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### Treatment as Heuristic Construction: A Case Study in Cutting Fluid Selection

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### Abstract

This is the final report of the General Reasoning Engine and Selection Environment (GREASE) project. The GREASE project is an investigation of the application of artificial intelligence to cutting fluid selection and blending for metal machining operations. The problem is to first diagnos the machining operations to determine what fluid characteristics are required, then to select a cutting fluid which satisfies the required characteristics. The problem is exacerbated by the need to select a single fluid to be used by multiple types of operations on a variety of materials. Diagnosis is relatively simple, but treatment specification is difficult due to the variety of operations to be handled.

GREASE uses heuristic search in which the evaluation function is *heuristically constructed*. The construction of the evaluation function begins with the determination of the characteristics of an optimal fluid based on deep knowledge of the machining operations and materials. This is then altered heuristically, according to problems diagnosed with the current fluid. Once the evaluation function is complete, it is used to select an existing fluid from the product line.

GREASE has been tested extensively with results which equal that of the experts. It is now being field tested by the Chevron Corp.

In 1984, our research group was presented with the problem of designing a system for the diagnosis and treatment of problems related to the use of cutting fluids in the machining of metals. Cutting fluids are used to provide lubrication, cooling, and to prevent the welding of the metal being machined to the machining tool. At first glance, it appeared that the problem was an instance of heuristic classification (Clancey 1983), and would be amenable to rule-based diagnosis techniques pioneered by MYCIN [48] and Prospector [13]. The techniques utilized in these systems have reached a stage of development that a variety of systems are now in "production use", in domains such as medical diagnosis [1], turbine diagnosis [17], telephone line diagnosis [50]. Consequently tools are available to aid in the construction of these applications, e.g., S.1 (Teknowledge), and Personal Consultant (Texas Instruments).

After further analysis, our initial view turned out to be incorrect; only portions of the problem are amenable to shallow rule-based reasoning techniques. The problem has two parts. The first part diagnoses the current fluid to identify solution requirements. The second part identifies a cutting fluid which best satisfies these requirements. The first part is quite simple and amenable to shallow causal reasoning. It is the second part, treatment, which requires "deep" reasoning, and utilizes analytical and qualitative causal knowledge to represent relationships between fluid characteristics and their chemistries. The approach we have taken to treatment specification involves the heuristic construction of an evaluation function. The characteristics of an optimal fluid are first constructed for each operation/material pairing. These are modified by the requirements specified by the diagnosis. These modified, optimal characteristics are then used to grade each of the fluids in the product line. In the case of fluid blending or synthesis, the same evaluation function would be used during search.

The result of our analysis is a system we called **Grease**.<sup>1</sup> Grease is a heterogeneous diagnosis system in that it must combine both heuristic classification with heuristic search in designing optimal fluids, and then selecting the best matches from a pre-defined set of fluids. It is composed of the following phases:

- DIAGNOSIS Interpretation of machining diagnostics and special machining requirements in terms of cutting-fluid property inadequacies;
- TREATMENT Specification of compositional alterations to a cutting-fluid to treat inadequate property values identified by the DIAGNOSIS phase;
- DESIGN Formulation of an 'optimal' cutting-fluid to best satisfy the operations on specific materials in a machine shop. The 'optimal' fluid design includes alterations from the TREATMENT phase;
- SELECTION Selection of cutting-fluids from a product line which best match the 'optimal' fluid for the shop as determined during the DESIGN phase;
- EXPLANATION Interpretation of the reasoning at each phase to provide sound justification for the cutting-fluid selections.

<sup>&</sup>lt;sup>1</sup>Acronym for "General Reasoning Engine And Selection Environment."

In conjunction with these phases, a blend of qualitative and quantitative information which is known with varying degrees of certainty is utilized.

The approach taken in GREASE provides two benefits:

- A straightforward semantic representation of the domain, including cutting-fluid chemistries, their properties, materials, and machining operations;
- Reduction of the work required to add new fluids to the knowledge-base to a simple database entry;

The importance of this approach is demonstrated in this report.

This report provides the reader with insight into the issues in designing a multi-functional system which must perform diagnosis, treatment, design, and selection successively. We begin by reviewing the domain. Next, the variety of functions required of Grease are described and is followed by a description of the issues which are in this domain.

The second portion of the paper describes the implementation architecture of GREASE, including its performance evaluation in selecting cutting fluids relative to an expert and a salesman experienced in cutting fluid selections.

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In order to understand how cutting fluids are selected and designed, it is necessary to understand the different functions of cutting fluids, and the characteristics of the cutting fluids, materials being machined, and machining operations.

### 2.1 Cutting Fluid Roles

Primarily, a cutting fluid contributes in three ways to the machining process. It acts as a lubricant, a coolant and an anti-weld agent.

As a lubricant, it reduces the heat generated during the machining process by reducing the friction between the workpiece and the cutting tool. As an antiweld agent, it counteracts the tendency of the work material to weld to the tool, under the heat and pressure generated in the cutting operation.

To perform satisfactorily as a lubricant, the cutting fluid must maintain a strong protective film at the portion of the area between the tool face and the metal being cut where hydrodynamic conditions can exist. Such a film assists the chips in sliding readily over the tool. Besides reducing heat, proper lubrication reduces the wear of the tool and lowers the power requirements.

If a cutting fluid performs its lubricating function satisfactorily, the problem of heat generation from the cutting tool, workpiece and chip is minimized but cooling still remains an important function. To perform this function effectively, a cutting fluid should possess a high thermal conductivity. Water has a high thermal conductivity and is a very effective coolant, but its lubricating properties are practically nil. As a result, water-based cutting fluids – emulsions – are good coolants but poor lubricants. On the other hand, straight oils have relatively low thermal conductivities so that they must depend on fluidity for effective cooling ability; hence, the faster they flow over an operation the more heat they can absorb and carry off per unit of time.

In some instances, extreme temperatures and pressures at the cutting interface cause the chip or segments of it to weld to the tool face. The build-up resulting from such welding may occur to a degree that the effective tool shape is drastically changed and all phases of the operation are seriously affected. To overcome welding, effective antiweld characteristics may be imparted to the cutting fluids by incorporating various additives. These are usually materials such as fatty oil, sulfur or chlorine, which by chemical reaction form a surface film of low shear strength at the chip-tool interface. The effectiveness of these chemical films is understood to be limited by their respective melting points.

The primary functions of a cutting-fluid appear to be closely interrelated. A cutting-fluid which is a good lubricant will generally be a poor coolant, and vice versa. Properly selecting a cutting fluid consists in satisfying these particular requirements for specific machining processes on materials.

A cutting fluid must also satisfy various secondary requirements, less directly related to the machining process, but nevertheless important. A cutting fluid, for instance, should flush chips away from the work area; protect the finished work surfaces, the tool and the machine against corrosion

ecologically safe and non-toxic.

Special-purpose requirements may also be imposed to a cutting fluid. A "grinding fluid" involved in a lapping operation, for instance, must act not only as a lubricant but also as a medium for suspending the abrasive powder.

### 2.2 Cutting Fluid Properties

We distinguish two categories of cutting fluids: cutting oils and emulsions. It is convenient to think of a cutting fluid as the application of one or more "products" – straight oils or soluble oils – to a machining process. This distinction allows us to define a cutting oil as a straight oil, or a blend of straight oils; and an emulsion as a water-based solution of a soluble oil. An emulsion is thus characterized by both a soluble oil, and a dilution ratio.

The effectiveness of a cutting oil is determined by its physical properties which in turn are determined by its chemical composition:

The viscosity of a cutting oil affects its cooling and lubricity properties. The greater the viscosity of the oil, the better its lubricating power, the poorer its cooling performance. Severe machining operations require high viscosity fluids to enable the oils to adhere better to the tool and workpiece. Less severe operations are generally run at higher speeds which create more heat and consequently utilize lower viscosity fluids since cooling is the most important factor. In addition to better satisfying lubricity requirements, viscous fluids carry more easily metallic chips and help flush them away from work areas.

Another important factor which affects the lubricating power of a cutting oil is its fatty oil percentage. The higher the fatty oil percentage, the greater the lubricating power of the oil.

The total sulfur, active sulfur,<sup>2</sup> chlorine and phosphorus percentages of an oil account for its antiweld properties. By chemical reaction, these additives form a surface film of low shear strength at the chip-tool interface. The effectiveness of these chemical films is understood to be limited by their melting points : iron chlorides are effective up to 600°C; iron sulfides, 1000°C. Cutting oils containing active sulfur are classified as "active". They stain copper and its alloys, and cannot be recommended for the machining of such materials.

Secondary properties of cutting fluids include antimist, antifoam, antirust, antiwear, rust inhibitor, corrosion inhibitor, and odor masking capabilities.

The dilution ratio associated with an emulsion is a very important factor. It is directly related to the cooling and lubricating powers of the fluid. The greater the dilution ratio of an emulsion; the better its cooling power, the poorer its lubricating performance.

<sup>&</sup>lt;sup>2</sup>Active sulfur chemically reacts with copper at a temperature of 150 deg. Celsius.

The total sulfur, active sulfur, and chlorine percentages of an emulsion account for its antiweld properties as n cutting oils.

Unique properties of emulsions include stability of the emulsion and degradability.

## 2-3 Machining Operations

Most machining operations may be described and understood as variations of a cutting tool shearing a workpiece or material. Metal ahead of the cutting edge of the tool is compressed, and removed from the workpiece in the form of a chip, by a process of plastic deformation and shearing. Chips fall into three basic categories: discontinuous, continuous, and continuous with built-up-edge. In the latter case, a fragment of work material - the built-up edge (BUE) - sticks to the tool in the region of the cutting edge and protects it against excessive wear. However, too large a built-up edge may result in poor surface finish.

There are several hundred machining operations which are variations or combinations of drilling, milling, planing and shaping, turning, and grinding.

Each machining operation, in turn, has several properties characterizing it and which affect cutting fluid selection. These include:

- speed of machine tool
- feed rate of material machined
- depth-of-cut
- tool material composition (affecting hardness and brittleness)
- · geometry and characteristics of cutting operation

The most common operations can be ranked into classes based upon increasing severity of the operation; this is a rough classification based upon experience and is a complex function of the properties of the operation. Specific machines may not be easily classified into the severity hierarchy since their geometry or operating conditions may be substantially different than those classified. In addition, some machines perform a multiplicity of operations of different severity.

The characteristics that a cutting fluid must satisfy are different for different severity operations as previously mentioned. As a result, selection of a cutting fluid for a multiple-operation machine must satisfy more characteristics.

### 2.4 Material Machined

The ease that a material can be machined is referred to as its machinability. The machinability is a function of the machine operation conditions, and the material composition and conditions.

The material properties affecting machinability include:

- MICROSTRUCTURE This is the grain structure of a material. Materials with similar microstructures machine similarly. Uniformity of microstructure favors long machine-tool life.
- GRAIN SIZE Small grain size render a metal ductile and easily machined, but hard to obtain good surface finish. Intermediate grain sizes are best.
- HARDNESS The hardness is the material's resistance to indentation. A higher hardness generally results in good surface finish, but usually is less easily machined.
- METALLURGICAL CONDITION OF THE METAL DUE TO HEAT TREATMENT Heating and cooling operations change the physical properties such as the hardness and the microstructure of the material. These operations include annealing, normalizing, tempering, quenching, etc.
- METALLURGICAL CONDITION OF THE METAL DUE TO WORKING Metalworking operations affect the physical properties of the material. These operations include casting, forging, hot- and cold-rolling, etc.
- COMPOSITION The chemical composition of the material greatly affects the overall machinability. Different percentages of different elements within steels, for example, greatly affect all physical properties such as hardness, ductility, and tensile strength. An 'AISI' classification system exists which relates the material's composition, and its approximate machinability under standard treatment conditions using a standard machining operation.

Materials are generally machined in a soft, easily machinability condition. However, due to varying control in production, variability does exist in the machinability for specific materials.

# 3. Functional Requirements

To ascertain the functionality required by Grease, several meetings were held with sales and research engineers of the sponsor. The following summarizes the results.

Selection for a particular specification of machining operation and material. Selection based upon these specifications corresponds to rare, but ideal and well-understood situations, where much empirical knowledge has been gathered and compiled into tables. With the use of such tables, the recommendation of a satisfactory cutting oil does not require a deep understanding of the phenomena involved in the machining process. This type of situation is generally handled by sales engineers. However, a finer understanding of the process, integrating various other parameters, may lead to the recommendation of an optimal product, which could differ from the more general ones recommended by the tables. In other cases, when operating conditions or other constraints are atypical, a deeper understanding of the phenomena is required, and an expert must be consulted.

Selection for a range of machining operations and range of materials. This situation represents more than 70% of selection cases in the field. A machine shop may have a variety of operations to perform on different machines with different materials. Rather than using a specific cutting-fluid for each (operation-material) combination, the best selection of two or three fluids for the shop to result in satisfactory overall performance is desired. Quite often, the selection process consists in satisfying the requirements of fewer combinations involving the most salient constraints imposed by the sets of operations and materials.

Selection which most closely matches a competitor's product currently used. This procedure requires a match of the cutting-fluid properties for the range of machining operations and materials rather than the specific chemistry of the fluid itself, although approximating the chemistry would result in similar properties. This case represents less than 10% of ail selection cases encountered in the field.

Selection which most closely matches a customer's specifications in terms of properties. This requirement is very similar to matching a competitor's product except that some set of requirements may be specified which doesn't currently exist in any commercially-available cutting fluid.

Selection based upon diagnosis. In this instance, an improved recommendation is formulated based upon the diagnosis of why the current fluid selection is unsatisfactory, and the properties of the current fluid utilized. Diagnostics are only encountered in about 5% of cases in the field. However, due to salesman psychology, improvements in the current cutting fluid properties are generally promised in order to encourage a cutting-fluid purchase.

The functionality required by Grease is quite diverse. Of course, one could focus on one part of the problem and ignore the rest, the result being a simpler architecture. The approach taken in the Grease project is to explore the issues surrounding the design and construction of a system which can span all the functions described above. In particular, how are knowledge representation and problem-solving affected when input can take many forms (e.g., properties, signs, symptoms), and the

analysis must transform from selection to.diagnosis and treatment when an earlier attempt is found to be unsatisfactory.

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# 4. Issues In The Design Of Grease

### 4.1 Functional Issues

Selection of cutting-fluids for the manufacturing industry is a knowledge-engineering application that has the features of several types of expert systems including design, selection, planning, diagnosis and debugging.

In terms of design, the system must develop a cutting-fluid of a particular composition to possess properties that satisfy the constraints of the design, which are to provide adequate cooling, long tool life and other properties for a particular combination of machine type and material machined. A specific fluid design may not exist in the actual product line, requiring that the system perform a selection of existing fluids ordered in terms of how well they minimize an objective function relating satisfaction of the design constraints. Planning system behavior is incorporated in terms of mimicing the experts methods of developing inferences based on their own implicit models relating machining property and material behavior. Planning includes organizing the set of problem specifications into appropriate hierarchies of constraints. Diagnosis behavior is used when a customer complains about a material property such as finish or machine property such as tool life which is not optimized. The system will then relate the diagnostics with their underlying causes which manifest themselves in the wrong values of some fluid properties to satisfy the existing machining and material property values or constraints. Debugging behavior will then make a recommendation of a different fluid to satisfy the diagnostic behavior which will have the correct values of the fluid properties.

The following subsections develop in greater details several important aspects.

#### 4.1.1 Diagnosis

The system utilizes diagnosis to infer the reasons for deviations from the optimal state for an existing machining operation and material combination where the cutting fluid does not perform as expected. Most often, in cutting-fluids, the reasons can be directly identified with certainty, such as 'blued chips' always resulting from insufficient 'cooling'. In other cases, the observed diagnostic has an underlying cause not directly inferable, or is a more general diagnostic which may have several underlying causes. An example of this is 'poor tool-life' in a machining operation which may result from an imbalance of either cooling, lubricity, or antiweld in the cutting-fluid if other machining conditions are not at fault. Directly inferable diagnostics can be 'compiled' for efficiency [9], whereas more complex diagnostics would require a 'deep' understanding of the diagnostic in terms of a causal model of its dependencies. These models can be in the form of hierarchical trees with general diagnostics high in the tree, and specific diagnostics at the nodes [8,19, 9].

The solution space in cutting-fluids is narrow as in many medical diagnosis systems and is signified by the oils in the product line. Medical systems typically utilize a backward-chaining technique to arrive at the disease identification 'initial' state from a 'goal' state of observed symptoms, such as in MYCIN [7]. The initial state in the cutting-fluids domain would be a recommended fluid satisfying the combination of machining operation and material. Forward-chaining control mechanisms are used in systems comprising many goal states and few initial states [18, 39, 35]. In these systems, knowledge can be used in directing the search to prevent the combinatorial search expansion [8]. Other systems benefit by using both forward- and backward-chaining control mechanisms where appropriate [35].

In cutting fluids, a forward-chaining mechanism is appropriate in the design of a desirable cutting fluid for a particular combination of machining operation and material. Diagnostic information, if available, can be represented as a causal network to determine the inadequate properties of the current cutting-fluid as knowledge to constrain the design process.

#### 4.1.2 Treatment of Cutting Fluid Problems

It is often necessary to minimize the number of different cutting-fluids in a shop. This requires choosing the best set of oils which perform adequately for all machine operations and materials within the shop. In numerous cases, a particular machine performs several functions but utilize a single cutting-oil. Selection of the best oils which best satisfy the constraints in all machine operation, material combinations without any severe diagnostics resulting is necessary. These oils generally maximize the highest level property of cutting fluids: *tool-life*.

The treatment problem in GREASE may be described as follows.

Input:

- A set of goals (such as improve tool life or improve finish)
- A set of materials
- A set of operations
- A set of processes
- A set of diagnoses of process problems
- A set of user constraints
- A current fluid

Output: A ranking of the fluids in the product line which will best satisfy the goals, result in maximum *tool-life*, and be compatible with the user, material, operation, and process constraints.

The treatment problems faced by GREASE are different from and more difficult than the treatment problems faced by some other diagnosis systems described in the literature.

Compare the treatment problem in GREASE to the treatment problem in MYCIN. [7]. In the case of MYCIN, the diagnosis portion of the program identifies the micro-organisms that are present in a patient. The treatment problem may be described as follows.

- A set of constraints based upon the weight, age, health, etc. of the patient

Output: A set of drugs that kills all of the micro-organisms present, is compatible with the constraints, and has members compatible with each other. The exact dosages can be calculated by a simple algorithm.

#### 4.1.2.1 Similarities Between GREASE and MYCIN Treatment Problems

It is easy to discern certain fundamental similarities between these treatment problems.

- In each case there is a patient. In the MYCIN case the patient is a human being; in the GREASE case the patient is a machine process.
- In each case there is a diagnosis. In the MYCIN case the diagnosis is a list of the micro-organisms present; in the GREASE case the diagnosis is an estimate of which desirable cutting fluid properties are not present in the correct amount.
- In each case a remedy is proposed for each problem. In the case of MYCIN the remedy is a drug; in the case of GREASE the remedy is an increase or decrease in particular properties which fail to match the optimal values.
- In each case a proposed remedy must satisfy constraints. In the case of MYCIN the constraints are imposed by the age, weight, health etc. of the patient; in the case of GREASE the constraints are imposed by the materials, processes, operations, and user.
- In each case the proposed remedies for each problem must be combined into an overall solution. In the case of MYCIN there are constraints upon which drug combinations are allowable; in the case of GREASE only certain combinations of properties appear in the product line.

#### 4.1.2.2 Differences Between GREASE and MYCIN Treatment Problems

There are also a number of important differences between these treatment problems which make the treatment problems faced by GREASE significantly more difficult.

- Unlike MYCIN, GREASE has to treat more than one patient at once. This means that there may not be any one ideal solution for all of the problems present.
- When MYCIN, presents a possible remedy, it is simply the selection of a particular drug. However, when GREASE suggests a possible remedy, there are still a multitude of ways of realizing that goal. For example, an increase in lubricity can be accomplished by any number of different combinations of increases in fatty content and increases in viscosity.
- In MYCIN, there are a comparatively large number of loosely coupled solutions to each individual problem. This means that if individual problems are solved separately, the probability is high that some combination of the individual solutions will yield an acceptable global solution. On the other hand in GREASE, the number of possible

and the solutions are very tightly coupled. This tight coupling occurs in two ways. First of all, a solution to one problem might call for increasing a given property, while the solution to another problem might call for decreasing the same property. This is not unlikely because of the small number of properties to manipulate. Second of all, different properties are also coupled with each other; fluids low in viscosity tend to be low in lubricity for instance. This means if the solution to one problem calls for a low viscosity, and the solution to another problems calls for a high lubricity, the solutions will conflict with each other. This makes it unlikely that an "ideal" fluid which could solve all of the problems perfectly exists.

