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Development of an Instructional Expert System for Hole Drilling Processes

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ABSTRACT

An expert system which captures the expertise of workshop technicians in the drilling domain was developed. The expert system is aimed at novice technicians who know how to operate the machines but have not acquired the decision-making skills that are gained with experience. This paper describes the domain background and the stages of development of the expert system.

1 INTRODUCTION

Human expertise is essential for process planning in the manufacturing environment. In a workshop, process planning is concerned with determining the sequence of individual machining operations needed to produce a given part. The decision process is guided by a multitude of variables which include the process requirements and equipment capability. The process plan involves a set of machining operations. Each of these operations demands skill and knowledge derived from experience on the part of the technician. The goal of this project is to capture the expertise of the technicians in an expert system. The domain of this project will be restricted to the hole drilling operations performed in a workshop on manually controlled machines.

Several expert systems have been developed for generative process planning [1]. GARI was developed in 1981, its domain is restricted to the metal cutting industry. In 1984, EXCAP was developed to generate process plans for machining of rotational components, and CUTTECH was developed to select cutting tools, speeds and feeds.

Our expert system is aimed at the novice, or apprentice, in the workshop who has been formally taught to operate the machines but has no experience. A novice will usually be trained by observing the experienced technicians propose a process plan, and then execute each machining operation in the plan. When a novice asks the technicians to justify a certain plan of action, they will usually attribute their decisions to "experience." In order for the novice to learn from their experience he needs to follow the reasoning process involved in such decisions. With the aid of an expert system a novice will be able to follow the decision-making process. Eventually the novice should acquire the experience required for the job, and he will be able to expand the expert system by adding his own judgments.

2 DESCRIPTION OF DOMAIN

There is hardly a product that does not contain one or more holes. Holes are produced in a variety of ways; for example, they may be drilled, punched, or sawed. Drilling accounts for more than 80% of the metal-cutting operations in a workshop [2]. Drilling is generally not a precision operation. In order to produce holes within a specified tolerance and with a good surface finish, the drilling operation is followed by precision sizing operations. The most common one being reaming.

In this section the process of drilling a hole will be discussed. This process begins with the engineer designing a part to be manufactured by the technician. The technician will receive a blue-print of the part, and then it is up to him to generate the process plan. The process plan is the sequence of individual machining operations needed to produce a given part, keeping within the specifications on the blue-print and any special instructions it may contain.

2.1 The Blue-Print

In order to produce a process plan, the technician is supplied with a blue-print of the part to be machined. The blue-print is an engineering drawing of the part. It provides two or three views (front, top, side) of what the final product should look like. The material and dimensions of the part are specified. The hardness of the material may be specified on the blue-print. It is usually given as a Brinell Hardness Number (BHN).

For parts with holes, the position of the hole, on the part, and its diameter are given. If the hole needs to be machined within a certain tolerance then its value is also given. The tolerance value is specified as an upper and a lower allowable limit for the hole diameter. For example, a hole with a diameter D and a tolerance of +/- t can have a diameter size anywhere between (D+t) and (D-t).

2.2 The Drilling Process

The position of the hole must first be located, in accordance with the specifications on the blue-print. Once the position of the hole has been marked then the drilling process can begin. The machine and drill tool to use for machining a particular hole are selected. The choice is based on factors such as the depth of the hole, the accessibility of the hole, and the material hardness.

The drill tool is selected by specifying its type, diameter, tool material, the shape of the shank and the flutes. The shank of a drill tool is the part by which it is held and driven, it may be straight or tapered. The flutes are the helical grooves on the drill body which permit the flow of coolant and the removal of chips. These are illustrated in figure 1.

