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# RULE BASED PROCESS SELECTION OF MILLING PROCESSES BASED ON GD&T REQUIREMENTS

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***Abstract:*** *The IMPlanner is an ongoing CAPP software project that enables rapid and detailed process selection of manufacturing processes based on specific details of CAD models such as GD&T requirements and feature recognition. A mapping of the different manufacturing routes possible for a given CAD design are outputted by the software, electing the optimal solution. Previously this software focused mainly on hole making operations however, further research has enabled its expansion towards milling operations.*
***Key words:*** *CAPP, Process Planning, Milling Sequence*

**Pravila za izbor tehnoloških procesa obrade glodanjem baziranih na GD&T zahtevima**. *IMPlanner je aktuelni CAPP softver koji omogućava brz i detaljan izbor tehnoloških procesa obrade na bazi specifičnih detalja CAD modela kao što su GD&T zahtevi, kao i na bazi prepoznavanja tipskih oblika. Softver na izlazu daje različite mapirane strategije obrade koje su moguće za dati CAD model uz izbor optimalnog rešenja. Prethodno je ovaj softver bio fokusiran uglavnom na operacije izrade rupa, ali su dalja istraživanja omogućila njegovo proširenje na operacije glodanja.*
***Ključne reči:*** *CAPP, Tehnološki procesi, zahvat glodanja*

## 1. INTRODUCTION

Process planning is fundamental to ensure an optimize relation between design and manufacturing [1]. By implementing CAPP (Computer Aided Process Planning) tools, the translation of design features and tolerances in to manufacturing processes are no longer dependent of work-force knowledge. A CAPP tool is capable of extracting all of the necessary knowledge from a CAD (Computer Aided Design) design file and allocate the necessary sequence of processes, tools and machines capable of producing such product. The knowledge base and rules with which the CAPP tool functions is the key for an improved result [2]. In this work, the expansion of the IMPlanner CAPP software into the field of milling operations is addressed. Section 2 contains a review of previous work developed, 3 explains modules developed in the software, section 4 presents case studies and section 5 concludes the paper.

## 2. PREVIOUS WORK

CAPP tools have been a highly researched topic for a few decades now, having been studied through varied methodological approaches as can be seen in [1]. Knowledge based systems are the foundation for the work here developed and a thorough review of these systems can be read in [3]. More recently CAPP systems are being devised to aid as virtual manufacturing tools [4], distributed process planners [5] and integration tools [6]. Process selection is an important task of process planning as it ensures which process and tools are capable of producing a given feature while meeting design specifications. Usually during process selection a series of alternative processes and manufacturing paths are evaluated to determine which are more capable of achieving the desired objectives, such as production speed, cost, accuracy, among others [3]. For a CAPP tool, the process selection segment will verify which equipment/tool set is capable of producing a given feature regarding geometrical and/or dimensional tolerances, or if needed which series of process are needed to obtain the desired result. Simultaneously, CAPP tools are also able to estimate production time and cost for each manufacturing step.

When performing process selection tasks, regarding a certain process or machine shop, it is necessary to consider three existing levels of knowledge: universal, shop and machine level knowledge [7]. As indicated by the name, universal knowledge does not address the specifics of a process, is usually encountered in handbooks and is only used when details of a process are unknown. Shop level knowledge is drawn upon the specifications of equipment and tools to predict process outcome. Machine level knowledge considers the capabilities of a specific equipment, such as achievable tolerance, based on on-site experience, e.g. on collected data via statistical process control, allowing to quantify the exact capability of an equipment. When equipped with these levels of knowledge in a data base, it is possible to create an accurate and reliable process selection and planning. Even thought this paper will only address universal knowledge, the robustness of the model developed can be easily adapted to any type of knowledge base.

Extensive work has been developed regarding process planning of hole making operations by authors in [8], [9] and [10] however, milling operations are still lacking research depth due to higher variation of process equipment, tools and feature geometries.

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## 3. METHODOLOGY

### 3.1 IMPlanner Software

The IMPlanner CAPP tool is an ongoing software project under development at Ohio University [11] that aims to allow the end user to generate alternate, precise and detailed manufacturing process selection, sequencing and scheduling plans, using CAD design files as a starting point. This is achieved due to the different modules encoded in the IMPlanner software than can convert design features into manufacturing steps and attribute them to specific manufacturing process. A few examples of some important modules in the IMPlanner tool are: the process plan object module which encompasses all of the information relative to manufacturing processes, their hierarchy and propertiesof materials, cutting tools, equipment etc.; the rule-based process selection module (RBPS) that detains the knowledge regarding capabilities of a given process, reasoning against GD&T information such as feature dimension, tolerances and their relation; the feature mapping module which captures design information from the CAD model. Process precedence is also evaluated in order to ensure the correct order of manufacturing processes and steps. The overview of the IMPlanner architecture can be seen in Fig. 1.

