Knowledge representation and expert system based operation selection in a process planning and fixturing system

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ABSTRACT

Process Planning is the prime interface between CAD and CAM systems. At Coventry University an Intelligent Knowledge Based Process Planning for prismatic parts has been developed. The system, called **EPPSU**, is able to produce process plans automatically. This paper introduces the knowledge representation within the system and describes the notation for representing knowledge. The structure of the knowledge base developed for operation selection is overviewed and one specific subset area in process planning namely selection of processes is presented.

1. INTRODUCTION

CAD and CAM systems have increased productivity, reduced overall costs and offered more flexibility in industry. Nonetheless, the integration of such two systems has not yet been fully accomplished. The main obstacle to be overcome is the automation of Computer Aided Process Planning (CAPP). When developing a CAPP system initially a method must be selected to capture process planning knowledge, experience and logic in a computer environment. Conventional algorithmic programming techniques are considered unsuitable to accomplish this task, because process planning problems are usually solved heuristically, based on human judgement, experience and empirical rules. Hence, Intelligent Knowledge Based System (Expert System) techniques are considered better to automate process planning activities.

A flexible, fully automated, generative CAPP system called **EPPSU** for prismatic parts using Expert System techniques and the STEP (Standard for the Exchange of Product Model Data) standard to communicate with CAD systems has been developed [1].

An English-like knowledge base for process selection, process sequencing, selection of reference surfaces, cutters and machine tools has been designed. Reading the knowledge base, the Inference Engine draws necessary conclusions using a backward or forward chaining technique with the aid of the User Interface. After receiving 3D B-rep CAD data in STEP format, the system converts it into a PROLOG format, selects a stock size and designs a blank for the part. Having calculated the angles between faces the neighbouring relationships and convexity-concavity relationships of the faces are found. The blank part and finished part models are then represented in a special format called Face Oriented Neighbouring Graph (FONG) which has been designed for the system.

In addition to selection of a reference surface, operation selection for each feature and sequencing of operations, calculation of machining parameters, selection of cutters and machine tools are carried out. Fixturing for each stage of operation is also addressed.

After each operation the material is removed from the part and a new intermediate part model is generated in FONG. Therefore, sound decisions about process planning and fixturing for subsequent operations can be done. The expert system developed draws necessary conclusions for the process planning system by consulting the heuristic knowledge that is composed of facts and rules in the knowledge base the same way an expert process planner does. The inference engine, which is able to read rules and facts from the data base, can do backward or forward chaining and depth first search to reach conclusions. During the inferencing session the inference engine can answer WHY questions and show HOW it has reached a conclusion.

The expert system comprises the following major components:

1. Knowledge Base,
2. Inference Engine (Control Mechanism),
3. User Interface,
4. Explain Facility,
5. Knowledge Acquisition and Maintenance.

The system characteristic features can be summarised as follows:

- English-like rules and facts in the knowledge base,
- backward and forward chaining strategy with depth first search technique during inferencing,
- AND/OR graph technique to represent the production (IF-THEN) rules,
- answering WHY and HOW queries to show the chain of reasoning,
- knowledge base editing and modifying in a text editor shell environment.

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The rules and facts, which are structured in English syntax, can be updated very easily in an editor environment. Instead of editing one rule or fact at a time by retrieving the knowledge base, which is in ASCII format, the user can alter or edit the text by moving the cursor and using the editor functions such as page up, page down, find-replace, delete word, line etc. similar to a word processor or text editor functions. The system also includes a translator to convert English-like knowledge base into a PROLOG clauses form.

The final output of the process planning system consists of a process plan, fixturing information and intermediate part models which can be used to check operations and for NC code generation. The system is implemented in PROLOG and runs under Unix.

2. KNOWLEDGE BASE REPRESENTATION

A knowledge base may be represented in different formats such as production rules, frames and semantic networks [2,3,4,5]. In this work production rules are utilised to represent the knowledge since it is the natural form of expressing knowledge.