- In MYCIN, there are a comparatively large number of possible global solutions (combinations of drugs). In GREASE, the number of possible global solutions is limited to the product line.<sup>3</sup> This, together with the tight coupling of the solutions in GREASE, makes it very unlikely that the available global solutions to GREASE problems are "ideal",
- The MYCIN treatment problem is a satisficing problem whereas the GREASE treatment problem is an optimizing problem. MYCIN can divide possible solutions into exactly two categories: those that are satisfactory and those that are not satisfactory. The problem for MYCIN is to find a satisfactory treatment. GREASE, as pointed out above, is highly unlikely to be able to find an "ideal" solution in the existing product line. It must evaluate solutions on a continuous scale of adequacy. The criteria by which GREASE must evaluate a fluid are in turn satisfied to a greater or lesser degree on a continuous scale. The problem for GREASE is to find the optimal product in the product line.

#### 4.1.2.3 Previous Approaches to the Treatment Problem

A number of different approaches to the treatment problem are available in the literature.

ACE is a rule-based system for diagnosing and treating faults in telephone lines. [50] The precise type of rules used in suggesting treatments was not explained.

MYCIN used a divide and conquer method of treatment. First, the treatment problem is divided into a number of sub-problems (one for each organism present). An initial list of drugs to which each organism is sensitive is ranked, mainly according to the drug sensitivity information for the organisms growing in cultures taken from the patient. The drugs are then further divided into three drug preference categories corresponding to 1st choice drugs, second choice, and third choice. These lists of drugs for each organism constitute possible solutions for each subproblem. Then the solutions to each subproblem (a list of drugs) are combined into a global solution (a subset of the lists of drugs). Finally, the proposed global solution is tested to make sure that global constraints are satisfied. The drugs are first tested to make sure that all of the most likely organisms are tested. If that test is passed, they are tested to ensure that each drug is in a unique class (and hence nonredundant). Finally, they are tested for patient-specific contraindications.

<sup>3</sup> 

If cutting-fluid additives are considered, the number of possible solutions would be extended. However, selections are generally restricted to a very limited product line. Additives are considered if a new product is being designed to be added to the line.

The first recommendation that passes these tests becomes the recommended treatment.

#### 4.1.2.4 Why the Previous Methods Were Not Used

The fact that the treatment problem faced by GREASE is substantially more difficult than previous treatments made the approaches taken by previous systems inadequate.

The MYCIN treatment approach is unsatisfactory for GREASE. In MYCIN, the problems are basically broken down into a number of subproblems (one for each micro-organism present). Solutions to these subproblems are found, and the combined into a global solution. Then the global solution is tested to make sure that global constraints are satisfied. Searching is stopped once a satisfactory solution is found.

This approach is unsatisfactory for two reasons:

- 1. The treatment problem in GREASE is an optimizing problem, not a satisficing problem. The method used by MYCIN does not explore the entire solution space; it stops as soon as a satisfactory solution is found. In GREASE, there typically exists many satisfactory solutions, but the 'most' satisfactory, or 'optimal' solutions are sought that result in maximum values for the top-level cutting fluid property: *tool-life*. This can be accomplished by generating an 'ideal' solution, then determining the closest matches from the product line to the ideal.
- 2. The division of the problem into subproblems which are individually solved and then combined into a global solution is only appropriate where the subproblems are not tightly coupled, and there is a reasonable chance that the combined subsolutions will form a satisfactory global solution. In GREASE, the problem arises in enumerating rules to express the interdependence of cutting-fluid properties for each subproblem (i.e., different operation/material combinations), and then combining these rules for the global problem.

#### 4.1.2.5 GREASE - A Modified Divide and Conquer Algorithm

GREASE uses what we call heuristic search to determine the appropriate treatment (i.e., cutting fluid selection). The treatment problem faced by GREASE is divided into subproblems at three levels. First, each process is treated as a separate problem. Second, within each process, treatment problems are divided into distinct classes, such as symptoms (blue chips, long chips, poor tool life, etc.) or process characteristics (deep cut, fast feed, etc.). Finally, each class of treatment problems is divided into individual problems (e.g., deep cut).

Next, solutions are found to each individual subproblem at the lowest level. The method for this is to take as a starting point an "ideal" fluid. This "ideal" fluid is thought on empirical grounds to be the best fluid for a given process, assuming no "unusual" conditions. This fluid will optimize the top-level property of cutting-fluids: *tool-life*.

When unusual conditions are present, such as symptoms indicating problems, or unusual operating conditions, then the ideal fluid must be modified to reflect the changed circumstances. The treatments for each indivídual symptom or unusual operating condition are stored in a network

i^iculuy oyiH}Jiuul lypv-7 lu ncrclilicitt. III^ u^uunclu uuuolow ul laloul^ ul IUVVCluly me valuc VJI a, relevant property of the ideal fluid.

The solutions to individual problems are then combined into solutions for classes of problems. The method of combination depends upon the class of problems. The solutions to problems in some classes are added together; *in* other classes the maximum or minimum of the solutions is taken.

Next, the solutions to classes of problems are then combined by taking the maximum of the treatments for ail classes. This ensures adequate treatment of all subproblems in all classes. An exception occasionally occurs when a subproblem requires taking the minimum treatment. At this stage, the solution for the treatment problem of an individual process has been constructed.

It is at this stage that the deviation from the divide and conquer method occurs. The divide and conquer method has been used to construct a description of an ideal 'optimal' fluid for a given process together with its problems and unusual conditions. However, this optimal fluid does not serve as a possible solution to the treatment problem. Rather, it serves as a tool to evaluate possible solutions to the treatment problem.

A -mathematical rating function is associated with each fluid property that compares the optimal process value with the same property value of an actual cutting-fluid. These functions return ratings on a scale of 0 to 1, which are then additively combined for all properties to form the overall rating of the fluid for the specified process.

The same actual fluid is rated against the 'optimal' fluid for each process in the shop. The ratings are then combined into an 'overall' fluid rating for the shop which is simply a weighted average of the individual ratings for each process. The weighting factor is entered by the user, and is intended to allow some processes to count more heavily than others for any of a variety of reasons. For example, the tools used in one process might be more expensive than those used in other processes, causing the tool life of that process to be especially important. Another weighting factor could be the percentage of the shop that each process represents.

The GREASE solution, corresponding to the best fluids for the shop, are those with the overall highest fluid ratings.

#### 4.1.3 Explanation

A number of different models of explanation have been used in Al.

#### 4.1.3.1 HempeTs Model of Explanation

One system of explanation used in Al is in effect based upon Carl Hempel's model of explanation ([27]). Hempel's "deductive-nomonoiogicar model of explanation was that an explanation of some description X of a phenomenon consisted of a sound deductive argument with a set of general laws and initial conditions as premisses and X as a conclusion, with the further proviso that the laws that occurred in premisses were necessary for the deduction of the conclusion. Although Bromberger ([4]) showed that this was not an adequate characterization of the sufficient conditions for an

programs "explain" a conclusion by listing the rules that were used by the program to deduce the conclusion.

#### 4.1.3.2 Truth Maintenance Explanation

Another method of explanation that can be used in either rule-based or non-rule based programs uses "truth maintenance systems" In a truth maintenance system, each fact in a data-base is accompanied by a set of justifications. (The truth maintenance system does not itself provide the justifications. They are provided by the users of the truth maintenance system.) These justifications are primarily used to automatically update the data-base; if all of the justifications for a fact are removed then the fact should be removed also. However, these justifications can also be used to provide "explanations" of facts.

Doyle has shown how a truth maintenance system can provide different "levels" of explanation ([11]). According to Doyle:

Consider, as an exaggerated example a centralized polling machine for use in national elections. At the end of Election Day, the machine reports that John F. Kennedy has won the election, and when pressed for an explanation of this decision, explains that Kennedy won because Joe Smith voted for him, and Fannie Jones voted for him, and Bert Brown voted for him, et cetera, continuing in this way for many millions of voters, pro and con. The desired explanation consists of a summary total of the votes cast for Kennedy, Nixon, and the other candidates. If pressed for further explanations, breakdowns of these totals into state totals follows. The next level of explanation expands into city totals, and only if utterly pressed should the machine break the results into precincts or individual voters for some place, say Cook County.

#### 4.1.3.3 Explanation in Grease

Explanation in GREASE consists of first explaining and justifying the "optimal" fluid for each process, then explaining why individual fluids received their ratings by how closely they match the "optimal" fluids.

Explanation of how an "optimal" fluid is generated consists of a trace of the actions taken by the program to solve each individual treatment problem.

Explanation of the rating of a fluid consists of breaking down the composite rating of a fluid into the ratings for individual processes, and ratings of individual properties.

Explanation in GREASE consists of 'cause' and 'effect' explanation, as in a rule-based system, for treatment of subproblems arising from diagnostics or atypical operating conditions, and a simplified version of Bobrow and Brown's synthesis, contingent knowledge, and analysis paradigm for understanding systems. The contingent knowledge consists of records of the solution of individual treatment problems and the calculation of overall ratings. Synthesis, the abstraction of results, is performed by the program as it constructs the optimal fluids, and uses the optimal fluids to rank the actual fluids, while recording its "observations". Finally, a simple analysis is performed in which the recorded observations are summarized at various levels of abstraction.

Cutting fluids have a number of attributes by which they may be judged as selection candidates. These include price, effect on tool life, effect on finish, anti-misting properties etc. The problem of choosing the most desirable cutting fluid from among a group of cutting fluids which may be better in some respects but worse in others is a multi-attribute decision problem. A number of techniques have been devised to aid in making such decisions ([28], [30]).

One simple technique is choice by dominance, if there is a cutting fluid which is at least as good as every other cutting fluid in every respect, it should be chosen. However, obviously this technique is of limited use, since there won't always be a cutting fluid meeting these conditions.

A second ordinal technique is lexicographic choice. Using this method, the various attributes are ranked in order cf importance. Then, the cutting fluid that is best in the most important attribute is chosen; if there are several cutting fluids that are equally good in the most important attribute, the tie is broken by choosing from among these the cutting fluid that is best in the second most important attribute; if there is still a tie, the third most important attribute is the tie-breaker, etc. While this technique is simple to apply, it does takes into account neither how much better one cutting fluid is than another, nor how much more important one attribute is than another. For example, if cutting fluid A provides just slightly better too! life than cutting fluid B, but is much more expensive, then cutting fluid B should be considered superior, even if generally tool life is considered more important than price.

A rational technique which attempts to take into account how much better one choice is than another with respect to a given attribute, and how much more important one attribute is than another, is the trade-off procedure. It is designed to find alternatives equivalent to the original set of alternatives, but differing in the scale level of one of the attributes. The basic steps (described in [28]) are:

- 1. choose a "surviving" attribute;
- 2. choose base levels for the attributes remaining;
- 3. devise some alternatives equivalent to the existing set but with attributes other than the surviving attribute changed to the base level;
- 4. compare the attributes still surviving to choose the preferred alternative.

While this technique obviously remedies some of the problems encountered in applying the lexicographic technique, it is also obviously a complex technique, and difficult to implement properly. And if more than two attributes are being considered, proper implementation is extremely difficult. It is clearly too elegant a technique to be employed in Grease.

The simplest technique is to present the person making the choice with all *ihe* alternatives and have them make a direct choice. This technique cannot be employed if the number of choices is overwhelmingly large. Fortunately, in the case of Grease only a few cutting fluids would be at all appropriate for a given situation, and it would generally be possible for a customer to make a direct choice from among these few alternatives.

#### 4.2 Knowledge Acquisition

Measurement of variables for a cutting-fluid selection are human-made and sensor-based including type of operation, material machined, degree of finish, and others relating both property values, and diagnostic information. The attempt is made to infer as accurately as possible the underlying state of the system from these observables which have the following characteristics:

- qualitative & quantitative measurements Measurements can be in terms of an exact rational measurement such as machine speed "35 feet/minute", or qualitative such as the diagnostic "too much built-up edge". Conversions between measures may be necessary by the system.
- incomplete information All measurements necessary to make a correct cutting-fluid selection may not be available to the system initially. For example, special metallurgical tests for difficult selection situations might be required. Too much information should not be required where use of the system would become unwieldy.

### 4.3 Issues of Representation

#### 4.3.1 Property Representations

A wide variety of properties have to be represented in **Grease**. Depending upon the scale used to measure a property, only certain operations upon, and relations between the measurements of that property are meaningful ([28]). It useful to distinguish between the following types of scales of measurements of properties, which require different types of representations. They are:

- 1. Quantitative:
  - a. Ratio: These are scales of measurement which have a "natural zero". In such scales it is meaningful to rank the measurements according to size, to take the difference between two measurements, and to take the ratio of two measurements. An example of such a scale is speed in surface feet per minute. Suppose for example that measurement M1 is 30 sfm (surface feet per minute) and that measurement M2 is 60 sfm. It is meaningful to say that M1 is less than M2; that the difference between M1 and M2 is 30 sfm; and that M2 is twice as large as M1.
  - b. Interval: These are scales of measurement which have no "natural zero". In such scales it is meaningful to rank the measurements according to size, and to take the difference between two measurements; it is *not* meaningful to take the ratio of two measurements. An example of such a scale of measurement is temperature in degrees Celsius. Suppose for example that measurement M1 is 30 degrees, and measurement M2 is 60 degrees. It is meaningful to say that M1 is less than M2 and that the difference between M1 and M2 is 30 degrees. It is not meaningful to say that M2 is twice as great as M1.
- 2. Qualitative:
  - a. Ordinal: These are scales of measurement in which it is meaningful to rank the measurements according to size, but it is not meaningful to take the difference

Suppose for example that operation M1 had a severity of 1, and operation M2 had a severity of 2. It would be meaningful to say that M1 is more severe than M2, but not that M1 is 1 more severe than M2, or that M1 is twice as severe as M2.

b. Nominal: These are scales of measurement in which it is not meaningful to rank measurements according to size, to take differences of measurements, or to take ratios of measurements. For example, the metallurgical treatment of metals is described by a nominal scale of measurement; a metal can be forged or cold-rolled, etc. It is meaningful to say that two metals have had the same metallurgical treatment; but it is not meaningful to say, for example, that forging is less than cold-rolling.

Some properties can be measured using several different kinds of measurement scales. For example, machinability can be described as a percentage (as compared to an arbitrarily chosen standard), which is an interval scale, and with a group number, which is an ordinal scale. In this case, it is easy to translate from the interval scale to the ordinal scale, because the group number (the ordinal scale) is defined in terms of the percentage (the interval scale).

It is important in GREASE to have some representation of the vague linguistic rules of the experts. For example, one rule might be:

It is important to maintain a low viscosity.

"A low viscosity" is represented in GREASE by a function which given any value of viscosity returns a number between 0 and 1, which provides a rating of how "low" that viscosity is. However, this function is not really the same as a fuzzy set, since the rules used to form boolean combinations of properties are not the rules of fuzzy set theory.<sup>4</sup>

### 4.4 Knowledge-Engineering Issues

The information used to derive the knowledge base comes from a variety of sources.

- 1. There are a number of published documents containing empirical information about the properties of metals, machining operations, and cutting fluids.
- 2. There are a number of relevant internal Gulf documents. These include summaries of past experiences with Gulf cutting fluids, and training documents teaching sales engineers in the proper choice of cutting fluids.
- 3. The testimony of experts in the design and selection of cutting fluids, as well as the diagnosis of problems with cutting fluids. Also, experienced sales engineers were interviewed. The testimony described in detail a number of actual case histories. Also,

<sup>&</sup>lt;sup>4</sup>In GREASE, the vague linguistic terms of the experts are often represented in a manner analogous to fuzzy sets. The theory of fuzzy sets introduced a membership function that could assume values between 0 and 1. If S is a set, and F is a fuzzy subset of S, the membership function vF(s) is a measure of the degree to which s belongs to F.

experts provided information about the written documents they used as references, and answered general and hypothetical questions about cutting fluids.

4. Finally, an important source of knowledge will come from the use of prototype versions of Grease on past cases, hypothetical cases, and current actual cases. Such applications will reveal a lack of knowledge about part of the domain whenever it makes recommendations that are incorrect.

### 4.5 Interface Issues

It is important that the interface to users of Grease be flexible. This is because Grease is designed to solve a number of related but different problems. Thus it must be able to accept a variety of different kinds of inputs, depending upon the particular problem. In each case it must determine what a sufficient amount of data needed to solve that problem is, and be able to prompt for the relevant information; it is important to know what information is relevant to the particular problem at hand, in order not to annoy the user with a large volume of unnecessary questions.

The interface to **Grease** should also be flexible enough to be used by users of varying degrees of sophistication. The system could be employed both by sales engineers on the one hand, and by cutting fluid experts as an advisory system.

Finally, since actual use of the system will be an important source of information about what knowledge is lacking in the system, it is important that there should be an interface which will allow expert users to easily add knowledge to the system.

# **5. Implementation of GREASE**

The multiple functions of GREASE, including selection, diagnosis, treatment, and explanation are implemented as a series of successive processing stages. (Figure 5-1). GREASE first characterizes the cutting-fluid selection problem, performs diagnosis of any known inadequacies of the current fluid, then begins treatment by calculation of an 'optimal' fluid or fluids. Treatment continues as GREASE then evaluates candidate fluids and determines the best fluids which approximate the 'optimal' condition.

Each processing stage in GREASE is summarized as follows:

#### • SHOP DEFINITION:

All data characterizing a cutting-fluid recommendation problem are defined during this stage. These include:

 a specification of all machine operations for which a cutting-fluid is being recommended;

the materials being machined;

- the machining processes relating operations and materials, along with their corresponding:
  - exceptional operating conditions,
  - machining diagnostics observed;
- o specification of the currently used fluid and its chemistry, if known;
- o any special user requirements.
- DIAGNOSIS:

The next stage diagnoses any problems observed by interpreting them in terms of imbalances in the cutting-fluid property values, which are ultimately reflected in the cutting-fluid chemistry.

#### • GENERATION OF GOALS:

This stage generates goals which, if achieved, would solve the problems associated with the diagnostics, and other requirements of the system such as operator preferences, and exceptional machining conditions. Other goals reflect experience about what fluids have performed well in similar situations. The goals are satisfied by adjusting the property values of reference fluids representing either the 'ideal' cutting-fluid for each machining process in the shop without diagnostics or exceptional conditions, or the 'current fluid' specified in the shop definition. This adjusted fluid becomes the 'optimal' fluid with properties that will satisfy the recommendation requirements.

• GENERATION OF CANDIDATES:

This stage generates candidate fluids to be evaluated as possible recommendations. In selection, this will be the existing product line; if binary blending is considered, the candidate fluids correspond to a list of blendable fluids.

#### • EVALUATION OF CANDIDATES:

GREASE then examines each candidate fluid and evaluates it with respect to the 'optimal' fluid for each machine shop process. 'Fixed-goals', which must be satisfied, first screen the candidate fluids. The remaining fluids are then rated on their performance in matching the 'optimal' fluid properties.

• GENERATION OF AVERAGE SHOP RATINGS:

The shop rating for a candidate fluid is a measure of how well the fluid performs on all machining processes in the shop relative to the other fluids evaluated. The rating is computed as the sum of the ratings for the individual processes defined in the shop.

• OUTPUT RESULTS:

The GREASE system finally outputs the fluids in order of decreasing performance, listing how well each fluid performed for each cutting-fluid property. Fluids which failed 'fixedgoals' are then listed. An explanation facility provides detailed information on which goals were posted for each machining process, the 'optimal' fluid for each process in terms of its property values, and the rating of the fluid for each process.

GREASE is implemented on a Digital Equipment Corp. VAX computer in Common Lisp and a knowledge engineering system named Knowledge-Craft.<sup>5</sup> "Deep" knowledge of the cutting fluids domain is represented as schemata and the relations among schemata. This provides a flexible and easily comprehensible structure for the implementation of GREASE. It also makes implementation of explanatory capabilities easy. Rather than simply employing an unstructured set of production rules, GREASE uses the "deep" knowledge of its domain that is embedded in the schemata and their relations to reason from first principles.

### 5.1 Knowledge Representation

Knowledge within the system is represented within a number of taxonomies, which are hierarchical classification networks. These include:

- 'domain' taxonomies representing knowledge about cutting-fluids and its application;
- a 'symptom' taxonomy classifying information about possible diagnostics, operating conditions and requirements;
- a 'property' taxonomy, relating high-level cutting-fluid properties such as tool-life and finish to low level cutting-fluid compositional and physical properties;
- a 'goal' taxonomy classifying all possible requirements that can imposed on a cuttingfluid for a GREASE recommendation.



Figure 5-1: GREASE Implementation Architecture

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Three taxonomies characterize cutting-fluids and their application:<sup>6</sup>

- the 'materials' taxonomy, which classifies metallic materials which are machined using cutting-fluids;
- the 'operations' taxonomy, which classifies machining operations which require cuttingfluids;

© the 'fluids' taxonomy which classifies the cutting-fluids themselves.

