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A Knowledge Based Approach for Automatic Process Plan Generation for Machining

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Abstract: The present paper is aimed at developing an intelligent Computer-Aided Process Planning methodology based on application of a KBS for automatic generation of process plans for machining. It takes, as input, information about the different machining features present in the part and automatically generates a detailed sequence of machining operations including the precedence constraints, the different machining setups in accordance with the given Tool Approach Directions, the list of operations to be performed within each setup, the locating and clamping faces needed for fixturing the component as well as the setup sequence. To accomplish the above, a set of knowledge based rules have been developed and implemented using an Expert System Shell. The application of the proposed approach has been demonstrated using an example part. By using the proposed approach, it is anticipated, that process planning can be accomplished automatically and quickly by investigating a very limited amount of time making it attractive for applications in industry.

Keywords: Computer-Aided Process Planning, knowledge based system, operation planning, setup planning, fixture planning

1. Introduction

Modern manufacturing industries faced with various challenges like growing product variety, improved productivity and quality, and lower costs are increasingly turning towards automation and computer based technologies for design and manufacturing like CAD, CAM, CAE, etc. Further, it is becoming increasingly important for modern manufacturing industries to develop a CIM system by integrating the various operational and information processing functions in design and manufacturing. In developing a CIM system, Computer–Aided Process Planning (CAPP) can play a key role particularly in CAD/CAM integration and therefore it has been the focus of much attention and research. The present work is aimed at developing a CAPP approach of automatic process plan generation for machining by the use of a knowledge based system (KBS). The key process planning issues that have been addressed are automation of operation planning, setup planning, and fixture planning.

The KBS approaches have found number of applications in the recent past. Erve et al. [1] developed XPLANE – a generative CAPP system that uses an expert system for automatic tool selection, machining operation selection and sequencing. Giusti et al. [2] developed KAPLAN - a KBS using IF-THEN rules for rotational parts. Yeo et al. [3] attempted to model the knowledge of an experienced process planner and NC programmer by employing an expert system. Yeo [4] adopted a software tool, 'GoldWorks III' to develop a knowledge-based feature modeller for machining. A KBS for hole machining process selection has been reported by Khoshnevis et al. [5]. Wong et al. [6] have proposed an expert system for process selection and sequencing for prismatic parts. An expert system has been developed by Lin et al. [7] for fixture planning in face milling. Sabourin et al. [8] have used an expert system to generate a sequence of machining operations using production rules based on technological attributes of features of the part, modelled using a feature-based modeller.

Jiang et al. [9] developed a CAPP system that extracts form features, represented by GT coding and automatically generates process plans for prismatic components using an expert system. An expert system for machining operation planning including tool selection, machining condition determination and evaluation in internet environment was proposed by Kozima et al. [10]. Radwan [11] reported development of an expert system based CAPP approach for machining of different kinds of surfaces and holes by matching the surface parametric data and required quality with the process capability matrices of each surface type. Zhao et al. [12] developed a KBS for cutting tool and condition selection for turned components starting from a CAD model. Park [13] proposed an expert system for process plan generation for hole making. Liu et al. [14] proposed a KBS for sequencing of interactive features for process planning of prismatic components. An Expert System Shell has been used by Deb et al. [15] for automating the various setup planning tasks for machined rotational parts. Yet another approach reported by Hazarika et al. [16] used an Expert system for automating setup planning tasks for prismatic parts and Fuzzy set approach for automatic updating of the Knowledge Base of the expert system. Vukelic et al. [17] implemented another expert system based approach combining the knowledge base and data base based on a modular principle for fixture design. From the above literature survey, it appears that knowledge based approaches hold a lot of potential for application in automation of process planning. The next section presents our adopted methodology for automatic process plan generation.