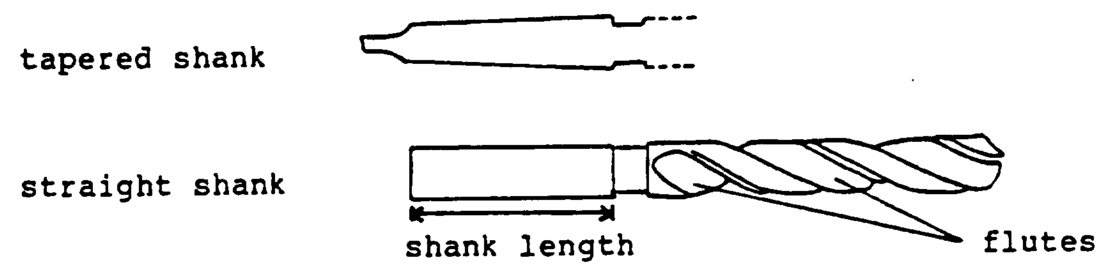

Figure 1 Shank and Flutes on a Drill Tool

2.3 The Reaming Process

When the size of the drilled hole must be kept within a tolerance of at least +/- 0.005 inch or a good surface finish is needed then the hole needs to be reamed. After drilling, the hole diameter is measured and then an appropriately sized reamer is selected to remove whatever material is left to bring the hole size within the specified tolerance.

The reamer is selected by specifying its type, material, and diameter. These depend on the hole diameter, amount of material left by the drill for reaming, the number of holes to be reamed, and the required surface finish.

2.4 The Machines

The three manual machines which can perform the drilling and reaming operations in the workshop are the lathe, the drill-press, and the milling machine. The part to be manufactured is referred to as the workpiece.

On the lathe, the cutting tool (i.e. drill tool or reamer) is held in the tailstock and the workpiece is held in the chuck. The tailstock is advanced manually into the rotating workpiece. The speed of the drilling operation is the speed of rotation of the workpiece, specified as the number of revolutions per minute (rpm). The feed is the number of inches moved by the drill-tool into the workpiece per revolution of the workpiece (ipr).

On the drill-press, the workpiece is placed on the stationary horizontal table and the cutting tool is moved towards it manually. The speed is specified as that of the cutting tool rotation measured in revolutions per minute (rpm).

In the process of drilling a hole using the milling machine, the workpiece is placed stationary on the horizontal table and the cutting tool approaches it. The speed of the tool is measured in revolutions per minute (rpm).

3 FEASIBILITY STUDY

This expert system is aimed at the apprentice. An apprentice is someone who has been formally trained to use the machines but has no experience. He is usually asked to follow the instructions given to him by a more experienced technician. If the output does not match his expectations then he may have difficulties in producing an alternate plan.

The system developed is an instructional system, which contains an explanation facility. When confronted with the task of drilling a hole, the apprentice can consult the expert system and can expect to receive advice on the decisions that need to be made in order to carry out the task. At any stage of the questioning, the apprentice can ask the system to clarify the question.

The experience of the technicians is accumulated in the form of rules of thumb. In the domain of this expert system, there are tables which match the diameter of the hole with the required speeds and feeds for a particular material. Most of these tables do not take into account the practical aspects of the problem, such as the production rate. However, the technicians will tend to rely on their experience when setting these variables by balancing the number of pieces that need to be produced and the time allocated for the production. Also the technicians tend to think more in terms of a range of speeds, rather than absolute values as given on some tables, and in terms of the production rate required.

Since the nature of the knowledge is in the form of rules of thumb and their combinations, then this domain is well-suited to be implemented with a rule-based expert system shell. The goals of the expert system are the selections of machines, drill-tools, reamers, speeds, and coolants. These are all of the specifications that a technician needs to determine before starting to drill. The expert system will ask for information which is given on the blue-print of the part to be drilled.

4 KNOWLEDGE ACQUISITION

The experts in the workshop are the technicians. They are usually asked to make an object from its description on the blue-print. Hence it is up to their ingenuity to decide on the most feasible machine to use for drilling and all of the other decisions that are involved in the operation. There are many variables which control this decision-making process. The experience of the technician is gained by the amount of variety in the jobs encountered, and not necessarily in the number of years spent working in a workshop.

The experts consulted for this domain will be referred to as A, B, and C. Expert A has 12 years of experience and he is a tool and die-maker which is the highest training for a technician. Expert B has 10 years of experience, and expert C has 20 years of experience.

The knowledge acquisition phase of the project was the most time-consuming. This phase was divided into three stages:

1. Initial consultation - the experts were consulted to determine the feasibility of the proposed problem.

2. Knowledge solicitation - the experts were consulted when building the knowledge base.

3. Feedback during implementation - the experts were consulted when an inconsistency appeared or when more clarification was needed during the implementation.

4.1 Initial Consultation

The original intention of the project was to produce a process plan for any part which could be manufactured on the manually operated machines in the workshop. The process plan was to list the sequence of operations, the tools, machines, and their settings in order to manufacture the part.