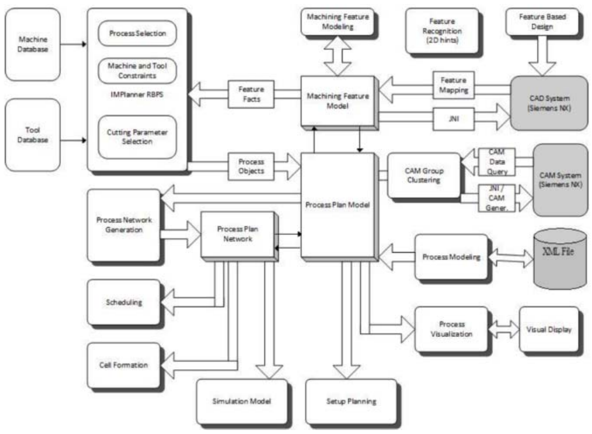


Fig. 1. IMPlanner CAPP tool architecture.

### 3.2 Rule-based Process Selection Module

The RBPS module selects the appropriate manufacturing processes for the feature requirements captured from the CAD file by the feature mapping module, as well as testing for machine and tool availability (rules are essentially If-Then statements coded in Jess (Java Expert System Shell)) [12]. Rules can be grouped into the following areas of action [13]:

1. Process selection rules to decide which processes are compatible with captured features and specifications;
2. Precedence rules for the relation between features, tolerances and quality, returning for instances, the order of processes to manufacture a single or set of features or the machining operations needed;
3. Machine and tool selecting rules;
4. Resting face selection rules for machining operations;

Rules can be separated into two major groups: specific rules and general rules. Specific rules encompass the necessary knowledge for process selection and are reasoned based on a two-way or multi-way relations between design features, manufacturing operations, machines and machine tools. These set of relations can be seen in Fig. 2. Following this diagram, features have a two-way relation with manufacturing operations, meaning that reasoning must be done between the shape of the desired feature to produce and the manufacturing operations capable of producing it (e.g. a face mill produces a flat face perpendicular to the rotating axis of the tool). Manufacturing operations has a multi-way relation between process tools and machines simultaneously, showing that to execute a given operation it is necessary to have the correct tool and machine for the job. Lastly, there is a two-way relation between tools and machines to ensure cross compatibility between these knowledge bases.

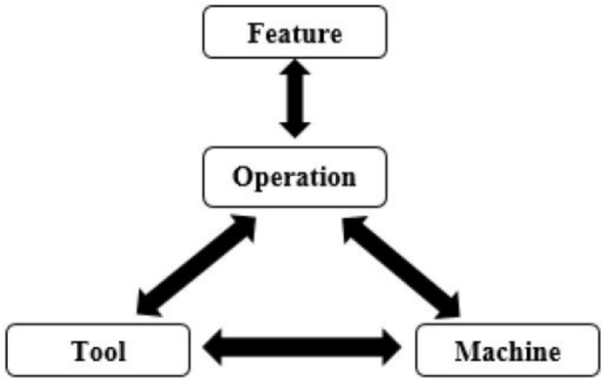


Fig. 2. Relation tree between knowledge branches.

Generic rules are used when knowledge base is separated from the inference mechanism, so that the same set of rules may be used with different knowledge bases. The generic set of rules have been implemented in the earlier work on IMPlanenr development as reported in [13]. Those generic rules have been used in the developing milling capability knowledge base as described in this paper.

### 3.3 Milling Capabilities

Milling is a machining process that uses cutting tools to remove material from a raw block or a pre-formed shape to achieve a desired final geometry. Material removal is achieved via the engagement between the surface of the part and a rotating multiple-tooth cutting tool, originating small chips due to the interrupting cutting action of the tool teeth [14]. Milling techniques can be distinguished according to the tool's axis position relative to the work piece. Some examples are:

- Peripheral milling – performs machining via the cutting edges located on the periphery of the cutting tool, in a horizontal position relative to the work piece (tool rotation axis is parallel to work piece plane). Depending on the tool orientation relative to the feed direction, the cutting action can be classified as upward milling or downward milling [15];
- Face milling – has a tool rotation axis perpendicular to the plane of the part being machined. The part is

machined by the cutting edges located on the periphery of the cutting tool.

- End milling – is similar to face milling with the same tool orientation however, the tools have cutting edges both on the end and periphery of the tool, being able to generate two machined faces simultaneously (such as a pocket or a shoulder profiles).

Due to the variability that exists in manufacturing, tolerances are set to establish limits/boundaries on the degree of variability [16]. It is somewhat difficult to encounter milling process boundaries beyond the realm of universal knowledge. This is due to high versatility of milling operations and great dependence on machinist skills, maintenance procedures. Process capabilities are often treated as a proprietary information and knowledge for individual companies and they are seen as competitive advantage of one organization against its competitors. Nevertheless, some authors have been able to compile several specific tolerance values, such as the values in Table 1 and Table 2 adapted from [17] and [16] respectively. The table 1. Show the value in both inches and millimeters.