2. Adopted Methodology for Automatic Process Plan Generation

In order to generate a process plan, first of all, for each feature present in the part, the machining operations are selected by proper operation planning. Then the operations need to be grouped and ordered based on the corresponding Tool Approach Direction (TAD), and ordered in accordance with various manufacturing precedence constraints by proper setup planning. During machining, all the Degrees of Freedom (DOFs) of the part need to be restricted by proper fixturing. Figure 1 shows the above sub-functions of process planning and the data interactions between them.

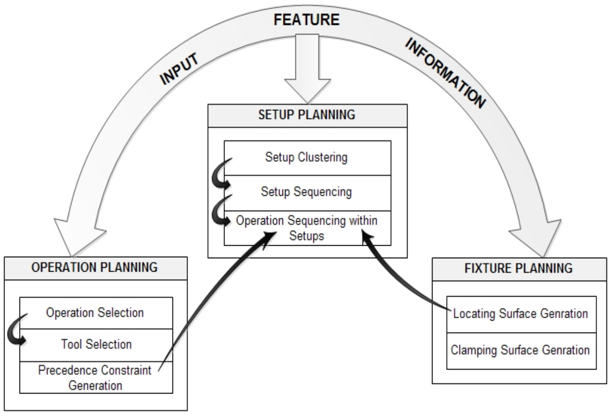

Figure 1. Data interactions between the components of the Process Planning System

In the present work, the above process planning tasks have been automated using a KBS approach implemented using an Expert Shell called CLIPS. The following sections provide a brief outline of CLIPS, followed by our proposed implementation strategy of automatic process generation.

2.1 CLIPS Expert System Shell

CLIPS is an expert system shell that was first developed at NASA. It consists of mainly three components namely, a Data Base, a Knowledge Base, and an Inference Engine. In addition, it has a User Interface and an Explanation Facility. The CLIPS architecture and flow of information have been shown in figure 2. The database consists of a list of facts about the problem being solved, which forms the input to the Expert System and must be entered by the user. The facts are represented using the concept of template that is an organized structure of input data used to define and store values for a fact description in a field called, the ‘slot’. The operation template is presented in figure 3, along with a sample input data fact for an operation given in figure 4. The Knowledge Base contains the domain knowledge encoded in the form of IF-THEN rules, to be used by the Expert System. Sample rules for the knowledge base have been presented later in this section for illustration. The Inference Engine serves as the brain of the knowledge based system. It is a computer program, used for making inferences from the given data facts, through a process of reasoning. In CLIPS, the knowledge being stored in the form of rules, the inference engine makes inference by deciding as to which of the rules from the knowledge base are satisfied by the database facts, and then it prioritizes the order of firing the satisfied rules. CLIPS further has an explanation facility with debugging mechanism to check the syntax of the facts against the respective template as well as the existing rules in the knowledge base. CLIPS also contains a display mechanism to monitor each and every processing step during the execution of a program.

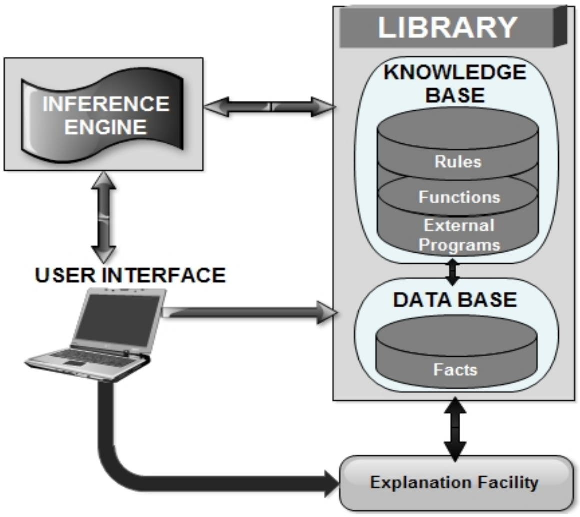

Figure 2. Architecture of the CLIPS Expert System Shell

```
(deftemplate MAIN::operation
(slot number(type INTEGER))
(slot type(type SYMBOL)
(allowed-symbols FACE_MILL END_MILL
DRILL DRILL_REAM DRILL_BORE))
(slot on_feature(type INTEGER)
(default ?NONE))
(slot tool(type SYMBOL)
(allowed-symbols face_mill end_mill
drill reamer boring_bar))
(multislot TAD(type SYMBOL)
(allowed-symbols AD-1 AD-2 AD-3
AD-4 AD-5 AD-6))
(multislot relation_with_feature
(type INTEGER)(default 0))
(multislot tolerance(type NUMBER)
(default 0)))
```

