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KNOWLEDGE ACQUISITION FROM EXPERTS
IN CONCEPTUAL DESIGN
OF ENVIRONMENTAL ENGINEERING SYSTEMS

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Lori Schutz-Riley

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KNOWLEDGE ACQUISITION FROM EXPERTS

IN CONCEPTUAL DESIGN

OF ENVIRONMENTAL ENGINEERING SYSTEMS

By

Lori Schutz-Riley

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ABSTRACT

KNOWLEDGE ACQUISITION FROM EXPERTS IN CONCEPTUAL DESIGN OF ENVIRONMENTAL SYSTEMS

By

Lori Schutz-Riley

This thesis describes a methodology for knowledge acquisition useful for knowledge representation in the Hierarchial Classification tool. The domain is conceptual design for environmental engineering systems, specifically wastewater treatment. The conceptual design problem is solved by decomposing expertise using design criteria. Basic concepts are defined such as experts versus novices, paradigms, and why there is a need for such an expert system. Knowledge acquisition and knowledge representation are discussed, with descriptions of the two knowledge acquisition tools used. The repertory grid reveals how the expert relates the features and design criteria to technologies. Constraint based representation reveals how the expert compares design criteria against waste features independent of the technologies.

A methodology for knowledge acquisition and representation is presented. The important design criteria of the competing technologies are identified. Next, the features

relative to the design criteria are identified. Input from three experts was translated into the knowledge representation units, or matchers, within the Hierarchial Classifier.

To my husband Rick with love

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0. INTRODUCTION

1.1. MISSION STATEMENT

The objective of this study is to develop a knowledge acquisition methodology that will lead to knowledge representation in the Hierarchial Classification tool. The knowledge acquisition methodology outlined attempts to model the map which an expert must traverse to reach a conceptual design decision. The methodology must satisfy the following criteria:

1. The domain is environmental engineering conceptual design, or the selection of technology(s) for waste remediation and treatment.

2. The repertory grid is used as the knowledge acquisition technique.

3. The process can be automated. A computer program can be written to execute the methodology.

4. The knowledge captured from experts by the methodology can be transferred into matchers of the Hierarchial Classification (HC) tool.

5. When the HC tool classifies a case, the reasoning can be explained as to why a node establishes or rejects.

1.2. OVERVIEW

Environmental engineering design consists of three steps - conceptual, preliminary and final design. Conceptual design is the identification of appropriate technology or sequence of technologies for the remediation of compounds in a waste stream which exceed regulatory standards. Preliminary design involves the selection and sizing of technology components, while final design involves the equipment and operational specifications.

Conceptual design in wastewater treatment can be compared to medical diagnosis. Individuals share common symptoms when affected with same disease organism. Medical diagnosis is the task of identifying these shared symptoms, which then dictates the prescribed treatment. Diagnosis in the case of environmental engineering means identifying the contaminating agents and developing an appropriate treatment technology (or sequence of technologies) for the removal or treatment of the undesirable compound(s). Using collective analytical parameters, commonalities are observed within the same industry or the same industrial process. Analytical test results, site evaluation and economic factors all contribute to the choice of technology implemented for treatment.

Engineers responsible for the conceptual design task make complex, difficult decisions when they evaluate systems for wastewater treatment. This process requires the understanding of diverse and changing legal requirements, and complex chemical and biological interactions. Frequently, their choice is among many competing technologies. It is difficult to discriminate among competing technologies in a rational manner since engineering expertise is diffuse and specialized.

As more technologies develop, so does the dilemma confronting engineers and regulators. Experts in conceptual design of environmental engineering systems are faced with the challenge of a developing and changing domain. Selection of the most efficient and cost effective remediation scheme to comply with regulatory standards becomes complex and difficult. To maintain expertise in this discipline, an expert must constantly incorporate new knowledge in the areas of technology, regulations and basic scientific research. The popular environmental solutions change over short time periods due to emotional and political influence. Since this domain is moving forward at such a rapid pace, it is nearly impossible to maintain expertise except in a very narrow scope. Therefore, in response to new regulations and technological breakthroughs, experts in conceptual design should ideally alter their decision making process to incorporate the latest developments. Unfortunately, their inability to do so results in conflicts and omissions when recommending remedial solutions.

One aspect of this dilemma centers on the conflict between conventional and innovative methods of treatment. Conventional methods are expensive, subject to increasing restrictions, and are not effective for certain wastes. Innovative technologies are likely to be cheaper, faster and more efficient, but are not widely implemented.

A knowledge-based system could provide relief from this dilemma for those making conceptual design decisions. An expert system to assist environmental engineers with conceptual design offers a mechanism to evaluate and select the most effective and efficient remediation system. Specifically, a system for computer-aided conceptual design of environmental engineering systems could provide answers to these problems by providing assistance to engineers in the selection and design of technologies and regulators in the evaluation of engineered designs.

Knowledge-based systems placed at the disposal of the decision makers can enhance their effectiveness (Klein, 1990). The computer-aided design tool for conceptual design has such potential. Data and models are used to recognize and formulate the problem, and ultimately evaluate alternative solutions. There is a need for a system which can process data and numeric relationships, and by reasoning, transform this data into opinions, judgments, evaluations and advice. Knowledge-based systems (KBS) fulfill this need by formalizing and automating the expert's paradigm and decision-making process.

The proposed system employs two knowledge-based tools, the hierarchial classifier and the assembler, to efficiently select appropriate treatment technologies and to permit rapid and efficient assembly of treatment trains that satisfy the treatment goals. The hierarchial classifier acts as a heuristic filter, eliminating technologies that do not satisfy the goals of the problem. The assembler takes the output of the classifier and presents a sequence of technologies (as many as feasible and required) to satisfy a set of goals while simultaneously satisfying any other problem constraints.

This thesis describes a methodology for knowledge acquisition useful for knowledge representation in the Hierarchial Classification tool. The domain is conceptual design for environmental engineering systems, specifically wastewater treatment. First, basic concepts are defined such as experts versus novices, paradigms, and why there is a need for such a tool. Then, knowledge acquisition and knowledge representation are discussed, with descriptions of the two techniques used- repertory grids and constraint based representation. A step-by-step methodology is presented with three examples. Finally, a discussion and concluding remarks close this presentation.

1.3. APPROACH

The product of this knowledge acquisition methodology is knowledge representation at the design level of the pre-determined hierarchy shown in Figure 1. Theoretically, any of the designs which branch from the design level in the hierarchy are appropriate solutions if the technology could be designed and operated with unlimited funds, space and supplies. However, not every alternative is practical to implement. The goal of the expert system is to model an expert's conceptual design decision for the most effective alternative.

Complex problems are easier to solve if partitioned, or decomposed into parts. First the smaller parts are solved, and then recombined for a result or decision (Kidd, 1987, Wright & Bolger, 1992). To model the decision-making process, the manner of decomposition must be identified. Kidd (1987) suggests that a methodology should specify a strategic division of tasks. In the case of conceptual design, the assumption is that the problem is decomposed on the basis of design criteria. When selecting a technology, in effect, the values of design criteria are selected which will most effectively achieve the goal of treatment. The conceptual designer assigns values to the design criteria based on the nature of the waste, effluent standards, space constraints and resources of the client. Then he selects

Table 1. Activated sludge design criteria.

Design option		COMPLETE MIX	PLUG FLOW	EXTENDED AERATION	CONTACT STABILIZATION	HIGH RATE	PURE OXYGEN
Design Criteria	Units						
Organic loading	pounds BOD / pounds MLSS-day	0.05-0.06	0.2 - 0.4	0.05 - 0.2	0.2 - 0.6	1 - 2.5	0.4 - 1
Space loading	pounds BOD / day-1000 ft^3	< 60	20 - 40	< 15	25 - 50, 60 - 75	1.5 - 3.5	120
Hydraulic retention time	hours	4 - 36		16 - 36		1 - 2	1 - 3
Sludge age	days	3 - 30	5 - 15	12 - 30	5 - 15	0.5	8 - 20
MLSS in reactor	grams / liter	3 - 6	1.2 - 3	3 - 6	1 - 3, 4 - 9	5 - 10	6 - 10
Dissolved Oxygen	milligrams / liter	< 2	< 2	< 2	< 2		4 - 10
BOD removal	percent	80 - 90	85 - 95	75 - 95	80 - 90	75 - 95	85 - 95
Recycle Rate	percent	50 - 150	25 - 75	50 - 300	50 - 150		25 - 50

MLSS = mixed liquor suspended solids, BOD = biochemical oxygen demand

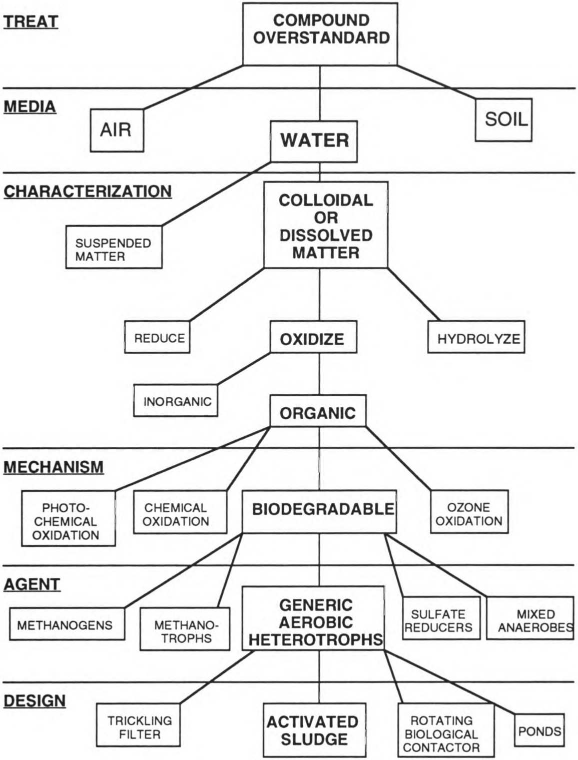


Figure 1. Hierarchy for conceptual design of environmental engineering systems.

the technology or method which incorporates the design values assigned. When choosing from competing design applications of, for example, the many variations on activated sludge, the engineer may refer to a chart similar to Table 1. The most effective technology design will be the one with the best match to the design values assigned by the engineer.

When the knowledge acquisition methodology reveals these differences of design as the expert views them, then the subsequent knowledge representation could model the process by which the decision is made. Toward this goal, the proposed methodology is based on the decomposition of the conceptual design problem by design criteria values. A four-step approach to knowledge acquisition and representation is proposed by Kidd (1987). First, component terms are elicited with a repertory grid in a familiar language. Second, criteria that the expert uses to organize concepts are identified. Next, a structure is formed through analytical techniques such as cluster analysis. This structure is represented and then transformed into rules and a framework using constraint based representation and the raw grid. Finally, the results are expressed in the matchers within the Hierarchial Classifier.

To classify a case, select a treatment design for a waste stream, an engineer could use an expert system. The proposed expert system poses questions about the waste influent and effluent and other relevant factors to determine appropriate design values for remediation. These questions are determined from two knowledge acquisition techniques - the repertory grid and constraint based representation (CBR). A map drawn of the internal decision tree structure indicates the expert's internal organization of knowledge. This expertise is then transferred into a matcher, the knowledge representation unit, for each technology represented as a goal state in the Hierarchial Classifier.

In a fully functional expert system, comment windows will explain the reasoning behind the decisions presented by the expert system along with related design specifications. Each expert may see these criteria differently, which will be expressed in the final expert system built based on the knowledge acquisition and representation.

2.0. BACKGROUND

2.1. DEFINITIONS OF TERMS

Constraint based representation - a knowledge acquisition technique, expert responds to groupings of concepts independent of context, identifies association and conflict among constructs

Constructs - bipolar characterization of elements in a repertory grid, ie. design criteria

Elements - represent the examples or instances within domain in a repertory grid, ie. technologies

Establish and refine - process of eliminating inappropriate solutions to the problem early in the hierarchy

Expertise - goes beyond just knowledge and experience by incorporating the process by which the knowledge and experience are structured and accommodated for use in decision-making.

Hierarchial classification - a step-wise problem solving technique which acts as a filter eliminating categories which are not appropriate for achieving the goal, hierarchy of nodes or steps the end node is the solution

Knowledge acquisition - communication and capture of expertise - goal to obtain and express the rules which the expert uses in the decision-making process

Matcher - table of rules or questions in a particular sequence, according to the answers to the questions, applicability is based on a calculated degree of match which when compared to a pre-determined threshold determines if node will establish

Repertory Grid - a knowledge acquisition technique, designed to help experts recognize and verbalize the breakdown of a problem, provides a forum for the expression of the picture of how a person views their world with a minimum of observer bias

Repertory grid analysis - FOCUS - provides exhibition of structure and pattern of the elements and constructs, identify which elements and constructs are highly correlated according to the expert

2.2. EXPERTS VERSUS NOVICES

Wright & Bolger (1992) offer an objective definition of an expert as "anyone who demonstrates significantly more valid judgement than persons or systems not accredited with expertise". Expertise is certainly more easily recognized than defined (Hart, 1986). An expert's perspective reveals an enlightening observation - domain knowledge is not adequate for expertise (Wright & Bolger, 1992). It is not just what an individual knows, but how that knowledge is absorbed, processed, accommodated and structured, which in turn determines how they use what they know (Hart, 1986, Wright & Bolger, 1992). Expertise goes beyond just knowledge and experience by incorporating the process by which the knowledge and experience are structured and accommodated for use in decision-making. Therefore, decision-making and expert judgement are skills which can be learned through enhanced intuition and creativity (Wright & Bolger, 1992).

A decision can be defined as an irrevocable allocation of resources under the control of the decision maker (Henrion, 1991). Preferences describe a decision maker's relative ordering of the desirability of possible states of the world. Successful decision analysis includes techniques for structuring problems, computing implications, analyzing sensitivities, and explaining results. Personal experience, heuristics and paradigms along with knowledge collectively narrow the search space for decision-making. When a person has created an internal structure for knowledge storage and retrieval, and can perform in a manner which others judge successful, they are considered to have expertise, and are recognized as an expert. It is this internal structure which expert systems attempt to model and emulate.

Problem solving is the process of transforming an initial situation into a desired situation, or a goal state found by carving a path through the search space. Experts operate from a search space which is their personal internal (mental) representation of a problem where problem-solving takes place (Klein, 1990). Individual behavior influences problem solving depending upon the structure of the problem. In a task with less structure, the individual experience has a greater influence. Therefore, by lending more structure to the task, the solution will be based more on objective knowledge, rather than subjective opinions.

Klein (1990) identifies three development stages from novice to expert. The first stage, cognitive, involves the encoding of declarative knowledge which is interpreted by general procedures. Next, in the associative stage, the novice compiles knowledge into procedures specific to the performance of the task at hand. Attention is required in the formulation of a solution to a problem, but knowledge is no longer stored in declarative form. Finally, expertise is achieved in the autonomous stage. Procedures become automated, and decisions are made without attention to the process itself. A recognized drawback, and sometimes noted as the evidence of expertise, is that verbal reporting of the thought process is lost. A knowledge engineering paradox is that the more competent domain experts become, the less able they are to describe the knowledge they use to solve problems (Ford, 1991). Knowledge acquisition attempts to model the autonomous stage by decoupling the declarative domain 'facts' from the rules used by the expert.

Wright and Bolger (1992) go on to say that experts exhibit a number of psychological characteristics which are not expressed in novice decision-making behavior. Some significant differences between novices and experts are 1) the definition of the initial state, 2) how the operators are used to navigate the problem space, and 3) what information is considered relevant and important.

Experts develop a calculative plan which pre-selects what to do at each stage with the shortest path to the goal with the least difficulty. Operators, as rules and heuristics, guide the search through the problem space. Some critics of experts say that these very rules and heuristics which are essential to their expertise often limit and restrict the search space to the point that the best or even appropriate solutions are overlooked. This is especially prevalent in domains where the knowledge base is changing rapidly. Also, some alternatives will be eliminated from the solution set early on in the decision process depending on the sequence that the heuristics are brought to bear on the problem.

The ability to simplify complex problems with their superior pattern recognition abilities is another common trait shared by experts across many domains. By making sense out of chaos, they can overcome adversity by identifying and adapting to exceptions. One strategy involves attacking smaller pieces of a problem and making continuous adjustments (Chorafas, 1990). This results in less critical errors which are correctable, thereby avoiding big mistakes. The way in which the problem is decomposed also differs from experts and novices. Experts group together items which share a commonality which is not recognized by the novice. This is a crucial element of expertise which knowledge acquisition techniques express.

There is a cognitive science difference between novices and experts (Wright & Bolger, 1992). Experts develop a perception of a limited domain from which they extract information well. Experts predefine their informational needs, where novices recognize them as they progress through the problem-solving task. They can sense what is relevant when making decisions through pattern-recognition.

Experts predefine the informational needs, and categorize according to principles. First they select the equations useful for the solution. This, in turn, prompts more knowledge that determines the equations useful for the arriving at the solution. Now the expert has the knowledge or data required for a decision or conclusion. Described as forward thinking, these processes known as protocol analysis (Wright & Bolger, 1992), are automatic and functionally independent. Protocol analysis for raw data is the skill component of expertise which expert systems attempt to model. Therefore, experts follow forward reasoning by utilizing stored functional units of knowledge from the given data to the goal.

In contrast, novices use means-end analysis (Wright & Bolger, 1992). They examine the data, and choose the appropriate equations, and attempt a solution. The acquisition of appropriate schema for forward thinking is, therefore, restricted. The novice will examine the goal state and reason backward, then select the goal which best fit the path. Deliberate reasoning with each step dependent on the previous forecasts the direction to continue.

Novices develop patterns through deductive thinking during the process of evaluation, rather than recognizing the pattern as experts do.

Judgment is an inferential cognitive process by which an individual draws conclusions about unknown quantities or qualities on the basis of available data (Wright & Bolger, 1992). However, often not all the data required is available. Experts and novices differ in the manner they handle uncertainty. Sometimes the novice will tend to immediately remove himself from the process, claiming the situation is out of his knowledge domain. They express a desire to avoid judgement mistakes.

Experts allow for the flexibility of uncertainty, and are willing to risk a decision as they are confident in their expertise. Experts will assume that they can synthesize a judgment when knowledge is insufficient (Wright & Bolger, 1992). With uncertainty, there is the increased tendency to generate additional alternatives which must be evaluated. To handle uncertainty, experts allow intermediate degrees of truth between true and false for factors being considered (Henrion, 1991). Heuristic methods used in dealing with uncertainty allow experts to continue through the search space in pursuit of the solution.
Experts have a highly developed faith in their own ability

(Wright & Bolger, 1992), and are effective, efficient problem-solvers (Hart, 1986). Their self confidence often manifests itself in arrogant behavior. They know when to adapt the decision strategy, and moreover realize when the problem is outside the realm of their expertise. Timing is the key to recognizing when the conditions have changed. Experts have a strong sense of responsibility for their decisions, and will seek help from others as they recognize that isolation can lead to inferior decisions (Wright & Bolger, 1992). They acknowledge other experts, and respect the contribution from them in areas where their own knowledge is lacking.