#### 5.1.1.1 Materials

Materials within GREASE are limited to those which are machined with cutting-fluids and are categorized into a ferrous group (i.e., steels), and a non-ferrous group of metals and alloys (Figure 5-2), Non-metallic substances, such as plastics, etc. are not included. The materials are also considered to be in a 'machinable' annealed condition, except when they are subjected to 'grinding' operations, where they are considered to be in a hardened condition. The ferrous group is divided into four sub-groups: (groupi -> group4), each of which includes similar steels in terms of machinability. The non-ferrous group is divided into six sub-groups: (groupSa -> group7b) also based upon machinability characteristics and similar cutting-fluid composition requirements.<sup>7</sup> An example of a composition requirement would be 'group7a' requiring that cast aluminum be machined with cutting-fluids containing no active sulfur.<sup>8</sup>

{{ ALUMINUM-CAST IN-GROUP: GROUP7A USE-OF: ALUMINUM ACTIVATES: (NO-SULFUR 1.0)}}

<sup>&</sup>lt;sup>6</sup>Information contained in these taxonomies was derived primarily from Gulf Oil internal documentation [22, 23, 24], other publications [32, 36], and personal conversations with the Gulf cutting fluid experts.

<sup>&</sup>lt;sup>7</sup>The material groups correspond historically to materials which are similar in machining difficulty requiring similar cutting fluids for machining. The numeric group *number* assignments are arbitrary. It was discovered, however, that after categorizing the non-ferrous materials into groups •> group7, that a finer classification into sub-categories was necessary: hence group5a, group5b....group7b.

<sup>&</sup>lt;sup>\*</sup>The ACTIVATES slot contains *goals* that are generated which affect the cutting-fluid composition to result in proper machining of the material. The goal in this case is to eliminate fluids with an *act/ve-sullur* content.

The machinabilities associated with the material groups are as follows:

GROUP#	MACHINABILITY
Ferrous:	
GROUP1	Easy - 100-70% based on 100% for B1112
GROUP2	Easy/Moderate - malleable & cast irons
GROUP3	Moderate - 70-50%
GROUP4	Difficult - <50%
Non-ferrous:	
GROUP5a,5b	Easy - >100% based on 100% for leaded
	yellow brass
GROUP6a,6b	Easy/Moderate - below 100%
GROUP7a,7b	Difficult - below 100%

GREASE makes no machinability distinction between materials within the same groups, even though they might possess somewhat different machinability values. GREASE would generate similar recommendations for these materials unless the materials generated different material constraints. An example of this would be the generation of a 'no-chlorine' goal by copper in Group7a, but no corresponding goal by nickel which is also in Group7a.

The schema MATERIAL-GROUP forms the root of the 'group' classification of the materials taxonomy:

{{ MATERIAL-GROUP
USE-OF:
GROUP-CONTAINS:
IS-A + INV: NON-FERROUS-GROUP FERROUS-GROUP
ACTIVATES:
LOW:
HIGH:}}

The slot USE-OF records the names of chemical elements in the composition of the materials. The relation GROUP-CONTAINS with inverse IN-GROUP, holds the names of the terminal schemata representing the actual materials that correspond to members of the MATERIAL-GROUP set. The slots LOW and HIGH define the machinability range characterizing the material group, and is represented as numeric values relative to a reference material. The slot ACTIVATES contains goals or 'material constraints' generated by the various materials.

The schemata FERROUS-GROUP and NON-FERROUS-GROUP divide the 'material' taxonomy into two sub-groupings:

{{ FERROUS-GROUP IS-A: MATERIAL-GROUP IS-A + INV: GROUP4 GROUP3 GROUP2 GROUP1}}





The sub-groupings contain the group classifications: **GROUP1, GROUP2, .**.., **GROUP7A, JROUP7B** that represent categories of similar composition and machinabilities:

### {{GROUP1

IS-A: FERROUS-GROUP MEMBER-OF: CLASS1 GROUP-CONTAINS: B-8735\* B-8637\* B-8635\* B-8632 B-8630... HIGH: 100 LOW: 70}}

Material classes have been defined to group ferrous and non-ferrous materials into sets which lave similar machinabilities, but not necessarily similar composition and material requirements:
#### {{ MATERIAL-CLASS INSTANCE: SET HAS-SUBSET: CLASS4 CLASS3 CLASS2 CLASS1 CLASS0}}

CLASS0 --> CLASS4 correspond to increasing difficulty in machining, or decreasing machinability.

This classification scheme allows the relative machinabilities of the ferrous and non-ferrous materials to be correlated. The ferrous group GROUP1 and the non-ferrous group GROUP6a, for instance, are members of the same material class CLASS1:

#### {{ CLASS1

INSTANCE: SET SUBSET-OF: MATERIAL-CLASS HAS-MEMBER: GROUP1 GROUP6A MACHINABILITY-SATISFIED-BY: TBL106A TBL101 TBL96A ...}}

The material classifications for all material groups is defined as follows:

CLASS #	COMPONENT GROUPS		
	Ferrous	Non-Ferr	ous
CLASSO CLASS1 CLASS2 CLASS3	Group1, Group2, Group3.	Group5a, Group6a Group6b Group7a	Group5b
CLASS4	Group4,	Group7b	

The ferrous materials have also been classified according to the SAE indexing scheme. The schema STEEL forms the root of this classification. The taxonomy branches into 9 material categories modeled by the schemata 1XXX to 9XXX:

{{ 4XXX

IS-A: STEEL USE-OF: MOLYBDENUM IS-A + INV: 48XX 46XX 43XX 41XX NAME: MOLYBDENUM-STEELS}}

Each schema is characterized by two slots; NAME and USE-OF. The NAME slot holds the name of the steel category, the USE-OF slot records the name of the primary elements occurring in the steel alloy composition. The schema 4XXX, for instance, denotes the class of "molybdenum steels", containing the "molybdenum" element

categories.

Finally, individual steels are represented as terminal schemata of the STEEL taxonomy.<sup>9</sup>

{{B-1111 IN-GROUP: GROUP1 IS-A: 11XX MACHINABILITY: 94}}

Each schema is characterized by a MACHINABILITY and an IN-GROUP slot. The first slot holds the machinability rating of the steel, the second slot records the corresponding machinability group. The individual steels are also the terminal schemata of the MATERIAL-GROUP taxonomy related by the IN-GROUP relation.

The SAE classification scheme is not used for the non-ferrous materials. Non-ferrous metals or alloys are represented in the MATERIAL-GROUP taxonomy by their common names:

{{ ALUMINUM-CAST IN-GROUP: GROUP7A USE-OF: ALUMINUM ACTIVATES: (NO-SULFUR 1.0)}}

#### 5.1.1.2 Operations

There are several hundred machining operations possible requiring cutting-fluids, but all are considered variations of the basic operation types included in the 'operation' taxonomy (Figure 5-3).

The **OPERATION** schema is the root of the operations taxonomy:

{{ OPERATION
 HAS-SEVERITY:
 IS-A + INV: GRINDING-OPERATION SAWING SHAPING PLANING ...
 DEPTH-OF-CUT:
 SPEED:
 TEMPERATURE:
 TOOL-DESIGN:
 TOOL-DESIGN:
 TOOL-MATERIAL:
 FINISH:
 HYDRAULIC-REQUIREMENT:
 LUBRICITY-REQUIREMENT:
 COOLING-REQUIREMENT:
 ACTIVATES:}}

The slot HAS-SEVERITY holds the severity class. The slot ACTIVATES records possible goals that are generated when the operations are present in the machine shop. The remaining slots such as DEPTH-OF-CUT, SPEED, FEED-RATE, COOLING-REQUIREMENTS, etc. record specific properties or machining characteristics of an operation.

Operation types such as BROACHING-OPERATION, THREADING-OPERATION, GEAR-OPERATION, DRILLING-OPERATION, etc. are descendants of the OPERATION schema and represent the basic operation types in GREASE.

{{ BROACHING-OPERATION IS-A: OPERATION HAS-SEVERITY: SEVERITY1 IS-A + INV: BROACHING-EXTERNAL BROACHING-INTERNAL FINISH: HIGH ACTIVATES:}}

Where operation types are themselves classes, such as BROACHING-OPERATION, their descendants, such as BROACHING-INTERNAL or BROACHING-EXTERNAL, represent the basic operations.

{{ BROACHING-INTERNAL IS-A: BROACHING-OPERATION SPEED: LOW}}

Operations are specified to GREASE corresponding to the specific operation types corresponding to, or 'most similar' to the actual operations desired.



Figure 5-3: GREASE Operation Taxonomy

The basic operation types fall into ten decreasing severity classes (SEVERITY1 »> SEVERITY1O) which measures the difficulty of the operation type (Figure 5-5). Some basic operations which are components of an operation class, such as DRILLING-OPERATION, don't possess the same operation severity due to unique characteristics of the particular operation.



Figu re 5-4: Complex Operation Types

#### 5.1.1.3 Cutting-Fiuids

GREASE contains two cutting-fluid representations:

- « tho Gulf product line fluids which are recommended by GREASE;
- 'ideal' cutting-fluids with cutting-fluid property values corresponding to optimal selections for the machining processes embodied in the empirical selection causal network (Section 5.1.5,). The property values in the 'ideal' fluids have been tuned by cutting-fluid experts. Further discussion of the 'ideal' fluids is deferred until Section 5.1.6.

The cutting-fluid product-line taxonomy in GREASE is classified into 'straight-oils' comprising the bulk of the available fluids, 'soluble-oils', and 'chemical-cutting-fluids'. This classification is based upon significant cutting-fluid behavior differences, and correlations of composition to cutting-fluid behavior. Special fluids which are considered 'base oils' and 'blending oils' are not distinguished

OPERATION	SEVERITY	CLASS
broach ing-internal broaching-external	severi	ltyl
thread ing-pipe threading-plain tapping gear-shaving	sever	ity2
gear-hobbing gear-shaping gear-cutting	sever	ity3
deep-driil ing gun-drill ing trepanning	severi	ty4
automatics-multiple-spindle	severi	tyS
drill ing reaming mill ing-face milling-plain milling-multiple-cutter milling-end boring turning lathes-turret automatics-light-feed	severi	ty6
grinding-form	severi	Lty7
pianing shaping sawing	severi	ty8
grinding-plain grinding-surface grinding-cylindrical grinding-centeriess	severi	ty9
honing lapping superfinishing	severi	.ty10

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within the classification. " (Figure 5-6)



(CUTTING FLUID PRODUCT LINE)

Figure 5-6: GREASE Cutting Fluid Taxonomy

<sup>&</sup>lt;sup>10</sup>Specific instances of cutting fluids corresponding to the classification categories are not represented here for proprietary reasons.

The CUTTING-FLUID schema is the root of the cutting-fluids taxonomy:

{{ CUTTING-FLUID IS-A + INV: CHEMICAL-CUTTING-FLUID SOLUBLE-OIL STRAIGHT-OIL TYPE: INSOLUBLE **DILUTION-RATIO:** SULFUR-ACTIVITY: TYPE-OF-SERVICE: SUV: KINEMATIC-VISCOSITY: TOTAL-SULFUR-PERCENTAGE: **ACTIVE-SULFUR-PERCENTAGE:** CHLORINE-PERCENTAGE: PHOSPHORUS · PERCENTAGE: FATTY-OIL-PERCENTAGE: **SAPONIFICATION-NUMBER:** ANTIMIST PROPERTY: ANTI-OXIDANT-PROPERTY: ANTI-FOAM-PROPERTY: ANTI-RUST-PROPERTY: ANTI-WEAR-PROPERTY: **CORROSION-INHIBITOR-PROPERTY: ODOR-MASKANT-PROPERTY:** DENSITY: COOLING: LUBRICITY: ANTIWELD: ACTIVITY: PRICE: RESULTS: }}

The slot TYPE holds the type of the fluid - 'insoluble' or 'soluble'. In the case of a soluble oil, the slot DILUTION-RATIO records the water ratio. SULFUR-ACTIVITY flagged as 't' or 'nil' indicates whether the fluid is an 'active' fluid containing active sulfur. TYPE-OF-SERVICE refers to the intended duty of the fluid. The slots SUV to FATTY-OIL-PERCENTAGE characterize the chemical composition and physical characteristics of the fluid. Additional slots such as ANTIMIST-PROPERTY, ANTI-RUST-PROPERTY or ODOR-MASKANT-PROPERTY refer to specific properties of the cutting-fluid. The slots COOLING, LUBRICITY, ANTIWELD and ACTIVITY hold measures of cutting-fluid performance in terms of their fundamental functions. The slot PRICE holds the relative price of the fluid. The slot RESULTS will record a detailed list-description of the evaluation of the fluid.

Cutting-fluids are classified into three distinct types, as previously stated - 'straight-oil', 'soluble-oil' and 'chemical-cutting-fluid'. 'Straight-oils' are further sub-classified:

# {{ STRAIGHT-OIL

IS-A: CUTTING-FLUID IS-A + INV: SULFO-CHLORINATED-MINERAL-FATTY-OIL PHOSPHO-CLORINATED-MINERAL-FATTY-OIL SULFO-CHLORINATED-MINERAL-OIL SULFURIZED-MINERAL-FATTY-OIL SULFURIZED-MINERAL-OIL MINERAL-LARD-OIL MINERAL-OIL}

The SULFO-CHLORINATED-MINERAL-FATTY-OIL, PHOSPHO-CLORINATED-MINERAL-FATTY-OIL, SULFO-CHLORINATED-MINERAL-OIL, SULFURIZED-MINERAL-FATTY-OIL, SULFURIZED-MINERAL-OIL, MINERAL-LARD-OIL and MINERAL-OIL schemata represent seven classes of straight oils. One level deeper, schemata represent the cutting-oils currently available in the Gulf product line.

The class of soluble oils represent cutting-fluids that are diluted with water in their usage. Specific dilution ratios of these oils are represented as distinct products.

The class of chemical cutting fluids are synthetic materials whose chemistry correlates with cutting fluid properties differently than for soluble oils and straight oils.

### 5.1.2 Symptom Causal Network

Observed conditions or user requirements that result in constraints to the selection process in GREASE are known as 'symptoms'. Other conditions that constrain the selection process originate from either the operations or materials specified in the shop definition. An example of a material constraint was that of cast aluminum requiring 'no active sulfur' in the cutting-fluid as explained earlier.

There are several symptom types within GREASE:

- SHOP REQUIREMENTS are requirements global to all machining processes in the shop such as the 'ecological safety' requirement or the 'no solubles' restriction on the fluids that can be recommended (Figure 5-7);
- PROCESS CHARACTERISTICS are exceptional machine operating conditions such as a 'high speed' operation specific to individual machining processes (Figure 5-8);
- PROCESS DIAGNOSTICS are observed diagnostic conditions for a particular machining process such as 'blued chips';

The symptom types are instances of the SYMPTOM schema:





{{ SYMPTOM

ISA + 1NV: SHOP-REQUIREMENT PROCESS-CHARACTERISTIC PROCESS-DIAGNOSTIC ACTIVATES: IMPORTANCE: 1 STATUS:}}

The slot ACTIVATES indicates which goals are generated to constrain the selection process. The IMPORTANCE slot isn't currently used, but is intended to permit a prioritization of different symptoms. The STATUS slot contains the machining process names that exhibit this symptom.

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# {{ HIGH-SPEED is-a: PROCESS-CHARACTERISTIC ACTIVATES: (TOOL-LIFE COOLING 1.0) (TOOL-LIFE ANTIWELD 1.0) status:}}

Process diagnostics are classified into either 'fixed' or 'change' categories. A 'fixed-processdiagnostic' indicates a diagnostic requirement that must be met for the process, such as NO-RUST: (Figure 5-9)

# {{ RUST

IS-A: FIXED-PROCESS-DIAGNOSTIC ACTIVATES: (NO-RUST 1.0) IMPORTANCE: 10 STATUS:}}





A 'change' process diagnostic results in the alteration of one or more fundamental cutting-fluid properties: (Figure 5-10)

# {{ LUBRICITY · DIAG

IS-A: CHANGE-PROCESS-DIAGNOSTIC ACTIVATES: (TOOL-LIFE LUBRICITY 1.0) STATUS:}}

An example of a 'shop requirement' is the restriction of the cutting-fluid selections to only soluble fluids:





# {{ SOLUBLES-ONLY IS-A: SHOP-REQUIREMENT ACTIVATES: (SOLUBLES 1.0) STATUS:}}

#### 5.1.3 Property Representation

Properties in GREASE signify characteristics of operations, materials, and cutting-fluids. Properties of materials and operations that affect the cutting-fluid selection are represented as material and operation constraints. An example of a material constraint was discussed previously (Sec. 5.1.1.1). These constraints generate 'goals' which are used to constrain the desired cutting-fluid properties during the fluid evaluation stage.

Cutting-fluid properties in GREASE are represented both as slots in the CUTTING-FLUID schema (Figure 5-11), and by separate schema, as instances of the PROPERTY schema (Figure 5-12).

Some cutting fluid properties, such as ODOR-MASKANT-PROPERTY are simple properties, whose values can be directly measured and are independent of any of the other properties. However, the values of some properties, such as lubricity and antiweld, are functions of the values of other properties. Representing cutting-fluid properties as schemata allows the functional relationships between these properties to be easily represented.

The cutting fluid properties are represented both as a taxonomy depicting classes of properties

{{ CUTTING-FLUID IS-A + INV: CHEMICAL-CUTTING-FLUID SOLUBLE-OIL STRAIGHT-OIL TYPE: INSOLUBLE **DILUTION-RATIO:** SULFUR-ACTIVITY: TYPE-OF-SERVICE: SUV: KINEMATIC VISCOSITY: TOTAL-SULFUR-PERCENTAGE: ACTIVE-SULFUR-PERCENTAGE: CHLORINE-PERCENTAGE: PHOSPHORUS-PERCENTAGE: FATTY-OIL-PERCENTAGE: SAPONIFICATION-NUMBER: ANTIMIST-PROPERTY: ANTI-OXIDANT-PROPERTY: ANTI-FOAM-PROPERTY: ANTI-RUST-PROPERTY: ANTI-WEAR-PROPERTY: CORROSION-INHIBITOR-PROPERTY: ODOR-MASKANT-PROPERTY: DENSITY: COOLING: LUBRICITY: ANTIWELD: ACTIVITY: PRICE:

RESULTS: }}

#### Figure 5-11: Cutting Fluid Properties

upon each other. A cutting fluid property which is functionally dependent upon another cutting fluid property is said to "vary-with" that property. This "varies-with" hierarchy is depicted in figure 5-14.<sup>11</sup>

As an example, an instance of the property TOOL-LIFE is examined more closely.<sup>12</sup> TOOL-LIFE is an estimate of how well a given cutting fluid will reduce the cost of tool replacements in a given shop; this value is represented as the value of a slot in each cutting fluid schema. Its functional dependence upon other properties is represented by the "varies-with" relations of the TOOL-LIFE schema to other schemata.

<sup>&</sup>lt;sup>11</sup>The deepest level of properties of the "varies-with" hierarchy is not specified here for proprietary reasons.

{{

PROPERTY		
c(PRE - REQUISITE: )T		
i(comment): <pre> <must evaluate="" for="" in="" order="" pre="" property<="" to="" true=""></must></pre>		
to have a non - nil value. This can be		
used to restrict the applicability of		
properties.>.		
UNITS:		
c(VARIES: )		
i(comment): <the a="" are="" function="" of="" properties="" td="" that="" the<=""></the>		
given property.>		
VARIES • WITH:		
i(comment): <i given="" he="" is<="" properties="" property="" td="" that="" the=""></i>		
a function of.>		
CHANGED -BY:		
I(comment). <a for="" goals="" list="" of="" td="" this<=""></a>		
i(comment): How important the property is to the		
costomer This applies only to		
top - lovel properties such as		
b/TOOL = LIFE) and $b(FINISH) >$		
i(comment): The name of the slot in the cutting fluid		
schema where the value of this property		
is stored, if it directly measured.		
otherwise it is nil.>		
CHANGE-MEASURE:		
MEASURE - CHANGE		
i(comment): <the calculates="" function="" of<="" td="" the="" value="" which=""></the>		
the given property in terms of the		
values of lower level properties.>		
Figure 5-12: The Property Schema		



Figure 5-13: Cutting Fluid Property Taxonomy

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(CHEMICAL AND PHYSICAL COMPOSITIONAL PROPERTIES OF CUTTING-FLUIDS) (e.g. fatty-oil content, sulfur content, etc.)



# {{ TOOL·LIFE IS-A: PROPERTY VARIES-WITH: LUBRICITY COOLING ANTIWELD VISC CHANGED-BY: NIL *comment*: <Since there are no "change" goals which directly affect tool life, the value is NIL.> DERIVES: T44 T43 comment: <A list of "change" goals which indirectly affect tool life by changing the properties tool life "varies-with".> VALUE-FOUND-IN: NIL comment: <Since this is always a calculated property, rather than a measured property, the value is nil.> VALUE: NIL }}

#### 5.1.4 Goal Network

Constraints within GREASE affect the selection and rating of the cutting-fluids through 'goals' to the fluid evaluator. The 'goals' are posted to satisfy 'symptoms' identified during the 'shop definition' phase of GREASE, which are diagnostics, atypical operating conditions, and user requirements. 'Goals' also satisfy 'operation' and 'material' constraints such as the 'no-active-sulfur' constraint for cast aluminum as explained earlier.