The knowledge base is composed of RULES and FACTS. The general form of a production rule (conditional statement) is

IF condition 1 **AND**
condition 2 **AND**
...
condition N
THEN
conclusion (or action)

This means the **conclusion** is true if **condition 1** and **condition 2** , **...** and **condition N** are all true. Each condition in the **IF** part is referred as a **subgoal.**

In the knowledge base if one rule is not enough to solve a problem it can refer to another rule(s). That is rules may be connected to each other as shown in Figure 1.

2.1 Representation of Facts

A fact begins with the word of "**FACT**" and a unique fact number followed by a colon "**:**" and then the fact expression is specified. The fact expression consists of a name, a verb such as **is, are, let, has, have**, etc. or a comparison operator namely >, <, >=, =< followed by an expression or a number and its unit.

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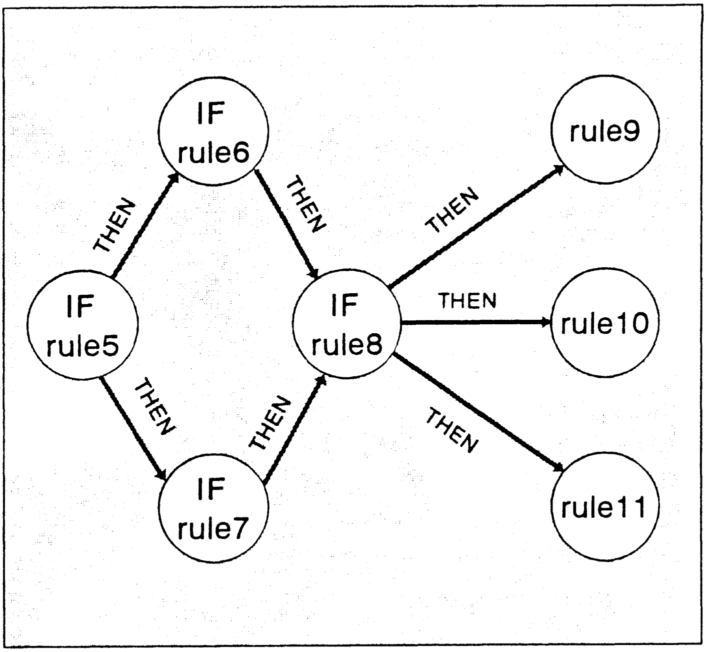

Figure 1. The rules can be nested as often as required

An example of a fact in the knowledge base is represented as

```
FACT 180 :  the surface_roughness is 32 Mm
        |    |   ________|________  |  |  |
        A    B           C          D  E  F
```

where

A unique number of the fact
B article
C name
D (auxiliary) verb
E value (number)
F unit (Micro metre in this occurrence).

2.2 Representation of Rules

Likewise a rule is composed of a **rule name**, an **IF** part and a **THEN** part. Rule names begin with "**RULE**" followed by a unique rule number and a colon. The **IF** part contains condition(s). Conclusion forms the **THEN** part. An example of the rules modelled within the system is illustrated as follows,