2.3. PARADIGMS

Three keys to the future are anticipation, innovation and excellence according to Barker (1992). All three are necessary for success in the next century. One important component of excellence is the capability of how to do the right thing the first time. Innovation is the way excellence is incorporated into action. Anticipation provides the information that allows for the excellent innovation to be implemented properly. All are relevant in the area of environmental engineering conceptual design.

Corporate and individual entities facing environmental compliance search for the best, most cost effective and reliable means to remediate and treat their waste problems. They turn to experts in the regulatory and consulting community for assistance in the appropriate technology and design for their situation. These experts, as in many domains, operate within paradigms. A paradigm is defined by Barker as a set of rules and regulations (written or unwritten) that does two things: 1) it establishes or defines boundaries; and 2) it dictates behavior inside those boundaries in order to be successful. There is an interrelationship of several paradigms which guide an expert's decision making and ability to solve problems. There are scientific paradigms as well as cultural, specifically regulatory, in the case of environmental engineering applications.

Paradigms are the heuristics or rules used in solving problems. New technologies and regulations attempt to change the paradigms from which we operate. When paradigms change, the rules change, and the problem solving exercise results in different solutions. In environmental engineering, both the scientific and regulatory paradigms are changing rapidly. The regulatory paradigms are not optional - laws must be obeyed. However, not so with the scientific. They are subject to individual evaluation and opinion and certainly are not all universally accepted. Herein lies the controversy of appropriate treatment technology. While the regulatory paradigm changes uniformly across both the consulting and regulatory community, the scientific paradigm occurs in all stages from the most conservative to the most progressive.

Dealing with incomplete or uncertain data can lead to new paradigms. Although we would assume that only experts have the knowledge to develop new ideas, sometimes the novice comes forward with revolutionary concepts. This is because their search space is not so narrowed as to eliminate possibilities from consideration. Unfortunately, the novice will seldom gain acceptance, or even an audience, where the expert will receive more immediate recognition and respect.

Every expert will, in the process of finding new problems, uncover problems he cannot solve. And those recalcitrant problems provide the catalyst for a paradigm shift, which alters the rules of the game. This is necessary when there are problems to solve, and there are no reasonable solutions. In the environmental arena, the conventional methods have solved many problems, however, there are increasing hazardous waste situations which conventional means are too expensive and inefficient. Innovative methods are a solution, they just need to be implemented. The proposed computer-aided tool for conceptual design assist in the acceptance of new paradigms in the approach to environmental problems.

2.4. WHY WE NEED A COMPUTER-AIDED CONCEPTUAL DESIGN TOOL

The conclusions of a commercialization plan for a computer-aided conceptual design tool found in Appendix A indicate a need for this product (Schutz-Riley, 1992). A survey of competitive computer programs revealed an unfulfilled niche for a decision-making program which could discriminate among competing remediation technologies. The distinguishing features of the proposed Hierarchial Classifier tool are that it is an expert system with decision making capability, draws knowledge from interfaced databases, and includes innovative technologies. Unique to the proposed system is its portability to all major PC'sdue to the use of the Smalltalk 80 language .

Experts develop a framework from which they can be successful. Two paradigms, the scientific and the regulatory, make up the framework from which the conceptual design expert operates. Rules of the paradigm, or heuristics, are applied to narrow the search space for the sake of making it manageable. Although good decisions are made from within this narrowed search space, often applicable alternatives are removed from consideration early in the decision process. The commercialization plan (Schutz-Riley, 1992) identified five heuristics implemented in the choice of remediation: 1) regulatory, 2) total cost, 3) past personal experiences, 4) knowledge about environmental contaminants, and 5) knowledge about technology alternatives. The order in which these heuristics are applied to a problem can greatly affect the solution. Above is the sequence imposed most often in conceptual design decisions in environmental engineering, where regulatory issues drive the process. Implied are the state and local regulatory climates which dictate the probability of government approval for implementation. The final decision is not based on the best scientific evidence, but rather on political possibility.

While perhaps not scientifically sound, this is the path of least resistance. Expertise is more easily acquired based on the regulatory climate and past experience than on the scientific evidence. A paradigm based on regulatory heuristics is more stable and embraced by a wider audience. The risk of being wrong is less when dealing with uncertainty and incomplete data as is often the case in environmental problems. The solution of choice is the alternative which appears most cost effective and achieves regulatory approval in the least amount of time.

Consequently, environmental consultants have become expert in preliminary design rather than conceptual design. That is, they can optimize the design which is most acceptable from the regulatory standpoint to fit the remediation problem, rather than optimizing the choice itself. This behavior is reinforced by the regulatory agencies and legal community. Thus, expertise develops with the past experience and regulatory heuristics influencing their decisions. Consultants gain expertise in predicting the regulator's judgement, and base their decisions on this line of reasoning. Consequently, the best scientific solution is often not even considered as a viable option.

The scientific paradigm is unstable. Many paradigm pioneers are challenging the rules of the scientific paradigm by developing new technologies to deal with the hazardous wastes which contaminate our earth. These researchers are willing to take the risks necessary to invest their time and energy into ideas for which the outcome is uncertain. They have been successfully rewriting the rules of the scientific paradigm at a very rapid pace. The fruits of their efforts are many new and exciting innovative ideas for coping with pollution especially in the realm of environmental biotechnology and advanced oxidation techniques.

While consultants attempt to overcome regulatory obstacles, the scientific community attempts to overcome natural physical, chemical and biological obstacles. Alternative methods of remediation are emerging through innovative technological development. However, these methods are not readily implemented. One reason is that regulators often lack the scientific expertise needed to evaluate these new methods, and there may be insufficient experience to risk implementation. Consultants are hesitant to recommend innovative methods if regulatory approval is unlikely. The implementation of promising new technologies can only be expected when the new scientific paradigms are embraced by the regulatory community.

One could suggest that experts simply change the way they make conceptual design decisions by changing the sequence in heuristics. Even though the regulatory world is changing, the scientific world is changing at an even faster pace. Therefore, the landscape of the expert's search space is also changing in an attempt to incorporate new knowledge. The re-evaluation of the search space by replacing new rules for old to accommodate this new information is very difficult. Rather than take the more difficult path of re-evaluation, many consultants instead will strengthen their present paradigm to block this process. The result is a less than optimum knowledge base from which decisions and judgements are made.

What if there was a computer tool available which contained the rules of the new scientific paradigm and knowledge to fill the gaps of uncertainty? It is likely that those making conceptual design choices would be willing to accept a broader range of possible answers to remediation problems. Simply by considering a change in the sequence in which the heuristics are applied to a conceptual design study, the probability of implementing new innovative methods improves. If such a scientific-based paradigm begins with the contaminant characteristics and technology alternatives, a wider assortment of methods will be presented. Regulators might recognize alternative methods to the conventional treatment regimes for many remediation problems. In some cases, more money may need to be spent in waste characterization and bench-scale testing to verify a decision, however the cost of implementation and operation has proven time and time again to be favorable. The result is overall cost reduction while achieving the same or better level of remediation.

There are many factors which are unpredictable and undetectable with respect to technology performance. This is especially true with biological treatment processes. So, of course, bench and pilot scale testing is always recommended prior to full scale implementation. To reduce the cost and enhance the effectiveness and applicability of bench and pilot scale tests, the design parameters can be estimated and defined with the assistance of an expert system. The purpose of the proposed conceptual design tool is to limit the alternatives using design criteria that are most appropriate for a specific waste stream.

The following statement (Schutz-Riley, 1992) summarizes the sentiment of potential customers of a knowledge-based expert system for conceptual design.

> *"The problem with implementing innovative technologies is not awareness that they exist, but the confidence that they will perform. Detailed information regarding design, costing, and performance is needed to overcome this insecurity. Until conventional methods become too expensive, they will remain the method of choice."*

3.0. KNOWLEDGE-BASED SYSTEMS

Knowledge-based systems (KBS) are computer programs which have a wide base of knowledge in a restricted domain, and use complex inferential reasoning to perform tasks which a human expert could do (Hart, 1986). Rich, (1991) refines this definition to include only tasks executed by computers which presently are performed better by people. Expert system technology improves human decision making by formalizing human expert knowledge (Henrion, 1991). KBS's have a wide base of knowledge in a restricted domain in which they use complex inferential reasoning to perform a task which human experts do well. They simulate expert problem solving by processing data and numeric relationships, and then by reasoning, transform data in to opinions, judgement, evaluations and advice (Klein, 1990).

Experts are effective, efficient users of their knowledge (Hart, 1986), and a good KBS will reflect these traits. Building the KBS model is only the beginning. For an expert system to be judged a success, it must also perform successfully in providing acceptable answers to the same problems currently solved by experts. Sound justification for problem-solving process by the KBS will lend confidence for it's use.

Experts develop a superior strategic awareness of possibilities within the search space, or problem space (Wright & Bolger, 1992). The structure of the task determines the structure of the search space. Search is the process of finding a path through the internal structure. Experts calculate a plan which preselects what to do at teach stage of the path, and ensures that successive steps follow (Wright & Bolger, 1992). They select the plan with the shortest path to the goal with the least difficulty.

An informed search is performed using heuristic search functions that are operators which guide the search. A heuristic is a rule of thumb, or judgmental technique that leads to a solution some of the time, but provides no guarantee of success. The purpose of heuristics are to reduce the number of alternatives from an exponential number to a polynomial number. This allows the designer to obtain a solution in a tolerable amount of time. Instead of exploring every possible situation, the search is narrowed and only a limited number of alternatives are examined. This is a constrained rather than exhaustive search. The risk is that the heuristic may eliminate the best answer to the problem. However, a good heuristic will identify good, workable solutions most of the time using heuristic information, which is information about the problem used to guide the search more efficiently.

An important characteristic of expert systems, KBS's, is the ability to explain reasoning and justify the solution provided. When a node establishes within the hierarchy, a comment window indicates what data and criteria are responsible for the matcher assigning a confidence factor which exceeds the threshold, therefore establishing the node. Additional design considerations, consequences and anticipated events are also included in support of the final decision.

3.1. HIERARCHIAL CLASSIFICATION

According to Parsaye & Chignell (1988), when the number of eventual selections is large, the decision making will be in a hierarchial form. This is certainly the case with decisions in conceptual design. Hierarchial classification efficiently compares a set of pre-enumerated categories with particular situation to find those categories that "best" apply. The hierarchial classification approach can and has been used successfully in a number of problem-solving roles including areas of medicine, nuclear power and chemical engineering. As part of the conceptual design process, hierarchial classification is used as a heuristic filter, pruning categories which are not appropriate for achieving the goals of the problem.

Categories are organized into a hierarchy shown in Figure 1.

The connected nodes at the next level down in the hierarchy represent a subcategory of the node and the connected node one level up in the hierarchy represents a super-category of the node. Categories become more specific as the hierarchy is traversed from top down. A node can be thought of as an expert in determining if the category it represents is relevant to the problem at hand.

Each node of the hierarchial tree contains a matcher. The matcher is a structured representation scheme which relates small chunks of knowledge together as a unit. This simplifies processing operations since knowledge required is usually contained within the node itself, or is easily accessed as a unit from another object through just a few linkages. Execution of a matcher, or matching, is the controlled sequence of operations to determine the best alternatives according to stored rules which consumes a large portion of the processing time of execution.

The function of the matcher is to calculate the 'degree of match' between the category and the present problem. Questions about the problem are answered by the user classifying a case. The questions within the matcher are representative of expert's decomposition of decision-making strategy. Questions reflect the heuristics which guide the search through the internal structure of the expert. These answers are the input to the matcher, which returns a computed degree of match. For environmental technologies, the degree of match depends upon the chemical and physical characteristics of the contaminated media, the technology or class of technologies under evaluation and other practical considerations such as space and cost. Confidence factors, assigned based on the results of knowledge acquisition, are additive, and contribute to the calculated degree of match.

The path throughout a search space is defined by the nodes that establish. The establish and refine process is a way of eliminating inappropriate and inapplicable solutions to the problem as early as possible in the hierarchy. The more data and information known about the problem, the stronger the confidence in the returned value. The degree of match is compared to a pre-determined threshold to determine if the node will establish or reject. This ultimately reduces the number of goal states to be evaluated.

Figure 2 shows an example of a defined search space of conceptual design. The shadowed boxes represent nodes which have established. Further search toward the goal is limited to sub-categories of shadowed boxes. The other paths will not be considered, as they lead to inappropriate conclusions. For example, at the mechanism level of the hierarchy, the node for 'oxidized by ozone' did not establish, which implies that this mechanism will not be effective in achieving the remediation goal. Therefore, it is not necessary to explore any of the sub-categories of this node. By limiting alternatives, the overall search restricted to potentially appropriate solutions, and is therefore, more efficient.

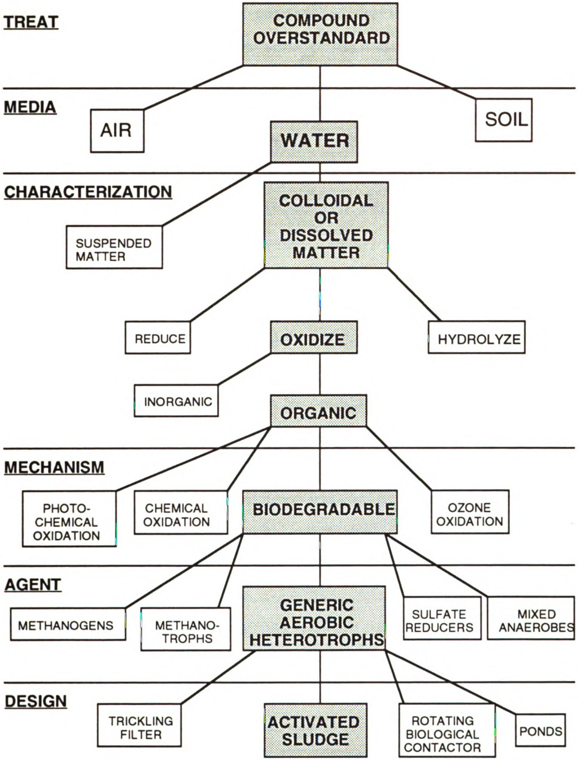


Figure 2. Refined hierarchy for conceptual design of environmental engineering systems.

3.2. KNOWLEDGE ACQUISITION

Knowledge acquisition is largely a matter of communication, beginning when experts in some domain determine they have valuable information to share (Bradshaw, 1992). The goal of knowledge acquisition is to obtain and express the paradigm from which the expert operates. Kidd (1987) proposes two functions of knowledge acquisition, the elicitation and analysis of data. Data elicitation refers to what data is needed and how it will be used. Analysis refers to the transformation of data into an interpretive framework.

Knowledge acquisition techniques provide a means of capturing and representing expertise within the Hierarchial Classifier. One difficulty in constructing expert systems is that experts often cannot explain what they do or how they use their knowledge to reach conclusions. Although experts are skilled at pattern recognition and communicating results, they lack the verbal protocols to identify the decision process itself (Klein, 1990, Wright & Bolger, 1992). Tools such as the repertory grid and constraint based representation overcome this difficulty and allow the expression of expertise from some experts.

Kidd (1987) defines knowledge acquisition as the transformation of data into an implementation formalism. Kidd, along with other knowledge engineers (Gruber, 1987 and

Wright & Bolger, 1992) regard knowledge acquisition as the bottleneck in building expert systems. Although many dispute the label "bottleneck" when addressing the knowledge acquisition issue, they agree that effective acquisition of knowledge is crucial to building an effective KBS. Gruber (1992) maintains that the design of a KBS should anticipate the acquisition process and make it easy for experts to express their knowledge. Further, some recognize the problem of knowledge acquisition as a representation mismatch. The primary contribution of acquisition design is to enable the expression of knowledge in a more comprehensible and accessible manner. Without the proper model for expression, the expert will not fully be able to divulge his knowledge in a representable fashion.

An analysis of successful knowledge acquisition tools according to Gruber (1987) suggests that they satisfy two primary requirements. First, they must identify the type of knowledge to expect from the expert. Then, they should provide a functional mapping from the user input to representation in the knowledge based system. When the underlying architecture supports representation in the first step, then the second step is simplified.

A review of knowledge acquisition techniques for expert systems is offered by Welbank (1987) and Neale (1988).

Klein (1990) identifies three strategies of knowledge acquisition: 1) expert-driven, 2) machine-driven and 3) knowledge engineering-driven. The expert-driven strategy is observed when the expert encodes their own expertise. Since many experts cannot verbalize their decision making process, this strategy is not effective as a general solution (Wright & Bolger, 1992). The second approach is machine-driven techniques involving machine learning. A criticism of this method is that the limiting operating structure includes irrelevant knowledge and omits necessary information for appropriate results. The resulting knowledge representation scheme do not produce decisions which accurately reflect those of the expert.

Knowledge engineering-driven approaches include direct interaction with experts to model the task and performance of the decision process. Methods include the interview, protocol analysis, repertory grid, constraint based representation, and others (Chorafas, 1990). With complex decision-making, there is a problem with observation methods, such as interviews and protocol analysis according to Wright & Bolger (1992). Experts often arrive at decisions quickly. Due to their rapid combinatorial assessment of information, they seldom can provide details of the process. Researchers of knowledge acquisition have found that methods such as interviews only cover possible considerations concerning a particular case, without providing the scope for the rules which apply to the domain of expertise. Methods such as repertory grids and constraint based representation overcome these problems by addressing the full scope of the decision domain, and are therefore accepted as more reliable methods in the field of knowledge engineering.

A combination of knowledge engineering-driven and machine-driven techniques appears to offer the best strategy for knowledge acquisition. Repertory grids and constraint based representation can be used to gather the knowledge, and a computerized program assists the expert in the arrangement, modification and final representation of knowledge.

3.3. REPERTORY GRID TECHNIQUE

The repertory grid (also referred to as simply 'grid') is based on the personal construct theory first introduced by George Kelly in 1955. Kelly's theory proposed that people partition experiences into constructs which make up a model of their world. They classify and categorize experience and knowledge, and then develop theories about their world. Their behavior and decisions are directed by these theories because they anticipate events and act based upon their expectations.

Shaw (1981) describes grids as "the seductive promise of accurate measurement of subtle perceptions". Grids appear simple at first, however, through proper design and elicitation using skill and sensitivity, they can be a powerful knowledge acquisition tool. The grid accomplishes several tasks including eliciting distinctions, decomposing problems, combining uncertain information, incremental testing and integration of data types (Boose, 1989). They are most applicable for analysis problems, or portions of synthesis problems that can be reduced to analysis problems. Boose (1989) discusses the use of several repertory grid-centered tools.