#### 5.1.4.1 Goal Types

There exist two types of 'goals' within GREASE:

- FIXED GOALS These goals reflect conditions which 'must' be satisfied for all processes during the fluid evaluation. If any 'fixed goals' that are posted fail for a particular fluid being evaluated, that fluid is rejected.
- CHANGE GOALS These goals require a change in a cutting fluid property from some current or 'ideal' starting value. 'Change goals' affect the properties of lubricity, cooling, antiweld, and viscosity and are posted for the individual machining processes affected in the shop.

The GOAL schema is the root of the goal network:

{{GOAL

IS-A + INV: CHANGE-GOAL FIXED-GOAL IMPORTANCE: STATUS:}}

The STATUS slot is set to a *process-id* list for those processes posting a particular CHANGE goal; otherwise, *nil*. The IMPORTANCE slot, not currently used, is reserved to allow a prioritization of goals.

'Fixed goals' are instances of the FIXED-GOAL schema:

{{FIXED-GOAL IS-A: GOAL !S-A + iNV: NO-CORROSION NO-ODOR NO-CHLORINE NO-RUST NO-CHEM-SYNTHETICS SOLUBLES STRAIGHT-OILS ECOLOGICAL-SAFE ANTI-OXIDANTS NO-SULFUR TEST:}}

The TEST slot contains a predicate function which determines if the goal is met for the specific fluid being tested. An example of a fixed goal is NO-CHLORINE:

{{ NO-CHLORINE IS-A: FIXED-GOAL TEST: NO-CHLORINE-TEST IMPORTANCE: 10 STATUS:}}

'Change goals' are instances of the CHANGE-GOAL schema:

{{ CHANGE-GOAL
 is-a: GOAL
 CHANGES:
 DERIVED-FROM:
 GOAL-OF:
 DEGREE: 0.0
 GOAL-FUNC: MAINTAIN-HIGH}}

Each 'change goal' is specific to a particular machining process and is generated dynamically as it is being posted. The slots are defined as follows:

- CHANGES A relation indicating the fundamental cutting-fluid property affected by the goal (i.e. cooling, lubricity, antiweld, or viscosity).
- DERIVED-FROM A relation indicating the higher-level property (such as tool-life or finish) that the goal attempts to optimize.
- GOAL OF The machining process that the goal is affecting.
- DEGREE The absolute value of the fundamental property resulting from the goal (i.e. the target value of the property for the process).
- GOAL-FUNC Contains the name of a function which compares the value of the fundamental property for this goal against a tested fluid, and returns a fluid rating.

#### 5.1.4.2 Goal Activation

Goals are activated in the function 'setgoals' by processing posted constraints originating from materials, operations, and symptoms identified in the shop requirements phase. The ACTIVATES slot is used to identify the goals specified by the constraints. FIXED goals and CHANGE goals are identified differently.

An example of a FIXED goal is the 'no-sulfur' constraint of cast-aluminum:

IN-GROUP: GROUP7A USE-OF: ALUMINUM ACTIVATES: (NO-SULFUR 10)}}

FIXED goals are specified as two element lists - the first element is the name of the schema representing the FIXED goal, and the second element optionally contains a value used by the test function to indicate, for example, the maximum acceptable percentage level of the property.<sup>13</sup> When multiple goals exist for a constraint, they are appended to the ACTIVATES slot.

CHANGE goals are specified by three element lists as in the example of 'high-speed':

{{ HIGH-SPEED IS-A: PROCESS-CHARACTERISTIC ACTIVATES: (TOOL-LIFE COOLING 1.0) (TOOL-LIFE ANTIWELD 1.0) STATUS:}}

The first element specifies the 'high-level' property being optimized by the goal (The current GREASE implementation always specifies TOOL-LIFE); the second element specifies the cutting-fluid property whose alteration will satisfy the posted constraint; the third element represents the amount that the cutting-fluid property will be altered (indicated as a multiplier to a 'typical change' of the property, as discussed in the next section.)

#### 5.1.5 Empirical Selection Causal Network

Integral to GREASE is an empirical selection causal network which specifies the ideal cutting fluid chemistry and properties corresponding to specific machine processes. This network embodies the results of using cutting fluids in actual machine operations, and therefore represents a wealth of experimental knowledge. The network is augmented by expert system knowledge of how to satisfy fundamental property requirements in a selection situation in terms of chemistry alterations which affect these properties.

The network is represented in terms of individual schemata assigned to specific 'processes' in GREASE. There exist a schema for each possible combination of operation severity and machinability group. Each schema

- represents the "Ideal Fluid" in terms of cutting-fluid properties for the specified machining process;
- contains property values representing the granularity of change for a "change goal";

<sup>&</sup>lt;sup>13</sup>The *no-chlorine* goal has a second argument of '1.0' indicating that a fluid containing up to 1% chlorine can still pass the goal. FIXED goals that don't use the second argument have been arbitrarily set to a value of 10.

- specifies sensitivites of each property for the specified process.

Each schema in the network are instances of the TBL schema:

### {{ TBL

SATISFIES-SEVERITY-OF: SATISFIES-MACHINABILITY-OF: INSTANCE + INV: TBL11 TBL12 TBL13 ... OIL-NAME: COOLING: 50.0 LUBRICITY: 40.0 ANTIWELD: (190.0 STANDARD-CHANGE) ACTIVITY: 230.0 VISC: 3.5 TOOL-LIFE: FINISH: RECOMMENDATIONS:}}

The slot SATISFIES-SEVERITY-OF denotes the operation severity referred to; SATISFIES-MACHINABILITY-OF designates the machinability class of the material. The slot OIL-NAME specifies the name of an 'ideal' cutting-fluid with fundamental properties that best satisfy the process (Section 5.1.6).

The slots COOLING, LUBRICITY, ANTIWELD, ACTIVITY, and VISC contain values that represent the magnitude of a 'typical change' or increment in the properties if atypical operating conditions are used, or a machining diagnostic is observed. These same values also specify the width of the utility functions used by the fluid evaluator.<sup>14</sup> If the slot values are represented as a list, the last list element represents the utility function to be used to rate the specified property by the fluid evaluator.<sup>15</sup>

The slot TOOL-LIFE contains a meta-slot attachment that contain facets representing the 'sensitivity' of each fundamental cutting-fluid property to affecting 'tool-life' for the process. The slot FINISH is intended to be used similarly in a future expansion of GREASE.

An example of a schema associated with a process of operation severity 'severity1' and material machinability 'group2' is below:

<sup>&</sup>lt;sup>14</sup> If the slot contains two values, the first represents the utility function width parameter, and the second represents the diagnostic increment parameter.

<sup>&</sup>lt;sup>15</sup>If the utility function is unspecified, the 'default' utility function - MAINTAIN-HIGH will be used to rate the property by the fluid evaluator.

{{TBL12 INSTANCE: TBL SATISFIES-SEVERITY-OF: SEVERITY1 SATISFIES-MACHINABILITY-OF: CLASS2 OIL-NAME: FERROUS12 COOLING: 25.0 LUBRICITY: 100.0 ANTIWELD: (150.0 STANDARD-CHANGE) VISC: 3.5 TOOL-LIFE: *INSTANCE*:TL1 FINISH: *INSTANCE*:FINISH1}}

#### 5.1.5.1 Sensitivities

The sensitivities, as previously mentioned, refer to the ability that each fundamental cutting-fluid property, such as lubricity, has to influence tool life or finish. The sensitivities are represented as meta-slots associated with either the TOOL-LIFE or FINISH slot of an instance of the TBL schema. The meta-slots themselves, are instances of the M-TOOL-LIFE schema:

{{M-TOOL-LIFE IS-A + INV: TL10 TL9 .. .. TL3 TL2 TL1 LUBRICITY: 2.0 ANTIWELD: 2.0 COOLING: 2.0 VISC: 0.0 ACTIVITY: 0.0}}

The **TL1** schema is the meta-slot of the **TBL1**2 TOOL-LIFE slot in the previous example:

{{TL1 IS-A: M-TOOL-LIFE LUBRICITY: 0.77 ANTIWELD: 4.62 COOLING: 0.77 VISC: 3.85 ACTIVITY: 0.0}}

The slot values, or facets represent the individual property sensitivities. The values were determined from interviewing the experts as to how significant, or important each of the properties was for each machining operation. Each property was rated according to a six-valued ordinal scale ranging from 'low' to 'very-high'. The ratings were then converted to the numeric scale: 1 • 6, and the

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#### 5.1.5.2 Utility Functions

The utility functions are rating functions used by the fluid-evaluator to determine how we 'candidate' fluid from the product line or blend, matches the designed 'optimal' fluid. The shape these functions is based both upon cutting-fluid property behavior and empirical testing. 1 significant functions depicted in Figure 5-15 are maintain, maintain-high, maintain-low, £ standard-change. The properties of these functions are as follows:

- maintain used when a property must be restricted to a narrow range, such as 'maintaining' a viscosity value in 'deep-drilling<sup>1</sup>.
- *9* maintain-high used as the default, returns a low rating when when the fluid has a value less than the 'optimal', but a maximum rating for higher values. Cooling and lubricity generally have this property.
- maintain-low returns a high rating when the desired property value is below or equal to the optimal, but a low rating when it exceeds the optimal.
- standard-change generally used by antiweld, returns a low rating if the value of the fluid is both lower than the optimal, and greater than a 'typical change' higher than the optimal value. The tool-life drops off as antiweld is increased beyond a reasonable value for a machining process.

The functions are variations of a mathematical 'normal' curve. The curve width is determined by 'typical change' value for the property in the empirical selection causal network and corresponds the variance in the 'normal' curve formula.<sup>17</sup> The functions return a rating with values between 0 1.0.

The 'typical changes' have been determined by interviewing the cutting-fluid experts regarding h much a property must *typically* change to satisfy an upset resulting in a diagnostic symptom, o satisfy an atypical operating condition - this can be interpreted as the granularity of the prop' change. Examples of typical changes include the amount that 'cooling' must be changed to satis 'blued chips' diagnostic, or to correct for a 'high speed' operation. Multiples of these 'typ changes' are used by GREASE to satisfy posted goals.

<sup>&</sup>lt;sup>16</sup>The ACTIVITY slot is not utilized in the current GREASE prototype. Also, the meta-slots TL1 -> TL10 have k initialized to the same sensitivities for the different machinability groups of each operation severity. This is onlapproximation. Tuning of GREASE win reveal distinct sensitivities which are a function of both operation severity and mat machinability. In this case, specific meta-slots, such as TL12, attached to slot FOOL-LIFE of schema TBL.12, may be adde GREASE to reflect this.

<sup>&</sup>lt;sup>17</sup> In tuning GREASE, it was found that a curve width approximately 1.5 \* 'typical change' for a propery symptom resul GREASE selections in better agreement with the experts in most cases.



Figure 5-15: The Four Utility Functions

#### 5.1.6 'IDEAL' Cutting-fluids

'Ideal' cutting-fluids in GREASE are hypothetical fluids with property values corresponding to optimal selections for the machining processes embodied in the empirical selection causal network (Section 5.1.5.). The property values in the 'ideal' fluids have been tuned by cutting-fluid experts.

```
{{ IDEAL-FLUID
     INSTANCE + INV: FERROUS11 FERROUS12 ... NON-FERROUS104
     LUBRICITY:
     ANTIWELD:
     COOLING:
     KINEMATIC-VISCOSITY:}}
```

The 'ideal' fluid is a function of the operation severity and machinability determined by the materialclass. In addition, a distinction is made between 'ideal' fluids for ferrous and non-ferrous materials. As a result, there are forty 'ideal' fluids for operation severities 'severity1' through 'severity10' and ferrous material 'class1' through 'class4'. The naming convention is 'FERROUSmn' where 'm' represents the operation severity and 'n' represents the material class.

{{ FERROUS11
 instance: IDEAL-FLUID
 Lubricity: 100.0
 Antiweld: 300.0
 Cooling: 600.0
 Kinematic-viscosity: 38.6}}

Similarly, there are fifty 'ideal' fluids for the non-ferrous materials corresponding to material classes 'class0' through 'class4' and operation severities 'severity1' through 'severity10'. (note: The empirical selection causal network contains 100 machining processes since there are ten material groups and ten severity classes. There are only 90 'ideal' fluids since 'group5a' and 'group5b' share the same material class 'class0')

{{ NON-FERROUS11 INSTANCE: IDEAL-FLUID LUBRICITY: 30.0 ANTIWELD: 35.0 COOLING: 600.0 KINEMATIC-VISCOSITY: 32.0}}

# **5.2 Processing Stages**

GREASE utilizes an activation network in performing its different functions. After the shop has been defined, the command 'R' evaluates the RECOMMEND function which triggers each successive processing stage indicated in Figure 5-1. RECOMMEND uses the object programming paradigm of sending messages to specific slots in schemata to activate procedures attached to the slots. An example of this is activating the generation of goals by sending a message to the GENERATE slot of GOALS:

{{ GOALS GENERATE: SET-GOALS STATUS:}}

The function 'set-goals' is then evaluated which posts the goals.

GREASE operation is coordinated through a user command menu allowing access to its several functions.<sup>18</sup>

This section includes an architectural description of each GREASE processing stage and includes illustrations from the detailed GREASE example described in Appendix III. That example presents a complete description of the GREASE user interface, including all available commands, and input/output screens. Internal representation of the shop network and goal structure is also presented in that example.

#### 5.2.1 Shop Definition

The shop is defined by generating a model representing the plant where the cutting-fluid is to be recommended. This model includes information about the machining operations performed, the materials to be machined, the processes relating operations and materials, the current cutting-fluid used, and additional customer requirements.

#### **5.2.1.1 Operation Specification**

A machining operation specified by the user is represented by an instance of the OPERATION-SPEC schema:

{{ OPERATION-SPEC OPERATION-IS-A: STATUS: T WORN-MACHINERY:}}

This schema is characterized by two slots OPERATION-IS-A and WORN-MACHINERY. Each instance points to an element of the operations taxonomy, by means of the inherited slot OPERATION-IS-A. The slot WORN-MACHINERY is currently used to indicate if the machine contains brass or bronze components which would be affected by active sulfur in the cutting-fluid.<sup>19</sup>

<sup>&</sup>lt;sup>18</sup>The command menu is an instantiation of the Knowledge Craft<sup>TM</sup> Command System. Several of the commands generate reports and require user specifications. These utilize the Window System enhanced with several Common Lisp input/output functions, and VMS operating system call-out procedures.

<sup>&</sup>lt;sup>19</sup>Originally WORN-MACHINERY indicated that the machine was worn and contained brass and bronze components. Cuttingfluid would seep into these machines causing corrosion.

An example of an operation specification would be the following:

Machine operation (if not in system, closest type) ? automatics-mult Brass, bronze or copper in machinery (y/n) ? n

This signifies a multiple spindle automatic machine without brass bearings. GREASE would generate the schema:

#### {{ T33

INSTANCE: OPERATION-SPEC OPERATION-IS-A: AUTOMATICS-MULTIPLE-SPINDLE WORN-MACHINERY: NIL }}

#### 5.2.1.2 Material Specification

A material specified by the user is represented by an instance of the MATERIAL-SPEC schema:

This schema is characterized by two slots MATERIAL-IS-A and MATERIAL-PERCENTAGE. Materials can be specified by their AISI number or machinability group. A material specified by its AISI number will be an instance of the AISI-MATERIAL-SPEC schema; otherwise, it will be an instance of the **ANONYMOUS-MATERIAL-SPEC** schema. Each instance will point to an element of the materials taxonomy, by means of the inherited slot MATERIAL-IS-A. The slot MATERIAL-PERCENTAGE representing the percentage of the specified material in the shop, is used as a measure of the importance of the specified materials machined in the shop.

An example of a material specification would be the following:

```
AISI #, group #, or material ? titanium % of all materials ? 30
```

This signifies that the shop would contain 30% titanium. GREASE would generate the following schema:

#### 5.2.1.3 Process Specification

A machining process corresponds to a couple (operation, material). A process specified by the user is represented by an instance of the PROCESS-SPEC schema:

{{ PROCESS-SPEC **INVOLVES-MATERIAL:** INVOLVES-OPERATION: **OPERATION-PERCENTAGE: IMPORTANCE: 1 PROCESS-PERCENTAGE:** TABLE-POSITION: NAME: **HIGH-SPEED:** EXTRA-DEEP-CUT: **HIGH\* FEED-RATE:** CARBIDE-TOOLS: THIN-WALL-SECTIONS: EXCESSIVE-TOOL-WEAR: LONG-CHIPS: **DISCOLORED-TOOLEDGES: HOT-WORK-PIECES:** SMOKE: COOLING-DIAG: SOFT-DRAGGY-METAL: LUBRICITY-DIAG: CHIP-WELDING: LARGE BUILT-UP-EDGE: TOOL-SEIZURE: ANTIWELD-DIAG: POOR-FINISH: RUST: CORROSION:}}

This schema is characterized by the three slots INVOLVES-MATERIAL, INVOLVES-OPERATION and OPERATION-PERCENTAGE. Each instance points to an instance of the OPERATION-SPEC schema and an instance of the MATERIAL-SPEC schema, by means of the inherited slots INVOLVES-OPERATION and INVOLVES-MATERIAL, respectively. The slot OPERATION-PERCENTAGE records the proportion of the specified operation among all the operations performed on the corresponding material. The slot IMPORTANCE holds a number representing the importance of meiintaining the tool-life corresponding

percentage of the specified process relative to all machining processes in the shop. This processpercentage is internally computed as follows:

#### *Process percentage* = $op \times mat$

where *op* represents the value of the slot OPERATION-PERCENTAGE, and *mat* is the value of the slot MATERIAL-PERCENTAGE of the corresponding instance of the MATERIAL-SPEC schema. TABLE-POSITION holds a pointer to a table entry of the empirical selection causal network that represents the process (Sec 5.1.5). NAME holds a string corresponding to the name of the process.

The slots HIGH-SPEED, EXTRA-DEEP-CUT, HIGH-FEED-RATE, CARBIDE-TOOLS and THIN-WALL-SECTIONS contain the operation characteristics of the process.

In a similar fashion, the slots EXCESSIVE-TOOL-WEAR, LONG-CHIPS, DISCOLORED-TOOL-EDGES, HOT-WORK-PIECES, SMOKE, SOFT-DRAGGY-METAL, CHIP-WELDING, LARGE-BUILT-UP-EDGE, TOOL-SEIZURE, POOR-FINISH, RUST and CORROSION record the various diagnostics related to the process. The slots COOLING-DIAG, LUBRICITY-DIAG and ANTIWELD-DIAG contain the results of diagnostic analysis of symptoms that indicate imbalances in cutting-fluid cooling, lubricity, and antiweld.

An example of a process specification is as follows:

```
Material ? titan
Operation ? ?
Possible responses:
AUTOMATICS-MULTIPLE-SPINDLE
TAPPING
Operation ? auto
% of this material ? 100
Importance of maintaining tool-life [1-10] 1?
High speed (y/n) ?
Extra deep cut (y/n) ?
High feed rate (y/n) ?
Carbide tools (y/n) ?
Thin wall sections (y/n) ?
Excessive tool wear (y/n) ? y
Long Chips (y/n) ?
Discolored tool edges (y/n) ?
Hot work pieces (y/n) ?
Smoke (y/n) ?
Chip welding (y/n) ?
Large built-up edge (y/n) ?
Tool seizure (y/n) ?
Poor or sub-standard finish (y/n) ?
Rust (y/n) ?
Corrosion (y/n) ?
```

This process indicates the machining of 100% of the titanium by a multiple spindle automatic machine, and observing excessive tool wear. GREASE would generate the following schema process representation:

{{T36

INSTANCE: PROCESS-SPEC **INVOLVES-MATERIAL: T34** INVOLVES-OPERATION: T33 **OPERATION-PERCENTAGE: 100 IMPORTANCE: 1** PROCESS-PERCENTAGE: 30.0 **TABLE-POSITION: TBL57B** NAME: (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) **HIGH-SPEED: NIL** EXTRA-DEEP-CUT:NIL **HIGH-FEED-RATE:NIL** CARBIDE-TOOLS: NIL THIN-WALL-SECTIONS: NIL EXCESSIVE-TOOL-WEAR:T LONG-CHIPS: NIL DISCOLORED-TOOL-EDGES: NIL HOT-WORK-PIECES: NIL SMOKE: NIL COOLING-DIAG: NIL SOFT-DRAGGY-METAL: NIL LUBRICITY-DIAG:NIL CHIP-WELDING: NIL LARGE-BUILT-UP-EDGE: NIL TOOL-SEIZURE: NIL ANTIWELD-DIAG:NIL POOR-FINISH: NIL RUST: NIL CORROSION: NIL}}

Figure 5-16 is an example that illustrates how the shop definition specifications just introduced combine with each other to create a network description of the shop.

In this example, two operations - reaming and drilling - have been specified by the customer, Two instances of the OPERATION-SPEC schema - op-sped and op-spec2 - have been dynamically generated and linked to the corresponding elements of the operations taxonomy - the schemata **REAMING** and **DRILLING** - by the means of their OPERATION-IS-A slot.