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```
RULE 46 :
 IF
   the feature is a through_hole              AND
   the hardness =< 48 HRC                     AND
   the surface_roughness >= 0.80 Mm           AND
   the depth =< 10 * the diameter             AND
   the diameter >= 1 mm                       AND
   the diameter =< 75 mm                      AND
   the diameter_tolerance is acceptable_for_twist_drilling_(with_bushings)
                                               AND
   the location_tolerance is acceptable_for_twist_drilling_(with_bushings)
                                               AND
   bushings are used                           AND
   the straightness_tolerance >= 0.6 mm        AND
   the roundness_tolerance >= 0.05 mm
 THEN
   the operation is twist_drilling
```

The legal words used to represent the knowledge base are shown in Table 1.

Table 1. Reserved words that can be used to represent knowledge

FACT	can	<
:	lets	+
RULE	let	-
/*	a	*
*/	an	/
IF	the	HRC
is	>	mm
are	>=	AND
has	=	THEN
have	=<	Mm

2.3 AND/OR Graph for Structuring Rules

The rules are structured in the form of AND/OR graph. By applying AND/OR graph the problems to be solved are decomposed into subproblems. Decomposition into subproblems is advantageous if the subproblems are mutually independent and can hence be solved independently of each other [6,7]. A solution to the problem structured in AND/OR graph depends on the successors. If the successors of the problem are **OR** nodes then either of them is solved. On the other hand should the problem have **AND** successors then all of them are solved. Such AND/OR relationship is shown in Figure 2. AND connection is indicated with a horizontal line connecting two components, whereas OR connection is shown with an arc.

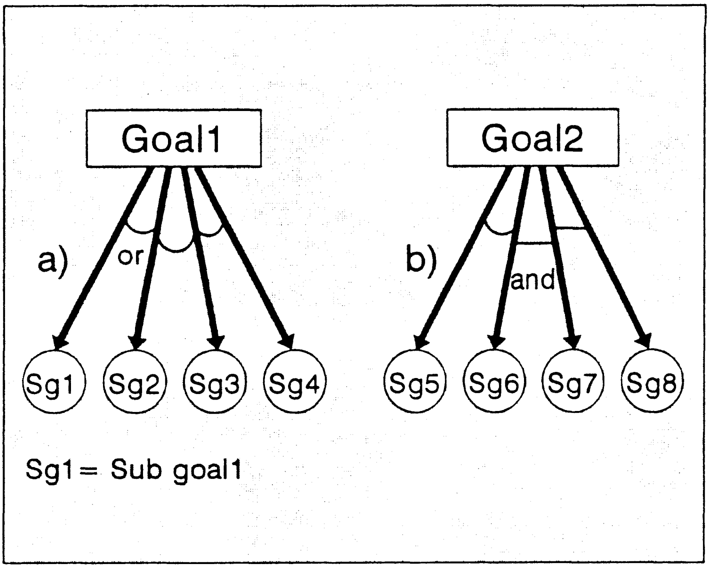

Figure 2. a) In order to solve Goal 1 solve either Sg1, Sg2, Sg3 or Sg4.
b) To solve Goal 2 solve either Sg5 or (Sg6, Sg7 and Sg8).

For example, the AND/OR graph for the rules given below is structured as illustrated in Figure 3.

RULE 2 :
IF
the feature is a plane_face AND ——— **A**
the surface_roughness > 0.2 Mm AND ——— **B**
the hardness < 56 HRC AND ——— **C**
the tolerance is acceptable_for_face_milling ——— **D**
THEN
the operation is face_milling ——— **Goal 1**
RULE 6 :
IF
the length > 50 mm AND ——— **E**
the length =< 200 mm AND ——— **F**
the location_plus_tolerance > = 0.075 mm AND ——— **G**
the location_minus_tolerance > = 0.075 mm ——— **H**
THEN
the tolerance is acceptable_for_face_milling ——— **Sg1**
RULE 4 :
IF
the length > 0 mm AND ——— **I**

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the length =< 50 mm AND ——— J
the location_plus_tolerance >= 0.05 mm AND ——— K
the location_minus_tolerance >= 0.05 mm ——— L
THEN
the tolerance is acceptable_for_face_milling ——— Sg2
RULE 8 :
IF
the length > 200 mm AND ——— M
the location_plus_tolerance >= 0.1 mm AND ——— N
the location_minus_tolerance >= 0.1 mm ——— O
THEN
the tolerance is acceptable_for_face_milling ——— Sg3

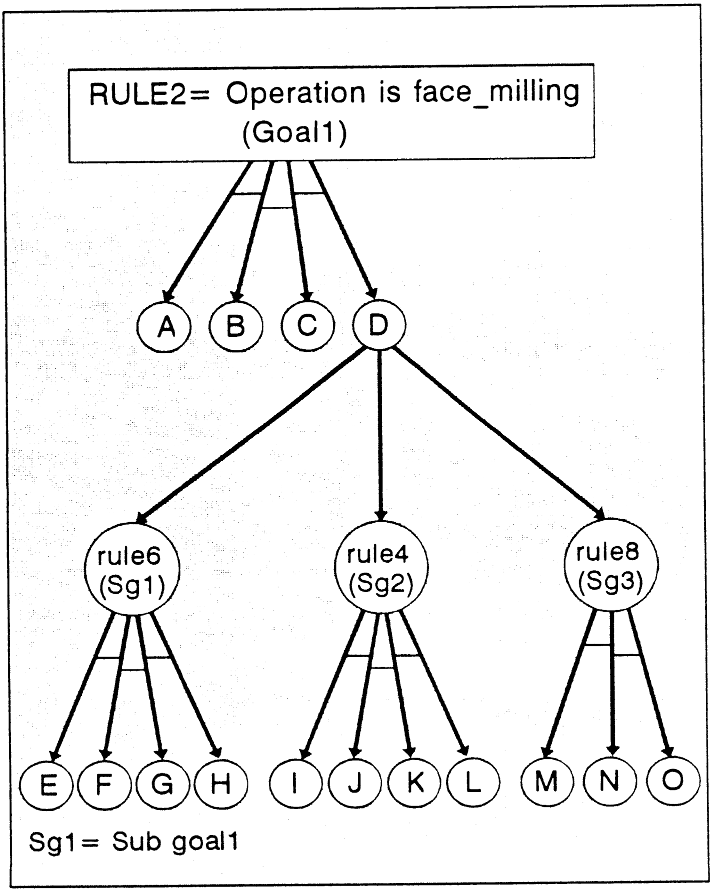

Figure 3. AND/OR graph of production rules