| **Boundaries** | **Milling Approach** | | | | | |
|---|---|---|---|---|---|---|
| | **Face** | | **Peripheral** | | **End** | |
| | **Roughing** | **Finishing** | **Roughing** | **Finishing** | **Roughing** | **Finishing** |
| Dimensional Tolerance (in/mm) | 0.002/ 0.0508 | 0.001/ 0.0254 | 0.002/ 0.0508 | 0.001/ 0.0254 | 0.004/ 0.1016 | 0.004/ 0.1016 |
| Flatness (in/mm) | 0.001/ 0.0254 | 0.001/ 0.0254 | 0.001/ 0.0254 | 0.001/ 0.0254 | - | - |
| Angularity (in/mm) | 0.001/ 0.0254 | 0.001/ 0.0254 | - | - | - | - |
| Perpendicularity (in/mm) | 0.001/ 0.0254 | 0.001/ 0.0254 | - | - | - | - |
| Parallelism (in/mm) | 0.001 /0.0254 | 0.001/ 0.0254 | - | - | 0.0015/ 0.0381 | 0.0015/ 0.0381 |
| Surface Finish (μm) | 50 | 30 | 50 | 30 | 60 | 50 |

Table 1. Process tolerances ranges ( [17])

| | **Typical Tolerance** | | **Surface Roughness** | |
|---|---|---|---|---|
| **Machining operation** | **mm** | **In** | **μm** | **μ-in** |
| **Milling** | | | 0.4 | 16 |
| Peripheral | ±0.025 | ±0.001 | | |
| Face | ±0.025 | ±0.001 | | |
| End | ±0.05 | ±0.002 | | |
| **Shaping, Slotting** | 0.025 | 0.001 | 1.6 | 63 |
| Planing | ±0.075 | ±0.003 | 1.6 | 63 |
| Sawing | ±0.50 | ±0.02 | 6.0 | 250 |

Table 2. Process tolerances ranges adapted from ( [16])

A broader analysis has been done in [15] where the author defines the expected accuracy of a machining processes based on the international tolerance grade defined in the ISO 286 Standard, which defines the given tolerance a process can achieved based on the dimension of the part that it is producing.

| **Milling approach** | **ISO 286 Tolerance Grade** | **Surface roughness $R_t$ (μm)** |
|---|---|---|
| Peripheral | IT 8 | 30 |
| Face | IT 6 | 10 |
| Form | IT 7 | 20 – 30 |

Table 3. Achievable accuracies based on part dimensions (from [15])

In addition to presented milling capability knowledge it was also important to define precedence between various milling operations. Usually milling operations are divided into rough and finish operations (sometimes semifinish is included too), in addition to taxonomy of milling operation based on tools used, such as face milling, end milling, side milling, peripheral milling, etc. In this work we have proposed milling operation precedences as shown in Fig. 3. The obvious precedence is that rough operations must precede finish operations. In addition to the above-mentioned processes, we have included plunge milling which is required to precede end milling for closed slots and pockets, and rudimentary treatment of planar grinding operations which may follow finish milling if part tolerance requirements are higher than milling capabilities.