Figure 3. Operation template

```
(operation (number 1) (type FACE_MILL)
(on_feature 1) (tool face_mill)
(TAD AD-3) (relation_with_feature 0)
(tolerance 0))
```

Figure 4. A sample operation fact

2.2 Implementation strategy of Automatic Process Plan Generation

In this section, we shall discuss, the implementation method of automatic process plan generation for operation planning, setup formation, and fixture planning using CLIPS. Sample rules from the knowledge base have also been included for illustration.

Operation Planning

This step selects suitable machining operations for each feature of the part based on the dimension, tolerance, and surface finish requirements. A single feature may require one or more operations to be performed. Each operation requires a particular type of cutting tool. Keeping these factors in view, a set of knowledge based rules has been developed for selection of the machining operations and cutting tools. A sample rule is shown in figure 5. Sometimes, a single operation may have the possibility to be performed by more than one type of tool. So there is a scope for further optimizing the tool selection considering various factors such as its cost, machining time, availability of the cutting tool, etc.

```
(defrule MAIN::FACE_MILL
(feature (number ?a)(name FACE)(TAD $?b)
(relation_with_feature ?c)(tolerance ?d))
=>(assert(operation (number ?a)
(on_feature ?a)(type FACE_MILL)(TAD $?b)
(tool face_mill)(relation_with_feature ?c)
(tolerance ?d))))
```

Figure 5. A sample rule for operation and tool selection

There always exist certain relationships among the features comprising a part, which restrict the order of processing of them. The same also holds good in case of the operations selected for machining each feature. They are called, feature precedence relationships and operation precedence relationships, respectively that give rise to precedence constraints during machining. Some of these constraints are illustrated with the help of a sample part shown in figure 6. These constraints may arise due to various reasons, which can be classified into the following categories:

1) Fixturing constraints: In figure 6, the slot F5 should be milled before milling the protruded surface F2 in order to avoid the difficulty in fixturing the part.

2) Datum/referencing constraints: Refering to figure 6, if the location of this slot F5 is defined with respect to datum surface F1, then F1 has to be machined prior to F5.

3) Constraints due to good manufacturing practice: There are certain constraints that follow from good manufacturing practice. For example, the hole F4 should be machined prior to that of milling of the inclined surface F3 as otherwise, it will be difficult to guide the drill on an inclined surface.

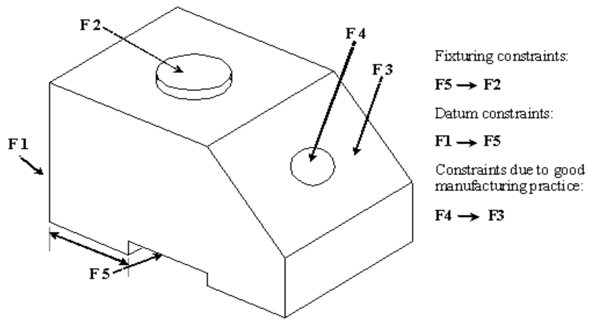

Figure 6. Illustration of different machining precedence constraints

The above precedence relationships are identified, and suitable knowledge based rules framed for generation of precedence constraints among all the features and operations. The figures, 7 and 8 represent sample rules for feature and operation precedence constraint generation respectively.

```
(defrule MAIN::feature_precedence_constraint_1
(feature (number ?a)
(reference_features $? ?b $?))
(test (> (nth$ 1 (create$ $?b)) 0))
=>(assert
(feature_precedence ?b ?a)))
```