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3. TRANSLATION OF ENGLISH-LIKE KNOWLEDGE BASE INTO PROLOG CLAUSES FORM

A parser and lexical analyzer are employed to translate the English-like facts and rules into PROLOG clauses form which is the form of Horn Clauses. The parser program reads one fact or rule at a time. The translation is performed on the basis of words. The input stream is the English-like knowledge base file and the output stream is the translated knowledge base in Prolog format to enable it processible by the system (Figure 4).

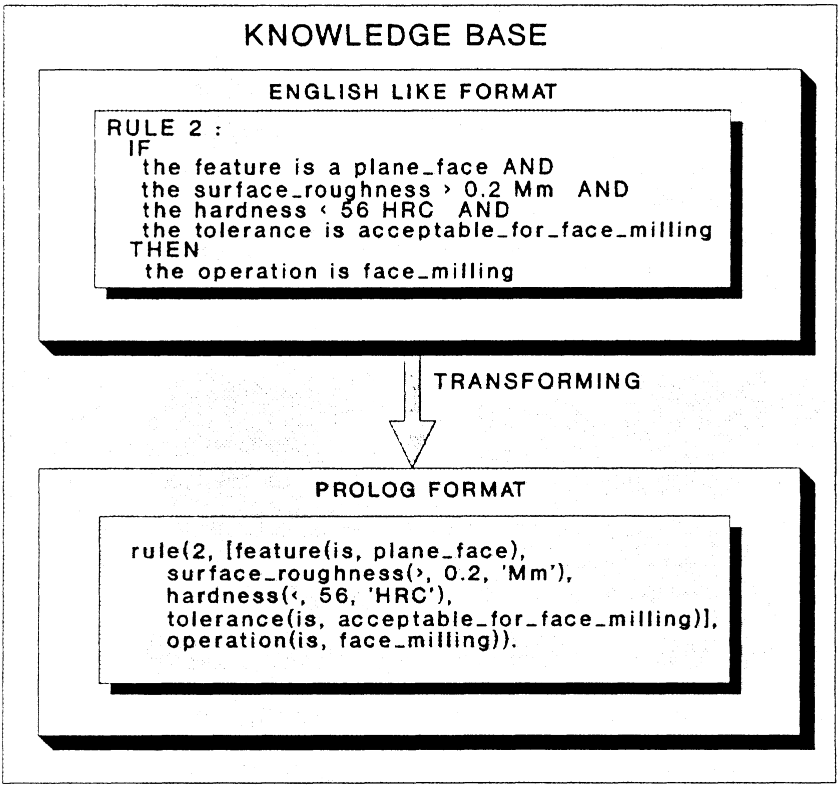

Figure 4. Translation of English like knowledge base into Prolog format.

4. MANUFACTURING OPERATION SELECTION

The task of process selection is one of the major activities and plays an important role in process planning. Selection involves the task of choosing a particular manufacturing process to produce each of the machined surfaces of the part.

The process selection system developed, which selects a set of feasible processes for features/faces of the component, is based on expert system concepts. The system extracts the required information (location, size tolerances, dimensions, material, etc) of the component from the STEP file and asserts such information as facts in the data base. With the help of the **inference engine** and **user interface** operations for each face/feature which can transform the raw material to the finished product are selected using the related rules and facts in the knowledge base. Since the system utilizes a **forward planning** strategy it begins with the blank part modelled in the data base and generates **intermediate part models** by choosing and applying the operations corresponding to faces/features. The material is removed after each operation, until the final part model is reached.

Operation selection is the task of selecting appropriate processes to produce each of the features of the part according to the required specification by removal of material from a larger initial mass. Every machining operation has a unique way of changing the state of material [8,9,10,11].

With the help of the **inference engine** and **user interface** operations for each face/feature, which can transform the blank part to the finished product are chosen using the related rules and facts in the knowledge base (Figure 5). The selection of processes is recursive and continues until the finished product shape is established. More than 100 rules have been set up for manufacturing operations selection. Having identified and refined the features in the component the inference engine matches and executes related rules and defines the machining operations necessary to produce the required geometry by applying a **backward chaining** principle and **depth first** search strategy.

Prior to finding rules for the feature, associated technological information is retrieved from the data base and taken into account. If there is associated information, the inference engine finds more than one solution for machining the feature. During the inferencing session the user is allowed to ask WHY and HOW questions to follow the inferencing route.