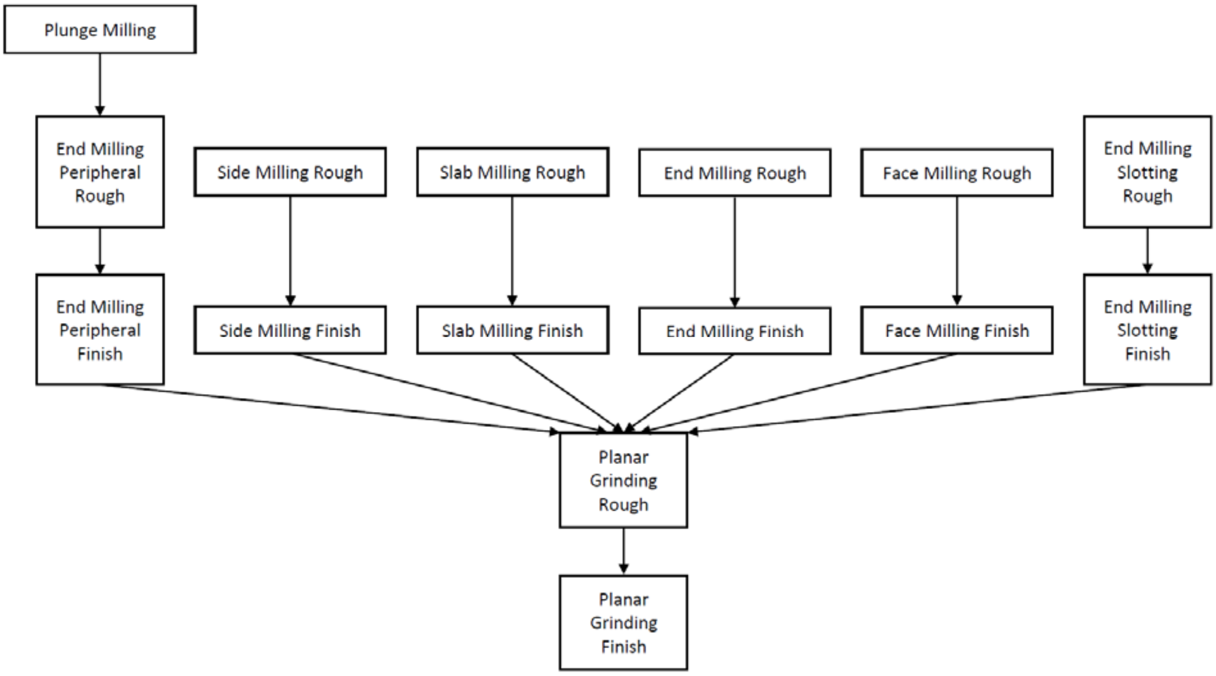


Fig. 3. Precedence of milling operations

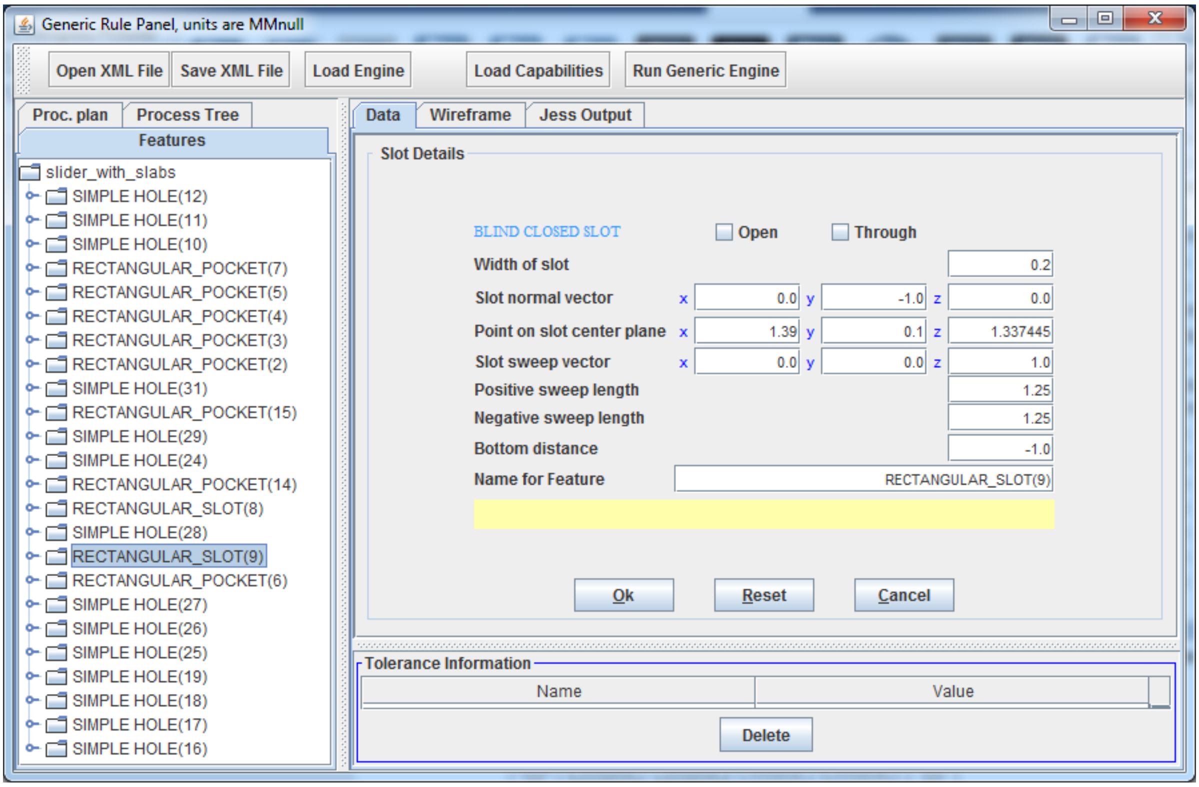


Fig. 4. User interface of IMPlanner running milling process selection

## 4. IMPLEMENTATION

The above-mentioned milling capability knowledge has been implemented as a module in IMPlanner. Implementation consists of three parts:

- Development of process selection rules,
- Milling knowledge representation
- Rules for triggering milling processes for different feature types.

The IMPlanner running an example for milling process selection is shown in Fig. 4.

### 4.1 Process Selection Rules

The process selection rules have been implemented according to the procedure shown in Fig. 5. This procedure allows for selection of sequence of multiple processes, when design tolerance requirements can not be satisfied by a single process. The rule details have been explained in [13] and further discussion is beyond the scope of this paper. This also allows for customized selection of planning knowledge, ie. the same set of rules can be used when knowledge base is augmented to increase the manufacturing capability coverage. The method to do that is explained in section 3.2.

The rules for initial trigger of reasoning process have to be implemented for each individual feature type. This is the entry point for reasoning algorithm. Those rules may depend also on feature dimension and subtype. For example, to machine Slab (the feature that represents resulting flat face in the part) it is enough to always start with face milling or slab milling. On the other side, when considering slots and pockets, it is necessary to consider if they are open or closed. For open slots and pockets, we can start with end milling (and side milling for slots), while for closed slots and pockets we do have to start with a plunging operation. Illustration of those rule is shown in Fig. 6 for closed slots and pockets. The key information in the figure is bolded and underlines to emphasize the reasoning process. Similarly, Fig. 7 shows the rule for open slots, in which case we start reasoning by considering end milling and side milling processes.