Figure 7. A sample rule for feature precedence constraint generation

```
(defrule MAIN::operation_precedence_constraint_1
(feature (number ?a))
(operation (number ?a1)(on_feature ?a))
(feature (number ?b))
(operation (number ?b1)(on_feature ?b))
(feature_precedence ?a ?b)
=>(assert (operation_precedence ?a1 ?b1)))
```

Figure 8. A sample rule for operation precedence constraint generation

Setup Planning

In order to generate a feasible process plan, the operations need to be carried out in different setups according to the Tool Approach Directions (TADs) of the operations. There can be maximum six possible TADs in case of a Vertical Machining Center (VMC), for the cutting tool to access a feature for machining, as shown in figure 9.

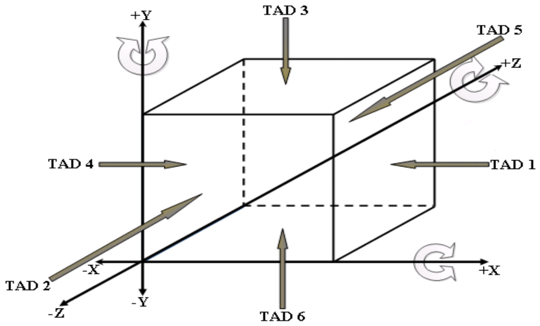

Figure 9. Possible TADs in a prismatic component

All operations having the same TAD are grouped under the same setup forming a setup cluster. A program for setup cluster generation is presented in figure 10.

```
(defglobal ?*setup1_cluster* = 0
   ?*feature_cluster_setup1* = 0)
(defrule MAIN::SETUP_1
?f<-(feature(number ?n)(TAD $? AD-1 $?))
=>(bind ?*feature_cluster_setup1*
(fact-slot-value ?f number))
(if (eq ?*setup1_cluster* 0)
 then (bind ?*setup1_cluster*
(delete-member$ (create$ ?*setup1_cluster*
?*feature_cluster_setup1*) 0))
else (bind ?*setup1_cluster*
(create$ ?*setup1_cluster*
?*feature_cluster_setup1*))))
(defrule MAIN::report_setup_1_cluster
=>(assert (setup (number 1)(TAD AD-1)
(feature_nos (create$ ?*setup1_cluster*)))))
```

Figure 10. Program for setup cluster generation

After the setup clusters are obtained, the setup sequence needs to be determined considering the availability of pre-machined locating and clamping surfaces for a particular setup. The locating and clamping surface selection depends on the fixturing method adopted and is to be carried out by proper fixture planning discussed in the next section. Before generating a setup sequence, it is, however, necessary to identify three mutually perpendicular pre-machined faces that can be used for locating the part for the first setup, and then using this information, the program presented in figure 11 is used to automatically generate a feasible setup sequence. Depending on the set of locating surfaces chosen for the first setup, a number of different feasible setup sequences are possible, which may be further analyzed to determine any further scope for optimization.

```
(defglobal ?*seq* = 0
   ?*feat* = 0)
(defrule MAIN::SEQUENCE
(declare (salience 100))
(already_machined_locating_surfaces
(feature_nos ?n4 ?n2 ?n3))
(setup (number ?n)(TAD ?AD)
(feature_nos $? ?n1 $?))
(locating_clamping_surfaces
(for ?n1)(locating_surfaces
?n4 ?n2 ?n3))
=>(bind ?*feat* ?n1)
(if    (eq ?*seq* 0)
 then (bind ?*seq* (delete-member$
(create$ ?*seq* ?*feat*) 0))
else (if    (eq (member$ ?*feat*
(create$ ?*seq*)) FALSE)
then (bind ?*seq*
(create$ ?*seq* ?*feat*)) ) )
(defrule MAIN::print
(declare (salience 50))
=>(printout t "A feasible sequence is
" ?*seq* crlf))
```

Figure 11. Program for setup sequence generation

Finally, the feasible operation sequences within each setup are determined by a set of rules based on the previously established precedence constraints. Although our developed program can generate feasible operation sequences for each setup, there is scope for further optimization of the operation sequence based on various criteria like say, minimizing the number of tool changes, idle tool travels, etc.