In a similar fashion, two instances of the MATERIAL-SPEC schema have been created to represent the two materials specified by the user, mat-sped represents a material (or a set of materials) corresponding to a group3 machinability. Since the material is not explicitly specified by its aisi name, the schema mat-sped is created as an instance of the ANONYMOUS-MATERIAL-SPEC schema. mat-spec2 refers to a b-1111 steel and therefore corresponds to an instance of the **AISI-MATERIAL-SPEC** schema, mat-sped and mat-spec2 are related to their corresponding elements of the materials taxonomy - the schemata B-1111 and GROUP3 - by their MATERIAL-IS-A slot.



Figure 5-16: Example of Shop Network

Proc-spec1 and proc-spec2 represent two machining processes specified by the customer. prospec1 corresponds to a reaming on a group3 material, while proc-spec2 represents a drilling on b-1111 steel. They have been dynamically generated as instances of the PROCESS-SPEC schem. Their slots INVOLVES-MATERIAL and INVOLVES-OPERATION point to the corresponding instances of the MATERIAL-SPEC and OPERATION-SPEC schemata.

### 5.2.1.4 Current Fluid Specification

The current fluid specification identifies the currently used cutting-fluid in the shop. The current fluid specification is necessary if diagnostic information is to be used for the shop. The current flu chemistry allows GREASE to determine what cutting-fluid property levels resulted in the specific diagnostics, and what final property levels will be necessary to treat the diagnostics. The current flu is also used to assist GREASE in determining levels of cutting-fluid properties to maximize tool-life minimum cost.

The CURRENT-FLUID schema contains the current fluid chemistry and properties:

INSTANCE: NAME: TYPE: DILUTION-RATIO: EMULSIFIER-PERCENTAGE: KINEMATIC-VISCOSITY: TOTAL-SULFUR-PERCENTAGE: ACTIVE-SULFUR-PERCENTAGE: CHLORINE-PERCENTAGE: FATTY-OIL-PERCENTAGE: COOLING: LUBRICITY: ANTIWELD: ACTIVITY:}}

The chemical composition of the fluid is characterized by the slots: KINEMATIC-VISCOSITY, TOTAL-SULFUR-PERCENTAGE, ACTIVE-SULFUR-PERCENTAGE, CHLORINE-PERCENTAGE, FATTY-OIL-PERCENTAGE. The slot TYPE holds the type of the fluid, *oil* or *soluble*. In case of a waterbased fluid, the slot DILUTION-RATIO will be set to the corresponding value.

The NAME slot contains the name of the user-specified current fluid. If the current fluid is in the product line, the schema CURRENT-FLUID is specified to be an instance of that corresponding product in the cutting-fluid taxonomy. The chemical properties of the current fluid are then inherited via the INSTANCE link. If the name refers to a soluble oil, a dilution ratio is prompted for.

If the current fluid is not in the product line, the user is prompted for the entire chemical composition. The cooling, lubricity, antiweld, and activity levels of the cutting-fluid are then internally computed according to the values of the chemical composition slots.<sup>20</sup> These properties are then stored in the COOLING, LUBRICITY, ANTIWELD and ACTIVITY slots.<sup>21</sup>

An example of a current fluid specification follows:

Current cutting fluid name ? 31b

The specified fluid '31B' is in the product line. GREASE will represent this specification in the CURRENT-FLUID schema as an instance of '31B':

<sup>&</sup>lt;sup>20</sup>The empirical formulas correlating cutting-fluid properties with chemical composition are proprietary, and not described here.

<sup>&</sup>lt;sup>21</sup>GREASE cannot calculate the cutting-fluid properties of 'chemical synthetic fluids' since the effect of different chemical species in these fluids relative to the cutting-fluid properties is unknown. GREASE will reject these fluids as invalid current fluids.

{{CURRENT-FLUID INSTANCE: 31B NAME: 31B TYPE: OIL DILUTION-RATIO: EMULSIFIER-PF.RCENTAGE: KINEMATIC-VISCOSITY: TOTAL-SULFUR-PERCENTAGE: ACTIVE-SULFUR-PERCENTAGE: CHLORINE-PERCENTAGE: FATTY-OIL-PERCENTAGE: COOLING: LUBRICITY: ANTIWELD: ACTIVITY:}}

# 5.2.1.5 Additional Requirements Specification

The schema REQUIREMENTS records specific user requirements for the shop as a whole:

{{ REQUIREMENTS ECOLOGICAL-SAFETY: STRAIGHT-OILS-ONLY: SOLUBLES-ONLY: NO-CHEM-SYNTH:}}

The interpretation of these slots follows:

- ECOLOGICAL-SAFETY disposal of fluid will oe ecologically safe;
- STRAIGHT-OILS-ONLY don't recommend solubles
- SOLUBLES-ONLY only specify soluble fluids;
- NO-CHEM-SYNTH don't recommend chemical synthetic fluids.

An example of specification of additional requirements to GREASE follows. A 'yes' specification to any question will result in T' being assigned to the corresponding slot value:

```
ecological safety required (y/n)?
Recommend only straight oils (y/n)?
Recommend only soluble oils (y/n)?
Can synthetics be recommended (y/n)?
```

GREASE performs special treatment of processes where the specified operation is 'deep-hole drilling' or 'gun-drilling'. These processes have viscosity requirements which are a function of the material type, and the bore diameter of the drill. GREASE represents this correspondence in the HOLE schema. During the process specification, GREASE solicits the bore diameter, then sets the KINEMATIC-VISCOSITY slot of the 'ideal' fluid associated with the process.

#### 5.2.2 Diagnosis

Diagnostics encountered with the current-fluid are recorded by the various symptom slots corresponding to the instances of the PROCESS-SPEC schema.

The function 'diagnose' scans all the PROCESS-SPEC's. For each one of them, the function 'interpret-symptoms' looks for active symptoms, and interprets them in terms of cooling, lubricity, antiweld, or viscosity problems as specified in the ACTIVATES slot of each symptom.

An example of a GREASE diagnosis for the previous example of the process where titanium was machined with a multiple spindle automatic and resulted in excessive tool wear follows:

```
**** Interpretation of Diagnostics ****
In Process : (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
Excessive tool wear
==> Cooling Problem.
Excessive tool wear
==> Lubricity Problem.
Excessive tool wear
==> Antiweld Problem.
```

1.

#### 5.2.3 Goal Generation

As previously described, goals are generated to satisfy the requirements of a particular machining process, such as treating diagnostics, satisfying operator preferences, and correcting for exceptional machining conditions. Goal generation within GREASE is performed by the function 'setgoals'.

The function 'analyze-constraints' posts 'fixed goals' resulting from operation and material constraints, user preferences, and those process diagnostic symptoms which result in 'fixed goals'.

The function 'analyze-processes' generates 'change goals' for each fundamental cutting-fluid property (i.e., cooling, lubricity, antiweld, viscosity) for each process identified in the 'shop-definition' phase. These goals are primed with fundamental property values corresponding to the 'ideal fluid' for the machine process.

The function 'set-degree' posts the 'change goals' for identified symptoms including process

characteristics (i.e., 'high-speed', 'deep-cut', etc.) and process diagnostics (i.e., 'built-up-edge', 'poor-finish', etc.).

Goals resulting from process characteristics such as 'high-speed' and 'deep-cut' are 'additive' requiring a goal associated with a machine process to sum the contributions from all identified process characteristic symptoms for the affected property. The sum is then added to a 'reference point' for the property to create an absolute 'optimal' value, which if met, will satisfy the symptoms. The 'reference point' is derived from either a 'current fluid' identified in the shop definition phase, or the 'ideal fluid' indicated in the 'empirical selection causal network'.

Goals from process diagnostics, are 'maximizing', where the affected property value is the maximum value for any identified diagnostic. Process diagnostic generated goals are only posted if a 'current fluid' is indicated that serves as a reference for which the goals can improve upon.

Goal generation attempts to optimize the cutting-fluid recommendation wherever possible (Figure 5-17). It does this by using the property values of the 'ideal fluid' in its reference point selection, rather than the 'current fluid' values which may be an *improperly recommended fluid*. If diagnostics are posted, GREASE uses the 'current-fluid' as a reference point upon which to maximize the diagnostic goals, but then compares the result with the corresponding 'ideal fluid' property, adjusted by process characteristic goals, and selects the maximum value to better correct the diagnostic conditions.<sup>22</sup>

An example of the goals that would be generated from the previous example of machining titanium with a multiple spindle automatic that results in excessive tool wear is as follows:

	**** Activation of Goals ****
No goals	OPERATIONS CHARACTERISTICS ====================================
======================================	MATERIALS CHARACTERISTICS =========
satisfying	goal> NO-CHLORINE
No goals	USER PREFERENCES ====================================
No goals	FIXED PROCESS DIAGNOSTICS ========= posted
No goals	PROCESS CHARACTERISTICS ====================================
	CHANGE PROCESS DIAGNOSTICS ========
In (AUTOMAT)	CS-MULTIPLE-SPINDLE TITANIUM) maximizes 31B LUBRICITY by 30.0
In (AUTOMAT)	CS-MULTIPLE-SPINDLE TITANIUM) maximizes 31B COOLING by 50.0
In (AUTOMAT) to 167.0	CS-MULTIPLE-SPINDLE TITANIUM) maximizes 31B ANTIWELD by -100.0

In this example, titanium generated a 'fixed-goal' of *no-chlorine*, and the excessive-tool-wear diagnostic generated maximized 'change goals' for cooling, lubricity, and antiweld. Since a current-fluid was specified '31B', the cooling, lubricity, antiweld, and visc property levels for the initial optimal fluid for the process were primed with the corresponding '31B' fluid values.

The 'change-goals' that were generated for this example are illustrated as in Figure 5-18. Schemata 'goal1, goal2, goal3, goal4' specify in the DEGREE slot, the optimal property values for lubricity, cooling, and visc for the designated process.

#### 5.2.4 Candidate Fluids Generation

The candidate fluids correspond to the search space used by GREASE from which a recommendation is determined.

The candidate fluids are selected from the cutting-fluid product line. Six dilution ratios for each soluble fluid have been determined along with the property values corresponding to these dilutions. Each dilution ratio determines a separate product. If a current fluid had been specified, it is included to allow it to be rated relative to the product line.




Selection in GREASE is performed by a process known as fluid evaluation. Fluid evaluation attempts to optimize the value of the highest-level cutting-fluid property for a machine shop *tool-life.*<sup>23</sup> Optimal tool-life will result in minimal tool replacement costs, and optimized production.<sup>24</sup>

Fluid evaluation is accomplished by comparing the cutting-fluid properties of each candidate fluid with the 'optimal' fluid for each specified machining process. An 'optimal' fluid is defined as one containing *ideal* property values to satisfy a specified machining process as determined by posting 'goals' against the 'ideal' fluid for a process (Sec 5.2.3). The relative approximation of a candidate fluid to each 'optimal fluid', as determined by utility functions, generates the overall rating of how well that fluid will perform.

The evaluation of a cutting-fluid in terms of its properties is distinct for each cutting-fluid property level (Figure 5-19 sec. 5.1.3).<sup>25</sup>

#### 5.2.5.1 Evaluation of Low Level Properties Relative to a Process

Low level properties are properties whose values do not depend upon the values of any other properties. They are generally measured chemical properties such as the percentage of active sulfur, or physical properties such as viscosity. The values of these properties are not calculated by GREASE. In the case of GULF products, these values are already known and stored in the GREASE knowledge base. In the case of non-GULF products, the values of these properties are prompted for. (e.g., Current Fluid Specification)

#### 5.2.5.2 Evaluation of Middle Level Properties Relative to a Process

Middle level properties are properties whose values depend upon the values of other properties, and which have other properties whose values depend upon them. An example of such a property is lubricity. Its value depends upon the values of fatty content and viscosity; in turn, the values of tool life and finish depend upon the value of lubricity.

For efficiency, since the values of the middle-properties are functions of the chemistry of the cutting-fluids, which very seldom change, they are pre-calculated and stored in the knowledge base. In the case of non-GULF products which haven't previously been encountered, the values of these properties are calculated from the values of the lower level properties during the current fluid specification.

<sup>23</sup> 

The property *finish* is also a highest-level cutting fluid property. In the cutting-fluid industry, however, optimal tool-life is of paramount importance, as long as finish is adequate. Consequently, optimal finish isn't attempted by lhe system. Inadequate finish is corrected for by a 'poor finish' diagnostic.

<sup>24</sup> 

Strictly speaking, of course, the customer wants to reduce overall costs, not only tool replacement costs, as much as possible. In order to estimate overall costs, however, it would be necessary to know the price of the cutting fluid. Since the price of a cutting fluid is a matter of negotiation between the salesman and the customer, this information is not known ahead of time. Therefore, we settle for giving information about the estimated costs of tool replacement, and leave it up to the salesman and customer to take into account the prices of the cutting fluids.

 $<sup>^{25}</sup>$ The specific cutting-fluid properties at the deepest level haven't been specified here for proprietary reasons.



(CHEMICAL AND PHYSICAL COMPOSITIONAL PROPERTIES OF CUTTING-FLUTDS) (e.g. fatty-oil content, sulfur content, etc.)

Figure 5-19: The 'Varies-With<sup>1</sup> Hierarchy of Cutting Fluids

5.2.5.3 Evaluation of High-level Properties Relative to a Process

The single high-level property of cutting-fluids to be evaluated is tool-life. It is measured on an arbitrary scale in which 1 is the worst value and 10 is the best value.

The tool-life of a cutting fluid is evaluated on the basis of how closely it matches a theoretical 'optimal' fluid for a process in terms of properties. The contribution of a particular property to the tool life value of a fluid depends upon two factors:

- « *rating* measuring how closely the value of the property matches the 'optimal' value of that property,
- *coefficient* measuring how important that property is in determining the tool life known as the 'sensitivity' (Sec 5.1.5.1).

The contribution of each property to the value of tool life is the product of the two factors listed above. The total tool life value is simply the sum of the contributions from each individual property.

To write the value of the tool life as an equation, let 'rating(property)' represent how closely the actual value of that property matches the 'optimal' value of the property. Then the equation for tool life is represented:

The determination of the rating and importance of a given property that tool-life depends upon will now be explained and illustrated with specific examples:

#### IMPORTANCE - 'sensitivity coefficient':

۰,

Tool-life is evaluated with respect to a given process since the sensitivity coefficients are process dependent. For example, the tool life value of a given fluid depends upon how well the lubricity of the fluid matches the ideal lubricity value for that process. But how important it is for a fluid to match the ideal lubricity value is dependent upon what process the fluid is being applied to. In *easy to machine* metals, the lubricity value of a fluid is relatively unimportant; this is reflected in a low lubricity sensitivity coefficient (a low value of *a* in (5.1)). In *difficult to machine* metals the lubricity value of a fluid is nore important; this is reflected in a high value of the lubricity sensitivity coefficient (a high value of *a* in (5.1)).

Since the sensitivity coefficients are process dependent, their values are stored in the in the empirical selection causal network which represents all possible processes that GREASE knows about. The empirical selection causal network schemata have a TOOL-LIFE slot. Attached to this slot is a meta-slot containing sensitivity coefficient facets for the middle-level properties upon which tool life depends, namely, COOLING, ANTIWELD, VISC, and LUBRICITY. The sensitivity coefficient of viscosity in the equation for tool life is stored in the VISC slot, etc.

To illustrate these concepts, examine the process in Figure 5-18. The TABLE-POSITION slot indicates the schema TBL57B within the empirical selection causal network. Figure 5-20 illustrates the schema TBL57B. The tool-life meta-slot has a lubricity facet with a value of 0.77 representing the lubricity sensitivity coefficient for PROCESS-SPEC2.

#### **RATING:**

In order to see how the rating of a property is calculated, consider how the optimal fluid is represented. A diagram of how an optimal fluid is represented was presented in 5-18. A goal schema is attached to each property that tool life "varies with". For example, GOAL1 is the 'optimal' goal for LUBRICITY in process PROCESS-SPEC2. Each goal schema serves two major functions:

- It contains the 'optimal' value that the attached property should have in order to maximize tool life for the process; (DEGREE slot)
- It specifies a function (GOAL-FUNC slot) which, when given an actual value of the property as input, returns a rating on a scale of 0 to 1 indicating how closely the actual value matches the desired value. (sec. 5.1., 5.2 utility functions)

For example, consider again LUBRICITY in Figure 5-18. The 'optimal' value of 'lubricity' to maximize tool life is stored in the DEGREE slot of GOAL1 - (i.e., 64). The utility function which measures how well an actual value of lubricity matches the optimal value is stored in the GOAL-FUNC slot of GOAL1 - (i.e., MAINTAIN-HIGH).





With this introduction, the steps the fluid evaluator performs in calculating the lubricity rating of a given cutting-fluid (e.g., '31B') relative to a given process (e.g., PROCESS-SPEC2) areas follows:

- It finds the tool life goal attached to the LUBRICITY schema. In this case, the tool life goal is represented by the GOAL1 schema;
- It extracts the 'optimal' value of lubricity residing in the DEGREE slot of the GOAL1 schema (i.e., 64);
- It extracts the value of the LUBRICITY slot of the cutting fluid in question 31B (i.e., 34) (Figure 5-21), and gives this as an argument to the rating function residing in the GOAL-FUNC slot of the GOAL1 schema (i.e. MAINTAIN-HIGH) along with the 'optimal<sup>1</sup> lubricity value;



fluid 31B approximated the desired 'optimal' value for the process - PROCESS-SPEC2. This value is then multiplied by the sensitivity coefficient for lubricity whose determination was explained earlier, to give the overall contribution of lubricity to tool-life for the process PROCESS-SPEC2. The other properties: cooling, viscosity, and antiweld are determined similarly.

#### 5.2.6 Average Shop Rating Determination

The fluid evaluator evaluates each high level property relative to a given process. It then combines these individual values into one composite value. The calculation of the tool life value will be used as an example.

An estimate of how a given cutting fluid will affect the tool replacement costs of a given job shop depends upon three factors:

- how the fluid affects the life of each individual tool (tool-life);26
- the percentage of jobs in the shop that are performed with that tool (process pct);<sup>27</sup>a
- how much that tool costs (or the tool life importance importance).28

The equation combining these quantities into an overall rating of the fluid is:

Shop Rating = 
$$\frac{\sum_{i=1}^{n} process pct_i \times tool \ life_i \times importance_i}{\sum_{i=1}^{n} importance_i}$$

The equation gives an average rating for the fluid, weighing the fluid's performance for n processes in the shop.

#### 5.2.7 Results and Explanation

GREASE displays its calculations and provides explanation at each processing stage.<sup>29</sup> A summary of the information provided at each stage follows:

SHOP DEFINITION

Each item in the shop definition, such as the process specification, displays a verification and summary of the entered shop data. A 'summary' option on the command menu also provides a shop summary at any stage of GREASE operation.

<sup>&</sup>lt;sup>26</sup>The calculation of how the fluid affects the life of a tool was explained in the previous section.

<sup>&</sup>lt;sup>27</sup>The percentage of jobs in the shop performed by a given tool is a simple calculation based upon the shop representation.

<sup>&</sup>lt;sup>28</sup>How much a given tool costs cannot be calculated by GREASE. However, the customer is prompted for an estimate of the relative cost of a tool on a scale from 1 to 10. The default is 1.

<sup>&</sup>lt;sup>29</sup>The GREASE example presented in Appendix III serves to illustrate all calculations and reports provided by GREASE

#### • DIAGNOSIS

This stage provides a diagnostic causal display of symptoms that correspond to upsets in the fundamental cutting-fluid properties of cooling, lubricity, antiweld, and viscosity.

#### GOAL GENERATION

An explanation is provided of the goals that are posted to satisfy all symptoms, operation and material constraints, and diagnostics. This stage explains the development of the 'optimal' fluid properties associated with each machining process.

#### • FLUID EVALUATION

As each candidate fluid is evaluated, it is first identified, and the high level property rating (i.e. tool-life) for the fluid relative to the 'optimal' fluid is displayed for each machining process in the shop. If a fluid is rejected from consideration due to failing a 'fixed' goal, an explanation is provided on which goal the fluid had failed.

#### • FLUID SHOP RATINGS AND RESULTS

At the conclusion of the fluid evaluation, the fluids are displayed ranked according to decreasing overall shop rating. The components of the rating in terms of fundamental cutting fluid property values are also displayed. An option to provide a more detailed explanation for a particular fluid in terms of its rating for each machining process is also available from the command menu.

# 6. Conclusion

Many decision problems are composed of two parts: diagnosis and treatment. Much of the work in expert systems have focused on the use of heuristic selection to perform diagnosis. The treatment of the diagnosed problem is either canned (Fox et al., 1983) or takes a divide and conquer approach assuming independence among solutions (Shortliffe, 1976). In GREASE, the specification of a treatment, i.e., selection of a cutting fluid, was further complicated by the need to use a single fluid for many different operations.