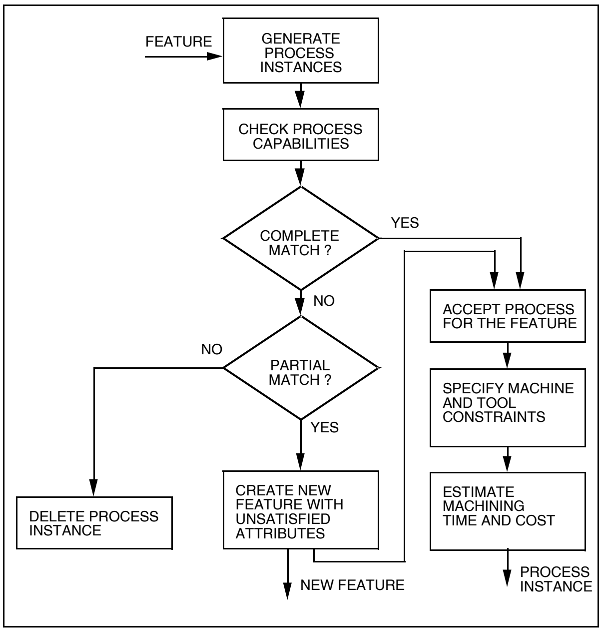


Fig. 5. Procedure for process selection

### 4.2 Milling knowledge representation

Implementation of milling knowledge for IMPlanner consists of the two steps: persistent knowledge storage, and knowledge representation model in the running application. For persistent storage we have adopted the XML format. Fig. 8 illustrates data that is stored for each milling process. For each milling process we store two types of data: process capability for each of feasible GD&T tolerances that can be accomplished by milling. This data is based on our discussion section 3. We also provide two alternative data sets, one for ISO units (in millimeters), and another for ANSI units in inches. In addition, we store required precedence between individual processes, and this serves as information when process selection traverses multiple processes for the same design feature. This is stored under <precedes> tag in the XML file. Once the external data file is loaded into live IMPlanner application the data in the XML file are converted into the process precedence graph (shown in Fig. 9) and table of capabilities (Fig. 10).

```
(defrule AssignPlungeMilling
  ?mf <- (MfgFeature (mayBeMachinedBy ?process&:(eq (call
        ?process toArray) (create$ )))
    (processes ?listOfProcesses&:(eq (call ?listOfProcesses
        toArray) (create$ )))
    (OBJECT ?o&: (and (not (?o isHole))(?o isClosed)))
        (mfgPartModelName ?part&:(neq ?part nil)) )
  (not (FeatureRelation (Feature ?mf)))
  =>
  (addToMaybeMachinedBy ?o "edu.ohiou.mfgresearch.
        implanner.processes.PlungeMilling" )
  (assert (FeatureRelation (Feature ?mf)
        (status MBMBAssigned) ))
  )
```

Fig. 6. Rule for closed slots and pockets

```
(defrule AssignSlotRoughMilling
  ?mf <- (MfgFeature (mayBeMachinedBy ?process&:(eq (call
        ?process toArray) (create$ )))
    (processes ?listOfProcesses&:(eq (call ?listOfProcesses
        toArray) (create$ )))
    (OBJECT ?o&: (?o isSlot)) (mfgPartModelName
        ?part&:(neq ?part nil)) )
  (not (FeatureRelation (Feature ?mf)))
  =>
  (addToMaybeMachinedBy ?o "edu.ohiou.mfgresearch.
        implanner.processes.EndMillingSlottingRough" )
  (addToMaybeMachinedBy ?o "edu.ohiou.mfgresearch.
        implanner.processes.SideMillingRough" )
  (assert (FeatureRelation (Feature ?mf)
        (status MBMBAssigned) ))
  )
```

Fig. 7. Rule for open slots

```
<edu.ohiou.mfgresearch.implanner.processes.SideMillingRough>
<precedes>edu.ohiou.mfgresearch.implanner.processes.SideMillingFinish</precedes>
    <Parameter flatness="0.0254"/>
    <Parameter dimensionTolerance="0.0508"/>
    <Parameter sizeTolerance=""/>
    <Parameter surfaceFinish="50"/>
</edu.ohiou.mfgresearch.implanner.processes.SideMillingRough>

<edu.ohiou.mfgresearch.implanner.processes.SideMillingFinish>
<precedes>edu.ohiou.mfgresearch.implanner.processes.PlanarGrindingRough</precedes>
    <Parameter flatness="0.0254"/>
    <Parameter dimensionTolerance="0.0254"/>
    <Parameter sizeTolerance=""/>
    <Parameter surfaceFinish="30"/>
</edu.ohiou.mfgresearch.implanner.processes.SideMillingFinish>
```