Expert A was the first to be consulted. He explained the overall decision-making that one would undergo when confronted with a blue-print and asked to manufacture the part. He emphasized that the sheer amount of variables that need to be taken into account in order to produce a complete process plan of a simple job was too many to be handled simultaneously. So at his suggestions, the problem was confined to one operation in the process plan. The drilling operation was chosen because most manufacturing products have at least one drilled hole, thus making it the most common operation in the workshop.

Even though the number of variables have been reduced considerably, there are aspects of the drilling domain which have been eliminated in order to produce the expert system during the allotted time. These aspects have been singled out by expert B. After consulting expert B over a period of four days, the decision to exclude the methods for positioning a hole on a workpiece and the drilling of threaded holes was made.

This initial consultation with the experts was essential in formally defining the domain of the expert system. Due to their expertise in the field, the domain was confined to a functional subset of a larger problem.

4.2 Knowledge Solicitation

The drilling and reaming operations are well documented in textbooks and handbooks relevant to the workshop operations. So the basic goals of the expert system were initially defined based on the literature [2,3]. All of the experts used these two books as their major sources of information.

Experts A and B were interviewed independently. During B's interviews, a series of open-ended questions were posed because the project was at the design stage and the problem domain was being refined. An example of a question posed to expert B is: "Under what circumstances would you choose the milling machine for drilling or reaming, and why?" Expert B was interviewed for four days, and each interview lasted approximately 2 hours.

Expert A was interviewed one week after expert B's interviews. By then the questions became more specific as the problem was better defined. An example of the questions that expert A was asked is: "If the Brinell hardness number was not specified on the blue-print how would you classify the material hardness, and when would you need to use this classification?"

Expert C was not consulted during the knowledge acquisition phase. The main reason being that he was not available during that time, and the interview format did not suit him. His collaboration was essential in the validation phase of the development of the expert system.

4.3 Feedback During Implementation

During the implementation of the expert system, expert A was consulted several times to clarify some of the points made during the interviews and to verify the rules extracted from the literature. Most rules which were extracted from the literature were revised to reflect what the experienced technician would use and do. For example, in [2] several types of reamers are suggested, whereas according to expert A the most commonly used reamer in the workshop is the chucking reamer because it is available in all sizes.

The knowledge acquisition continued into the validation phase, when the experts were presented with the output of the system for hypothetical problems. If the results from the expert system were not acceptable by the experts and a justification was given, then they were altered.

5 CONCEPTUAL DESIGN

The conceptual design phase established the necessary and optional inputs to the expert system. The minimum specifications required before drilling were also established. The relationships between the variables and the constraints imposed upon them were determined from consultations with the experts.

The level at which the knowledge is described is based on the level that the experts use to reason. The basic components of knowledge are naming, describing, organizing, relating, and constraining [4]. These components will be described as related to the project domain.

The naming process consisted of assigning names to the parameters involved in the domain. It was observed that even though both the drilling and reaming operations made use of the same input knowledge from the user, the experts tend to think of them as two separate processes. So all of the parameters related to the drilling process were superseded with DRILL, and all of the ones related to the reaming operation were superseded with REAMER. For example, DRILL-TYPE and REAMER-MATERIAL.

In order to describe the important properties of a parameter it is necessary to decide what the system has to know about them in order to be able to carry out its reasoning tasks. This is best illustrated by an example: the experts choose to apply the reaming operation when the hole needs to be made with precision and a high quality surface finish is required. However, there are instances when this information is not specified explicitly on the blue-print, but the technician may know that a good surface finish is needed for the specific part he wants to manufacture. So when deciding whether to ream or not the expert system needs to know all of the cases when reaming is necessary even if it is not stated in the blue-print.

The information that the experts gain from knowing the material is basically knowing whether they will be required to drill into a relatively hard or soft material. So the Brinell hardness number is used as an indicator of classifying the material as either hard or soft. For commonly used materials, the technicians know from experience which of them are hard and which are soft.

Constraints control the properties of the parameters. Values such as the size of the hole and the Brinell hardness number were given a range. Thus the diameter of the hole needs to be a positive number which will not exceed 4 inches, since this is the maximum size considered in the domain. The Brinell hardness number was constrained to be input as a positive number, because it cannot be negative. So if the user ignores these constraints, the system will reject his answers, thus preserving the integrity of the expert system.