4.1 Knowledge Base for Operation Selection

So as to make a decision on which operation is to be used the capabilities of available manufacturing processes should be understood [12,13,14]. The knowledge base for operation selection has been set up on the basis of process capabilities of each process. Such process capabilities are:

- The shape and size an operation can produce,
- Geometric tolerances that can be obtained by various processes,
- The surface finish attainable,
- Hardness

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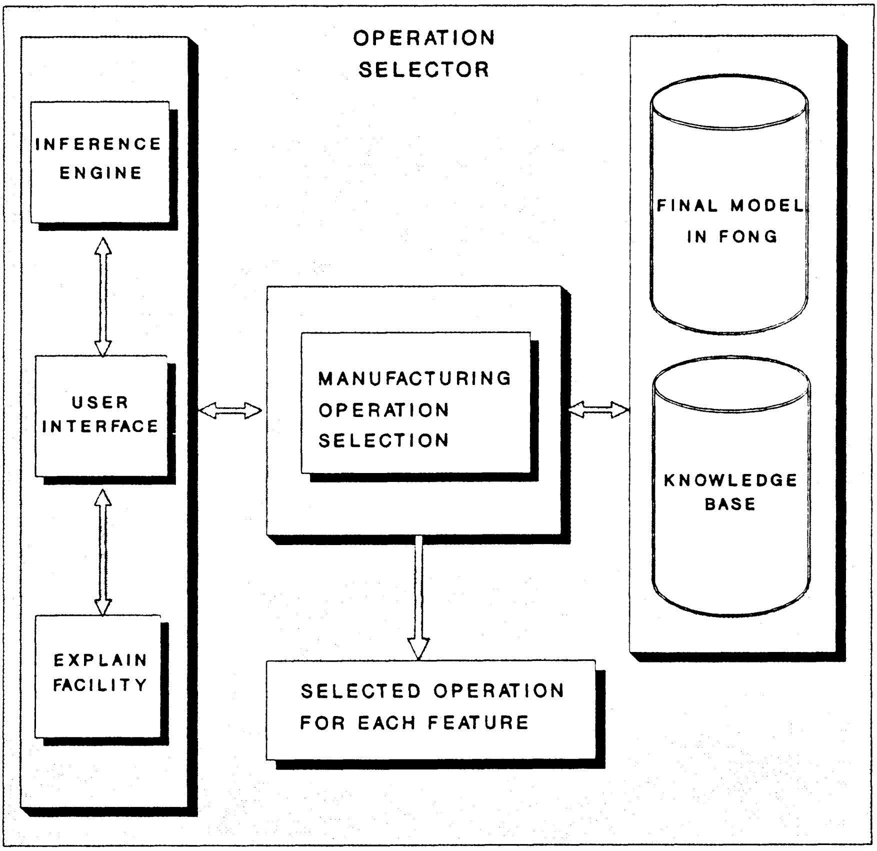

Figure 5. The overview of manufacturing operation selection

Machining processes are utilised to remove materials from a workpiece by which new surfaces are generated. The characteristics of the surfaces are dependent on the capability of the processes applied. Each process can produce a specific shape.

The **shape** producing capabilities of a process is determined by the geometrical shape a machining process can produce. For instance, face milling can generate a flat surface and twist drilling can produce a cylindrical hole. The **size** of the face/feature is also dependent on the operation. The size capability is determined by both the tool size and the machine tool work envelope. For example, the drilling operation can drill neither an infinitely large and deep hole nor a hole smaller than the size of the drill bit available. The depth of a hole is related to the diameter of the tool used. An ordinary twist drilling process cannot drill a hole with the depth greater than ten times the hole diameter. Should a hole have greater depth/diameter ratio it has to be drilled by a deep hole drilling process such as a gun drilling.

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The **tolerance** and **surface finish** requirements are closely related to the operation selected. Each process is able to produce surfaces with tolerances and surface finish within the certain range. For operation selection procedure it is important to consider the fact that in a real production the operation selected for a feature meets the required tolerances. Therefore, the concept of tolerancing must be taken into account. The operation should be capable of producing the accuracy and surface finish required. For example, a twist drill can produce a hole with certain accuracy and surface finish when the drill diameter is between 6.3 mm and 19 mm (with bushings) the diameter tolerance can be obtained is $\pm$ 0.076 mm and the diameter tolerance for a drill whose diameter is between 19 mm and 75 mm (without bushings and centre drills) is $\pm$ 0.2 mm. Face milling operations can produce a surface with a surface roughness greater than 0.2 μm and with twist drilling a surface roughness of 0.8 μm can be obtained. On the other hand through the use of a honing operation for a hole and surface grinding for a flat surface 0.025 μm surface roughness can be generated.