Since grids provide a forum for the expression of the mental map of how a person views their world with a minimum of observer bias, they offer improved process efficiency and faster knowledge base generation than other knowledge acquisition tools (Hart, 1986). When experts attempt to verbalize their decision-making process, they often have trouble identifying the key point which drives the result. In an attempt to isolate this point, they may become confused and embarrassed because their thought process suddenly appears without structure or basis. The grid captures the structure of the problem from the expert's perspective in a way which he cannot verbalize. Grids are particularly effective in domains where experts can detect subtle nuances that differentiate concepts, but cannot articulate the criteria by which they arrive at a decision (Shaw & Gaines, 1983). Through grid analyses, the structure and protocols are extracted in a manner which is both comfortable and non-threatening for the expert.

3.3.1. Components of the Repertory Grid

The repertory grid is composed of elements and constructs. The grid is designed to explore thought patterns by eliciting constructs which define the elements of a person's individual world.

3.3.1.1. Elements

Elements are the choices an expert must make, and are the examples or instances within the domain of interest. According to Hart (1986), elements must be representative of the pool from which they are drawn. The choice is determined by the reason for the investigation. Assuming that expertise is in a narrow domain, the number of elements will be limited.

Stewart & Stewart (1981) offer some guidelines regarding the selection of elements. Elements should be specific, discrete and precise as possible to allow for clear construct elicitation. The elements do not necessarily need to be evenly distributed across the search space, however they should not be sub-sets of each other. The outcome of the grid analysis is dependent upon one expert's understanding and definition of the elements compared to that of another expert.

3.3.1.2. Constructs

Constructs are distinguishing characterizations which are shared by the elements to some degree. Diaper (1989) describes constructs as mental "tools" which allow a person to discriminate between elements in one's world. Constructs are a way of transcending the obvious - lending structure to our outlook of our world. A construct is a way of describing how two or more things are alike, and therefore different from a third or more things.

Kelly asserted that people never affirm anything without simultaneously denying something else. Hence, constructs are bipolar, allowing a matrix of the pattern of interrelationships between elements. The bipolarity resides in the construct itself, not in the two sets of elements that are sorted by the construct (Hart, 1986). A detailed discussion of the bipolarity of the construct is offered by Diaper (1989).

3.3.2. Grid elicitation

The elicitation of elements and constructs is not trivial, but rather complex and iterative. Although the process appears simple, the design and elicitation of grids requires sill and sensitivity (Shaw, 1981). The knowledge engineer must state the clear objective for analysis. Level and extent of expertise will shape the grid to be analyzed.

There are three strategies for selecting elements for a grid (Stewart & Stewart, 1981). Elements can be supplied by the interviewer, which is helpful when several expert responses are being compared. The other options involve the expert supplying the elements, either directly or by elicitation using a predetermined sequence of questions.

The recognition of elements leads to elicitation of constructs. Kelly (1955) introduced a method for eliciting constructs known as the triad method. This method is based on the personal construct theory of how constructs are formulated in a person's mind. The expert is asked to compare three elements, and specify how two are alike and thereby different from a third. The contrasting pole is identified to ensure the constructs are bipolar. As the triad comparison progresses, more constructs and elements are added to the lists used to create a repertory grid. The triad comparison continues until the expert does not identify any new elements or constructs for the grid.

According to Hart (1986), two important factors must be kept in mind with regard to grid elicitation. First, the elements must be within the range of convenience of the constructs, and secondly, judgment should not be forced onto the expert. Kelly proposed that a construct always operates within a context and that there are a finite number of elements to which it can be applied. The range of convenience of a construct is described by the number and kind of elements that can be rated on it. Not every element can be rated on every construct. Some constructs have a very wide range of convenience, such as good-bad. A construct such as high oxygen transfer rate versus low oxygen transfer rate will not have as wide a range. Therefore, some constructs will not be applicable or relevant to all of the elements in a grid. The expert should not be forced to make a judgement on the relationship between elements and constructs where none exists.

3.3.3. Grid Scoring

Elements are rated according to each construct using one of three scales. Elements can be ranked against each other, or rated along a continuous scale. Rating scales have been used from a two-point to a nine-point scale. There is evidence to suggest that a seven-point scale is getting close to most people's limits of discrimination, and much above five points is very difficult to examine visually

(Stewart & Stewart, 1981). Ranking may force the indication of differences when in fact they don't exist.

A third technique calls for a positive or negative response, without indicating range. For fast visual inspection, a two point scale indicated by symbols of colors is useful. The trade-off is simplicity and speed for detail. A dichotomy rating scale allows for the expression of differences without the notion of scale.

3.3.4. Grid Analysis

Analysis of a grid provides the exhibition of structure and pattern of the elements and constructs. The cluster analysis technique known as FOCUS is a way of measuring the distance between a pair elements or a pair of constructs by summing the absolute differences between ratings for all pairs (Shaw, 1981, Hart, 1986). FOCUS identifies how the elements and constructs relate to each other by calculating the difference measures and similarity values.

3.3.4.1. Difference Measure (dij)

Elements are compared by calculating the difference in their scored ratings. The sum of the differences in the scored ratings of two elements for all of the constructs (dij) is calculated by the following formula:

$$dij = |E1C1-E2C1| + |E2C2-E3C2| + \dots |E_{i-1}C_j-E_iC_j|$$

where i = number of elements

j = number of constructs

To calculate the difference between constructs, sum the differences between two constructs for all elements (dji) as follows:

$$dji = |E1C1-E1C2| + |E2C1-E2C2| + \dots |E_iC_{j-1}-E_iC_j|$$

where i = number of elements

j = number of constructs

3.3.4.2. Similarity Value (SV)

The dij value reflects the dissimilarity in scores between two elements or constructs. The maximum dij value is the maximum distance in the rating scale times the number of constructs. A dissimilarity fraction is calculated by the formula:

$$\frac{dij}{k * l.}$$

where k = maximum distance in the rating scale
l = number of constructs or elements

For example, the maximum distance in the rating scale, k, for the rating scale -1 to +1 is k = 2. The maximum dij value us k * l.

A similarity fraction, or similarity value (SV) is calculated by the formula:

$$SV = 1 - \frac{dij}{k * l}$$

To remove the decimal point, multiply by 100. Two elements or constructs are considered similar if the SV is greater than 50 (Hart, 1986).

3.3.4.3. Cluster Analysis

The FOCUS technique is a means of identifying elements and constructs that are similar. The original grid is evaluated by calculating a difference measure (dij) and similarity value (SV).

Correlations are made between elements or constructs, and are visually displayed in a tree structure. Elements in the completed grid can be FOCUSed to derive the tree structure using the following procedure which is a modification of the original FOCUS technique introduced by Shaw (1981) and described by Hart (1986).

1. Calculate the difference measure (dij) between all the scored ratings for the pairs of elements. Create table of dij values.

2. Calculate a similarity value (SV) for each dij. Create a table of SV values.

3. Examine SV table for highest value greater than 50 (Hart, 1986). Fuse the two elements involved, creating a new element. Assign a new element number to the pair of elements which comprise this SV. The new element will contain all the constructs which the two fused elements scored the same. If one element scored "0", use the "-1" or "+1" from the other in the new fused element. If one element scored "-1" and the other scored "+1", then remove that construct score from the new fused element. In subsequent dij and SV calculations, the number of scored constructs, the value of l, will reflect the eliminated constructs.

4. Excluding the two elements which were fused into a new element, find next highest value in the SV table.

   a. If a higher SV exists between an unfused and fused element pair, proceed to next step. If not, then fuse this new pair, and assign a new element number.

   b. If there is a tie, that is, two pairs of elements have the same SV value, the three elements are fused into one.

5. Repeat step 1-2 using new fused elements with any remaining elements. Adjust the i, j, and l values accordingly when calculating the dij and SV.

6. Create a new raw grid, dij table, and calculate new SV's from the new dij table. Build onto the tree as in Step 3 above.

7. Repeat steps 5-6 until all elements are 'fused'.

3.4. CONSTRAINT BASED REPRESENTATION

Constraint based representation (CBR) offers an effective approach to knowledge acquisition, and is more flexible than the interview or grid technique (Gammack, 1989). An expert is allowed to respond to groupings of concepts rather than a sequence of independent questions. When the outcome of a decision procedure depends on features, often the order of presentation affects the outcome. This is true in the conceptual design process, as priorities and existing conditions often dictate the solution. Constraint based representation provides explicit representation of the probabilistic dependence and independence the design constructs (Henrion, 1991). Unrealistic combinations are removed from consideration, and strong associations are given priority in the decision-making processes.

Questions are posed to the user in all knowledge acquisition tools. In many expert systems, these questions may be irrelevant to the final decision but they are required by the structure and predetermined flow of control. Users are put off by irrelevant questions, and will tend to discredit the system when this occurs. Experts tend to restrict and define the search space so that irrelevant questions are not asked. This is observed especially in domains where solutions are reached by data or event-driven strategies.

Elicitation of knowledge supporting the decision-making process may be a problem using conventional techniques. When expertise consists in rapid combinatorial assessment of relevant information, Wright contends that these techniques are ineffective in identifying heuristics to constrain the search. In CBR, forward-chaining reasoning is constrained to narrow the search space, and then backward chaining is used to test the result (Gammack, 1989).

Constraint based representation provides a venue to capture and represent this problem-solving approach. The number of decisions the expert must make is reduced by pruning the decision tree that represents the internal structure for the expert. By grouping in this manner, the total number of individual responses gleaned from the process are more then the expert actually gave (Gammack, 1989).

3.4.1. Eliciting the CBR

From the design constructs elicited in the repertory grid technique, a triangle chart is developed. The expert is asked to set a range of probable values for each design construct, and then divide this range into three sub-ranges.

3.4.2. Scoring the CBR

The expert is asked to compare two design constructs at a time. For each of the three pre-selected sub-ranges, the expert will indicate a strong relationship between the pair of design values using a "+" for strong positive relationship, and "-" for strong negative relationship. Not every square will have a score. A score on the CBR indicates extreme situations.

3.4.3. Rules and Comments from CBR

When an expert has scored a pair of design constructs as "+" or "-" in the CBR, a strong relationship is indicated regardless of other design criteria. The results of the CBR chart are expressed in table form grouped by design constructs for easy reference. Results of the CBR can be used for:

1. Pruning the internal decision tree.

   Design constructs can be revealed by constraint based representation. If the tree contains a path which, according the CBR, is not a consideration, then the affected branches are deleted.

2. Conflict resolution

   CBR can also be used to find any conflicts within the repertory grid. After the tree is constructed, the results of CBR can be used to prune branches which violate the CBR rules which have been identified by the expert. If a branch is pruned which leads to an element goal state from the grid, then the expert is asked to examine the responses for that element in the grid and the design constructs in the CBR. The changes made by the expert can be used to corrected tree structure, and CBR pruning continues until there are no violations between CBR rules and the tree structure.

3. Comment windows

   Comments are written from the constraint based representation as an if/then statement presented in tabular form. These are summarized and revealed in the comment window of each node as they apply.

3.5. KNOWLEDGE REPRESENTATION

Knowledge representation is the model built of the expertise resulting from knowledge acquisition. Knowledge must be represented in such a way that objective expression of the expert's decision-making processes are reflected in the inferential reasoning of the knowledge-based system.

Models are devices used to attain or formulate the knowledge about a problem, dependent on the context and purpose from which they are derived (Bradshaw, 1992). The power of models lies in their ability to function as tools for thought, also known as cognitive artifacts. The way in which knowledge is brought to bear upon a problem depends upon the way in which knowledge is represented within the model. In the HC model, the results of the knowledge acquisition process are incorporated in matchers and comment windows for the nodes of the hierarchial tree.

The internal structure from which experts solve problems can be shown pictorially as a decision tree. A decision tree assumes the decision process is serial, composed of predecisional stages which contribute to the final decision. Keren (1992) observes that a decision may take place at a certain point in time, yet is usually preceded by several predecisional stages. The predecisional stages are represented in the HC tool in the primary and secondary matchers.

3.5.1. Decision tree structure

Using the following five-step procedure, a decision tree structure can be formed from grid analysis. Starting with the node at the top of the cluster analysis (CA) diagram,

(1) identify the branch with lowest SV score between two elements,

(2) list the design criteria constructs by which these two elements differ,

(3) create two branches using poles of the applicable design criteria,

(4) examine the next lowest SV and repeat steps 1-3.

(5) Continue steps 1-4 until the CA diagram is redrawn with the appropriate design construct at each branch of the tree. If a design construct was identified at a lower SV branch, it should not be repeated in a branch with a higher SV.

Branches that violate CBR rules can be pruned by applying the above procedure. If the pruning results in the elimination of an element, then the expert must re-examine the responses responsible for this conflict between the grid and the CBR chart. Any changes should then be incorporated.

3.5.2. Matchers

The purpose of a matcher is to represent the pattern of decisions used by the expert. Rules identified in the CBR and grid are represented as matchers at each node within the hierarchical classifier of the KBS. The user is presented a series of questions, and the answers are the input into the matcher. This input is represented as the confidence factor, derived from the concept of certainty factors used in the MYCIN program (Buchanan and Shortliffe, 1984). The output is a degree of match between the answers given for each feature and the goal state being evaluated.

Matchers are independent units based on local information (Punch, 1991). The output from one matcher does not affect the other matchers in the hierarchy. Changes in the queries, similarity values and weight factors within the matcher do not necessarily influence the operation and responses returned from others. This allows the expert to make adjustments to each matcher independently.

3.5.2.1. Building the Matchers

Two levels of matchers are used in the proposed HC, primary and secondary. The primary matchers calculate the degree of match from user input. There are three possible answers to the questions stored within the matchers - yes, no or don't know. A confidence factor is assigned to yes or no answers. If the answer is "don't know", then the secondary matchers return a confidence factor to the primary matcher. The value of confidence factors and degree of match ranges from

-1, indicating a low confidence factor or degree of match, to +1, indicating a high confidence factor or degree of match.

3.5.2.1.a. Primary Matcher

The primary matcher for a node is derived from the design constructs shown in the FOCUS structure. These design constructs make up the first column of the matcher and are listed in order of ascending SV. Rows in the matcher provide the response from the user for the corresponding design criteria. The sign of the confidence factor (CF) is taken from the tree structure for each node indicated by the elements in the original grid. A confidence factor of 1 is returned with a yes or no response to the question which returns a +1 or -1 as appropriate.

3.5.2.1.b. Secondary Matcher

If the user response to a design construct is "don't know", then by cascade condition, the user is presented with a secondary matcher. The confidence factor computed from the secondary matcher is returned to the primary matcher for the corresponding design construct. The maximum absolute value returned is 1.

3.5.2.2. Matcher questions and confidence factors

A four-step procedure is outlined to derive the matcher questions and assign confidence factors.

1. Create a table of dij and SV's for constructs as was done for the elements. Consider the portion of the table with design constructs on the horizontal axis and feature constructs on the vertical axis.

2. Examine the 1st branch in the tree from the original node. Identify the design construct(s) responsible for the split in this node. To do this, go back to the grid of 'fused' elements and determine which design construct scored differently. The SV value of the pair determine the sequence of design constructs in the primary matchers.

   If no design construct is different, then ask the user to compare the two fused elements and identify a design construct for which they do vary. Incorporate the new construct into the original grid, score, reFOCUS and continue.

3. The secondary matchers are derived from the SV table for constructs. For each design construct, list the feature constructs with a SV greater than 60 in descending SV value. (An SV greater than 50 indicates similarity, (Hart, 1986). A value of 60 is chosen to reflect a strong degree of similarity between constructs. The user of the system is asked a question based on the feature. The feature constructs are presented in order of SV, with the greatest value first.

4. The confidence factor (CF) is calculated as a function of the SV and the ratio of number of rules considered to number of rules available. The sign of the CF is taken from the grid score. If the answer to the rule is yes, then the sign of the SV is positive, if the answer to the rule is no, then the sign of the CF is negative. If the score was "0", ask the expert which sign would apply to the design construct. (This response does not change the score on the original grid, only affects the construction of the secondary matcher.) The expert has the option of deleting feature constructs from the secondary matcher. A formula algorithm (Boose, 1986) is used to calculate the CF for each combination in the table. If the computed CF has an absolute value greater than 1, default to a value of 1 OR -1. The confidence factor returned to the primary

matcher is computed based on the user responses to questions generated from the feature constructs. The algorithm for calculating CF is as follows:

a) Begin with rule with largest SV with yes (Y) answer. (A high SV indicates a strong correlation between constructs. The first rule in the CF computation has the most influence, therefore it should be the construct with the highest correlation, or SV.)

b) Divide SV by number of rules available.

c) For each additional rule to be considered, in sequence of greatest SV first, continue:

$$CF_n = CF_{n-1} + [\ (n/m) * \text{new SV} * (1-CF_{n-1})\ ]$$

where:
- n = number of rules considered
- m = number of rules available
- CF = confidence factor
- SV = similarity value

3.5.2.3. Weight factors

The expert has the option to prioritize the design criteria in each matcher independently. A weight factor from 0 - 1 may be assigned. A weight factor of 0.1 means that such a design criteria is 10 % as important as one with a weight factor of 1. The confidence factor is multiplied by the weight factor for the value returned to the right-hand column in the matcher. This value is used to calculate the degree of match.

3.5.2.4. Degree of Match

An overall degree of match is calculated from the confidence factors. The degree of match is computed as a weighted average of the values returned from each construct in the matcher. This is based on the concept of additive value function introduced by Klein (1990). The ratio of the weighted average to the best possible value is the degree of match, with a maximum absolute value of 1.

$$\text{degree of match} = \frac{CF_1W_1 + CF_2W_2 + \ldots CF_nW_n}{n}$$

where CF1 = confidence factor for design criteria 1
W1 = weight factor for design criteria 1
n = number of design criteria in matcher

Based upon a pre-determined threshold value assigned by the user classifying a case, the computed degree of match will cause the node to either establish or reject.

3.5.3. Comment window

A summary of the rules invoked to establish or reject each node are provided in the comment windows. Any applicable CBR rules are listed, along with other design criteria selected from the primary matcher. A second window will outline the feature constructs which relate to the primary matcher. This provides the explanation for the expert systems' reasoning in arriving at the particular goal state.

4.0. METHODOLOGY

A flow diagram for a proposed methodology of knowledge acquisition in environmental engineering conceptual design is shown in Figure 3. The responses from Expert # 1 are used in the examples provided in the following sections.

4.1. Elicitation

This procedure is adapted from methods developed by Kelly (1955), Kidd (1987), Shaw (1981), and Stewart & Stewart (1981). In the following sections, instructions for elicitation are provided. Underlined titles correspond to the steps in flow diagram of the proposed methodology shown in Figure 2.

Choose node to expand. Begin with a node whose children are design considerations of the parent. Refer to Figure 1. In the example, the node to expand is activated sludge.

List design applications which make up the children nodes of the node to be expanded. This is element elicitation. The elements make up the headings of the repertory grid as in Table 2.