Fig. 8. Process capabilities in persistent XML format

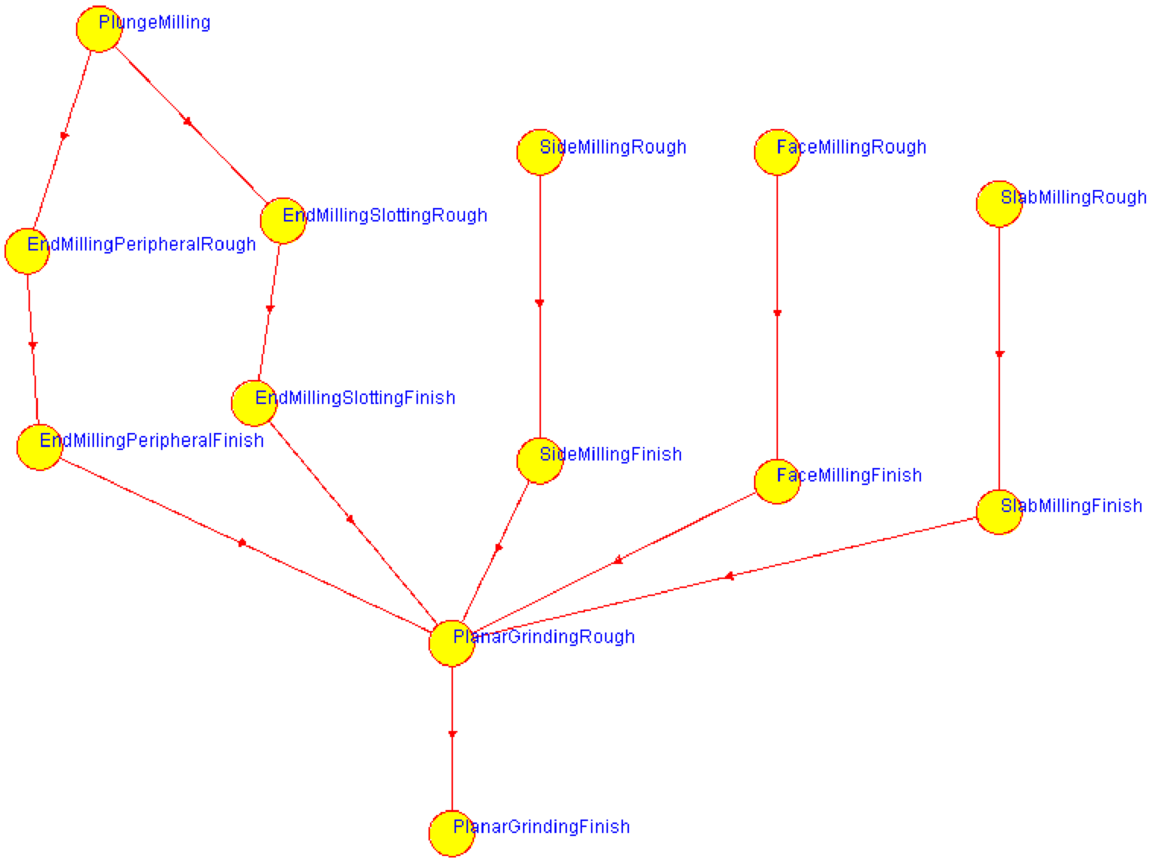


Fig. 9. Precedence of the milling operation in the IMPlanner prototype

process capability data

| Name | SlabMillingFinish | EndMillingPeripheralRough | EndMillingPeripheralFinish | EndMillingSlottingRough | FaceMillingRough | PlanarGrindingFinish | FaceMillingFinish |
|---|---|---|---|---|---|---|---|
| negativeTolerance | | | | | | | |
| positiveTolerance | | | | | | | |
| roundness | | | | | | | |
| largestToolDiameter | | | | | | | |
| smallestToolDiameter | | | | | | | |
| straightness | | | | | | | |
| parallelism | | | | 0.0381 | 0.0254 | | 0.0254 |
| truePosition | | | | | | | |
| surfaceFinish | 30 | 50 | 30 | 60 | 50 | | 50 |
| perpendicularity | | | | | 0.0254 | | 0.0254 |
| flatness | 0.0254 | 0.0254 | 0.0254 | | 0.0254 | | 0.0254 |
| angularity | | | | | 0.0254 | | 0.0254 |
| dimensionTolerance | 0.0254 | 0.0508 | 0.0254 | 0.1016 | 0.0508 | | 0.0254 |
| sizeTolerance | | | | | | | |

Fig. 10. Implemented process capability matrix

## 5. CASE STUDY

To illustrate the developed approach, we have run the process selection procedure on a sample real part called Slider (shown in Fig. 11). This is a part design that have served as test design for several research institutions to be able to compare their results.

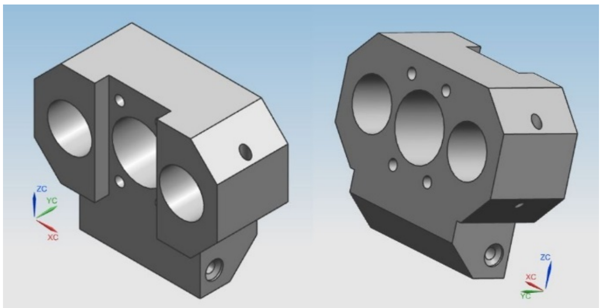

Fig. 11. Slider Example

In addition to geometric model (the CAD file) from which we have retrieved feature dimensions and orientations, it was necessary to supply GD&T requirements. From the mechanical drawing for Slider we took tolerance requirements (which also included some datums), but we have added additional tolerance and surface finish requirements in order to be able to test and verify the process selection procedure. Also, since Slider part has several Hole features we have executed the complete procedure for both hoel making and milling. The hole making knowledge base is used from our previous research [13]. The part model is loaded from XML file that contains the part model with the feature dimensions and tolerance requirements. The loaded part with all features before the process selection procedure starts is shown in Fig. 12, while an example of feature data is shown earlier in Fig. 4.
After the part model is loaded the system load process capability data and process selection rules. The process

selection is executed in the Jess inference engine and the final results are shown in Fig. 13.
The feature/process tree shown in Fig. 13 illustrates few results from the process selection procedure:

1. Process selection procedure was successful for all features as shown by change of the icon in the feature tree for all features (compare folder icon in Fig. 13 with a terminate node icon in Fig. 12, before the process selection is started).
2. For each design feature (shown in black in Fig. 13) the selected processes are shown in blue and intermediate features are shown in magenta.