When the rules are being structured the **hardness** constraint should also be considered since each operation employs a cutting tool which is able to remove material whose hardness is within certain limits. The general rule is: should the material hardness be smaller than 48 HRC both an HSS tool or indexable insert (carbide) tool can be used. However, if the hardness of the component is greater than 48 HRC then a carbide tool should be used.

Apart from the constraints explained above, **geometric** and **technological** constraints were also considered to set up the rules for operation selection. **Geometric** constraints are identified by the geometric relations of features. For example, boring or reaming operations can not be applied to a component unless a hole exists. Before machining a tee-slot there must be a slot for the tool shank clearance. Should the bottom of a hole be flat then a twist drill cannot be used, an end mill is utilised instead.

Technological constraints are those constraints identified by power consumption, material removal rate, cutting speed, etc. which are evaluated by the machine tool selection module.

The rules can be organised in any order in the knowledge base. A rule can refer to another rule(s). In other words the branching between rules can be done as often as desired. However, the rules for the same or similar operations were grouped under a specific heading for the sake of good organisation and to help the user find the related rules easily. A rule is composed of two major parts namely the **IF** part (also called condition part) and the **THEN** (action or conclusion) part. The IF part is in the form of expressions that must evaluate to true or false. During the inferencing such expressions might seek a rule or a fact to satisfy the **condition**. The THEN part consists of an action to be performed, which is generally a type of operation to be carried out.

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The IF part describes process boundaries. They express what would be the surface condition if the process is applied. The IF part might have one or more conditions. If there is more than one condition then all of them must be satisfied before the **action** part of the rule can be executed. Each condition consists of two or three parts and is in the form:

Name Operator Expression.

Names are composed of character strings and numbers. The **Operator** part can be either one of comparison operators such as <, >, >=, =<, etc. or one of a number of (auxiliary) verbs namely **is, are, has, have, let**, etc.

The **Expression** part can be any combination of arithmetic operations, numbers and character strings. The other major element of a rule is the **THEN** (condition or conclusion) part which consists of an action to be executed. The general format of a conclusion part is:

Conclusion_name Operator Expression

Conclusion_name is composed of characters and numbers. **Operator** and **Expression** are structured as explained earlier. Rules relate each feature to a manufacturing operation. Some of the typical rules modelled regarding the selection of operations are given in the following examples.