Table 2. Element elicitation for a repertory grid

ELEMENTS	COMPLETE MIX REACTOR	STEP FEED	DEEP SHAFT	SEQUENCING BATCH REACTOR	PURE OXYGEN	OXIDATION DITCH
CONSTRUCTS						

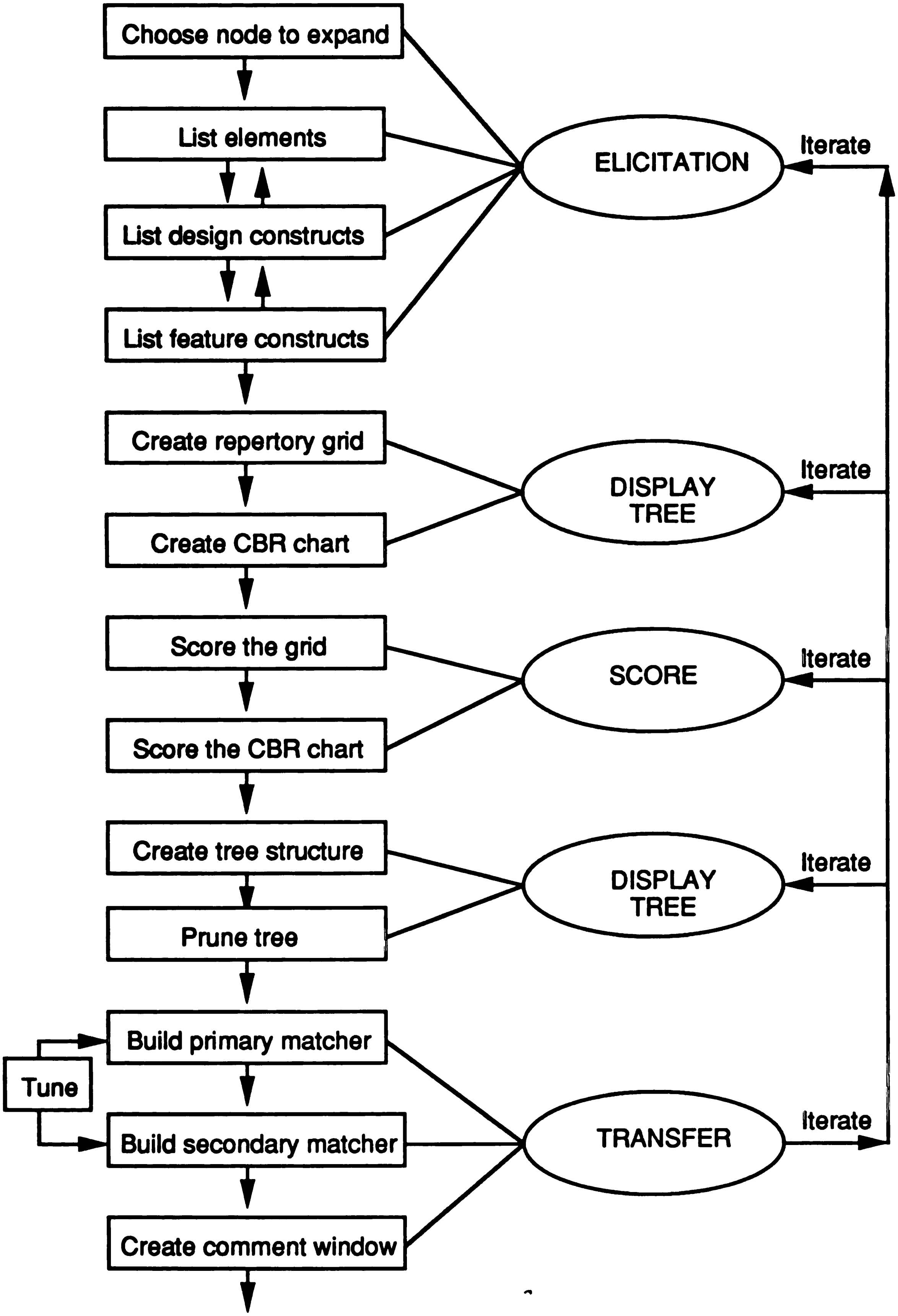


Figure 3. Flow diagram for proposed methodology of knowledge acquisition and representation.

List the criteria or parameters used in design. Compare two design applications to a third, and name a design criteria which is the same for the first two, but differs from the third. This is elicitation of design constructs. The constructs must be bipolar in nature, with an extreme pole indicated on the grid. The list of design constructs is placed in the first column of the repertory grid.

List features of the waste problem which describe the influent, effluent, and operational characteristics of the system. This is accomplished using the triad technique. Compare two design applications to a third, and name a characteristic which is the same for the first two but differs in the third. This is elicitation of the feature constructs. Add the feature constructs to the previously elicited design constructs as shown in Table 3.

Example: Step feed and deep shaft have high cost of construction, where the oxidation ditch has a low cost of construction.

Conventional mix and pure oxygen systems can tolerate shock loading, where step feed cannot.

Table 3. Construct elicitation for a repertory grid

ELEMENTS		COMPLETE MIX REACTOR	STEP FEED	DEEP SHAFT	SEQUENCING BATCH REACTOR	PURE OXYGEN	OXIDATION DITCH
CONSTRUCTS							
High cost of construction	1						
Tolerates shock loading	2						
Plug flow regime	3						
Space loading > 1.5	4						
Sludge age > 15 days	5						
Hydraulic retention time > 10 hours	6						
Soluble BOD removal > 90 %	7						

4.2. Display charts

Create a repertory grid with the elicited elements and constructs. The constructs are separated into two categories, the design and feature constructs. Design constructs are the parameters of the system where the value is set by the engineer. Feature construct value are a function of the waste stream and technology, and change only as a result of changing a design construct. In other workds, the feature constructs values are a function of the design construct choices. Feature constructs are listed first, followed by the design constructs in the final grid.

Create a CBR chart of design constructs. The constraint based design chart presents every possible interaction between pairs of relevant design constructs. Each combination of constructs is divided into three partitions of expression. For each design construct, choose a high, low and intermediate level in appropriate units. The pairs of constructs considered systematically by the expert. Both incompatible and compatible combinations are indicated.

4.3. Scoring

Score the repertory grid by assigning a "+" if there is a positive relationship between element and construct, a "-" if there is a negative relationship between element and construct, and "0" if neither extreme applies. Each box of the grid must be scored. Typically, each of the design constructs will score a "-" or "+", rarely a "0". If a "0" is scored, the user will be presented with the box a second time to verify the scores. See Table 4 for an example.

> *Example*: According to this expert, a conventional complete mixed reactor can tolerate an influent with fluctuating flow rate, so the expert scored a '+'. Deep shaft design cannot tolerate such fluctuating flows, so a '-' was scored. A sequencing batch reactor can tolerate minor fluctuations, so the expert scored a '0' in the appropriate box.

Table 4. Sample grid - scoring procedure

ELEMENTS		COMPLETE MIX REACTOR	STEP FEED	DEEP SHAFT	SEQUENCING BATCH REACTOR	PURE OXYGEN	OXIDATION DITCH
CONSTRUCTS							
1	Tolerates fluctuating flow	+		-	0		

Score the CBR chart by indicating a '+' for strong positive relationship between design criteria for the ranges indicated. Use '-' for a negative relationship. If there is no direct or strong relationship, leave blank. See Figure 4 for a sample of CBR scoring.

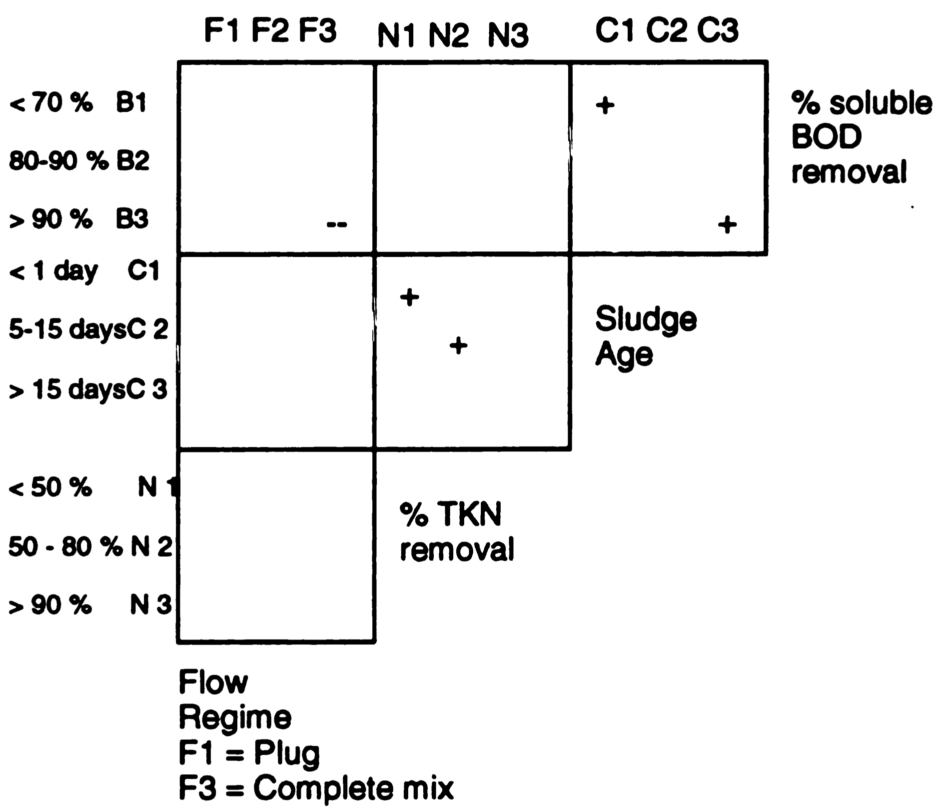


Figure 4. Sample of constraint based representation scoring.

4.4. Display tree

Create the tree structure from cluster analysis of the grid by using a modification of the FOCUS technique introduced by Shaw (1981). From the FOCUS analysis, the internal structure of the expert's internal decision tree is formed. The elements are focused and fused according to the procedure outlined previously. See Table 5 for a sample SV table.

Example: Examine the SV table from the original grid from Expert # 1 from calculations shown in Appendix B.

Table 5. Sample SV Table

ELEMENTS	2	3	4	5	6
1	48	58	72	72	*82*
2		*86*	64	60	50
3			70	70	60
4				60	*82*
5					54

E 2 and E 3 with an SV of 86 will be fused to become E 7. E 1, E 4 and E 6 with a score of 82 will be fused to become E 8. The next highest SV is 72, but since this score is with fused elements, ie. E 2 and E 4, they will not be fused at this level. Fused grid # 2 is created.

The FOCUS structure diagram has SV on the vertical axis and elements on the horizontal axis. For expert #1, begin as shown in Figure 5. Continue to fuse elements as shown in Appendix B to create a complete tree structure based on the design constructs.

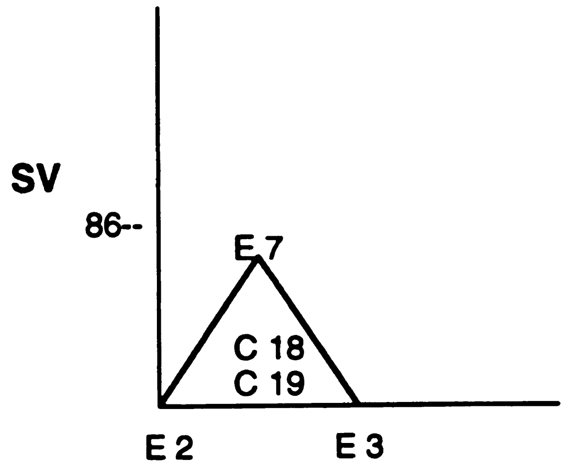


Figure 5. Beginning of FOCUS structure diagram.

A decision tree is created from the FOCUS tree. Begin with the lowest SV in the FOCUS tree. This SV was calculated from the dij of two elements. Review the scored constructs between the two elements and identify the design constructs which scored differently. Identify the design constructs responsible for each branching in the tree. Construct a decision tree structure representation as shown in Figure 6.

Example: The branch between E 2 and E 3 is due to a different score on design constructs 19 - soluble BOD removal > 90 %. This is found in the original grid.

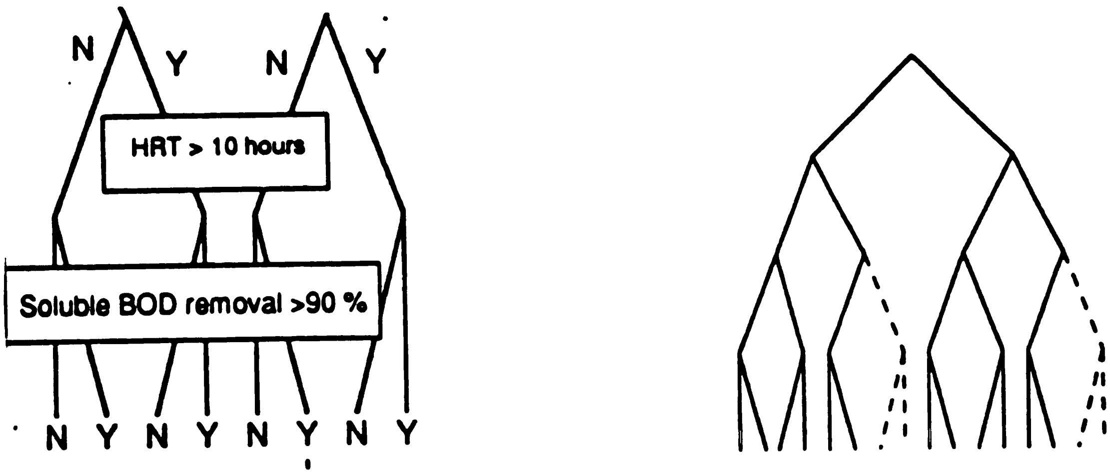


Figure 6. Beginning of decision tree and example of a pruned branch in a decision tree.

Prune the tree by eliminating branches indicated nonapplicable from CBR rules, see Figure 6.

> *Example*: From the CBR chart, the expert indicates th a sludge age < 15 days will not result in soluble BOD removal > 90 %. Consequently, any branch indicating > 90 % removal of soluble BOD will be pruned below the branch where sludge age is determined.

Iterate to resolve conflicts. If a pruned branch is also an element from the original grid, there is a conflict in the responses from the expert. The expert will be presented the portions of the grid and CBR which correspond to the conflict in the tree. The expert will have the opportunity to change a response, or override the "prune-effect" of the CBR.

Example: The element #1 is at the end a pruned branch. Figure 7 is the display offered to the expert for revision. The tree is adjusted accordingly per the experts response.

Design criteria Attribute	CONVENTIONAL COMPLETELY MIXED REACTOR
Soluble BOD removal > 90 %	+

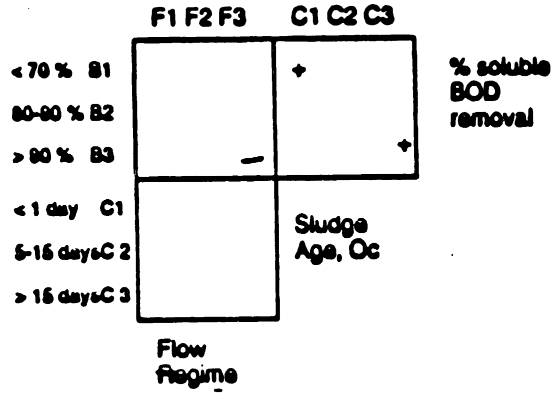


Figure 7. Portion of original grid and CBR chart offered for revision to resolve a conflict in the tree structure.

4.5. Transfer

The results from the knowledge acquisition tools are transferred into the knowledge representation units called matchers. A primary matcher and associated secondary matchers are created for each element in the grid. The sequence of the questions within the matchers are identified from the similarity values calculated in grid analysis.

<u>Build primary matchers.</u> Identify design construct(s) which govern each node, beginning at the top of the tree. Build a primary matcher for each element with design constructs listed in the sequence from the tree structure top-down. A

confidence factor of 1 or -1 is assigned to the yes and no responses. The sign of the confidence factor is taken from the original grid score. A portion of a primary matcher is shown in Table 6.

Example: For goal state for E 1, the sign for the response to C 17 is negative, and for C 23 is negative.

Table 6. Portion of a primary matcher, Expert # 1, Element 1.

DESIGN CONSTRUCT	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE VALUE
17-Sludge Age > 15 days		+1	-1		
23-Nitrification occurs		+1	-1		
DEGREE OF MATCH					

Build secondary matchers. The feature constructs are used to build the secondary matcher. List the feature constructs which correspond to each design construct along with the appropriate SV. Table 7 is a list for sludge age.

Table 7. Design constructs with associated feature constructs and similarity values (SV).

DESIGN CONSTRUCTS	FEATURE CONSTRUCTS	SV
C 17 - Sludge Age	Recycle rate Fluctuating flow Shock loads, toxic Risk of short circuiting Sludge dewatering capability	92 75 75 67 67

Table 8. Sample secondary matcher for Expert # 1 -sludge age

FEATURE CONSTRUCT	9	6	8	3	14
SV	+ 0.92	+ 0.75	+ 0.75	+ 0.67	+ 0.67

The sign of each SV in the secondary matcher, shown in Table 8, is taken from the fused grids as was the case for the primary matcher. If both of the fused elements score "0" for any associated constructs, there are two options. Since a score of "0" indicates there is not a strong relationship to either pole of the construct, this construct is not be a discriminating factor. The expert can specify to either omit the feature construct from the secondary matcher, or assign a positive or negative sign as appropriate. Confidence factors are computed using the formula algorithm as a function of the SV and the number of constructs being considered. The computed confidence factor is returned to the primary matcher as the value for the appropriate design construct used to calculate a degree of match for the node.

Tuning the matchers. The matchers are presented to the expert for fine tuning. Any conflicts will be presented to the expert for resolution. Matchers, both primary and secondary, can be changed independently to reflect the decision-making process of the expert. These changes include the addition or deletion of feature constructs from secondary matchers, and changing the weight factors in the primary matchers. In the course of fine tuning, the expert may realize additional feature or design constructs which should be included in the original grid, or changes to the CBR. These changes can be made, and subsequently incorporated into the knowledge representation. Automation of the methodology becomes very helpful in this phase of the methodology.

Comment windows

Create explanation table for each goal state based on CBR table and matcher results.

> *Example*: Comment window for E 1 for matcher completed. The confidence value for the matcher is computed by adding the confidence values returned for each design construct, and dividing by the number of constructs considered. In this case, the value 0.35 is returned, indicating a moderate positive response that E 1 technology would be appropriate. Note that the user did not answer yes or not to the questions about nitrification or flow regime. The corresponding hidden matchers were presented, and the indicated response returned.

The comment window for this completed matcher would look as follows:

Table 9. Sample comment window for node E 1, conventional complete mix reactor.