Setup Planning

A prismatic component can have six DOFs three translational and three rotational in space as shown in figure 9, which must be restricted properly by fixturing in a suitable work holding device called fixture, before commencing the machining operation. We have used the 3-2-1 fixturing principle for the present work. In this fixturing method, three surfaces of the work piece are needed for locating and two other surfaces for clamping in order to hold the job securely by applying sufficient gripping force and counter any deforming machining forces that may result in dislodgement of the work part. A set of knowledge based rules have been developed that are capable of automatically generating all the possible sets of locating and clamping surfaces for each setup. A sample rule is presented in figure 12.

```
(defrule MAIN::locating "Detection of
     possible locating surfaces"
(or (feature (number ?n1)(subtype PRIMARY)
    (prep_to $? ?n2 $? ?n3 $?))
    (feature (number ?n1)(subtype PRIMARY)
    (prep_to $? ?n3 $? ?n2 $?)))
(or (feature (number ?n2)(subtype PRIMARY)
    (prep_to $? ?n3 $? ?n4 $?))
    (feature (number ?n2)(subtype PRIMARY)
    (prep_to $? ?n4 $? ?n3 $?)))
(or (feature (number ?n3)(subtype PRIMARY)
    (prep_to $? ?n2 $? ?n4 $?))
    (feature (number ?n3)(subtype PRIMARY)
    (prep_to $? ?n4 $? ?n2 $?)))
(test (not (= ?n1 ?n2))) (test (not (= ?n1 ?n3)))
(test (not (= ?n1 ?n4))) (test (not (= ?n2 ?n3)))
(test (not (= ?n2 ?n4))) (test (not (= ?n3 ?n4)))
=>(assert (locating_surfaces (for ?n1)
          (features ?n4 ?n2 ?n3))))
```

Figure 12. A sample rule for generation of locating surfaces

3. Implementation using an Example Part

To illustrate the implementation of the developed methodology, a component shown in figure 13 to be machined on a VMC has been chosen. It has fourteen features, out of which, there are six primary surface features, and eight secondary features namely, a step, a slot, a chamfer, two pockets, and three circular holes. Features 13 and 14 are ‘nested in’ the stepped surface feature 2. The above part information that constitutes the input data to the KBS has been represented following the prescribed input data format of CLIPS and stored as data files.

In the first step, the Operation Planning module takes in, as input, the above data on features and automatically selects the machining operations for each feature and the cutting tools required for machining. The output data of this module is shown in table 1. Further, using the developed knowledge based rules, the feature and operation precedence constraints shown in figure 14 are automatically generated to be used later for the sequencing of operations and the setup sequencing.