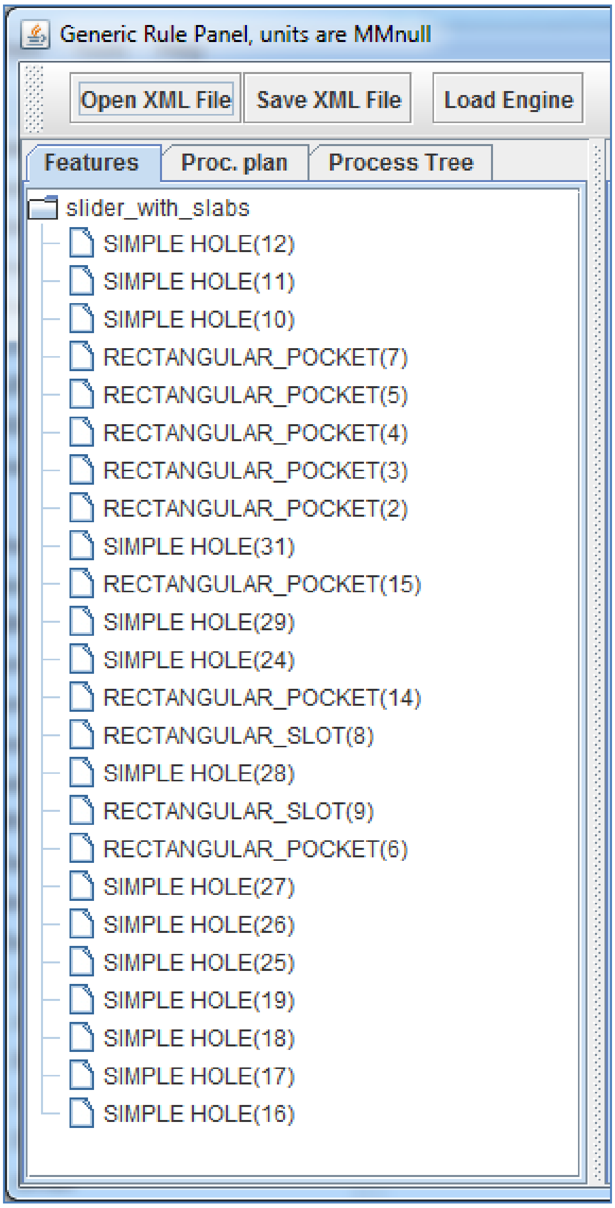


Fig. 12. Features of Slider Example

3. For each feature, the procedure considered alternate processes according to the knowledge base, for example *RECTANGULAR SLOT(9)* could be made by *EndMillingRough* or *SideMillingRough.*
4. If a single process satisfies all requirements, there is not further expansion, as shown for *RECTANGULAR SLOT(9).*
5. If there is a need to consider several processes to obtain the required tolerances, several processes are recommended, see for example *RECTANGULAR POCKET(7)*, for which four different processes in sequence are necessary.
6. If the design required tolerances are such that there is no a set of processes which would satisfy all of them, the last intermediate feature (for which nothing can be selected) is shown in red, as is the case for *SIMPLE HOLE(12)* after *HoleGrinding*. This case would require the change in design or consideration of new resources.