Design	sludge age > 15 days hydraulic residence time is > 10 hours dissolved oxygen < 4 mg/l
Then	TKN removal > 90 % Space loading > 75 lb BOD/ cu. ft-d High MLSS concentration Soluble BOD removal > 90 %

5.0. ANALYSIS OF RESULTS

Three experts participated in the evaluation of the methodology. The first two were geared toward the generating matchers for the design 'activated sludge' as shown in the hierarchy displayed in Figure 1. Expert # 1 is an environmental consultant who specializes in wastewater conceptual design. Expert # 2 is an expert in biological remediation processes. These two were presented the same pre-prepared grid. Each made adjustments according to their individual priorities. The CBR was developed from their final grid.

Expert # 3 is an expert in conceptual design specializing in groundwater remediation. An original grid was elicited from Expert # 3, however, due to time limitations, a CBR was not completed. This expert was not given a pre-determined hierarchy, rather asked to begin with a waste stream instead of a design category. The competing technologies were identified, and grid elicitation continued as outlined in the methodology.

A sample case of a wastewater with overstandard BOD (biological oxygen demand) is classified according to the results from Expert # 1. Calculations of secondary matchers confidence values and degree of match are explained.

5.1. EXPERT # 1

The repertory grid and constraint based representation chart scored by Expert # 1 are shown in Table 10 and Figure 8 respectively. Expert # 1 selected 6 design technologies, elements, as he considers himself to be an expert in distinguishing among these treatment technologies. The calculations of the FOCUS analysis are presented in Appendix B. Figure 9 shows the FOCUS structure derived from these calculations, and Figure 10 shows the decision tree. Each level of branching in the tree is determined by a design construct, or a group of feature constructs. The decision tree structure for Expert #1 includes the possible solutions, or elements from the repertory grid. The location in the tree is based on the design construct values. Several other possible design combinations are also identified which the map of the search space suggests that would be possible alternatives.

The CBR results are presented in Table 11. Based on these rules, branches of the decision tree can be pruned. The pruned tree for Expert # 1 is shown in Figure 11. A conflict is identified when pruning the tree for Expert # 1. From the CBR, a sludge age of greater than 15 days will have soluble BOD removal of less than 90 %. Element 1 was scored as having a sludge age less than 15 days but, is at the end of a pruned branch. In an automated situation, the expert

Table 10. Repertory grid for activated sludge node completed by Expert #1.

ELEMENTS		COMPLETE MIX	STEP FEED*	DEEP SHAFT	S B R*	PURE O2 COMPLETE MIX	OX. DITCH
FEATURE CONSTRUCTS							
High cost of construction	1	0	+	+	-	+	-
Low power input for aeration	2	0	0	0	0	0	0
Low risk of short circuiting flow	3	+	-	+	0	0	+
High operational costs	4	0	-	-	-	+	0
Low space requirement	5	0	0	+	0	+	0
Tolerates fluctuating flow	6	+	-	-	0	+	+
Sludge foaming and bulking problems	7	-	-	-	-	-	-
Tolerates shock loading, toxics	8	+	-	-	0	+	+
High recycle rate	9	+	-	-	0	-	+
Biodegrades suspended BOD	10	-	-	-	-	-	-
High oxygen transfer rate	11	0	0	0	0	0	+
Tolerates intermittent flow	12	-	-	-	-	-	-
SVI > 100, Sludge settleability	13	-	-	-	-	-	-
sludge easily dewatered	14	+	+	+	+	-	+
High biological solids production	15	0	0	0	0	0	0

Table 10 (cont'd). **ELEMENTS**		COMPLETE MIX	STEP FEED*	DEEP SHAFT	S B R*	PURE O2 COMPLETE MIX	OX. DITCH*
DESIGN CONSTRUCTS							
High MLSS concentration	16	-	+	+	+	-	+
Long sludge age, > 15 days	17	+	-	-	+	-	+
Dissolved oxygen > 4 mg/l	18	+	-	+	+	+	+
Soluble BOD removal > 90 %	19	+	-	+	+	+	+
complete mix flow regime	20	+	-	-	+	+	+
plug flow regime	21	-	+	+	+	-	-
Long HRT > 10 hours	22	-	-	-	-	-	+
Nitrification occurs	23	-	-	-	+	-	+
Denitrification occurs	24	-	-	-	+	-	+
Primary settling tank required	25	+	+	+	+	+	+

*STEP FEED = Step feed, plug flow reactor
*S B R = Sequencing Batch Reactor
*OX DITCH = Oxidation Ditch

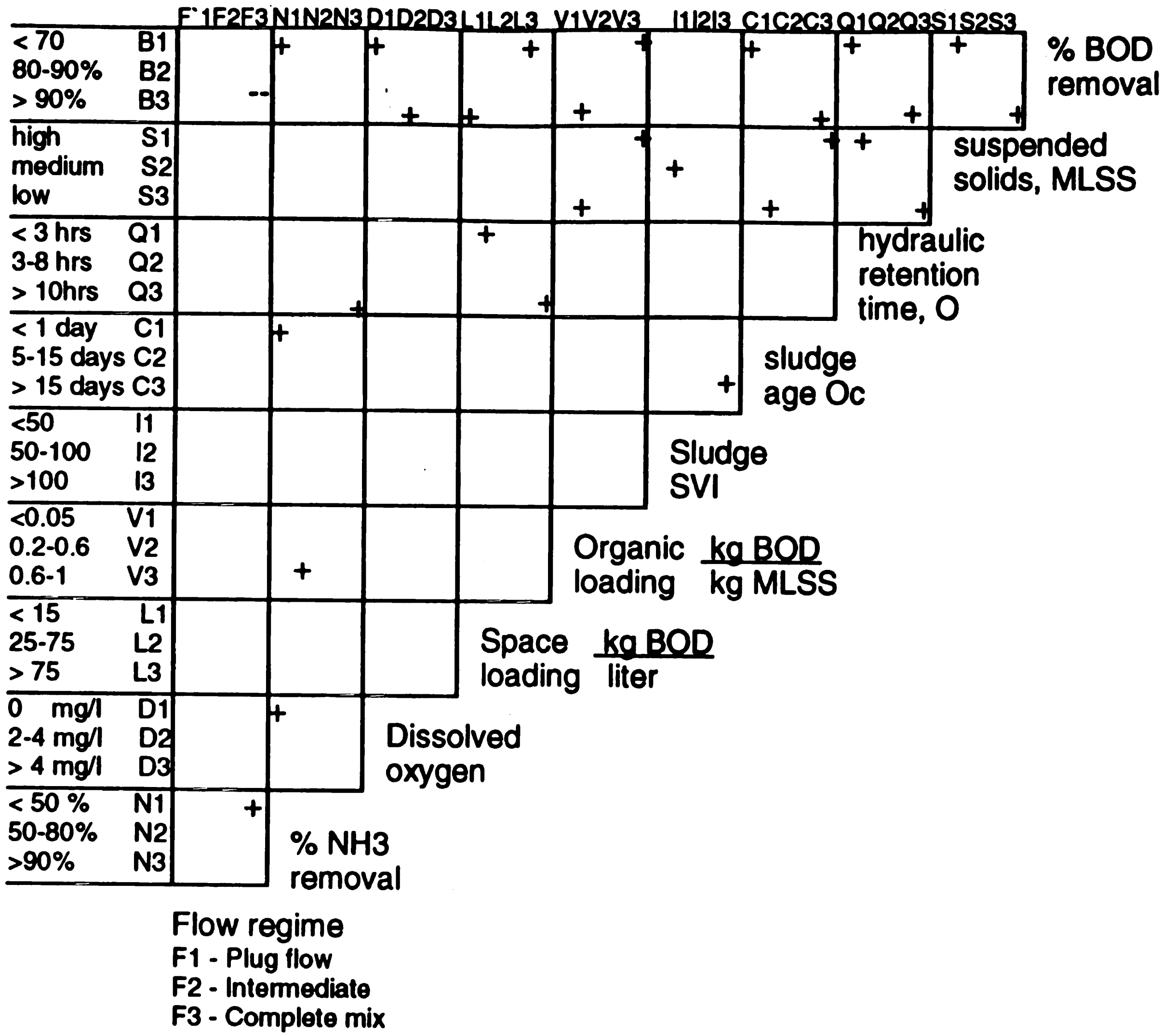
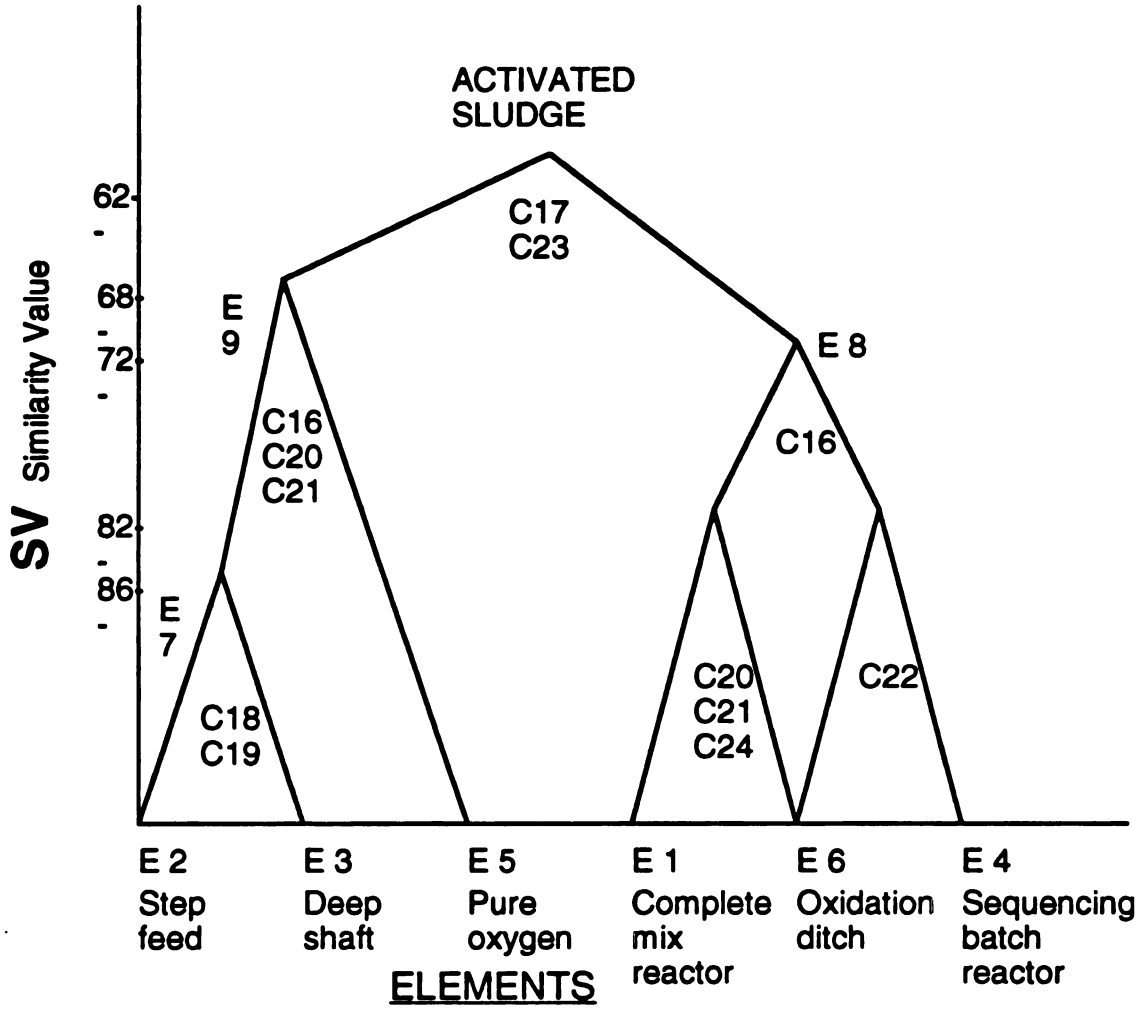


Figure 8. Constraint based representation scored by Expert # 1.

would be presented this conflict as shown in Figure 7 in the methodology section.

Expert # 1 first discriminates according to sludge age, then nitrification, followed by flow regime, and so on. This sequence is transferred into the primary matchers. A sample is shown in Table 12. The complete compliment of primary matchers is presented in Appendix B.

A sample of a secondary matchers is shown in Table 13. For each design construct, the dij and SV calculations reveal the feature constructs with an SV value of over 60, indicating a high correlation between them, see Table 14. This is the basis for the secondary matchers. Expert # 1 associates the design construct long sludge age with recycle rate, fluctuating flow, shock loading, short circuiting of flow and sludge dewatering. These are the factors which the expert considers when deciding on sludge age. A sample of a secondary matcher is shown in Table 14, while a complete compliment of secondary matchers is found in Appendix B. Rules derived from the scored CBR are used in the comment windows as shown in Table 11.



CONSTRUCTS
C16 -high MLSS concentration
C17 -sludge age > 15 days
C18 -dissolved oxygen > 4 mg/l
C19 -Soluble BOD removal > 90 %
C20 -complete mix flow regime
C21 -plug flow regime
C22 -hydraulic retention time > 10 hours
C23 -nitrification occurs
C24 -denitrification occurs

Figure 9. FOCUS structure for Expert # 1.

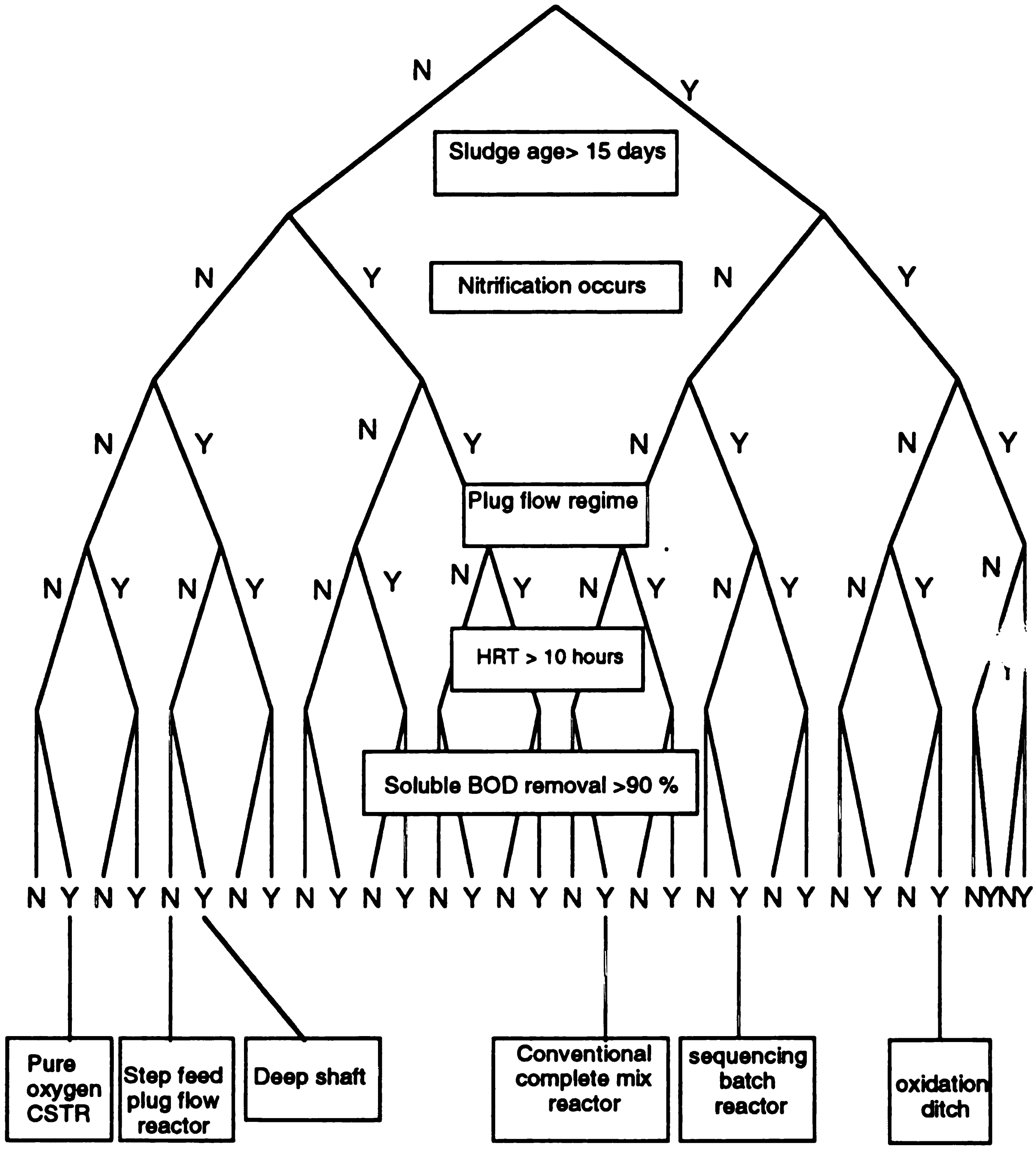


Figure 10. Decision tree for Expert # 1.

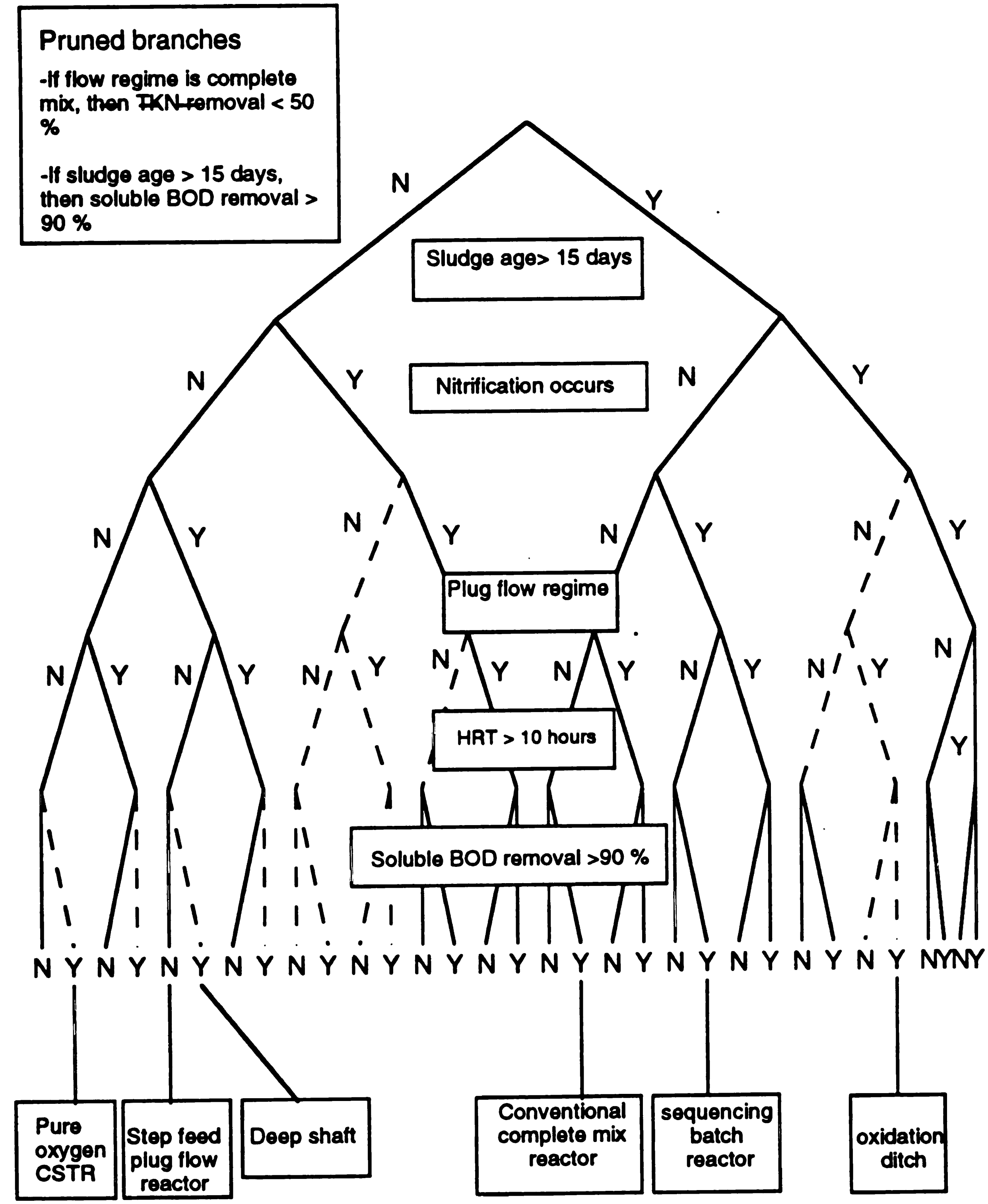


Figure 11. Pruned decision tree for Expert #1.