6 IMPLEMENTATION

The expert system was implemented using CLIPS. Forward chaining was used. The expert system requires some essential facts about the drilling problem before it can make any decisions. All of the input facts are derived from the blue-print and the required production rate. They are listed as follows:

1. The material of the part to be machined.

2. The size of the hole to be drilled.

3. The type of hole.

4. The time limit imposed on the operation, if any.

5. The number of pieces that require drilling.

Additional information such as the material hardness and the tolerance may or may not be available from the blue-print. Nevertheless, they are inferred by asking additional questions to the user.

The output parameters from the expert system have been chosen after consulting with the experts. They are determined by the information necessary before a drilling or reaming operation can be undertaken.

The expert system will produce recommendations which involve the specifications for choosing the cutting tools (type, material, and size), in addition to choosing the machines and their starting speed. When more than one machine is chosen, then the choice between them is not critical for that particular problem. The system will also make recommendations on whether the hole needs to be reamed and if a coolant is required.

7 TESTING AND VALIDATION

The expert system was evaluated for program accuracy and utility. The rules were checked for conflicts and redundancies. Rules were in conflict if for the same condition statement, two or more rules asserted conflicting facts. The conflicts were resolved by reviewing the accuracy of the knowledge. Rules were redundant when other rules assert the same facts by inferring with the same knowledge. The redundant rules were eliminated from the rule-base by either removing them or combining them together.

The utility of the results was confirmed by the experts during the knowledge acquisition phase. The specifications for the drill tool and the reamer in the conclusion of the consultation were unambiguous and the correct tool can easily be identified. Care was taken in mentioning that the recommended speeds were starting speeds, because as the hole is being drilled the technician may alter the speed depending on how rigidly the part was held.

The overall validity of the expert system was tested by posing several hypothetical problems. The technician, C, was consulted with the problems, and his recommendations for the choice of tools, machines, and speeds were recorded. Another expert, B, was shown the conclusions that the expert system produced and was asked if he would consider these as reasonable recommendations. The experts' comments are given with two problems below. The expert system's recommendations are given in Appendix A.

7.1 Problem 1

The top and side views of the part is shown in figure 2.

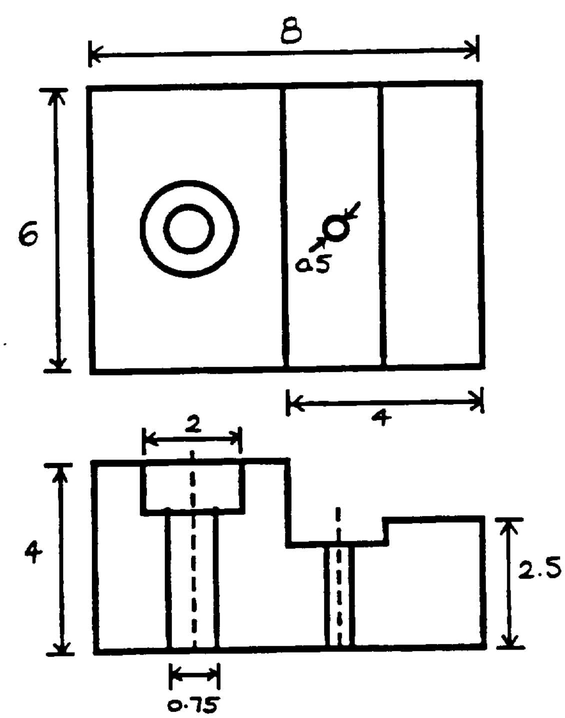

Figure 2 Part with Two Counter-Bore Holes

The specifications for the part are as follows:

material: mild steel
number of pieces to manufacture: 50
good surface finish required

The experts thought that the conclusions from the system were reasonable. The drill-tool recommended was for the smaller hole diameter, and the expert system suggests using a piloted-boring tool for the larger diameter. The experts expected the system to specify the piloted-boring tool specifications as it did for the drill-tool. This was not specified because the boring operation was not within the scope of the domain, and only a qualitative recommendation was given.

7.2 Problem 2

The top and side views of the part are shown in figure 3.