The approach taken in GREASE differed from heuristic selection due to the lack of causal relations between the diagnosis and the appropriate fluid. Instead, deep knowledge was used to construct a theoretical optimum for each machining operation. This "starting point" was then heuristically modified based on the diagnosis. The "heuristic optimum" was then used as an evaluation function to rate the fluids in the product line. Consequently, the treatment process can be viewed as the heuristic determination of an evaluation function to be used during the search for a fluid. Whether the search process is selective or synthetic, the same evaluation may be used.

# I. Knowledge Refinement within GREASE

Knowledge refinement within GREASE was an iterative procedure of analysis of GREASE recommendations by a cutting-fluid expert, followed by possible knowledge adjustment until GREASE produced acceptable results. Examples were carefully selected to verify the entire range of GREASE's applicability. These examples fell into three groups that were treated successively:

- Single 'Ideal' processes that GREASE has knowledge of
- Single processes containing symptoms and atypical operating conditions;
- Multiple shop processes

# I.1 Ideal Processes

The empirical selection causal network (sec. 5.1.5) contains machining processes for all materials and operation types that GREASE has knowledge about. Each of these processes specifies an 'ideal' cutting-fluid to satisfy the process, and 'sensitivities' for each cutting-fluid property of the fluid. The property values of the 'ideal' fluids, and the sensitivity of each property have been specified by a cutting-fluid expert and represents a wealth of knowledge obtained from years of experience. Knowledge refinement of the 'ideal' processes amounts to adjusting the 'ideal' fluid property values, adjustment of the 'sensitivities' of the cutting-fluid properties, as well as the 'increments' that affect the utility rating functions to result in appropriate product line selections for each process.<sup>30</sup>

The utility function shapes (sec. 5.1, 5.2) have been demonstrated to result in relative fluid ratings acceptable to the experts following adjustment of the curve width of the functions. The curve width is calculated as a factor times the 'typical change' increment.<sup>31</sup>

Knowledge refinement involved verifying the selections for the range of materials and operations that GREASE can recommend --> 40 ferrous processes, and 60 non-ferrous processes.

# I.2 Symptoms

Following knowledge refinement of the 'ideal' processes, adjustments of recommendations for 'atypical' processes followed. An 'atypical' process is one which has imbalance from the 'ideal' due to either special operation conditions, such as 'high speed', etc., or observed diagnostics such as 'built-up-edge'. Knowledge refinement for symptoms includes adjustment of the 'treatment' that GREASE applies to resolve the symptoms by altering the 'optimal' fluid specification for the specified

<sup>&</sup>lt;sup>30</sup>The adjustment procedure was to assume that the initial sensitivity values provided by the expert were reasonable, and to adjust the cutting-fluid property values. If satisfactory results could not be obtained, the sensitivity values would then be adjusted if GREASE was placing either too much or too little importance to a specific property. If GREASE would rate highly either too few or too many similar fluids based upon some property, then the 'typical change' increment affecting the utility function width would be adjusted.

'typical change\* increments for modification of the cutting-fluid properties of cooling, lubricity, antiweld, and viscosity.

The knowledge refinement procedure was to adjust the 'typical change' increments for a single 'process characteristic' for all processes. The additivity of 'process characteristics' such as 'deepcut<sup>1</sup> or 'high-speed' was then checked by specifying two characteristics. More than two characteristics is unlikely in a real situation.<sup>32</sup> The diagnostic 'excessive-tool-wear' was checked independently for several processes since this diagnostic can be the result of imbalances in cooling, lubricity, or antiweld. Other diagnostics were tested simultaneously for several processes since their affect is maximizing rather than additive.

# 1.3 Muiiiple Processes

After GREASE had been tuned for single process recommendations, GREASE had been checked for multiple processes. This corresponds to insuring that GREASE can properly recommend a single fluid for a shop containing several distinct machining processes. The tool-life importance factor and the process percentages are primary in developing the overall shop rating which combines the ratings from individual processes.

In verifying correct treatment for multiple processes, *two process* combinations were generated where either the material specification or the operation specification was varied. Process combinations reasonable to be encountered in the field were selected, as well as extreme combinations designed to test the effectiveness of GREASE.<sup>33</sup>

33

32

Some limited testing of processes with more than two characteristics indicated a greater amount of error in GREASE'S recommendations, due to either errors in the 'typical change' increments, or an error in the *additivity* assumption, or both.

Due to the large number of process combinations possible, a sampling was necessary.

# II. GREASE Recommendation Example

The following example of a GREASE recommendation demonstrates its operation in terms of the input/output interface, sections of the internal representation, and analyzes the selection results in terms of the specified shop. The example presents a cutting-fluid recommendation for a shop comprising two operations, three materials, and three shop processes, and a current fluid as follows:

- Operations
  - multiple spindle automatics
  - tapping
- Materials
  - (50% of shop) '1111' free machining steel
  - (20% of shop) group3 machinable steel
  - (30% of shop) titanium
- Processes
  - Tapping a group3 steel observing discolored tool edges, poor finish, and a large built-up edge on the tool;
  - Machining titanium on a multiple-spindle automatic, and observing excessive tool wear;
  - Machining '1111' steel on a multiple-spindle automatic at high speed.
- Current fluid is Gulfcut-31B

In discussing the example, comments are specified in italics, and terminal screens are delineated by horizontal bars.

#### **II.1 USER INTERFACE & COMMAND MENU:**

Following initialization of GREASE, the command menu is presented as follows:

	<<<<< GREASE cutting-fluid system »>> »	
?	Print this command menu	
I	Shop data initialization	
0	Machine operation specification	
М	Material machined specification	
Р	Process <operation-material> specification</operation-material>	
A	Additional Requirements	
R	Recommend a cutting-fluid selection	
С	<ul> <li>Current-fluid specification</li> </ul>	
S	Summary of shop data input specification	
Т	Report type specification	
W	Why? Detailed fluid recommendation data	
E	Exit	
		~ *

COMMAND?o

All commands to GREASE are specified as single letters. Upon completion of each command, the system will solicit and execute a new command. No pre-defined sequence of commands is enforced by the system, except for the requirement that a shop must be specified prior to performing a recommendation, and a recommendation performed prior to printing a report. In the example above, specification of the command 'o' indicates that an operation will be specified next. This triggers a prompt for the specification of the machine operation. If the allowable responses are unknown, specification of either'?' or 'help' will cause GREASE to print the legal responses. This 'help' feature is present for most shop definition questions.

# **II.2 OPERATION SPECIFICATION:**

The operation specification triggered by the 'o' command solicits the operation type and its characteristics.

Machine operation (if not in system, closest type) ? automatics-mult Brass, bronze or copper in machinery (y/n) ? n

The specified operation is a 'multiple spindle automatic' machine. Also, there is no coppercontaining materials in the machine which would be affected by 'active-sulfur' in the cutting-fluids.

```
Machine Operation Type : AUTOMATICS-MULTIPLE-SPINDLE
Brass, bronze, or copper in machinery : NO
```

COMMAND?©

Following specification of the operation information, a verification screen is printed signifying the internalized responses that GREASE will use. GREASE prints verification screens for all shop definition commands.

The next operation specification indicates 'tapping', which was abbreviated on input. GREASE will generally allow unique abbreviations to be used for the shop specification screens.

Machine operation (if not in system, closest type) ? ta Brass, bronze or copper in machinery (y/n) ? n

Machine Operation Type : TAPPING Brass, bronze, or copper in machinery : NO

COMMAND?m

#### **II.3 MATERIAL SPECIFICATION:**

The command 'm' designates a material specification which may be any specific material known to GREASE or machinability group that the material belongs. The following screens represent the material specification for the example. In these, a material percentage relative to all materials in the shop for a single cutting fluid must be specified. GREASE will not allow greater than 100% for all materials in the shop.

AISI #, group #, or material ? 1111 % of all materials ? 50

AISI #, group #, or material: B-1111 Material % : 50

COMMAND?m

AISI #, group #, or material ? titanium % of all materials ? 30

AISI #, group #, or material: TITANIUM Material % : 30

COMMAND?m

AISI #, group #, or material ? group3 % of all materials ? 30 GROUP3 can't exceed: 20.0% % of all materials ? 20

AISI #, group #, or material: GROUP3 Material % : 20

COMMAND?p

#### **II.4 PROCESS SPECIFICATION:**

Specification of shop processes, which are operations performed on specific materials, is triggered by command 'p'. Specification of atypical operating conditions and symptoms are somewhat subjective, since measurement scales are either unavailable or not used. If an operating condition or symptom is significant, it will generally be observed, and should be specified to GREASE to allow adjustment of its recommendations. The following screens define the processes for the example:

```
Material ? ?
Possible responses:
B-1111
GROUP3
TITANIUM
Material ? 1111
Operation ? auto
% of this material ? 100
Importance of maintaining tool-life [1-10] 1?
High speed (y/n) ? y
Extra deep cut (y/n) ?
High feed rate (y/n) ?
Carbide tools (y/n) ?
Thin wall sections (y/n) ?
Excessive tool wear (y/n) ?
Long Chips (y/n) ?
Discolored tool edges (y/n) ?
Hot work pieces (y/n) ?
Smoke (y/n) ?
Chip welding (y/n)?
Large built-up edge (y/n) ?
Tool seizure (y/n) ?
Poor or sub-standard finish (y/n) ?
Rust (y/n) ?
Corrosion (y/n) ?
```

GREASE next presents a verification screen for the entered process. Only symptoms that were indicated as present are signified.

```
Process Specification Summary:
(AUTOMATICS-MULTIPLE-SPINDLE B-1111)
material %: 100
process %:
            50.0
tool-life-importance: 1.0
HIGH-SPEED
Material ? titan
Operation ? ?
Possible responses:
AUTOMATICS-MULTIPLE-SPINDLE
TAPPING
Operation ? auto
% of this material ? 100
Importance of maintaining tool-life [1-10] 1?
High speed (y/n) ?
Extra deep cut (y/n) ?
High feed rate (y/n) ?
Carbide tools (y/n) ?
Thin wall sections (y/n) ?
Excessive tool wear (y/n) ? y
Long Chips (y/n) ?
Discolored tool edges (y/n) ?
Hot work pieces (y/n) ?
Smoke (y/n) ?
Chip welding (y/n) ?
Large built-up edge (y/n) ?
Tool seizure (y/n) ?
Poor or sub-standard finish (y/n) ?
Rust (y/n) ?
Corrosion (y/n) ?
```

Process Specification Summary:

(AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) material %: 100 process %: 30.0 tool-life-importance: 1.0 EXCESSIVE-TOOL-WEAR

COMMAND?p

COMMAND?p

```
Material ? tap
Invalid material...
Material ? ?
Possible responses:
B-1111
GROUP3
TITANIUM
Material ? group3
Operation ? tap
% of this material ? 100
Importance of maintaining tool-life [1-10] 1?
High speed (y/n) ?
Extra deep cut (y/n) ?
High feed rate (y/n) ?
Carbide tools (y/n) ?
Thin wall sections (y/n) ?
Excessive tool wear (y/n) ?
Long Chips (y/n) ?
Discolored tool edges (y/n) ? y
Hot work pieces (y/n) ?
Smoke (y/n) ?
Chip welding (y/n) ?
Large built-up edge (y/n) ? y
Tool seizure (y/n) ?
Poor or sub-standard finish (y/n) ? y
Rust (v/n) ?
Corrosion (y/n) ?
```

```
Process Specification Summary:
(TAPPING GROUP3)
material %: 100
process %: 20.0
tool-life-importance: 1.0
DISCOLORED-TOOL-EDGES
LARGE-BUILT-UP-EDGE
POOR-FINISH
```

COMMAND?c

# 11.5 CURRENT FLUID SPECIFICATION

Specification of the command 'c' signifies a specification of the current fluid. GREASE will accept an oil-based or soluble fluid, but not a chemical synthetic fluid for which GREASE has no cutting-fluid property correlations with chemical composition. GREASE will allow specification of a fluid in the product line, or a customer's fluid if its composition and physical properties are known. In the first example, a product line fluid was specified.

Current cutting fluid name ? 31b

Product Name : 31B

COMMANDTs

In the next example, a fluid not in the existing product line was specified.

```
Current cutting fluid name ? Rapidcut
Unknown product. Please specify chemistry...
Is this fluid a synthetic oil (y/n) ? n
Type (oil or soluble) ? oil
Kinematic viscosity (Cst ) ? 10.25
Total sulfur % ? 3.4
Active sulfur % ? 1.2
Chlorine % ? 1.0
Fatty oil % 5.6
```

Product Name : Rapidcut Type : OIL Kinematic Viscosity : 10.25 Total Sulfur Percentage : 3.4 Active Sulfur Percentage : 1.2 Chlorine Percentage : 1.0

# 11.6 ADDITIONAL REQUIREMENTS:

Additional requirements to the GREASE selection may be specified by command 'a'. These include restricting GREASE recommendations to either 'soluble-only' or 'oil-only' cutting fluids, specifying whether a chemical fluid may be specified, or whether only ecologically safe fluids must be recommended. Currently within GREASE, only soluble fluids can be rendered ecologically safe.

```
ecological safetyp required (y/n)?
Recommend only straight oils (y/n)?
Recommend only soluble oils (y/n)?
Can synthetics be recommended (y/n)?
```

COMMANDIS

# 11.7 INPUT SHOP SUMMARY:

A summary of the shop specification is displayed with the 's' command as follows:

====== OPERATIONS ====== TAPPING AUTOMATICS-MULTIPLE-SPINDLE ====== MATERIALS ======= GROUP3 20% TITANIUM 30% B-1111 50% ===== PROCESSES ====== (TAPPING GROUP3) material %: 100 process %: 20.0 tool-life-importance: 1.0 DISCOLORED-TOOL-EDGES LARGE-BUILT-UP-EDGE POOR-FINISH (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) material %: 100 process %: 30.0 tool-life-importance: 1.0 EXCESSIVE-TOOL-WEAR (AUTOMATICS-MULTIPLE-SPINDLE B-1111) material %: 100 process %: 50.0 tool-life-importance: 1.0 HIGH-SPEED ====== CURRENT FLUID ====== 31B

COMMAND?r

A summary of the shop network representing this example created by GREASE is in figure II-1 the network, CRL schemata have been dynamically generated to represent the three materials, operations, and three processes in the shop. These schemata contain slot values signify properties specified in the shop definition. For example, the schemata 'proc-spec1' representir multiple-spindle automatic operation on '1111' steel, has a value of 'T' for the HIGH-SPEED slot.





### **II.8 CUTTING FLUID RECOMMENDATION - DIAGNOSIS:**

Following specification of the shop, a cutting fluid recommendation may be performed by comm 'r'. There are three successive stages to a recommendation: diagnosis, goal generation, and f evaluation. At the conclusion of each stage, command 'r' will trigger the next stage.

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Diagnosis in GREASE is relatively straightforward: a diagnostic symptom will generally indicate a specific upset in a cutting-fluid property. GREASE presents this diagnostic analysis for each shop process as follows:

```
**** Interpretation of Diagnostics ****
In Process : (TAPPING GROUP3)
Discolored tool edges
==> Cooling Problem.
Large built-up edge
Poor Finish
==> Antiweld Problem.
In Process : (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
Excessive tool wear
==> Cooling Problem.
Excessive tool wear
==> Lubricity Problem.
Excessive tool wear
==> Antiweld Problem.
```

<Type R>r

# II.9 CUTTING-FLUID RECOMMENDATION #-# GOAL ACTIVATION:

The next stage of recommendation generates cutting-fluid goals from diagnostic symptoms, atypical operating conditions, and operation and material constraints. Goals are used by GREASE to convert the 'ideal' fluids for each shop process to 'optimal' fluids that satisfy the posted goals. GREASE presents a summary of the goal types, and the goals which are posted in each category. In the example, a 'no-chlorine' FIXED goal is posted to satisfy the titanium material constraint. CHANGE goals for the atypical operating condition of 'high-speed' increases the affected property values, while diagnostics maximize their property values. Treatment of 'excessive tool wear' additionally checks the absolute antiweld level with the 'ideal' fluid value for the specified process, and reduces the value if exceeded. Process diagnostics are only posted if a 'current fluid' is specified in the shop definition.

\*\*\*\* Activation of Goals \*\*\*\* No goals posted ... TITANIUM satisfying goal> NO-CHLORINE \_\_\_\_\_\_\_ USER PREFERENCES =========== No goals posted ... No goals posted... HIGH-SPEED In (AUTOMATICS-MULTIPLE-SPINDLE B-1111) increases COOLING by 50.0 to 64 In (AUTOMATICS-MULTIPLE-SPINDLE B-1111) increases ANTIWELD by 100.0 to 170.0 ======== CHANGE PROCESS DIAGNOSTICS ========= POOR-FINISH In (TAPPING GROUPS) maximizes 31B ANTIWELD by 177.0 to 404.0 ANTIWELD-DIAG In (TAPPING GROUPS) maximizes 31B ANTIWELD by 177.0 to 404.0 COCLING-DIAG In (TAPPING GROUP3) maximizes 31B COOLING by 50.0 to 778.429993 EXCESSIVE-TOOL-WEAR In (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) maximizes 31B LUBRICITY by 30 to64.0 In (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) maximizes 31B COOLING by 50.0 to 838.799983 In (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) maximizes 31B ANTIWELD by -10 to 167.0

<Type R>

Goal activation within GREASE for this example may be depicted as in Figures 11-2, 11-3, and I 'change-goal' alterations to the cutting-fiuid properties. Figure 11-5 illustrates the 'fixed-goal' chlorine'. This goal is a variable goal, where the status slot of 'no-chlorine' specifies the max allowable chlorine percentage level.





Figure II-3: Goal Generation for TAPPING GROUP3 Process



Figure II-4: Goal Generation for AUTOMATICS-MULTIPLE-SPINDLE B-1111 Process



Figure II-5: Fixed-goal Representation

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#### II.10 CUTTING-FLUID RECOMMENDATION #-# FLUID EVALUATION

Following posting of goals and generation of the 'optimal' fluid for each process, fluid evaluation proceeds. Each fluid in the product line is rated against the 'optimal' fluid for each process, in terms of how well each cutting-fluid property matches. A numerical rating from 0.0 -> 10.0 designates an approximate production efficiency or relative machine-tool-life on a linear scale. Fluids are first checked if they pass the fixed-goal requirements prior to being rated. If a fluid fails a fixed goal, it is not rated, and the goal is displayed which failed.

```
TESTED-FLUID ===> TS-970[1-10]
  TOOL-LIFE : 5.09516 (TAPPING GROUP3)
  TOOL-LIFE : 7.761122 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 7.077853 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> TS-970[1-15]
  TOOL-LIFE : 4.685835 (TAPPING GROUP3)
  TOOL-LIFE : 7.5351 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.845399 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> TS-970[1-20]
  TOOL-LIFE : 4.470248 (TAPPING GROUP3)
  TOOL-LIFE : 7.372068 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.679301 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> TS-970[1-30]
  TOOL-LIFE : 4.284325 (TAPPING GROUP3)
  TOOL-LIFE : 7.203899 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.508729 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> TS-970[1-40]
  TOOL-LIFE : 4.226549 (TAPPING GROUP3)
  TOOL-LIFE : 7.145961 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.4501 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> TS-970[1-50]
  TOOL-LIFE : 4.208121 (TAPPING GROUP3)
  TOOL-LIFE : 7.126882 (AUTOMATICS-MULTIPLE-SPINDLE TITANTUM)
```

```
TOOL-LIFE : 8.359404 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 7.638639 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> HD-SOLUBLE[1-15]
 TOOL-LIFE : 5.211062 (TAPPING GROUP3)
 TOOL-LIFE : 8.045646 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 7.358339 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> HD-SOLUBLE[1-20]
 TOOL-LIFE : 4.716611 (TAPPING GROUP3)
 TOOL-LIFE : 7.685061 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
TOOL-LIFE : 7.002547 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> HD-SOLUBLE[1-30]
 TOOL-LIFE : 4.337962 (TAPPING GROUP3)
 TOOL-LIFE : 7.298235 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 6.609777 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> HD-S0LUBLE[1-40]
 TOOL-LIFE : 4.228297 (TAPPING GROUP3)
 TOOL-LIFE : 7.158707 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 6.464857 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> HD-SOLUBLE[1-50]
 TOOL-LIFE : 4.211215 (TAPPING GROUP3)
 TOOL-LIFE : 7.135804 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 6.440841 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> SOLUBLE[1-10]
 TOOL-LIFE : 4.252699 (TAPPING GROUP3)
 TOOL-LIFE : 7.257539 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 6,569983 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> SOLUBLE[1-15]
 TOOL-LIFE : 4.236535 (TAPPING GROUP3)
 TOOL-LIFE : 7.217896 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
TOOL-LIFE : 6.529778 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> SOLUBLE[1-20]
  TOOL-LIFE : 4.224681 (TAPPING GROUP3)
  TOOL-LIFE : 7.1872 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.497617 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> SOLUBLE[1-30]
 TOOL-LIFE : 4.211986 (TAPPING GROUP3)
 TOOL-LIFE : 7.152773 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.460481 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> SOLUBLE[1-40]
  TOOL-LIFE : 4.205736 (TAPPING GROUP3)
 TOOL-LIFE : 7.135226 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
 TOOL-LIFE : 6.441114 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> SOLUBLE[1-50]
 TOOL-LIFE : 4.202881 (TAPPING GROUP3)
  TOOL-LIFE : 7.127079 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 6.43202 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
TESTED-FLUID ===> TS-988
 NO-CHLORINE <<failed»
TESTED-FLUID == => 41H
 NO-CHLORINE «f ailed»
TESTED-FLUID ===> 41B
  TOOL-LIFE : 5.580368 (TAPPING GROUP3)
  TOOL-LIFE : 7.830333 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)
  TOOL-LIFE : 9.297355 (AUTOMATICS-MULTIPLE-SPINDLE B-1111)
```