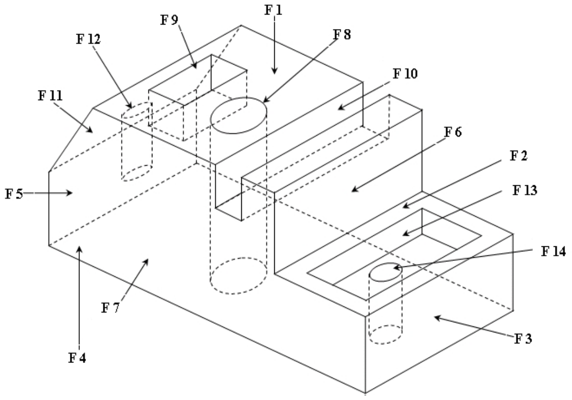

Figure 13. An example part

Table1. Output of the Operation and Tool selection rules

Feature No.	Feature Name	TAD	Operation Identifier	Operation Type	Tool Type
1	Face	AD-3	1	Face mill	face_mill cutter
2	Step	AD-1 AD-3	2	End mill	end_mill cutter
3	Face	AD-1	3	Face mill	face_mill cutter
4	Face	AD-6	4	Face mill	face_mill cutter
5	Face	AD-4	5	Face mill	face_mill cutter
6	Face	AD-5	6	Face mill	face_mill cutter
7	Face	AD-2	7	Face mill	face_mill cutter
8	Hole	AD-3	8	Drill	drill_bit
9	Pocket	AD-3	9	End mill	end_mill cutter
10	Slot	AD-3	10	End mill	end_mill cutter
11	Chamf er	AD-3 AD-4	11	End mill	end_mill cutter
12	Hole	AD-3	12	Drill	drill_bit
13	Pocket	AD-3	13	End mill	end_mill cutter
14	Hole	AD-3	14	Drill	drill_bit

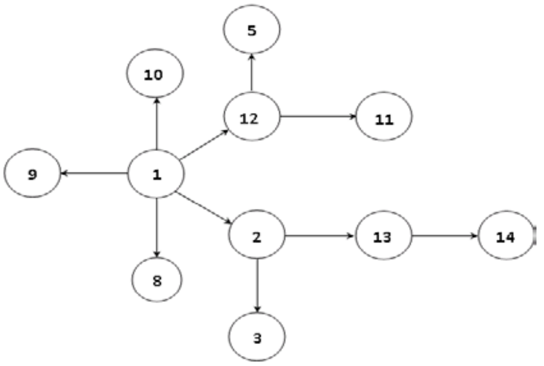

Figure 14. Machining precedence constraints for the example part

Then using the rules for setup clustering, the operations are grouped according to TADs, producing the setup clusters given in table 2.

Table2. Generated Setup Clusters

Sl. No.	TAD	Operations
1	AD-1	2, 3
2	AD-2	7
3	AD-3	1, 2, 8, 9, 10, 11, 12, 13, 14
4	AD-4	5, 11
5	AD-5	6
6	AD-6	4

Next it is necessary to identify any three mutually perpendicular pre-machined faces for the purpose of locating the part for the first setup. In the present work, surfaces 1, 7 and 5 have been chosen as the locating faces for the first setup. Then based on the developed rules for fixture planning, the sets of all the feasible locating and clamping surfaces for the remaining setups are generated. The previously generated information on the identified setups from the setup clustering output and the locating surfaces information from the fixture planning module are next used for generating the feasible sequence of setups using the program described earlier. Finally, operations are sequenced within each setup based on the operation precedence constraints obtained earlier. Table 3 shows the generated set-up sequence, operation sequences within each setup as well as the locating and clamping surfaces for each setup.

Table3. Generated process plan

Setup no.	TAD	Operation sequence in each setup	Locating surfaces	Clamping surfaces
1	AD-6	4	1, 7, 5	6, 3
2	AD-5	6	7, 4, 5	1, 3
3	AD-1	3	5, 4, 6	1, 7
4	AD-2	7	6, 4, 5	1, 3
5	AD-4	5	3, 4, 7	1, 6
6	AD-3	1→8→9→10→12 →11→2→13→14	4, 5, 7	3, 6

4. Conclusions

The knowledge based system developed in this work can automatically generate a detailed sequence of machining operations including the manufacturing precedence constraints subject to which the operation sequences are determined, the different machining setups in accordance with the given Tool Approach Directions, the operations to be performed within each setup, the locating and clamping faces of the component needed for fixturing it as well as the setup sequence. In order to accomplish the above, the heuristic rules representing the domain knowledge on process planning have been organized into different knowledge base modules for the selection of machining operations, cutting tools, precedence constraints, setup clusters, fixture planning, operation sequencing and setup sequencing, etc. The modular nature of the developed KBS gives added flexibility to the proposed approach. Any modification of the current process planning knowledge can be done readily by modifying the rules in the respective knowledge bases. Further any new process planning knowledge can be acquired easily by simply adding new rules to the knowledge base. The developed KBS approach has been successfully applied on different types of machined prismatic components. The time taken to generate the process plans has been found to be reasonably fast and therefore, it can be adopted to quickly generate process plans for industrial applications. Although our developed KBS can automatically generate feasible process plans, the optimality of the generated process plan is not necessarily guaranteed. So there is lot of scope for further research work on optimization of the process plan considering the various process plan alternatives.