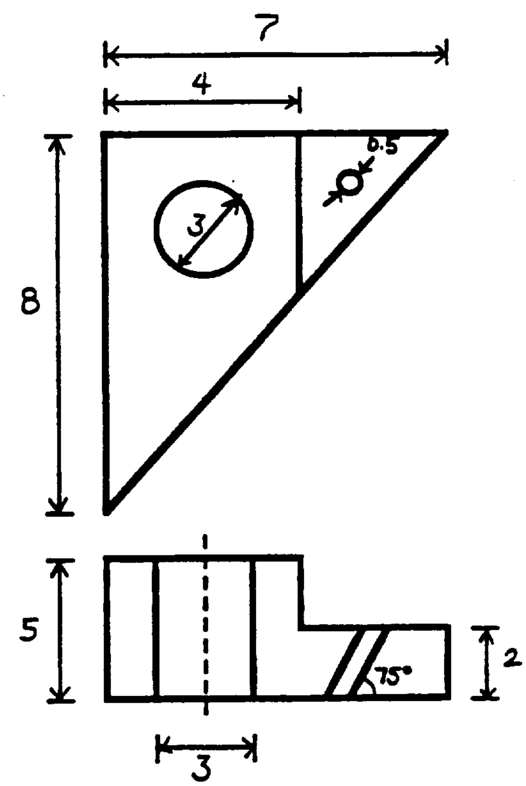

Figure 3 Part with Through Hole and Oblique Hole

The specifications for the part are as follows:

material: cast iron
tolerance of through hole : +/- 0.01 inch
number of pieces to manufacture: 50

The suggested coolant was compressed air, but the experts said that it is very messy for an apprentice to use because it will blow the metal chips all over the place. They suggested using a water-soluble coolant with rust inhibitor, or the aromatic coolant Cool-Tool for low production volumes.

8 FURTHER EXTENSIONS

The present expert system encompasses the major decisions that need to be made for the machine operation of drilling a hole, using manually operated machines. As mentioned earlier, the drilling operation is one of a series of operations that make up a process plan. Since a process plan consists of a collection of operations then the same expert system has the potential of being used with other systems which make the decisions for other operations. A set of meta-rules can be used to determine the order in which these operations are to be performed.

The expert system as it stands has a limited domain. The limits being set by the choice of materials and the types of holes. These may be extended without affecting the system, by including their relevant rules. Also trouble-shooting advice may be added, to help the user solve the common problems encountered when drilling or reaming.

The interview format was used for the knowledge acquisition phase. This knowledge acquisition method evolved from earlier expert systems such as MYCIN, whose experts are people in the medical field. They are usually more articulate than people in the engineering field [5]. Even though the experts consulted for this project articulated the knowledge to our satisfaction, but as the domain becomes more involved and the number of variables increases, the use of automated knowledge acquisition systems would be advantageous.

Appendix A
A Sample Consultation

Problem 1

```
CLIPS> (reset)
CLIPS> (run)

 This expert system helps you select the variables
 to be set in drilling a hole. The input to the
 system is the information supplied on the blue-print
 of the part to be drilled.

 If you need help in answering the questions
 then type - help - instead of answering the question
```

What is the type of hole to be drilled?

a. through hole
b. oblique hole
c. counter bore
d. counter sink

c
What is the depth of the hole to be drilled?
help

The depth of the hole is the thickness of the part to be drilled in inches. The minimum value allowed is 0.15 inch, below this limit the part is considered to be sheet metal and should be punched rather than drilled.
For counter-bore and counter sink holes give the depth of the smaller hole.

What is the depth of the hole to be drilled?
3
Enter the size of the hole to be drilled?
help

Enter the diameter of the hole in inches, as specified on the blue-print.
For counter-bore and counter sink holes give the diameter of the smaller hole.

Enter the size of the hole to be drilled?
0.75
Is the Brinell hardness specified on the blue-print?
no
What is the material of the work-piece?

a. aluminum
b. copper
c. cast iron
d. brass
e. mild steel
f. carbon steel
g. alloy steel

e
Is the production volume large?
help

If more than 100 parts with one or two holes, or one part with many holes need to be drilled then answer - yes -

Is the production volume large?
no
Is the tolerance of the hole specified on the blue print?
no

```
Is a good surface finish needed?
yes
Is the hole concentric with respect to the part?
help

If the hole lies along the center axis of the part
then answer - yes -

Is the hole concentric with respect to the part?
no
Is the production time limited?
no


Recommended machine is mill
Drill tool type: drill and piloted counter bore
Material of drill tool: HSS
Diameter of drill tool: 0.735 inch
Use tool with standard helix flutes and straight shank
Start drilling with a speed range between 500 and 600 rpm

Reamer type: chucking reamer
Material of reamer: HSS
Diameter of reamer: 0.75 inch
Reaming speed: 165 rpm

46 rules fired
```