```
/* REAMING */
RULE 126 :
 IF
  the feature is a blind_hole_with_conical_bottom   AND
  the hardness =< 56 HRC             AND
  there is a pre_hole              AND
  the surface_roughness >= 0.4 Mm   AND
  the depth >= 3 * the diameter      AND
  the depth =< 55 * the diameter     AND
  the diameter >= 1 mm             AND
  the diameter =< 75 mm            AND
  bushings are used               AND
  the diameter_tolerance is acceptable_for_reaming AND
  the location_tolerance is acceptable_for_reaming AND
  the straightness_tolerance >= 0.3 mm AND
  the roundness_tolerance >= 0.01 mm
 THEN
  the operation is reaming
```

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```
/* Slot milling (plain) */
RULE 184 :
 IF
  the feature is a slot    AND
  the hardness =< 56 HRC   AND
  the surface_roughness >= 0.2 Mm AND
  the location_plus_tolerance >=  0.05 mm  AND
  the location_minus_tolerance >=  0.05 mm AND
  the width >= 0.7 mm
 THEN
  the operation is slot_milling
```

The various machining operations currently modelled within the knowledge base which are listed in Table 2.

Table 2. Machining processes modelled in the knowledge base

MILLING OPERATIONS	DRILLING OPERATIONS
face milling	twist drilling (with/without bushings,centre drilling)
Slotting Operations	indexable insert drilling
tee-slot milling	solid carbide drilling
vee-slot milling	gun drilling
woodruff-key-seat milling	spade drilling (vertical/horizontal)
groove milling	oil-hole drilling
pocket milling	core drilling
step milling	reaming
vee-slot milling	counterboring
	countersinking
	spotfacing
	boring
	centre drilling
	tapping
	grinding
	honing
	lapping

It is possible to add more rules and facts (in any order) to acquire further knowledge through the **knowledge acquisition** facility and gradually improve the performance of the process selection system.

4.2 Inferencing For Process Selection

The **inference engine** determines how a process is selected for each feature in order to produce the finished part by applying related rules. It determines what rules are applicable based on what rules have already been applied. Hence, it links the rules together as it seeks to infer a solution. As the system utilizes backward chaining for operation selection the inference engine begins with the **THEN** (conclusion/action) part which is to be proved. The inference engine then seeks those rules that have such **conclusion** or goal as part of their **THEN** part. All the conditions of any rule possessing this conclusion as a consequence must be true. Each of these conditions is then set as a **subgoal** and the inference engine begins again to look for rules with these subgoals in their **THEN** part. Such procedure is repeated until the **goal** can or cannot be reached given the available information. The subcondition of the rule becomes a new goal for the inference engine, which needs to be satisfied. When the inference engine is trying to find an answer to a **goal** it first seeks a rule applicable to such a goal, if there is none, it searches for a fact that matches this goal. If a fact matching the goal is found then this fact is the answer for the goal, otherwise the inference engine asks to the user to supply the required information.

The main input information for process selection comes from the component model file represented in FONG in the data base. When specific information such as dimension, location tolerances, size, etc. is required from the STEP file it is extracted by the program. Such geometric and technological information is asserted in the data base so that the Expert System can utilize them when inferencing without asking to the user to provide the information. An example part and the process plan sheet generated by the system including selected operations are illustrated in Figure 6 and Figure 7, respectively.