TOOL-LIFE : 6.142008 (TAPPING GROUP3) TOOL-LIFE : 7.537755 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) TOOL-LIFE : 9.417368 (AUTOMATICS-MULTIPLE-SPINDLE B-1111) TESTED-FLUID ===> 41M TOOL-LIFE : 7.035658 (TAPPING GROUP3) TOOL-LIFE : 9.122429 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) TOOL-LIFE : 9.602408 (AUTOMATICS-MULTIPLE-SPINDLE B-1111) TESTED-FLUID ===> 43B TOOL-LIFE : 5.055504 (TAPPING GROUP3) TOOL-LIFE : 7.419925 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) TOOL-LIFE : 9.171376 (AUTOMATICS-MULTIPLE-SPINDLE B-1111) TESTED-FLUID =>> 45A NO-CHLORINE «fail ed>> TESTED-FLUID ===> TS-991 NO-CHLORINE <<failed>> TESTED-FLUID ===> 21D NO-CHLORINE «fail ed>> TESTED-FLUID ===> 44A NO-CHLORINE «f ailed» TESTED-FLUID ===> 44S NO-CHLORINE «failed» TESTED-FLUID ===> 45B NO-CHLORINE «f ailed» TESTED-FLUID ===> TS-944 TOOL-LIFE : 4.864865 (TAPPING GROUPS) TOOL-LIFE : 8,065817 (AUTOMATICS-MULTIPLE -SPINDLE TITANIUM) TOOL-LIFE : 7.249448 (AUTOMATICS-MULTIPLE -SPINDLE B-1111) TESTED-FLUID ====> 41E NO-CHLORINE «failed» TESTED-FLUID ===> TS-930 NO-CHLORINE «fail ed» TESTED-FLUID ====> 31A TOOL-LIFE : 8.729034 (TAPPING GROUP3) TOOL-LIFE : 8.893048 (AUTOMATICS-MULTIPLE • SPINDLE TITANIUM) TOOL-LIFE : 9.866111 (AUTOMATICS-MULTIPLE--SPINDLE B-1111) TESTED-FLUID ===> 31B TOOL-LIFE : 7.877955 (TAPPING GROUP3), TOOL-LIFE : 8.800831 (AUTOMATICS-MULTIPLh-SPINDLE TITANIUM) TOOL-LIFE : 9.763288 (AUTOMATICS-MULTIPLE-SPINDLE B-1111) TESTED-FLUID ===> 31G TOOL-LIFE : 7.947383 (TAPPING GROUP3) TOOL-LIFE : 7.061057 (AUTOMATICS-MULTIPLE •• SPINDLE TITANIUM) TOOL-LIFE : 8.376458 (AUTOMATICS-MULTIPLE--SPINDLE B-1111) TESTED-FLUTD ≠==> TS-901 TOOL-LIFE : 3.579253 (TAPPING GROUP3) TOOL-LIFE : 3.501276 (AUTOMATICS-MULTIPLE -SPINDLE TITANIUM) TOOL-LIFE : 5.152089 (AUTOMATICS-MULTIPLE-SPINDLE B-1111) TESTED-FLUID ===> 11A TOOL-LIFE : 5.301807 (TAPPING GROUPS) TOOL-LIFE : 5.707348 (AUTOMATICS-MULTIPLE[-SPINDLE TITANIUM) TOOL-LIFE : 6.64446 (AUTOMATICS-MULTIPLE-\*SPINDLE B-1111) TESTED-FLUID ===> 11D TOOL-LIFE : 4.582023 (TAPPING GROUP3) TOOL-LIFE : 7.805561 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM)

<b>TESTED-FI U1D</b>	•*	·> GUI.F∙	NO-372-OIL	
TOOILJFF.	:	5.591403	(TAPPING GROUP3)	
TOOL-LTFE	:	8.006153	(AUTOMATICSMULTJPLE-SPINDLE	TITANIUM)
TOOL-LTFE	:	8.673959	(AUTOMATICS-MULTIPLE-SPINDLE	B-1111)

### **II.11 RECOMMENDATION SUMMARY REPORT:**

At the conclusion of the fluid evaluation, a default recommendation report is generated which is initially set to a 'summary' report. This report lists the product line fluids in order of decreasing tool-life rating or production efficiency. The composition of each rating in terms of individual cutting-fluid properties is presented. Those property values followed with an asterisk (ie. '\*') indicate that a fluid has too much of the particular property to 'optimally' satisfy the shop requirements.

	• *** R	ecommendation ]	Results •***		· · · · · · · · · · · · · · · · · · ·
	Tool-1ife	Lubricity	Cool ing	Antiweld	Viscosity
Sensitivities:	10.01	0.77	1.54	4.62	3.08
31A	9.35	0.70	1.15	4.57*	2.92
31B	9.10	• 0.58	1.17	4.44*	2.91
41M	8.95	0.72	1.28*	4.11	2.84
41D	8.20	0.73*	0.62	4.07	2.77*
41B	8.11	0.58	1.00	3.58	2.96
31C	7.90	0.72	0.21	4.57*	2.40*
GULF-NO-372-OIL	7.86	0.43	1.25*	3.33	2.85
43B	7.82	0.54	0.69	3.64	2.95*
HD-SOLUBLE[1-10]	7.57	0.66	1.54*	4.34	1.03
HD-SOLUBLE[1-15]	7.14	0.54	1.54*	4.02	1.03
TS-944	7.02	0.39	1.54*	3.58	1.51
TS-970[1-10]	6.89	0.29	1.54*	4.03	1.03
11D	6.76	0.44	1.54*	3.33	1.45
HD-SOLUBLE[1-20]	6.75	0.45	1.54*	3.73	1.03
TS-970[1-15]	6.62	0.29	1.54*	3.76	1.03
TS-970[1-20]	6.45	0.29	1.54*	3.59	1.03
HD-SOLUBLE[1-30]	6.36	0.35	1.54*	3.45	1.03
SOLUBLE[1-10]	6.31	0.42	1.54*	3.33	1.03
SOLUBLE[1-15]	6.28	0.38	1.54*	3.33	1.03
TS-970[1-3G]	6.27	0.29	1.54*	3.42	· 1.03
SOLUBLE[1-20]	6.25	0.35	1.54*	3.33	1.03
HD-SOLUBLE[1-40]	6.23	0.30	1.54*	3.35	1.03
SOLUBLE[1-30]	6.22	0.32	1.54*	3.33	1.03
TS-970[1-40]	6.21	0.29	1.54*	3.36	1.03
HD-SOLUBLE[1-50]	6.20	0.30	1.54*	3.34	1.03
SOLUBLE[1-40]	6.20	0.30	1.54*	3.33	1.03
TS-970[1-50]	6.20	0.29	1.54*	3.34	1.03
SOLUBLE[1-50]	6.19	0.30	1.54*	3.33	1.03
11A	6.09	0.77*	0.04	3.33	1.96*
TS-901	4.34	0.46	0.92	0.00*	2.96
TS-930	failed NO-	CHLORINE			

failed	NO-CHLORINE
failed	NO-CHLORINE
	failed failed failed failed failed failed failed failed failed failed

COMMAND?t

# **II.12 REPORT SPECIFICATION:**

Alternate and 'on-demand' reports may be obtained with the 't' command. In the example, ' 'tuning' report is selected as the default report type, and it is demanded immediately.

Tuning report (t) or Summary report (s) default? t Immediate report? y

.

#### 11.13 RECOMMENDATION TUNING REPORT:

The 'tuning' report provides more detailed information than the 'summary' report. The actual differences in cutting-fluid properties between the 'optimal' fluid and the product fluid is listed in a second column following the property rating. The average 'optimal' fluid chemistry is listed in addition to the sensitivites as the 'summary' report included. This report only lists the ten highest rated fluids rather than the entire product line.

**** Recommendation Results **** (Extended Information Report)									
sens itivities:	Tool-1ife 10.01	Lu	bricity 0.77	Co	ooling 1.54	Anti	weld 4.62	Visco 3,	osity .08
Optimal fluid:			71.20	73	29.83	215	5.90	24,	,64
31A	9.35	0.70	-13.2	1.15	-5.2	4.57	104.1	2.92	-3.7
31B	9.10	0.58	-37.2	1.17	-1.4.	4.44	11.1	2.91	-4.2
41M	8.95	0.72	-1.2	1.28	19.7	4.11	-105.9	2.84	-5.8
41D	8.20	0.73	7.8	0.62	-136.9	4.07	-112.9	2.77	5.2
41B	"8.11	0.58	-38.2	1.00	-37.6	3.58	-185.9	2.96	-1.8
31C	7.90	0.72	-1.2	0.21	-204.9	4.57	97.1	2.40	10.1
GULF-NO-372-OIL	7.86	0.43	-55.2	1.25	13.2	3.33	-215.9	2.85	-5.5
43B	7.82	0.54	-42.2	0.69	-124.5	3.64	-178.9	2.95	0.9
HD-SOLUBLE[1-10	)] <b>7.57</b>	0.66	-24.2	1.54	270.2	4.34	-35.9	1.03	-24.6
HD-SOLUBLE[1-15	5] <b>7.14</b>	0.54	-42.2	1.54	270.2	4.02	-121.9	1.03	-24.6

COMMAND?w

#### 11.14 DETAILED FLUID RECOMMENDATION DATA:

A detailed explanation of the evaluation of a selected fluid is presented with the 'w' command. This report presents an analyis of each process in the shop, and how the selected fluid satisfied the process. Included in the information for each process are the process name, the importance of each process, the process percentage, and the overall process weight designating the relative weighing of each process. The 'STD.CHANGE' column designates the 'half-width' of the utility function for each property; 'SENSITIVITIES' represent to what extent a process is affected by each property; the 'ideal' fluid columns names the ideal fluid for the process and its property values; the 'optimal' fluid represents the 'ideal' fluid with all property constraints posted. A final column indicates the fluid rating for the process similar in format to the 'tuning' report. A detailed fluid recommendation report is presented below for the highest rated fluid in the example:

fluid name? 31a

FLUID NAME: 31A TOOL-LIFE LUBRICITY COOLING ANTIWELD VISCOSITY (TAPPING GROUP3) Importance: 1.0 Process %: 20.00 20.00 Weight: 177.00 Std. Change: 40.00 50.00 15.00 sensitivities: 10.01 0.77 1.54 4.62 3.08 FERROUS23 125.00 550.00 350.00 32.00 Optimal fluid: 125.00 778.43 404.00 32.00 8.73 0.41 - 67.01.19 - 53.84.39 -84.0 2.73 -11.0 (AUTOMATICS-MULTIPLE-SPINDLE TITANIUM) Importance: 1.0 Process %: 30.00 Weight: 30.00 Std. Change: 30.00 50.00 100.00 10.00 sensitivities: 10.01 0.77 1.54 4.62 3.08 NON-FERROUS54 53.40 838.80 167.00 18.14 64.00 838.80 167.00 Optimal fluid: 18.14 8.89 0.76 -0.0 0.48 -114.1 4.62 153.0 3.03 2.8 (AUTOMATICS-MULTIPLE-SPINDLE B-1111) Importance: 1.0 Process %: 50.00 50.00 Weight: Std. Change: 30.00 50.00 100.00 10.00 sensitivities: 10.01 0.77 1.54 4.62 3.08 FERROUS51 54.00 595.00 70.00 25.60 Optimal fluid: 54.00 645.00 170.00 25.60 1.54 79.7 4.62 150.0 2.94 -4.6 9.87 0.77 4.0 9.35 1.15 -5.2 4.57 AVERAGE: 0.70 -13.2 104.1 2.92 -3.7

COMMAND?e

Following completion of a recommendation, or to correct an error in the shop specification, GREASE may be initialized by the T command. Each section of the shop specification may be initialized independently.

Do you really want to initialize the shop model (y/n) ? y Initialize operations (y/n) ? y Operations deleted --> redefine operations and processes. Initialize materials (y/n) ? y Materials deleted --> redefine materials and processes. Initialize requirements (y/n) ? y User requirements deleted --> redefine user requirements. Initialize current fluid (y/n) ? y Current fluid deleted --> redefine current fluid.

### 11.16 ANALYSIS OF GREASE RECOMMENDATION FOR EXAMPLE

The cutting-fluid recommendations for the example shop may be analyzed from the different reports provided by GREASE.

The 'summary' report lists the product line fluids in decreasing order of satisfying the requirements of the shop. This report also specifies fluids which fail important requirements and should not be recommended under any circumstance.

From the 'goal activation report' and the 'tuning report', the top three fluid choices can be analyzed as follows:

Fluid '31 A' is the highest rated fluid followed by the current fluid '31B'. '31 A' has increased antiweld to satisfy:

- poor finish and a large built-up edge in tapping a group3 steel;
- excessive tool wear in machining titanium with a multiple spindle automatic;
- 'high-speed' multiple-spindle-operation performed on a'111V steel.

Fluid '31 A' also has increased lubricity over '31B' to satisfy:

- excessive tool wear in machining titanium with a multiple spindle automatic;
- 'high-speed' multiple-spindle-operation performed on a '1111' steel.

Cooling and viscosity properties of '31 A' and '31B' are similar.

The third choice fluid '41M' has less antiweld than the current-fluid '31 B\ and probably not improve on excessive tool wear or poor finish. However, the lower viscosity and increased cooling properties would result in improved high speed operation of multiple spindle automatics on '1111' steel. performance in individual processes. For example, in analyzing the best fluid choice '31A', the best performance is obtained for machining '1111' steel with a multiple spindle automatic machine which constitutes 50% of the shop. The worst performance is obtained with the lowest percentage process in the shop -- tapping a group3 steel. Finally, since all processes have high tool life ratings for fluid '31A', this single cutting-fluid will perform satisfactorily for the entire shop.<sup>34</sup>

<sup>&</sup>lt;sup>34</sup>This report can be also used to determine if a fluid will not perform satisfactorily for an important shop process (ie. low tool-life rating, or low cutting-fluid property values.) and should be rejected even though the overall composite rating for all processes is satisfactory.

#### 

# III.1 Introduction

Three sets of experiments were performed to evaluate the performance of GREASE subsequent to the primary phases of knowledge acquisition and enhancement. The experiment sets were designed to test the major capabilities of GREASE and included:

- Cutting-fluid recommendations for single shop processes without diagnostic symptoms and atypical operating conditions;
- Recommendations for single shop processes with a variety of symptoms and atypical operating conditions;
- Recommendations for shop containing multiple processes for which a single cutting-fluid is desired;

Each experiment set tests progressively more features of GREASE and its success depends upon the success of the prior sets of experiments.

The experiment sets included test cases selected both from actual customer shops and hypothetical shops. Individual experiments consisted of performing the same shop recommendations independently by GREASE, a cutting-fluid expert, and a cutting-fluid salesman. The salesman represents an experienced non-expert, who will be the primary user of the GREASE system.

Analysis of experimental results consisted of comparing the recommendations from each source to answer two primary questions:

- How well does GREASE agree with the experts and experienced salesmen?
- When GREASE returns a high rating for a fluid, does that really mean that in an expert's opinion it will do a good job?

To answer these questions two tests were performed for each recommendation:

- comparison of the top three choices from the different sources followed by an explanation of their differences;
- expert rating of the fluids that GREASE gave a high value on its rating scale. The expert ratings are good, satisfactory, or poor, and are based solely on expected performance.

### **III.2 Experimental Datasets**

GREASE was tested with several actual field cases. These cases represent a wide range of problems for GREASE, and test all features for a variety of commonly encountered customer shops excluding diagnosis, and compensation for atypical operating conditions. Several hypothetical cases were analyzed by GREASE and the cutting-fluid expert to test these features.

The field cases fall into two categories:

- Single process recommendations
- Multiple process recommendations

The field cases included a range of machining operations from the highest severity (ie broaching) to the lowest severity (ie grinding) that GREASE can consider, and a wide range of materials including members from all the ferrous groups, and selected non-ferrous materials.

The multiple process cases tested the ability for GREASE to properly average a shop for which a single cutting-fluid is desired. This averaging depends upon the ability of GREASE to properly recommend a single process shop, and in selected cases, to average both ferrous and non-ferrous recommendations.

A description of the field cases is in figure III-1.

A series of hypothetical test cases were devised to test the ability of GREASE to properly recommend fluids if diagnostics or atypical operating conditions were specified in the customer's shop. Actual field cases were unavailable, since it is not common procedure to currently collect this information. These cases are described in III-2. For the diagnostic cases, the current fluid '41B' was assumed. In order to observe the primary affect of the diagnostic or atypical condition upon the recommendations, and to minimize scatter, the material machined and machine operation were held constant in these cases.

CASE#	MATERIAL MACHINED	OPERATION	DIAGNOSTIC or OPERATING COND.
14	100% GROUP1	MULT-SPINDLE AUTO.	(control case)
15	100% GROUP1	MULT-SPINDLE AUTO.	HIGH-SPEED
16	100% GROUP1	MULT-SPINDLE AUTO.	HIGH-SPEED, DEEP-CUT
17	100% GROUP1	MULT-SPINDLE AUTO.	HIGH-SPEED,DEEP-CUT,HIGH-FEED
18	100% GROUP1	MULT-SPINDLE AUTO.	LONG CHIPS
19	100% GROUP1	MULT-SPINDLE AUTO.	LONG CHIPS, LARGE BUE
20	100% GROUP1	MULT-SPINDLE AUTO.	LONG CHIPS,LARGE BUE, TOOL-SEIZURE

Figure ill-2: Diagnostic and Atypical Conditions Test Cases

#### **III.3 Experimental Evaluation**

Two sets of experimental results were collected for each experiment. The first dataset represented the best three cutting-fluid choices for the customer's shop.<sup>35</sup> The results are compared to determine

<sup>&</sup>lt;sup>35</sup>All actual test cases, except case #13 were restricted to non-soluble cutting-fluid recommendations, since the

1	100% GROUP1 - 1144, LEADED STEELS	100% REAMING
2	40% <b>GROUP1 -</b> 12-L-14.12-L-15,1144 40% GROUP3 - 6150,8620 20% GROUP4 - 52100,4140	100% MULTIPLE-SPINDLE AUTOMATICS
3	10% GROUP1 - 416,4130 20% GROUP3 - 410,420 70% GROUP4 - 440C STAINLESS	100% MILLING
4	20% GROUP1 - 1117,1212 <sub>t</sub> LEADED STEELS 20% GROUP3 - 303 STAINLESS 60% GROUP6A- <b>BRASS, BRONZE</b>	100% MULTIPLE-SPINDLE AUTOMATICS
5	20% GROUP1 - LEADED STEELS 10% GROUP2 - CAST IRON 70% GROUP4 - HIGH CARBON - 1040,M2	80% MULTIPLE-SPINDLE AUTOMATICS 20% DRILLING
б	100% <b>GROUP4</b> - 52100(440C	100% FORM-GRINDING
7	80% GROUP3 - 203 STAINLESS 20% BRASS	50% MULTIPLE-SPINDLE-AUTOMATICS 50% TAPPING
8	100% GROUP1 - LEADED STEELS, 1144	100% GUN DRILLING-bore:0.218in.
9	100% GROUP4 - M2 STEEL	100% CENTERLESS-GRINDING
10	100% GROUP3 - 4047 LEADED	100% EXTERNAL BROACHING
11	100% GROUP4 - 4047 (NOT-LEADED)	100% DRILLING
12	100% GROUP4 - M1,M7 STEELS	100% FORM GRINDING
13	100% BRASS	100% MULTIPLE-SPINDLE AUTOMATICS

Figure ill-1: Actual Field Test Cases Used to Evaluate GREASE

how good an agreement exists between GREASE, the expert, and the salesman in terms of a fluid which meets the customer's needs. The intent is to determine if GREASE perform's worse, on a par, or better than its human counterparts.

The second dataset is a ranking by the expert of the high rated fluids recommended by GREASE for the customer shop. These results give an indication of how well a high-performance level fluid selected by GREASE might actually perform in a customer's shop.