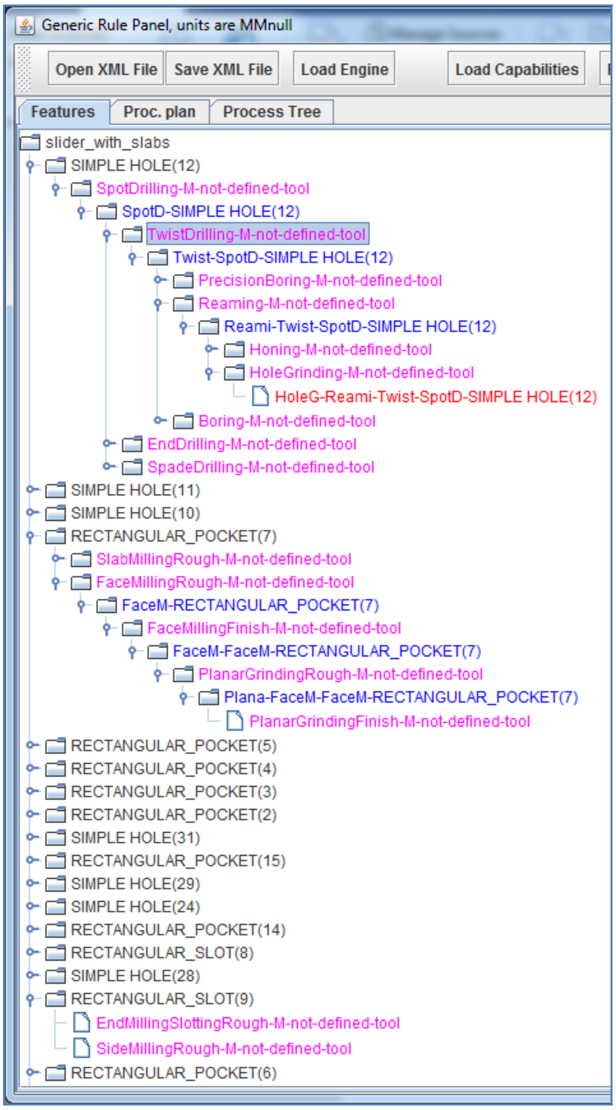


Fig. 13. Selected machining processes for several features

The result shown demonstrates the complete consideration of all available processes and their sequence in order to produce each feature in the part design with specified dimensions, tolerance, and surface finish requirements.
The next step is selecting the most efficient set of processes for each feature and sequencing processes of all feature to most optimize production.

## 6. CONCLUSIONS

This paper has demonstrated a successful development of the knowledge base for milling operations. While the knowledge base may not be complete for all machine shops, it provides a template for development that could include designed experiments in each shop and real-time monitoring of the machine performance to adjust the process capabilities.

Implementation of the knowledge base as part of the generic rule-based process selection procedure provides a roadmap for incorporating the shop floor knowledge into automated process planning.

Visualization of the process selection results provides a fidelity of the system and increase the trust between engineers and planning software.

While results demonstrate successful approach, there are few other actions that can be taken:

1. consider mil-turn operations by extending the knowledge base to turning processes
2. Extend reasoning to include machine and tool selection by integrating the process selection rule with process/machine/tool compatibilities.
3. Include real-time data collections from running machine (e.g. vibrations, forces, etc) that may have an impact on capabilities and adjust capability knowledge base for dynamic decision making.

## 7. REFERENCES


[1] X. Xu, L. Wang, and S. T. Newman, "Computer-aided process planning – A critical review of recent developments and future trends," International Journal of Computer Integrated Manufacturing, vol. 24, no. 1, pp. 1-31, 2011/01/01 2011.

[2] D. Sormaz, M. Wakhare, and N.-U. Arafat, "Rule-Based Process Planning and Setup Planning with Consideration of GD&T Requirements " International Journal ''Advanced Quality'',, vol. 45, no. 1, p. 8, 2017.

[3] D. Kiritsis, "A review of knowledge-based expert systems for process planning. Methods and problems," The International Journal of Advanced Manufacturing Technology, journal article vol. 10, no. 4, pp. 240-262, July 01 1995.

[4] M. F. Zaeh and H. Rudolf, "Agile Process Planning considering the Continuous Reconfiguration of Factories " in Preceedings of 3rd International Conference of Reconfigurable Manufacturing Systems, Ann Arbor, MI, 2005.

[5] L. Wang and W. Shen, "DPP: An agent-based approach for distributed process planning," Journal of Intelligent Manufacturing, journal article vol. 14, no. 5, pp. 429-439, October 01 2003.

[6] X. W. Xu and Q. He, "Striving for a total integration of CAD, CAPP, CAM and CNC," Robotics and Computer-Integrated Manufacturing, vol. 20, no. 2, pp. 101-109, 2004/04/01/ 2004.

[7] T.-C. Chang, Expert Process Planning for Manufacturing. Menlo Park, CA: Addison-Wesley, 1991.

[8] B. Khoshnevis, W. Tan, and D. N. Sormaz, "A process selection rule base for hole-making," in "Factory Automation Systems Division," Gaithersburg, MD1993.

[9] D. Sormaz, P. Khurana, and A. Wadatkar, Rule-Based Process Selection of Hole Making Operations for Integrated Process Planning. 2005.

[10] D. Sormaz and M. Wakhare, "Rule Based Process Selection for Hole Feature Considering Tolerance Capabilities," in Industrial and Systems Engineering Research Conference Miami, Fl, 2016, vol. 2016.

[11] D. N. Sormaz *, J. Arumugam, and S. Rajaraman, "Integrative process plan model and representation for intelligent distributed manufacturing planning," International Journal of Production Research, vol. 42, no. 17, pp. 3397-3417, 2004.

[12] F.-H. Ernest, Jess in Action. Manning Publications 2003.

[13] D. N. Sormaz, J. Arumugam, and C. Ganduri, "Integration of Rule-based Process Selection with Virtual Machining for Distributed Manufacturing Planning," in Process Planning and Scheduling for Distributed Manufacturing, L. Wang and W. Shen, Eds. London: Springer London, 2007, pp. 61-90.

[14] A. International, ASM Metals Handbook - Machining. 1997.

[15] H. Tschätsch and A. Reichelt, "Milling," in Applied Machining TechnologyBerlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 173-223.

[16] M. P. Groover, Wiley, Ed. Fundamentals of Modern Manufacturing - Materials, Processes and Systems, 4th ed. Wiley, 2010, p. 1028.

[17] R. A. Wysk. (2008). Process Engineering Basics for Process Planning for Computer Implementation - IE550 - Manufacturing Systems Fall 2008 [Personal Presentation].



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