Table 11. Constraint based representation rules for Expert # 1.

IF Design Construct	has the value	THEN additional
Sludge Age	> 15 days	- SVI > 100 - TKN removal > 90 % - high MLSS concentration - Soluble BOD removal > 90%
	< 1 day	- low MLSS concentration - Soluble BOD removal < 70% - TKN removal < 50 %
Flow Regime	Completely mixed	- TKN removal < 50 %
Hydraulic Retention Time (HRT)	> 10 hours	- TKN removal > 90 % - Space loading > 75 - Low MLSS concentration - Soluble BOD removal > 90%
	< 3 hours	- Space loading < 15 - Soluble BOD removal < 70%
TKN removal	< 50 %	- Organic loading 0.6-1 - Sludge age < 1 day - Soluble BOD removal < 70% - Plug flow regime
	> 90 %	- Dissolved oxygen 0 mg/l - Sludge age > 15 days - HRT > 10 hours
MLSS concentration	High	- HRT < 3 hours - Sludge age < 1 day - Organic loading 0.6-1 - Soluble BOD removal > 90%
	Medium	- SVI < 50
	Low	- HRT > 10 hours - Soluble BOD removal < 70% - Sludge age > 15 days - Organic loading < 0.05
Table 11 (cont'd). Soluble BOD removal	< 70 %	- Low MLSS concentration - HRT < 3 hours - Sludge age < 1 day - Organic loading 0.6-1 - Space loading> 75 - Dissolved oxygen = 0 mg/l - TKN removal < 50 %
	> 90 %	- High MLSS concentration - HRT > 10 hours - Sludge age > 15 days - Organic loading < 0.05 - Space loading < 15 - Dissolved oxygen 2-4 mg/l

Table 12. Sample primary matcher for Expert # 1.

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days					
Nitrification occurs					
Plug flow regime					
HRT > 10 hours					
Denitrification occurs					
High MLSS concentration					
Dissolved O_2 > 4 mg/l					
Soluble BOD removal > 90 %					
DEGREE OF MATCH					

Table 13. Secondary matcher for Expert # 1
Sludge age > 15 days

FEATURE CONSTRUCT	9	6	8	3	14
SV	+ 0.92	+ 0.75	+ 0.75	+ 0.67	+ 0.67

Table 14. Expert #1 - Design constructs with associated feature constructs and similarity values (SV).

DESIGN CONSTRUCTS	FEATURE CONSTRUCTS	SV
C 17 -Sludge Age	Recycle rate	92
	Fluctuating flow	75
	Shock loads, toxic	75
	Risk of short circuiting	67
	Sludge dewatering capability	67
C 23 -Nitrification	Recycle rate	92
	Fluctuating flow	75
	Shock loads, toxic	75
	Risk of short circuiting	67
C 21 -Flow regime	Fluctuating flow	83
	Shock loads, toxic	83
	Sludge dewatering capability	83
	Operational costs	75
	Recycle rate	67
C 22 -Hydraulic retention time	Recycle rate	92
	Fluctuating flow	75
	Shock loads, toxic	75
	Risk of short circuiting	67
	Operational costs	67
	Sludge problems	67
	Suspended solid biodegradation	67
	Intermittent flow	67
	Sludge settling, SVI	67
C 24 -Denitrification	Recycle rate	75
	Sludge problems	67
	Suspended solid biodegradation	67
	Intermittent flow	67
	Sludge settling, SVI	67
C 16 -MLSS concentration	Sludge dewatering capability	83
	Recycle rate	75
	Risk of short circuiting	67
	Sludge problems	67
	Suspended solid biodegradation	67
	Intermittent flow	67
	Sludge settling, SVI	67
		67
C 18 -Dissolved oxygen concentration	Risk of short circuiting	83
	Fluctuating flow	75
	Shock loads, toxic	75
	Space requirement	67
	Sludge dewatering capacity	67
Table 14 (cont'd).		
C 19 -Soluble BOD removal rate	Risk of short circuiting	83
	Fluctuating flow	75
	Shock loads, toxic	75
	Space requirement	67
	Sludge dewatering capacity	67

5.2. EXPERT # 2

The repertory grid and constraint based representation chart scored by Expert # 2 are shown in Table 15 and Figure 12 respectively. Expert # 2 selected 8 design technologies, elements, as he considers himself to be an expert in distinguishing among these treatment technologies.

Calculations for the FOCUS analysis from Expert # 2 is presented in Appendix C. The resulting FOCUS tree and decision tree are presented in Figures 13 and 14 respectively. Table 16 shows the rules resulting from the CBR scored by Expert # 2. These rules were used to prune the decision tree shown in Figure 15.

The decision tree is developed from the FOCUS structure. As shown in Figure 13, the lowest SV is 31, and is due to a collection of feature constructs relating cost factors. Recall that similarity is indicated by a SV value greater than 50. In an automated system, Expert # 2 would be asked for an additional design construct which would discriminate the Elements 13 and 14. The next discriminating design construct is soluble BOD removal rate, then dissolved oxygen concentration and so on. The sequence of design constructs for Expert # 2 is reflected in the sample primary matcher in Table 17. The complete compliment of primary matchers is presented in Appendix C. The secondary matchers for each design construct are built according to Table 18 as was done for Expert # 1. A complete compliment of secondary matchers is found in Appendix C.

A score of "0" on the grid presents an interesting interpretation on the decision tree structure. Element 1 was scored "0" in the constructs which discriminate the first branch of the decision tree. Since a score of "0" indicates neither strong positive or negative relativity, and due to the binary nature of the tree, Element 1 is found as a goal state in two places in the tree. Classifying a case where plug flow is a possible alternative would depend on the confidence value returned by the secondary matcher. However, analysis indicates that either branch of the tree could lead to the choice of Element 1 as a solution. Element 2 was scored "0" on two levels (Table 15). Therefore, there are four possible goal states on the decision tree.

When two elements at the base of the tree are not separated by a design construct, this could indicate that one is a sub-element of the other. In this example, Expert # 2 indicates that Elements 1 and 3 are not discriminated by a design construct (Figure 14 and 15). This expert may view step feed and conventional plug flow as closely associated, with one being a sub-grouping of the other. Or, upon review, he may add a design construct. In this case, the grid would be re-analyzed and presented once again incorporating this additional construct.

Automation of the methodology would allow iterations to refine the decision tree and resulting matchers. Expert # 2 had an opportunity to review the initial results of the knowledge acquisition exercise and indicated some changes he would make for the next iteration. He would add 'uniform oxygen supply' as a design construct to distinguish between step feed and plug flow. Recall these two elements were not separated by design construct, so appeared as sub-elements on the decision tree. Expert # 2 would change the response on Element 3 from "+" to "0" for the plug flow regime design construct. He also would add sequencing batch reactor as an element. Other changes include designating dissolved oxygen concentration as a feature construct rather than a design construct. Other additional design constructs include MLVSS concentration and oxygen transfer efficiency.

Table 15. Repertory grid for activated sludge node scored by Expert # 2.

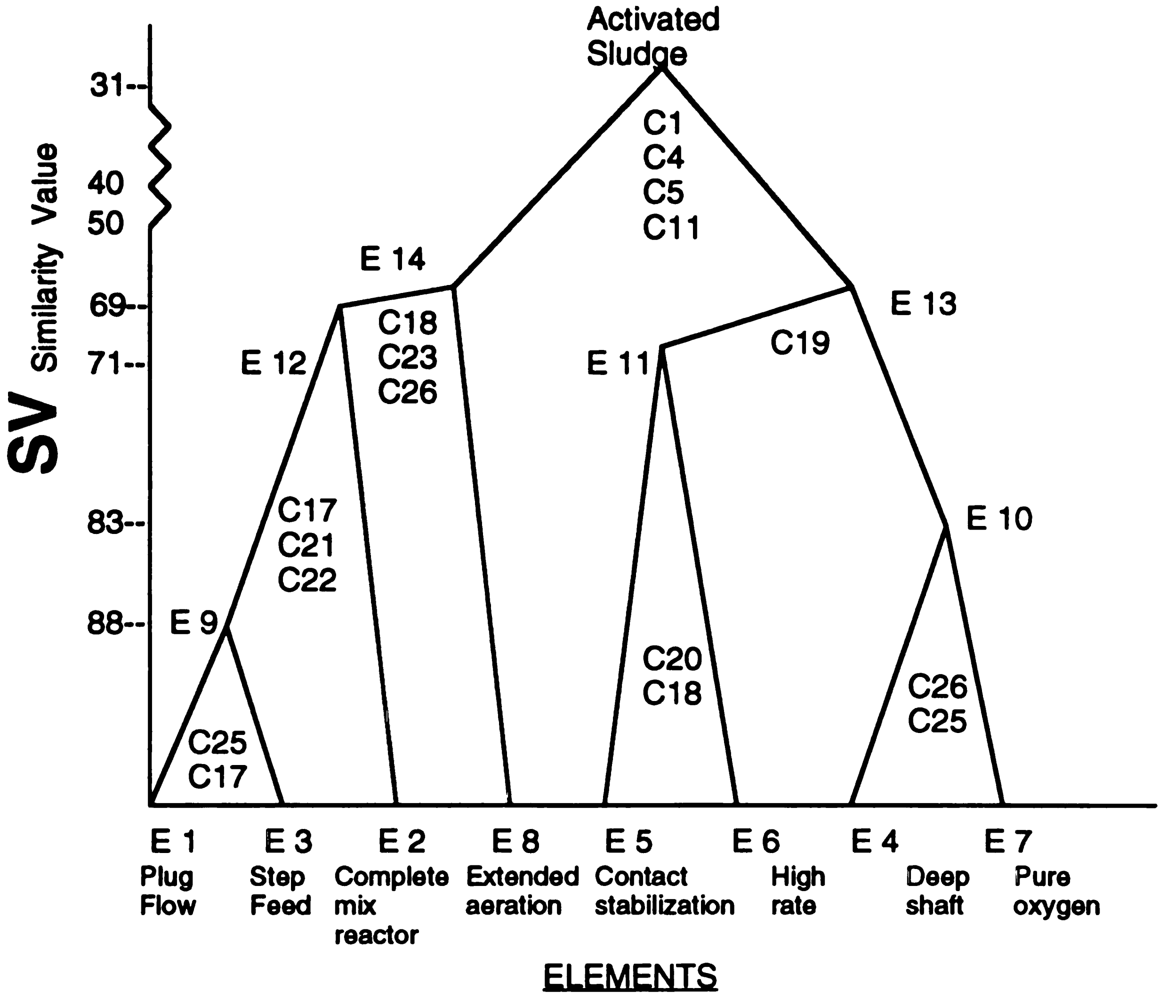
ELEMENTS		PLUG FLOW*	CSTR*	STEP FEED	DEEP SHAFT	C.S.*	HIGH RATE	PURE O_2	E.A.*
FEATURE CONSTRUCTS									
High cost of construction	1	0	0	0	+	0	0	+	-
Low power input for aeration	2	0	0	0	+	-	+	-	0
Low risk of short circuiting flow	3	+	0	0	+	0	0	+	+
High operational costs	4	0	0	0	+	0	0	+	-
Low area requirement	5	0	0	0	+	+	+	+	-
Tolerates fluctuating flow	6	0	+	0	0	0	0	0	+
Removes suspended BOD	7	+	0	0	-	+	-	+	+
Tolerates shock loading, toxics	8	-	+	-	+	+	0	+	+
High MLSS concentration	9	-	0	0	+	+	+	+	+
High recycle rate	10	0	0	0	-	+	-	+	0
Few sludge bulk/ foaming problems	11	0	-	0	0	+	+	0	-
High oxygen transfer rate	12	0	0	0	+	0	0	+	0
Tolerates intermittent flow	13	0	+	0	0	0	0	0	+
SVI < 100, Sludge settleability	14	+	-	0	+	+	-	+	0
Ease of operation	15	0	0	0	-	-	+	-	+
Low biological solids production	16	0	0	0	0	+	-	+	+

Table 15 (cont'd). **ELEMENTS**		PLUG FLOW*	CSTR*	STEP FEED	DEEP SHAFT	C.S.*	HIGH RATE	PURE O_2	E.A.*
DESIGN CONSTRUCTS									
Single stage denitrification	17	0	-	+	-	0	-	-	+
Long sludge age, > 15 days	18	-	-	-	-	0	-	-	+
Dissolved oxygen > 4 mg/l	19	-	-	-	+	-	-	+	-
space loading, >1.5 kg BOD/m^3 d	20	-	-	-	+	-	+	+	-
complete mix flow regime	21	-	+	-	-	-	-	-	0
plug flow regime	22	+	-	+	+	+	+	+	+
> 10 hr. Hydraulic retention time	23	-	-	-	-	-	-	-	+
Soluble BOD removal > 90%	24	+	0	+	+	-	-	+	+
Single stage nitrification	25	+	+	0	-	-	-	+	+
Primary settling tank required	26	+	+	+	-	+	+	+	-

* PLUG FLOW = Conventional Plug Flow Reactor
CSTR = Completely Mixed Reactor
C.S. = Contact Stabilization
E.A. = Extended Aeration

Range		F1F2F3	N1N2N3	D1D2D3	L1L2L3	V1V2V3	I1I2I3	C1C2C3	Q1Q2Q3	S1S2S3	
< 70	B1	- 0 0		+ 0 0	0 0 +	0 0 +	- 0 +	+ 0 0	+ 0 0	+ 0 -	% Soluble BOD removal
80-90%	B2	0 + +		0 0 0	0 + 0	0 + 0	+ + 0	- + +	+ + +	0 0 0	
> 90%	B3	+ + 0		0 0 0	+ 0 -	+ 0 -	+ 0 -	- + +	- + +	- 0 +	
high	S1		+ - -		0 - -	0 - -	0 0 +	0 - -	- 0 +	suspended solids in influent	
medium	S2		0 0 0		+ 0 0	+ 0 0	0 0 0	0 0 0	0 + 0		
low	S3		0 0 0		+ + +	+ + +	+ 0 0	0 + 0	+ + 0		
< 3 hrs	Q1		+ - -		- 0 +	- 0 +		+ 0 -	hydraulic retention time, O		
3-8 hrs	Q2		0 0 0		0 + 0	0 + 0		- + 0			
> 10hrs	Q3		0 + +		+ 0 -	+ 0 -		- + +			
< 1 day	C1		+ - -		- 0 +	- - +	- 0 +	sludge age Oc			
5-15 days	C2		- 0 0		0 + -	0 + -	+ + 0				
> 15 days	C3		- + +		+ 0 -	- 0 +	+ + 0				
<50	I1	+ + -		- 0 +	0 + +	0 + -	Sludge SVI				
50-100	I2	+ + 0		0 0 0	0 + 0	+ + 0					
>100	I3	0 0 0		+ 0 -	+ 0 0	0 0 +					
<0.05	V1		0 0 +		+ 0 -	Organic loading kg BOD/ kg MLSS					
0.2-1.5	V2		0 0 -		0 + +						
> 1,5	V3		+ - -		- + +						
< 20	L1		0 0 +	0 0 0	Space loading lb BOD/cu ft -d						
20-75	L2		0 0 -	0 0 +							
> 75	L3		+ - -	- 0 +							
< 2 mg/l	D1		+ 0 -	Dissolved oxygen							
2-4 mg/l	D2		0 0 0								
> 4 mg/l	D3		- 0 +								
< 50 %	N1	0 0 0	% TKN removal								
50-80%	N2	+ + 0									
>90%	N3	+ + 0									
		Flow regime									

Figure 12. Scored constraint based representation for Expert # 2.



CONSTRUCTS

C17 -single stage denitrification
C18 -sludge age > 15 days
C19 -Dissolved oxygen > 4 mg/l
C20 -space loading > 1.5 lbBOD/cu ft-d
C21 -complete mix flow regime
C22 -plug flow regime
C23 -hydraulic retention time > 10 hours
C24 -soluble BOD removal > 90 %
C25 -single stage nitrfication
C26 -primary settling tank required

Figure 13. FOCUS structure of Expert # 2.