5. CONCLUSIONS

An English-like knowledge base has been developed for an Expert Process Planning System. The rules and facts in the data base are explicitly defined, readable and accessible. We have described how a knowledge base for process selection is structured and operations are chosen automatically utilising Expert System techniques. The system is able to do intelligent reasoning to perform the task of operation selection. As the knowledge base is composed of English-like rules and facts further knowledge can be obtained or the modification of the rules and facts can be performed by the user without any knowledge of computer programming.

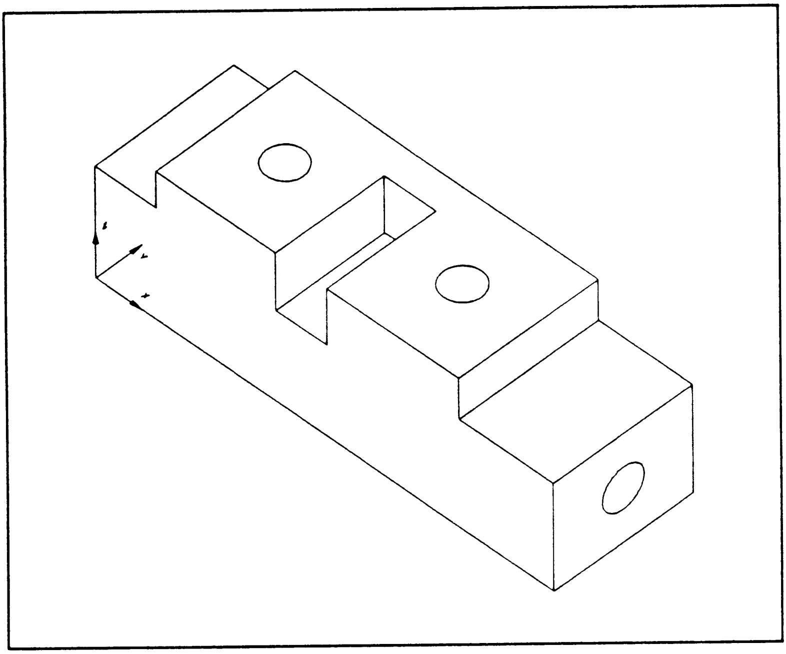

Figure 6. Sample part

P R O C E S S   P L A N

PART NAME : part2
BLANK SIZE : 200 x 65 x 70
MATERIAL : 1212
HARDNESS : 20 HRC

PLANNER NAME: M_Gulesin
FILE NAME : prplan2
DATE : 12/5/1992

OP NO	FEATURE ID	Type	OPERATION	TOOL	MACHINE	SPEED	FEED	TOOL LIFE
10	575	plane	face_milling	face_mill/11	milling_m/4	316.1	1011.6	540
20	545	plane	face_milling	face_mill/11	milling_m/4	316.1	1011.6	540
30	350	plane	face_milling	face_mill/11	milling_m/4	316.1	1011.6	540
40	385	plane	face_milling	face_mill/11	milling_m/13	316.1	1011.6	540
50	395	plane	face_milling	face_mill/11	milling_m/4	316.1	1011.6	540
60	400	plane	face_milling	face_mill/11	milling_m/13	316.1	1011.6	540
70	560	step	step_milling	end_mill/4	milling_m/3	1244.6	1120.1	540
80	565	step	step_milling	end_mill/4	milling_m/3	1244.6	1120.1	540
90	570	slot	slot_milling	end_mill/19	milling_m/1	2079.8	623.9	540
100	550	hole	tw_drilling	tw_drill/6	drill_m/4	979	293.7	1260
110	555	hole	tw_drilling	tw_drill/6	drill_m/4	979	293.7	1260
120	390	hole	tw_drilling	tw_drill/8	drill_m/5	870.2	261	1260

Figure 7. Process planning sheet with selected operations for features

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