5. References

1. Erve, A. H. and V., Kals, H.J.J., *"XPLANE, a Generative Computer Aided Process Planning System for Part Manufacturing"*, Annals of the CRIP, 35(1), (1986) 325-329.

2. Giusti, F., Santochi, M., and Dini, G., *"KAPLAN: a Knowledge-Based Approach to Process Planning of Rotational Parts"*, Annals of the CRIP, 38(1), (1989) 481-484.

3. Yeo, S. H., Wong,Y. S., and Rahman, M., *"Integrated knowledge-based machining system for rotational parts"*, International Journal of Production Research, 29(7), (1991) 1325-1337.

4. Yeo, S. H., *"Knowledge-based feature recognizer for machining"*, Computer Integrated Manufacturing Systems, 7(1), (1994) 29-37.

5. Khoshnevis, B., and Tan, W., *"Automated process planning for hole-making"*, American Society of Mechanical Engineers, Manufacturing Review, 8(2), (1995) 106-113.

6. Wong, T. N., and Siu, S. L., *"A knowledge based approach to automated machining process selection and sequencing"*, International Journal of Production Research, 33(12), (1995) 3465-3484.

7. Lin, Z. C., and Yang, C. B., *"An Expert System for Fixturing Design for Face Milling Using Modular Fixture"*, International Journal of Advanced Manufacturing Technology, 10, (1995) 379-388.
8. Sabourin, L., and Villeneuve, F., *"OMEGA, an expert CAPP system"*, Advances in Engineering Software, 25, (1996) 51-59.

9. Jiang, B., Lau, H., Chang, Felix T. S., and Jiang, H., *"An automatic process planning*

system for the quick generation of manufacturing process plans directly from CAD drawings", Journal of Materials Processing Technology, 87, (1999) 97-106.

10. Kojima, T., Sekiguchi, H., Kobayashi, H., Nakahara, S., and Ohtani, S., *"An expert system of machining operation planning in Internet environment"*, Journal of Materials Processing Technology, 107, (2000) 160-166.

11. Radwan, A., *"A practical approach to a process planning expert system for manufacturing processes"*, Journal of Intelligent Manufacturing, 11, (2000) 75-84.

12. Zhao, Y., Ridgway, K., and Ahmari, A. M. A. A., *" Integration of CAD and a cutting tool selection system"*, Computers & Industrial Engineering, 42(1), (2002) 17–34.

13. Park, S. C., *"Knowledge capturing methodology in process planning"*, Computer-Aided Design, 35(12), (2003) 1109–1117.

14. Liu, Z., and Wang, L., *"Sequencing of interacting prismatic machining features for process planning"*, Computers in Industry, 58(4), (2007) 295-303.

15. Deb, S., and Ghosh, K., *"An Expert System Based Methodology for Automating the Set-Up Planning in Computer-Aided Process Planning for Rotationally Symmetrical Parts"*, International Journal of Advanced Manufacturing Systems, 10, (2007) 81-93.

16. Hazarika, M., Deb, S., Dixit, U. S., and Davim, J. P., *"Fuzzy set-based set-up planning system with the ability for online learning"*, Proc. IMechE, 225 Part B, (2010) 247-263.

17. Vukelic, D., Tadic, B., Luzanin, O., Budak, I., Krizan, P., and Hodolic, J., *"A rule-based system for fixture design"*, Scientific Research and Essays, 6, (2011) 5787-5802.

Biography

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