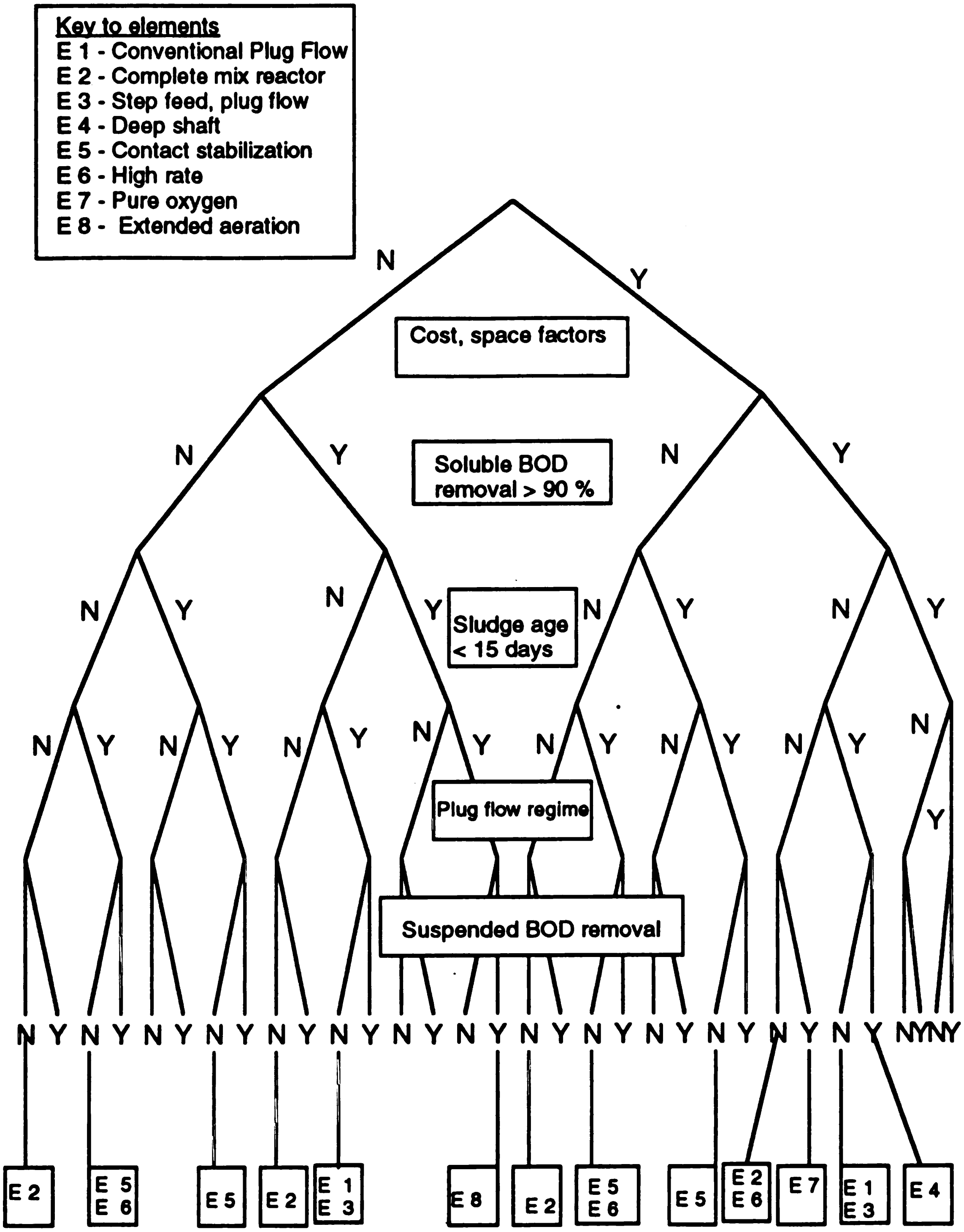


Figure 14. Decision tree for Expert # 2.

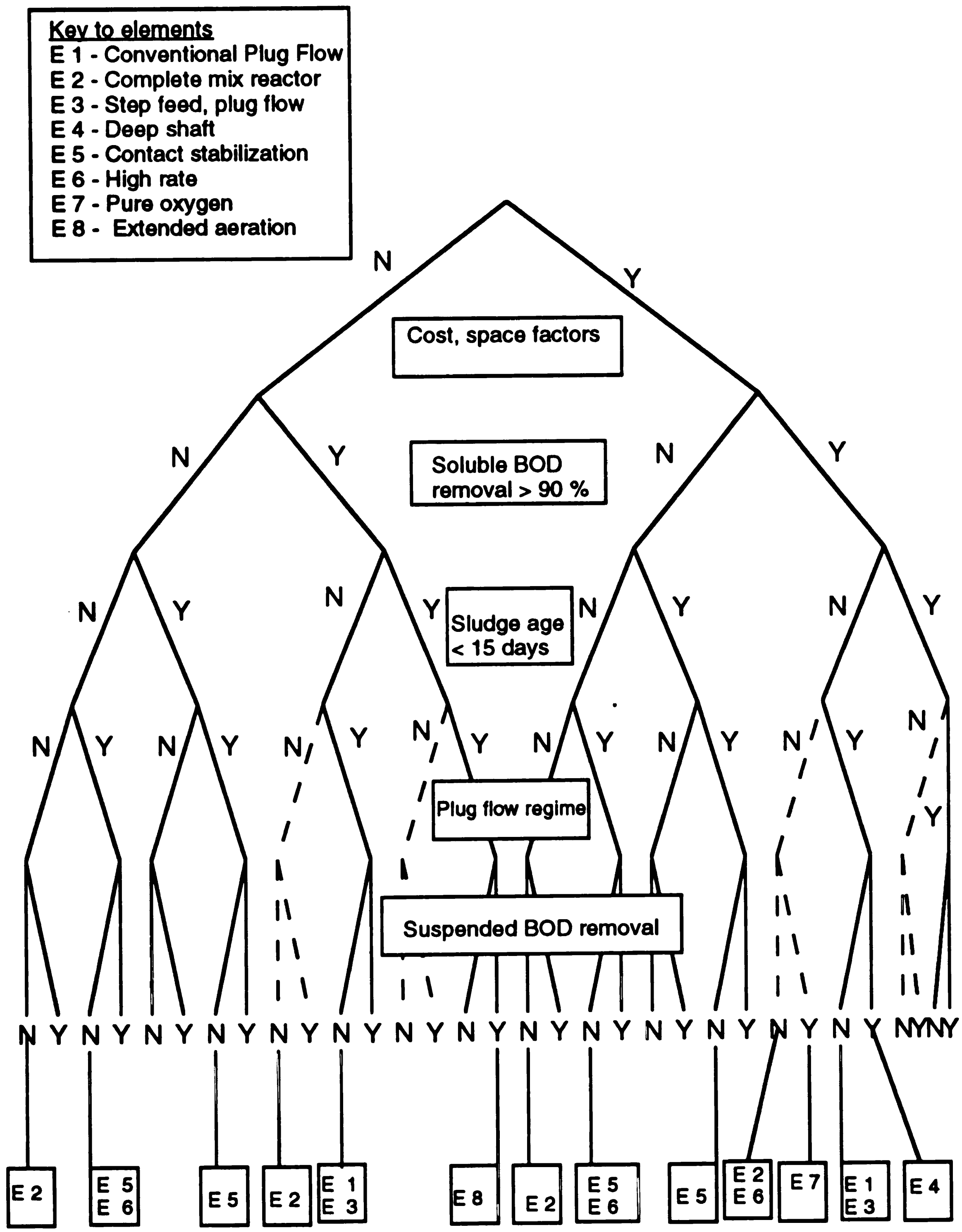


Figure 15. Pruned decision tree for Expert # 2.

Table 16. Constraint based representation rules for Expert #2.

IF Design Construct	has the value	THEN additional
Soluble BOD removal	< 70 %	- High suspended in influent - HRT < 3 hours - Sludge age < 1 day - SVI > 100 - Organic loading > 1.5 * - Space loading > 75 ** - Dissolved oxygen < 2 mg/l - Complete mix flow regime
	80 - 90 %	- Sludge age > 5 days - SVI < 100 - Organic loading 0.2 - 1.5 * - Space loading 20 - 75 ** - intermediate to complete mix regime
	> 90 %	- Low suspended solids in influent - HRT > 3 hours - Sludge age > 5 days - SVI < 50 - Organic loading < 0.2 * - Space loading < 20 ** - Intermediate to plug flow
Sludge age	< 1 day	- Soluble BOD removal < 70 % - HRT < 3 hours - SVI > 100 - Organic loading > 1.5 * - Space loading > 75 ** - TKN removal < 50 %
	5 - 15 days	- Soluble BOD removal > 80 % - Low suspended solids in influent - HRT > 10 hours - SVI > 50 - Organic loading 0.2-1.5 * - Space loading 20 - 75 ** - TKN removal < 50 %
	> 15 days	- Soluble BOD removal > 80 % - Medium suspended solids in influent - HRT > 10 hours - SVI > 50 - Organic loading > 1.5 * - Space loading > 75 ** - TKN removal > 50 %

Table 16 (cont'd). IF Design Criteria	has the value	THEN additional
Hydraulic Retention Time, HRT	< 3 hours	- Soluble BOD removal > 80 % - Low suspended solids in influent - Sludge age < 1 day - Organic loading > 1.5 * - Space loading > 75 ** - TKN removal < 50 %
	3-8 hours	- Soluble BOD removal > 80 % - Medium suspended solids in influent - Organic loading < 0.2 * - Space loading < 20 **
	> 10 hours	- Soluble BOD removal > 80 % - High suspended solids in influent - Sludge age 5-15 days - SVI < 50
Flow regime	Plug flow	- Soluble BOD removal > 90 % - SVI < 50 - TKN removal > 50 %
	Completely mixed	- Soluble BOD removal 80-90% - SVI > 50
Space loading lb BOD_5/ 10^3 ft^3 -d	< 20	- Soluble BOD removal > 90 % - Medium suspended solids in influent - HRT < 3 hours - SVI > 100 - Organic loading < 0.05 * - TKN removal > 90 %
	20-75	- Soluble BOD removal 80-90% - Low suspended solids in influent - HRT of 3-8 hours - Sludge age 5-15 days - SVI < 100 - Organic loading > 0.2 * - TKN 50 - 90 %
	> 75	- Soluble BOD removal < 70 % - Low suspended solids in influent - HRT < 3 hours - Sludge age < 1 day - SVI < 50 - Organic loading > 0.2 * - TKN removal < 50 %

Table 16 (cont'd). IF Design Criteria	has the value	THEN additional
Primary settling tank required, suspended solid concentration in influent	Low	- Soluble BOD removal > 90 % - HRT < 8 hours - Sludge age 5-15 hours - SVI < 50
	Medium	- HRT 3-8 hours - Organic loading < 0.2 * - Space loading < 20 **
	High	- Soluble BOD removal < 70 % - HRT > 10 hours - Sludge age < 5 days - SVI > 100 - Organic loading < 0.2 * - Space loading < 20 ** - TKN removal < 50 %
		* Organic loading kg BOD/kg VSS-d ** Space loading lb BOD/10^3 ft^3 -d

Table 17. Primary matcher for element 1 from Expert # 2 - conventional plug flow

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		+1	-1		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		-1	+1		
Plug flow regime		+1	-1		
Space loading > 1.5 lbBOD/cu ft-d		-1	+1		
Nitrification single stage		+1	-1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 18. Expert #2 - Design constructs with associated feature constructs and similarity values (SV).

DESIGN CONSTRUCTS	FEATURE CONSTRUCTS	SV
C 24 -Soluble BOD removal	Risk of short circuiting	75
	Suspended BOD removal	69
	Oxygen transfer rate	69
	Sludge settleability, SVI	69
	Biological solids production	69
	Operational costs	63
	Construction costs	63
C 19 -Dissolved Oxygen concentration	Construction costs	69
	Operational costs	69
	Shock loads, toxic	69
	Oxygen transfer rate	69
C 23 -Hydraulic retention time	Ease of operation	75
C 18 -Sludge age	Ease of operation	69
	Biological solids production	63
	Intermittent flow	63
	Recycle rate	63
	Suspended BOD removal	63
	Shock loads, toxic	63
C 22 -Flow regime	Risk of short circuiting	81
	MLSS concentration	81
	Area requirement	69
	Suspended BOD removal	69
	Oxygen transfer rate	69
	Sludge settleability, SVI	69
	Biological solids production	69
	Shock loads, toxic	63
C 17 -Denitrification	Ease of operation	75
	Intermittent flow	69
	Biological solids production	69
	Fluctuating flow	63
	Suspended BOD removal	63
	Recycle rate	63

Table 18 (cont'd). **DESIGN CONSTRUCTS**	**FEATURE CONSTRUCTS**	**SV**
C 20 -Space loading	Area requirement	75
	Construction costs	69
	Oxygen transfer rate	69
	MLSS concentration	69
	Operational costs	69
	Power input for aeration	63
	Shock loads, toxic	63
C 26 -Primary settling tank	Area requirement	75
	Suspended BOD removal	69
	Recycle rate	69
	Sludge settling problems	69
	Operational costs	63
C 25 -Nitrification	Removes suspended BOD	88
	Biological solids production	75
	Operational costs	75
	Ease of operation	69
	Fluctuating flow	63
	Oxygen transfer rate	63
	Intermittent flow	63
	Sludge settleability, SVI	63

5.3. EXPERT # 3

The repertory grid scored by Expert # 3 is presented in Table 19. Calculations for the FOCUS analysis from Expert # 3 is presented in Appendix D. The sequence of design constructs for primary matchers and SV values for secondary matchers were derived from Table 20. The FOCUS structure and decision tree are shown in Figures 16 and 17 respectively. A sample primary matcher is shown in Table 21, a secondary matcher in Table 22, with a complete compliment presented in Appendix D.

The elements elicited from Expert # 3 differ from those found the other two examples in that they are at various levels in the hierarchy in Figure 1. Air stripping, oxidation by hydrogen peroxide (H_2O_2) and activated carbon are mechanisms, where aerobic fixed film and anaerobic granular activated carbon (GAC) are from the level of design and agent. Nonetheless, the analysis did produce the internal mapping of the five elements according to the expert's responses.

The small number of elements, only 5, reflects the narrow search space of this expert. The expert also commented that the cost and regulatory component weigh heavily in the ultimate decision. This supports the statement that environmental consultants rely more on the preliminary design phase than conceptual design. The paradigm of operation is narrow, with only conventional technologies offered as alternatives. If the preliminary design results show that the conceptual design alternative is inappropriate, due to cost, regulatory or other factors, then the expert may extend beyond his current search space for additional design alternatives. This is further evidence that consultants rely more on the preliminary design phase than conceptual design. The paradigm of operation is narrow, with only conventional technologies offered as alternatives. If the preliminary design results show that the conceptual design alternative is inappropriate, due to cost, regulatory or other factors, then the expert may extend beyond his current search space for additional design alternatives.

Table 19. Repertory grid for contaminated ground water scored by Expert # 3.

ELEMENTS		AEROBIC FIXED FILM	ACTIVATED CARBON	ULTRAVIOLET OXIDATION	AIR STRIPPING	ANAEROBIC GAC FLUIDIZED BED REACTOR
FEATURE CONSTRUCTS						
High maintenance requirement	1	-	+	+	-	+
High power requirement	2	+	-	+	-	-
High operating costs	3	-	+	+	-	+
Highly chlorinated hydrocarbons	4	-	+	+	-	+
Toxic by-products of biodegradation	5	+	0	-	0	+
High lead concentration	6	-	-	-	+	+
Low mobility of contaminant in soil	7	+	-	-	+	+
High capital investment	8	-	-	+	-	+
No close electricity	9	+	+	-	+	+
BTEX concentration < 10 ppb	10	-	+	+	-	-
BTEX concentration > 10,000 ppb	11	+	-	-	-	+
TDS > 30,000 mg/l inorganic	12	+	-	-	-	-
Contaminant density > water	13	+	-	-	+	-
pH adjustment required	14	+	-	-	-	+
Iron removal required	15	+	+	+	+	+

Table 19 (cont'd) **ELEMENTS**		AEROBIC FIXED FILM	ACTIVATED CARBON	ULTRAVIOLET OXIDATION	AIR STRIPPING	ANAEROBIC GAC FLUIDIZED BED REACTOR
DESIGN CONSTRUCTS						
Removal rate to 1 ppb	16	-	+	+	-	-
Flow rate > 15 MGD	17	-	+	-	+	-
Long residence time	18	+	0	+	0	+
Contaminant destroyed	19	+	-	+	-	+
Low temperature	20	-	0	0	-	-

Table 20. Expert #3 - Design constructs with associated feature constructs and similarity values (SV).

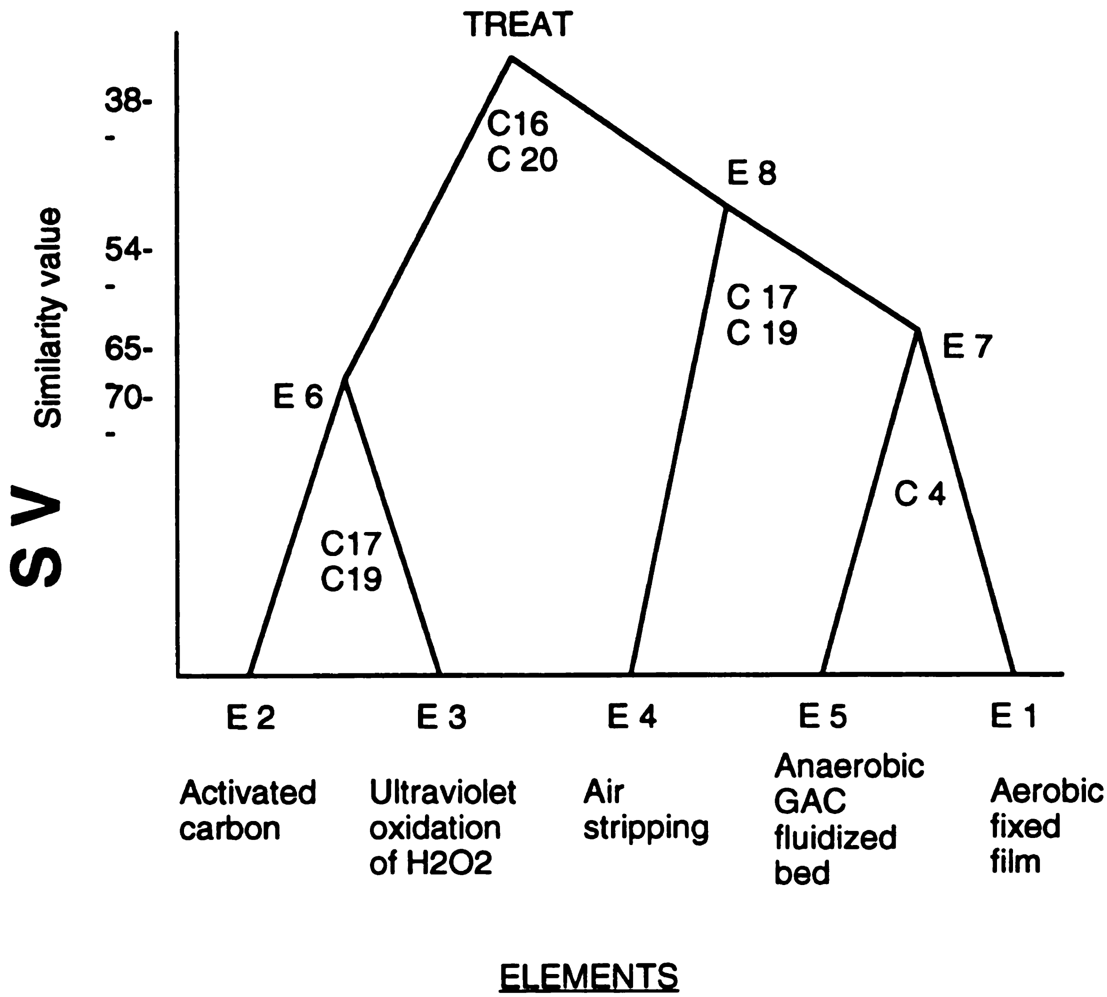
DESIGN CONSTRUCTS	FEATURE CONSTRUCTS	SV
C 16 -Removal rate to 1 ppb	BTEX concentration < 10 ppb	100
	High maintenance requirement	80
	High operating costs	80
	High chlorinated hydrocarbons	80
	Density of contaminant > water	80
	High power requirement	60
	High capital investment	60
C 20 -Low temperature	BTEX concentration < 10 ppb	80
	High maintenance requirement	60
	High power requirement	60
	High operating costs	60
	High chlorinated hydrocarbons	60
	High lead concentration	60
	High capital investment	60
	TDS > 30,000 mg/l inorganic	60
	Density of contaminant > water	60
Contaminant destroyed	High power requirement	80
	High capital investment	80
	BTEX concentration > 10,000 ppb	80
	pH adjustment required	80
	High maintenance requirement	60
	High operating costs	60
	High chlorinated hydrocarbons	60
	Toxic by-product of biodegradation	60
	Low mobility of contaminant in soil	60
	TDS > 30,000 mg/l inorganic	60
	Density of contaminant > water	60
	Iron removal required	60
Flow rate > 15 MGD	High lead concentration	80
	Electricity not in close proximity	60
	BTEX concentration < 10 ppb	60

Table 21. Primary matcher for element 1 from Expert # 3 - aerobic fixed film

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Removal rate to 1 ppb		-1	+1		
Low temperature		-1	+1		
Contaminant destroyed		+1	-1		
Flow rate > 15 MGD		-1	+1		
Highly chlorinated hydrocarbons		-1	+1		
DEGREE OF MATCH					

Table 22. Secondary matcher from Expert # 3

FEATURE CONSTRUCTS	10	1	3	4	13	2	8
SV	+ 1.0	+ .80	+ .80	+ .80	- .80	- .60	- .60



CONSTRUCTS

C16 -removal rate to 1 ppb
C17 -flow rate > 15 MGD
C18 -long residence time
C19 -contaminant chemically destroyed
C20 -low temperature

Figure 16. FOCUS structure for Expert # 3.