#### 111.3.1 Best Throe Choices

The three best cutting-fluid choices independently determined by the expert, salesman, and GREASE were correlated in table form. The selected fluids are indicated, followed by a 'rating' value which is an estimate by either the expert or salesman of how well this fluid would perform in the
'rating' values are G -good, S -satisfactory, and P -poor. It is important to note that three good choices might not always be possible in the cutting-fluid product line, in which case rating values less than good are indicated. The 'rank' indicates where the expert- and salesman- selected fluid falls in the GREASE recommendation table. The value 't.l.' indicating 'tool-life' indicates the performance level of the specified fluid as determined by GREASE. The 'score' of a particular choice is the percentage of the maximum rating possible (i.e., when all choices receive a 'good' rating).

Lastly, cutting-fluids which are currently used in a customer's shop are indicated with an asterisk in the first fluid choice of the salesman.<sup>37</sup>

#### III.3.2 High Rated Fluids

For each recommendation made by GREASE, the expert rated the fluids with tool-life ratings greater or equal to 8.00 in terms of how well they would perform in the customer's shop. The ratings were G -good, S -satisfactory, and P -poor.

## Hi.4 First Experiment Set - Single Shop Processes

The first set of experiments tested GREASE for single shop process recommendations without diagnostic symptoms and atypical operating conditions. Consequently, they tested the ability for GREASE to properly recommend a cutting-fluid for a shop comprising a single machine operation, and one or more materials within the same material group.

These experiments tested the reasoning ability of GREASE to effectively rate fluids. In doing so, GREASE utilizes cutting-fluid property sensitivities, utility functions that compare 'optimal' with actual fluid properties, and ideal fluids constrained by operation and material goals.

Experimentally testing each cutting-fluid selection in a physical shop is impossible. Best estimates, based upon experience and expertise of cutting-fluid properties, were used for the ratings.

The salesman generally recommended the current fluid as the first choice if he was aware of its identity.

#### III.4.1 Analysis of Three Best Choices:

The experimental results for the three best choices are in figures III-3,III-4, and III-5. Analysis of the results revealed that GREASE, the cutting-fluid expert, and the salesman made good recommendations as the first choice. All recommended fluids would perform well in the customer's shop.

CASE# GREASE						EXPER	T			SALESMAN				
	fluid	٢a	ating	t	. 1	. fluid	rati	rating rank		k t.1.	fluid	rati	ing rank	< t.1.
1	41B		G	9.	84	43B	G		4	9.35	31C*	G	10	<7.39
6	TS991		G	9.	87	TS991	G		1	9.87	TS991	G	1	9.87
8	TS991		G	9.	93	41M	G		3	9.84	31A	G	2	9.92
9	11D		G	9.	77	11D	G		1	9.77	11D	G	1	9.77
10	21D		G	9.	39	45A	G		5	6.48	45B	G	3	9.23
11	31C		G	9.	43						44A	G	9	6.41
12	TS991		G	9.	87	TS991	G		1	9.87	41H	G	10	2.93
13	41M		G	9.	98	43B	G		8	7.77	Soluble	* G	6	8.36
Ave	:			9.	76			З	3.3	8.99			5.2	7.98
	10	00%	Good				100%	God	bd		1	00% (	Good	
Sco	re: 10	00%	•				100%				. 1	00%		
						Figure III-3:	cure III-3: Single processes - fire							

In the second choice, GREASE generally performed slightly better than both the expert and the cutting fluid salesman.

CAS	E#	GF	REASE		EXPERT				tentententententet (d	*****	SAI	ESMAI	N	
	fluic		rating	t.1.	fluid	rat	ing	rank	t.1.	fluid	i ra	ating	rank	t.1.
1	TS991		G	9.57	. 41M		G	3	9.44	31A		G	10	7.39
6	41M	1	G	9.66	41M		S	2	9.66	31A		G	3	8.43
8	31A	۱	G	9.92	41B		S	8	9.16	31B		S	4	9.72
9	TS944	Ļ	G	8.54	41B		G	7	5.14	31A		G	9	4.63
10	444	۱	G	9.39	310		G	4	6.79	45A		S	5	6.48
11	31 <i>F</i>	۱.	G	8.63		-				21D		G	10	6.15
12	41	1	S	9.66	41M		S	2	9.66	TS991		G	1	9.87
13	TS991	L	G	9.91	41B		G	4	9.33	41E		G	11	7.17
Ave	:			9.41				4.3	8.45				6.6	7.48
	8	37%	Good			50%	Goo	d			75%	Good		
	1	13%	Satis	factory		50%	Sat	isfac	tory		25%	Sati	sfact	ory
Sco	re: 9	4%				78%					87%			

Figure III-4: Single processes - second choice

t.

CASE	 :#	GF	EASE			EXPE	RT				SALESMAN	·	
	fluid	r	*ating	t.1.	fluid	rat	ing	rani-c	t.1.	flui d	l rating	rank	t.1.
1	411	1	G	9.44	11D	:	Р	12	6.14	31B	Р	8	8.71
6	317	7	Р	8.43	11D		Р	8	6.25	41H	G	>10	<4.20
8	411	1	G	9.84	11D		Р	15	8.48	41B	Р	8	9.16
9	449	3	Р	7.25	#372	1	S	5	5.53	31B	S	8	4.86
10	· 45E	3	G	9.23	21D	(	G	1	9.39	31C	S	4	6.79
11	457	7	S	8.45						31A	G	2	8.63
12	#372		P	7.07	11D	1	Р	3	7.07				
13	#372		G	9.90	41D	(	G	9	7.36	•4IB	G	4	9.33
Ave::				7.82			•	7.6	7.17			6.3	7.38
	Į	50%	Good			29% (	Good	L			43% Good		
		L2%	Sati s	factory		14% :	Sati	sfact	ory		28% Sati	sfact	ory
	3	38%	Poor			57% ]	Poor				29% Poor		
Scor	e: 5	6%				36%					57%		
				Figure	e III-5: S	Single	Proc	esses	- Thire	d Choic	e		•

# III.5 Second Experiment Set - Atypical Conditions / Diagnostics

The second set of experiments tested GREASE for single shop process recommendations with a variety of symptoms and atypical operating conditions. These experiments tested the reasoning ability of GREASE to constrain the 'optimal<sup>1</sup> cutting fluid to correct for a variety of atypical operating conditions such as 'high speed' or 'deep cut' during a machining operation. Translation of diagnostic symptoms such as 'long chips' or 'excessive built up edge' into treatments constraining the 'optimal<sup>1</sup> fluid is also tested.

Three test cases for atypical conditions were recommended with an increasing number of operating condition requirements (i.e., test cases 15-17). In these cases, the material and operation were the same. A control case (i.e., test case 14), did not have any atypical conditions applied.<sup>38</sup> Similarly, three test cases for diagnostic conditions were recommended with an increasing number of diagnostics applied (i.e., test cases 18-20).

<sup>&</sup>lt;sup>38</sup>The control case was not included in the calculation of the 'score' values and the tool-life averages.

III.5.1 Analysis of Best Three Choices for Atypical Conditions:

The experimental results for the best three choices for recommendations with atypical operating conditions are in figures III-6, iII-7, and III-8. The results only included data from the expert and GREASE. The first choice resulted in close agreement between GREASE and the expert resulting in selections giving good performance in the shop.

CASE//	G	REASE		EXPERT								
	f'luid	ratiin	gt.l.	fluid	rating	rank	t.1.					
14	41D	G	9.89	41B	G	3	9.89	(control)				
15	31A	G	9.87	41M	G	4	9.60					
16	31A	G	9.75	31B	G	2	9.42					
17	31A	G	9.37	31A	G	1	9.37					
Ave:			9.66			2.3	9.46					
	1	00% G	bod		100%	Good						
Score:	1	00%			100%							

Figure 111-6: Atypical Conditions Test Results - First Choice

In the second choice, GREASE performed slightly better than the expert.

CASE//	GF	REASE			EXPERT			
	fluicJ :	rating	t.l.	fluid	ratinę <u></u>	j rańk	t.1.	
14	43B	G	9.87	43B	G	2	9.87	(control)
15	<b>TS991</b>	G	9.79	41B	S	7	9.30	
16	31B	G	9.42	41M	S	4	8.93	
17	31B	S	8.62	31B	S	2	8.62	
Ave:			9.28			4.3	8.95	
	75	5% Good	L		25%	Good		
	25	5% Sati	.sfactory		75%	Satisf	actor	Y
Score:	87	%			62%			

appropriate oils for the customer's shop.

The quality of the ratings is seen to decrease as more atypical conditions for a test case are applied. This is true for all three choices and is reflected in lower rating values and GREASE projected tool-life values. This is due to the unavailability of fluids in the product line to match the 'optimal' shop cutting-fluid properties.<sup>39</sup>

CASE#	· G	REASE		ł	EXPERT			
	fluid	rating	t.1.	fluid	rating	rank	t.1.	
14	41B	G	9.83	41D	G	1	9.89	(control)
15	31B	G	9.76	43B	S	8	9.17	. ,
16	TS991	G	9.36	41B	Ρ	10	8.09	
17	TS991	S	8.39	41M	Р	8	7.71	
Ave:			9.17			8.7	8.32	
	7	5% Goo	d		25%	Good		
	2	5% Sat	isfactory_		25%	Satis	facto	гy
		0% Poo	r		50%	Poor		•
Score:	8	7%			30%			

<sup>&</sup>lt;sup>39</sup>It has also been observed during the knowledge acquisition and tuning phase of GREASE that when two or more atypical conditions were applied, GREASE's recommendations were often in error and resulted in poor ratings. This is probably due to some error in the additivity assumption of satisfying goals (ie. cooling, lubricity) for atypical conditions, as well as error in the satisfying goal increments.

#### III.5.2 Analysis of Best Three Choices for Diagnostic Conditions:

The experimental results for the best three choices for recommendations with diagnostics are in figures III-9,III-10, and III-11. As in selections with atypical conditions, GREASE was well in agreement with the expert on its first choice, resulting in good performing oils in the customer's shop.

CASE#	G	REASE	******	 	EXPERT	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,		
	fluid	ratin	g t.l.	fluid	rating	rank	t.1.	
14	41D	G	9.89	41B	G	3	9.89	(control)
18	TS991	G	9.78	41D	G	1	9.78	
19	31A	G	9.82	41M	G	3	9.70	
20	31A	G	9.82	31A	G	1	9.82	
Ave:			9.81			1.6	9.77	
	1	.00% G	ood		100%	Good		
Score:	1	00%			100%			

Figure III-9: Diagnostic Condition Test Results - First Choice

GREASE performed on a par with the expert on its second choice, and selected good fluids for the customer shops.

CASE#	G	REASE		Ε	XPERT		
·	fluid	ratin	g t.1.	fluid	rating	rank	t.1.
14	43B	G	9.87	43B	G	2	9.87 (control
18	41M	G	9.72	41M	G	2	9.72
19	TS991	G	9.78	41D	G	7	8.54
20	TS991	G	9.78	31B	S .	4	9.67
Ave:			9.76			4.3	9.31
	1	00% G	ood		75%	Good	
		0% S	atisfactory		25%	Satis	factory
Score:	1	00%			87%		

CASE#	GR	EASE		E	XPERT		
	fluid r	atin	g t.1.	fluid	rating	g rank	t.1.
14	41B	G	9.83	41D	G	1	9.89 (control)
18	31A,31B	G	9.67	31B	G	4	9.67
19	41M	G	9.70	31B	S	4	9.67
20	41M	G	9.70	41M	G	3	9.70
Ave:			9.69			3.67	9.68
	10	0% G	ood		75%	Good	
					25%	Satis	factory
Score:	10	0%			87%		
	Figure	e <b>III-</b> 1	1: Diagnostic	Condition Test R	lesults	– Thirc	I Choice

GREASE also made its third choice well on a par with the expert for diagnostic treatment.

A degradation in the quality of the recommendation wasn't observed for diagnosis treatment as it was in 'atypical condition' cases when more diagnostics are posted. This is probably due to the fact that several diagnostics might indicate the same imbalance in cutting-fluid properties. Treatment would then be applied once, rather than in an additive fashion in 'atypical condition' cases.

## III.6 Third Experiment Set - Multiple processes

The third set of experiments tested GREASE for shop recommendations containing multiple processes for which a single cutting-fluid is desired. These experiments tested the ability of GREASE to correctly combine process ratings of cutting-fluids for individual processes within the shop into an overall shop average. In developing the shop average, GREASE assumes a linearity in the single process rating scale, and uses process percentages and process importances to weigh the average. The field cases tested the ability of GREASE to average within the same material classification (e.g., ferrous materials), as well as between material classifications comprising both ferrous and non-ferrous materials.

#### III.6.1 Analysis of Best Three Choices:

The experimental results for the best three choices are in figures III-12, III-13, and III-14. Analysis of the results revealed that GREASE, the cutting-fluid expert, and the salesman made good recommendations as the first choice. All recommended fluids would perform well in the customer's shop. The expert also was more in agreement with GREASE than the salesman on the first choice.

-															
CAS	E#	GR	EASE				EXPER	Т				SALESMAN			
	fluic	i r	ating	t	.1.	fluid	rati	ng	ran	k t.1.	fluid	rating	j rank	t.1.	
2	31A	١	G	9.	53	31B	G	i	3	9.30	31B*	G	3	9.3	
3	31A	١	G	8.	70	31A	G	i	1	8.70	31C	G	2	8.63	
4	TS991	l	G	9.	75	41D	G	i	1	9.75	41D*	G	5	8.15	
5	31A	١	G	9.	23	31A	G	i	1	9.23	31B	G	2	8.80	
7	TS991	L	G	9.	00	45A	G	í	5	8.25	31B*	G			
Ave	:			9.	24			2	2.2	9.05			3.0	8.72	
	1	100%	Good				100%	God	bd		1	00% Goo	bd		
Sco	re: 1	100%					100%				1	00%			

Figure III-12: Multiple Processes - First Choice

GREASE was on a par with the expert or salesman in terms of its second choice. All selections would result in good or satisfactory performance in the customer's shop.

CASE	CASE# GREASE					EXP	ERT		SALESMAN				
	fluid	I	ratin	g t.1.	fluid	rat	ting	ran	k t.1.	fluid	rating	rank	t.1.
2	TS991		G	9.32	45A		s	11	7.95	31A	G	1	9.53
3	310		G	8.63	31B		G	3	8.20	31A	G	1	8.70
4	41M		G	9.66	45A		G	10	6.94	41E	S	9	7.90
5	31B		S	8.80	41M		S	8	8.12	31A	G	1	9.23
7	41M		S	8.52	41M		S	2	8.52	31A	G		
Ave:				8.99				6.8	7.95			3.0	8.84
	6	0%	Good			40%	God	bd		8	0% Good		
	4	0%	Sati	sfactory		60%	Sat	isfa	ctory	2	0% Sati	sfact	ory
Scor	e: 8	0%				70%				g	0%		

Figure III-13: Multiple Processes -	Second	Choice
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CASE# GREASE		E	EXPERT			SALESMAN						
	fluid	ratí	ng t.l.	fluid	rating	j ran	k t.1.	fluid	rating	rank	t.1.	
2	31B	G	9.30	41M	Р	6	8.91	41E	Р	7	8.75	
3	31B	G	8.20	41M	S	9	6,90	31B	S	3	8.20	
4	#372	Р	9.24	43B	S	5	8.21	41B	S	4	9.13	
5	TS991	S	8.67	41D	S	5	8.53	31C	G	4	8.62	
7	41D	S	8.48	41D	S	3	8.48	41E	S	6	8.20	
Ave	:		8.78			5.6	8.21			4.8	8.58	
40% Good		0% Good			20% Good							
	40	1% Sat	isfactory	ory 80% Satisfactory		ctory	6	60% Satisfactory				
	20	)% Poo	r	20% Poor			·	2	0% Poor	Poor		
Sco	re: 60	1%			40%			5	0%			

GREASE generally performed well on its third choice compared to both the expert and salesman.

Figure III-14: Multiple Processes - Third Choice

## **III.7 Observations and Conclusions:**

#### III.7.1 Best Three Choices:

GREASE performed very well in comparison to the expert and experienced salesman as the summary of score values for the best three choices in figure III-15 demonstrates.

	CHOICE	GRE	EXPERT		SALESMAN		
		score	t.1.	score	t.1.	score	t.1.
Single Process:	1	100	9.76	100	8.99	100	7.98
	2	94	9.41	78	8.45	87	7.48
	3	56	7.82	36	7.17	57	7.38
Atypical conditions:	1	100	9.66	100	9.46		
	2	87	9.28	62	8.95		
	3	87	9.17	30	8.32		
Diagnostic conditions:	1	100	9.81	100	9.77		
C C	2	100	9.76	87	9.31		
	3	100	9.69	87	9.68		
Multiple Processes:	1	100	9.24	100	9.05	100	8.72
	2	80	8.99	70	7.95	90	8.84
	3	60	8.78	40	8.21	50	7.58

some interesting conclusions:

- Identical fluids were not always recommended for each test that resulted in identical fluid ratings. The reason is that there are generally multiple fluids in each performance class (eg. good, satisfactory, poor) for a particular shop.
- GREASE can often find more fluids that have good performance in a shop than either the salesman or expert. The reasons for this include:
  - GREASE considers the *entire* product line for each cutting-fluid selection. The salesman and expert often considers only a group of fluids that are generally used for a particular machine operation on a specific material without considering the merits of fluids not designed for a particular application.
  - In a multiple process case where a single fluid is desired for several machining processes, GREASE attempts to rigorously calculate the relative need of each individual process, rather than using estimation.
- The first choice of GREASE, the salesman, or expert always resulted in good performance in the customer's shop.
- The second choice of GREASE always resulted in good or satisfactory performance, but the expert and salesman sometimes made a poor performance choice.
- The third choice had some poor performance selections by GREASE, the expert, and the saleman.
- There was some general disagreement between the expert and salesman.

### III.7.2 High-rated Fluids

The analysis of recommendations with GREASE projected high tool-life ratings is to determine whether such selections will do a good job in customers' shops. Two datasets were collected for this analysis:

- tool-life values for the best three choices for GREASE, the expert, and the salesman;40"
- for every test case, the expert rated each GREASE recommendation with tool-life values greater than 8.0 into the categories of G-good, S-satisfactory, or P-poor, which reflect expected performance in a customer's shop.

Analysis of tool-life ratings for the best three fluids revealed:

- there exists a rough correlation of tool-life values with rating 'scores' within each experiment (i.e., a lower rating 'score' results in a lower tool-life value);
- tool-life values decrease with choice number within an experiment;

<sup>&</sup>lt;sup>40</sup>The tool-life values for the expert and salesman are GREASE projected values for their fluid selections.

 an absolute tool-life value could not be associated with a rating 'score' across all experiments including recommendations by GREASE, the expert and the salesman. An example of this is seen in the multiple process case in figure III-15. The first choice for GREASE, the expert, and the salesman all receive ratings of 100%, but the tool-life ranged from 9.76 for GREASE to 7.98 for the salesman. The 7.98 value is greater than the value that GREASE reports for its third choice - 7.82 which results in a rating score of only 56%.

The dataset comprising expert ratings of GREASE recommendations with tool-life ratings greate than 8.0 was compiled for all 20 test cases. Individual cases were not examined since it was the inten to determine if tool-life values by themselves could be correlated with good, satisfactory, or poor recommendations. A table was prepared relating tool-life range versus number of observations of good, satisfactory, or poor performance - figure III-16

TCOL-LIFE RANGE	GOOD	SATISFACTORY	POOR
9.9 - 10.0 9.8	5 12	0 0	0 0
9.7	15	0	0
9.6	9	1	0
9.5	2	0	0
9.4	3	3	. 0
9.3	8	2	1
9.2	2	1	3
9.1	1	3	4
9.0	1	2	2
8.9	0	2	2
8.8	0	3	2
8.7	1	1	2
მ.6	2	4	2
8.5	. 0	9	3
8.4	0	4	5
8.3	0	4	2
8.2	3	2	5
8.1	0	4	1
8.0	0.	3	1

Figure III-16: GREASE Tool-life Values Versus Performance

Analysis of tool-life versus performance reveals:

- Tool-life values greater than 9.4 always resulted in good performance.
- A range of tool-life values for satisfactory without poor performance could not be determined.
- A wide range of tool-life values exist for each performance classification. For example, the average tool-life value for 'good' was 9.5 with a standard deviation of 0.9.
- A large overlap of performance classes exist.

### III.7.3 Observations Concerning GREASE Evaluation by Expert and Salesman

Interviewing of the expert and salesman after the experiments revealed:

- they were satisfied with their cutting-fluid choices for the test cases;
- they sometimes didn't consider a fluid which GREASE recommended by either not thinking of it, or even considering it for a particular application. Some fluids new to the product line were often overlooked. They were excited over the utility of GREASE to be able to identify potential applications of fluids prior to actual field usage;
- they both generally considered GREASE to be very useful for performing cutting-fluid recommendations;
- there were differences in selections made by GREASE and the expert despite the fact that knowledge input of GREASE was obtained from the expert. There are two reasons for this:
  - GREASE is able to more rigorously calculate the effectiveness of a fluid for a given process.;
  - GREASE was designed to make conservative predictions and give the best choice in all cases, whereas the expert, in many cases, chose a slightly poorer performing oil which would be more cost effective in terms of performance and price.

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