed tool life then new cutting conditions will be calculated by the system.

5. Conclusion and future work

The EXCATS system, as a stand alone system, could be applied to automated manufacturing systems, which aim to optimise the performance of simple turning operations. In addition, the system offers the possibility of a novel and integrated approach to cutting tools and conditions selection for machining operations. It demonstrates the pivotal role of a knowledge-based system in achieving maximum flexibility in the process planning automation and development of fully integrated CIM systems. When an integrated and direct path to cutting tool selection can be provided, it is possible to move rapidly and accurately from the product design phase to manufacture.

An effective representation of the product model is an essential of any automated process planning system as any generative process planning system requires a detailed definition of the component geometry. This requirement is successfully solved in EXCATS by adopting a methodology for component representation. To perform cutting tools and condition selection for a component, the input to EXCATS comprises information related to the description of the component and the sequence of operations. Both the rough blank and finished component are described in terms of the cutting operations required.
The method developed for component representation is easy to use and understand and little knowledge of computers is required. The workpiece representation method forms a key feature in the EXCATS system. The system allows for an easy identification and direct relationship between the cutting tool and the component using operation key words, which describe both the workpiece and cutting tool. All toolholders supplied by any tool manufacturer can be represented in this manner.

The rule-based knowledge base is designed to be adapted to different working environments. The logic of the tool selection criteria is based upon a series of rules, which can be easily changed by users to meet specific needs. The utilisation of the machine tool power is optimised within the constraints imposed by the properties of the workpiece materials, tools and tool materials.

The EXCATS system, as it stands, concentrates on the selection of cutting tools and conditions, and is incapable of the determination the machining sequence and work holding methods, both of which are assumed to be provided by the user. When performing cutting tool selection, right hand tools are preferred to left hand tools and left hand tools are in turn preferred to neutral tools.

Although still in pilot form the demonstration illustrates that the system developed can select cutting tools (toolholders and inserts) and cutting conditions (depth of cut, feed and cutting speed) for major turning operations. The system initially determines all the feasible tool sets, which can completely machine the component and then selects the most suitable tool using the preference rules within the knowledge base. The tool preference rules are based upon the recommendations of cutting tool manufacturers. The rules can be changed by the users to suit their own machining environment.

Future proposed developments include:

- The integration with a similar package for milling operations [14].
- The integration of a CAD system for workpiece representation and final verification [21].
- The integration of a database management system into the system developed to improve management and control of the system.
- Development of the system into a complete process planning system.

6. Notation

- $C$ tool life constant
- $C_1$ constant, thrust equation
- $C_2$ constant, torque equation
- $C_{pc}$ cost per component
- $C_t$ cost of tool
- $d$ actual depth of cut/pass
- $D$ workpiece diameter
- $D_t$ diameter of cutting tool
- $d_{cut}$ maximum depth of cut to be removed
- $d_{max}$ maximum allowed depth of cut
- $d_{min}$ minimum allowed depth of cut
- $E_f$ efficiency
- $f$ feed rate
- $K_c$ specific cutting force
- $L$ length of workpiece
- $M$ total machine and operator rate
- $M_{max}$ maximum torque
- $M_t$ spindle torque
- $M_f$ force increase factor
- $n$ number of cuts, rough turning
- $n_1$ feed rate exponent for thrust equation
- $n_2$ depth of cut exponent for the thrust equation
- $n_3$ feed rate exponent for torque equation
- $N_t$ number of tools used
- $P_{max}$ maximum available power
- $P_a$ surface finish
- $r_e$ insert nose radius
- $T$ tool life
- $TH_{max}$ maximum tool thrust
- $t_i$ idle time
- $t_{ct}$ tool change over time
- $t_m$ machining time per component
- $V$ cutting speed
- $V_{max}$ maximum feasible cutting speed
- $V_{min}$ minimum feasible cutting speed
- $x$ tool life exponent, tool life
- $y$ tool life exponent, feed rate
- $z$ tool life exponent, depth of cut

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References