Problem 2

```
CLIPS> (reset)
CLIPS> (run)

 This expert system helps you select the variables
 to be set in drilling a hole. The input to the
 system is the information supplied on the blue-print
 of the part to be drilled.

 If you need help in answering the questions
 then type - help - instead of answering the question

What is the type of hole to be drilled?
     a. through hole
     b. oblique hole
     c. counter bore
     d. counter sink
b
What is the depth of the hole to be drilled?
2
Enter the size of the hole to be drilled?
0.5
```

Is the Brinell hardness specified on the blue-print?
no
What is the material of the work-piece?

a. aluminum
b. copper
c. cast iron
d. brass
e. mild steel
f. carbon steel
g. alloy steel

c
Is the production volume large?
no
Is the tolerance of the hole specified on the blue print?
yes
What is the tolerance of the hole in inches?
help

Enter the absolute value of the tolerance in inches.

What is the tolerance of the hole in inches?
0.01
Is the hole concentric with respect to the part?
no
Is the production time limited?
help

If the time allocated for machining the part is
limited then answer - yes -

Is the production time limited?
no

Recommended machine is mill with appropriate fixturing
Drill tool type: jobber drill
Material of drill tool: HSS
Diameter of drill tool: 0.485 inch
Use tool with standard helix flutes and straight shank
Start machining with an average speed of 300 rpm

Reamer type: chucking reamer
Material of reamer: carbide
Diameter of reamer: 0.5 inch
Reaming speed: 90 rpm

46 rules fired

Appendix B
Partial Code Listing

```
(defrule question-tolerance
   ?rem <- (ask-question)
   (tolerance-available yes)
   (not (tolerance ?))
   =>
   (retract ?rem)
   (printout t "What is the tolerance of the hole in inches? "
        crlf)
   (bind ?x (read))
   (if (eq ?x help)
   then
     (printout t crlf)
     (printout t "Enter the absolute value of the tolerance in
        inches. " crlf)
   else
     (assert (tolerance ?x))))

(defrule question-surface
   ?rem <- (ask-question)
   (tolerance-available no)
   (not (reaming ?))
   (not (surface-finish ?))
   =>
   (retract ?rem)
   (printout t "Is a good surface finish needed? " crlf)
   (bind ?x (read))
   (if (eq ?x help)
   then
     (printout t crlf)
     (printout t "When a good surface finish is needed then answer
        - yes -  this will determine whether the part needs to be
        reamed or not." crlf)
   else
     (assert (surface-finish ?x))))
(defrule reamer-speed1
   "reamer speed is one-third of drilling speed"
   (reaming yes)
   (speed ?var1)
   =>
   (bind ?var2 (* 0.3 ?var1))
   (assert (reamer-speed ?var2)))

(defrule no-reaming1
   "if no tolerance available and rough surface finish, then don't
ream"
   (tolerance-available no)
   (surface-finish no)
   =>
   (assert (reaming no)))
```

```
(defrule no-reaming2
   "if no tolerance available but a good surface finish needed,
then ream"
   (tolerance-available no)
   (surface-finish yes)
   =>
   (assert (reaming yes)))

(defrule ream-based-on-tolerance
   "if the specified tolerance <= 0.005 inch then ream"
   (tolerance-available yes)
   (tolerance ?var)
   (test (<= ?var 0.005))
   =>
   (assert (reaming yes)))

(defrule default-reamer-material
   "default reamer material"
   (declare (salience -10))
   (reaming yes)
   (not (reamer-material ?))
   =>
   (assert (reamer-material HSS)))

(defrule print-ream-recommendations
   " if reaming is required then print its recommendations"
   (print-drill)
   (reaming yes)
   (reamer-type $?type)
   (reamer-material ?mat)
   (reamer-diameter ?dia)
   (reamer-speed ?speed)
   =>
   (printout t "Reamer type: " $?type crlf crlf)
   (printout t "Material of reamer: " ?mat crlf crlf)
   (format   t "Diameter of reamer: %g inch" ?dia)
   (printout t crlf crlf)
   (printout t "Reaming speed: " ?speed " rpm" crlf crlf))
```

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