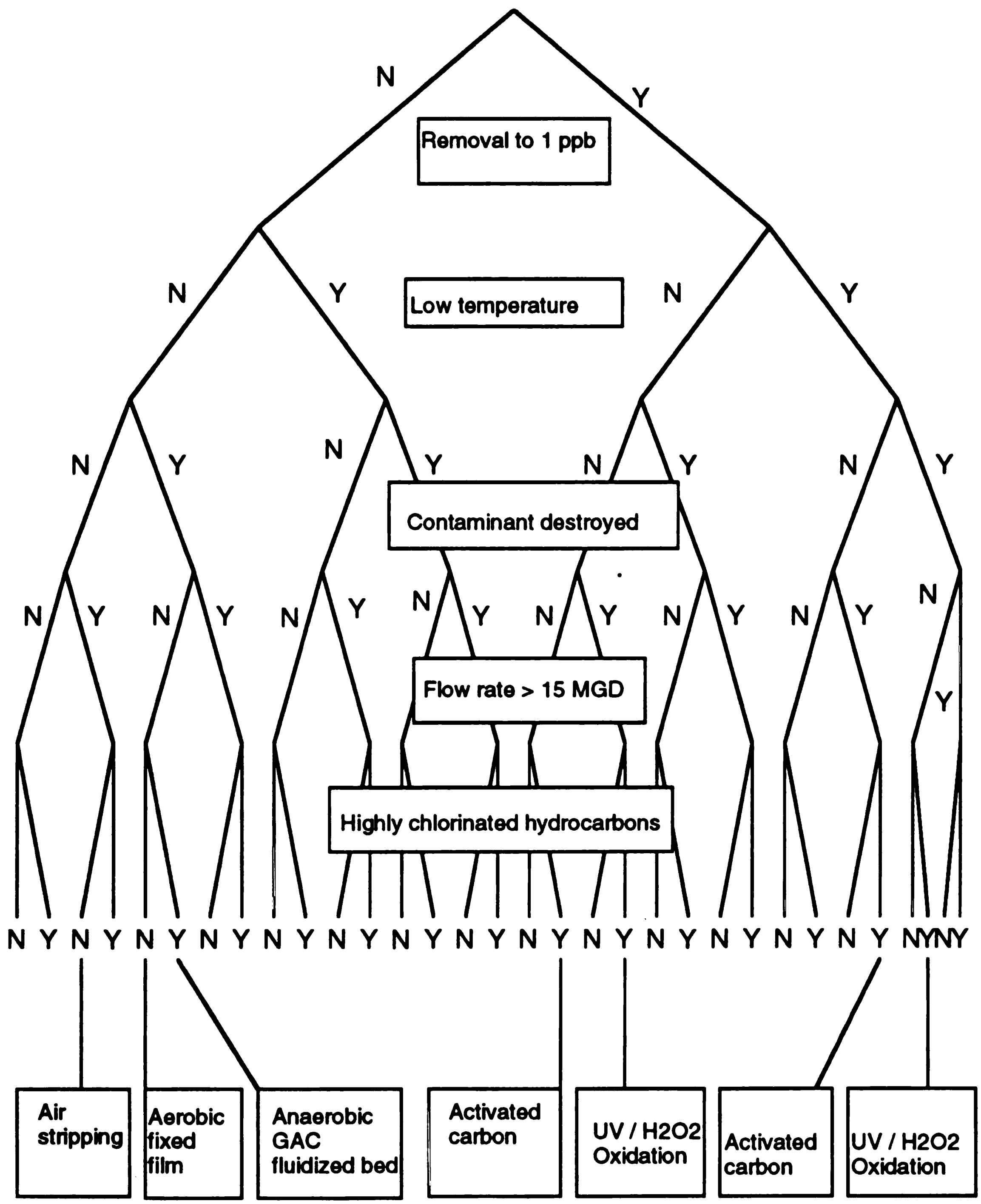


Figure 17. Decision tree for Expert # 3.

5.4. CLASSIFYING A CASE

The following is an explanation of how a matcher calculates a degree of match when classifying a case. The matchers for this example are taken from the knowledge acquisition from expert #1. The responses to the questions a representative of a wastewater with overstandard soluble BOD (biological oxygen demand) levels.

The primary matchers for the nodes from Expert # 1 are displayed in Appendix B. Table 23 shows the questions presented to a user of the KBS to determine appropriate activated sludge design, and the responses to our sample wastewater.

Table 23. Questions and responses for a sample case.

QUESTION PRESENTED BY THE KBS	RESPONSE
Is the sludge age over 15 days?	DON'T KNOW?
Is nitrification occur?	NO
Is the flow regime plug flow?	YES
Is the hydraulic retention time over 10 hours?	YES
Does denitrification occur?	NO
Is the concentration of MLSS high?	NO
Is the dissolved oxygen concentration over 4 mg/l?	DON'T KNOW?
Is the soluble BOD removal rate over 90 %?	YES

For the two questions with the response of 'don't know', the secondary matcher will invoke and the user will be presented additional questions. Table 24 shows the questions which would be presented if the answer to the sludge age is 'don't know", and the responses for the sample case, and table 25 for dissolved oxygen concentration.

Table 24. Questions and responses for the secondary matcher regarding sludge age for a sample case.

QUESTIONS ASKED REGARDING SLUDGE AGE	CONSTRUCT	SV	RESPONSE
Is the recycle rate high?	9	.92	YES
Is the flow fluctuating?	6	.75	YES
Are shock loads characteristic of the flow?	8	.75	DON'T KNOW?
Is there a low risk of short circuiting?	3	.67	DON'T KNOW?
Is the sludge easily dewatered?	14	.67	DON'T KNOW?

Table 25. Questions and responses for the secondary matcher regarding dissolved oxygen concentration for a sample case.

QUESTIONS ASKED REGARDING DISSOLVED OXYGEN CONCENTRATION	CONSTRUCT	SV	RESPONSE
Is there a low risk of short circuiting?	3	.83	DON'T KNOW
Is the flow fluctuating?	6	.75	YES
Are shock loads characteristic of the flow?	8	.75	DON'T KNOW
Are there space limitations?	5	.67	YES
Is the sludge easily dewatered?	14	.67	DON'T KNOW

The confidence factor from the secondary matchers are calculated with the formula algorithm. Consider the calculation of the confidence factor for sludge age. There are two of the five questions with a response. Begin with the response with the highest SV is from construct 9, where SV = 0.92. Since n=1, m=5 and $CF_{n-1} = 0$, the CF is computed as follows:

$$CF_1 = 0 + [\ (1/5 * 0.92 * (1-0)\ ]$$

$$CF_1 = 0.18$$

The second highest SV is 0.75, so to compute the confidence factor for two responses, n=2, m=5, CF_{n-1} = 0.18 and SV = 0.75. Therefore:

$$CF_2 = .18 + [\ (2/5) * 0.75 * (1-0.18)\ ]$$

$$CF_2 = \mathbf{0.43}$$

Then calculate the confidence factor for dissolved oxygen concentration using the formula algorithm in the same manner.

$$CF_1 = 0 + [\ (1/5) * 0.75 * (1-0)\ ]$$

$$CF_1 = 0.15$$

$$CF_2 = 0.15 + [\ (2/5) * 0.67 * (1-.15)\ ]$$

$$CF_2 = \mathbf{0.38}$$

In this sample case, each question from the primary matcher has a response, and therefore a confidence factor. The degree of match for each primary matcher can be calculated from the confidence factors by weighted average. An example is shown in Table 26 for Element 1, conventional complete mixed reactor. Answers to primary matcher questions are in bold, and from the secondary matcher are indicated in the appropriate column. The degree of match is calculated as:

$$\text{degree of match} = \frac{0.34 -1 -1 +1 +1 +0.38 +1}{8}$$

$$\text{degree of match} = \mathbf{0.35}$$

Table 26. Primary matcher with confidence factors and degree of match for Element 1 - Conventional completely mixed reactor.

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			+0.43	+0.43
Nitrification occurs	+1	-1		-1.0
Plug flow regime	-1	+1		+1.0
HRT > 10 hours	+1	-1		+1.0
Denitrification occurs	-1	+1		+1.0
High MLSS concentration	-1	+1		+1.0
Dissolved O_2 > 4 mg/l			+0.38	+0.38
Soluble BOD removal > 90 %	+1	-1	+1.0	+1.0
DEGREE OF MATCH				+0.60

A degree of match is calculated for each primary matcher representing each element and can be found in Appendix E. Table 27. shows the results of these calculations.

Table 27. Degree of match for all primary matchers for a sample case.

Activated sludge technology	Element #	Degree of Match	Establish ? threshold = +0.5
Conventional completely mixed reactor	1	+0.6	YES
Step feed, plug flow reactor	2	-0.35	NO
Deep shaft design	3	-0.06	NO
Sequencing Batch Reactor	4	-0.4	NO
Pure oxygen complete mix reactor	5	+0.5	YES
Oxidation ditch	6	+0.1	NO

Weight factors in the primary matcher allow the expert to prioritize the design criteria, which in turn influences the confidence factor values. Table 28 shows the same classification as Table 27 but includes weight factors. A complete display of primary matchers is in Appendix E.

Table 28. Degree of match for all primary matchers including weight factors for a sample case.

Activated sludge technology	Element #	Degree of Match	Establish ? threshold = +0.5
Conventional completely mixed reactor	1	+0.35	YES
Step feed, plug flow reactor	2	-0.42	NO
Deep shaft design	3	-0.02	NO
Sequencing Batch Reactor	4	+0.19	YES
Pure oxygen complete mix reactor	5	+0.21	YES
Oxidation ditch	6	+0.10	NO

6.0. DISCUSSION

The methodology described in this thesis satisfies the two primary requirements of a successful knowledge acquisition exercise according to Gruber (1987) by establishing the type of knowledge and functional mapping. The type of knowledge is identified as the design criteria and features used for conceptual design. The functional mapping from the user is represented in the matchers by way of the grid and constraint based rules. The structure of how the expert decomposes the problem is expressed decision tree with a limited number of possible goal states. Confidence factors when compared with a pre-determined threshold are used to eliminate inappropriate goal states from the final decision.

Conceptual design decisions are decomposed based upon design criteria. The engineer chooses the combination of design values which he believes will result in satisfactory treatment of a waste stream. Therefore, primary matchers are composed of the design criteria, represented as design constructs in the proposed methodology, by which the expert bases his decisions. The user, when classifying a case, will select the value for the design criteria, which the matcher computes into confidence factors, and ultimately a degree of match. This degree of match, compared to a pre-selected threshold, determines if the node will establish or reject.

Frequently, the user will not have sufficient information to determine the value of the design constructs. The secondary matcher contains the feature constructs which, according to the expert, have a high correlation to the design construct. The secondary matcher will calculate and return a confidence value to the primary matcher that indicates the appropriate design construct value based on those features of the waste, technology and effluent standards which are related to that particular design criteria.

Not every question in the matchers, both primary and secondary, need be answered when classifying a case. The more information included in the evaluation of each node, the higher the confidence factors, and therefore the higher the degree of match. This is analogous to human decision-making processes. The more information an expert engineer knows about a waste stream and the technologies available, the more confidence he will have in his decision of conceptual design.

6.1. KNOWLEDGE ACQUISITION DRAWBACKS

Building expert system models serves several functions. First, it is a way of formulating domain knowledge. Also, it is a means of communicating about the problem space from which the expert operates. Models bring a common language to the table of discussion, allowing for deeper understanding of the decision-making process among experts. According to Bradshaw, et. al. (1992), knowledge acquisition usually involves "inventing new languages for modeling previously unarticulated experience.". They provide a platform for mutual agreement, and consequently, respect and acceptance.

Another important benefit of building and using an expert system is not merely the recommended outcome, but the improved insight for decision makers. Expertise is developed from understanding why one goal state is chosen over another. The recognition of the assumptions and underlying uncertainties which lead to the conclusion are the building blocks of expertise in trained individuals. One assumption relevant to the methodology described is that the "Gold Standard" of the expert must be accepted (Punch & Sticklen, 1991). The Gold Standard means that there is one answer which is clearly the proper choice from the options available for a given set of circumstances. If the Gold Standard is not accepted, then the results of this knowledge acquisition methodology will not be received favorably.

This knowledge acquisition exercise may not be able to uncover the automatic processes of some experts. Knowledge and judgement is stored differently among experts. For some, knowledge acquisition may have the onion effect. When all the layers are pealed away and examined, they may not fit back together. Or, there may be nothing in the middle holding the layers together. In effect, the basis for the experts decision making capability may not be able to be represented from these methods. Perhaps the expert has decomposed the problem into so many partitions that these techniques are not able to recognize and reassemble the parts.

A hindsight bias will tend to impede the knowledge acquisition process and must be overcome if one is to achieve effective capture and representation of expertise. According to Fischoff (1982), the very outcome which gives the feeling of understanding about the past may prevent learning anything from it. There is a strong tendency to establish the criteria for evaluating decisions after the corresponding events have occurred and the outcomes are known. With the wisdom of hindsight, one is free to ignore all the "noise" created by irrelevant or unreliable cues. Knowledge based on hindsight may occasionally hinder the development of appropriate decision processes. Attempts to modify and reduce this bias have been met with relatively little success (Fischoff, 1982).

A drawback of the FOCUS technique is the equal weight of all constructs considered in analysis. This is seldom the case in design decisions. There should be a way to reflect these differences among constructs in the repertory grid. The proposed methodology allows the matchers to be reviewed and tuned using weight factors. Priorities imposed with weight factors in primary matchers address this problem once the grid has been scored. Secondary matchers could also include a weight factor, which could be multiplied with the SV to reflect the expert's prioritization. However, this does not overcome the inherent bias to the FOCUS technique. Shaw (1981) has several examples of automated FOCUS programs which may address this issue.

6.2. MULTIPLE EXPERTS

The proposed methodology represents the mapping of a single expert. The results of the tree representing an expert's map may not satisfy another expert's view. Since the grid technique is subjective, the result is a mapping of the individual expert. One criticism of the grid technique is it's subjectivity. That is, two experts considering the same problem can produce different solutions. Newell & Simon (1972) provide evidence that this variation in view is what distinguishes novices from experts, and experts from among themselves. If several experts in a domain are presented with a problem, they each produce a solution based on their own paradigm. These results may or may not agree, reflecting the inconsistency among experts in the same field. The grid will capture the internal structure of the paradigm which could explain these differences based on the rules or even the sequence of rules by which the expert reasons the problem. This can be viewed as a positive attribute, as many experts systems are built to capture the expertise of an individual rather than the common pattern of decision-making generally accepted within the domain.

There may indeed be disagreement about the design criteria for technologies. Even when presented with the same grid and CBR chart to complete, two experts may score the tools differently, resulting in conflicts when attempting to join them. For example, expert # 1 scored "+" for E 1 regarding long sludge age greater than 15 days. Expert # 2 scored "-" for this design criteria construct. Therefore, we would not expect agreement in their final representations. Has the technique failed? Quite the contrary, the representation accurately models the decision tree structure of each expert, whether scientifically accurate or not. If the results from two or more experts are to be combined into a single expert system, there would need to be a method for conflict resolution of this type.

Conflicts may arise between responses in the grid versus in the CBR chart scored by the same expert. There are several reasons why these discrepancies may occur. First, the CBR chart asks the user to relate two design criteria and the effect they have on each other exclusive of other aspects of a particular technology. The grid, on the other hand, asks the user to compare attributes of the technology as functional unit. The contradictions may be a result of the knowledge acquisition technique itself, which forces the expert to view a problem as they have not done before. This may cause confusion. When forced to answer a question which is unnatural to their thought processes, they can respond erroneously. Out of context, their judgement may be clouded or altered by a new framework. They may not be reporting accurately. By comparing the two representations when a conflict is expressed, the expert can review and hopefully resolve the contradiction by altering one or both responses to agree.

The proposed methodology can be used to compare the decision process among multiple experts by comparing the resulting decision trees. For Expert # 1, the first discrimination is based on removal rate, a regulatory requirement, much the same as with expert #2 where removal rate was the second level in the tree. This indicates that the paradigms overlap in the conceptual design decision process. Insight as to the point and extent of overlap can be identified from the analysis described in the methodology. For example, knowing which design constructs are influenced by cost feature constructs in the repertory grids can help experts focus on how to reduce costs. When these design criteria are minimized, then so should be the associated costs, resulting in less expensive remediation.

Incorporated in computer programs such as ETS and Aquinas, they can be used directly by experts with very little assistance from the knowledge engineer, thus lending to efficient knowledge acquisition. For multiple expert input, these programs are an invaluable asset.

This methodology can be used to build one expert system with the input from multiple experts. The experts involved would gain consensus in eliciting and scoring the grid and CBR. The combined knowledge would be used to form one decision tree and one set of primary and secondary matchers. Since experts recognize their own limitations respect others' abilities, this should be possible. Obstacles such as the potential language and ego barriers may present difficulties which would need to be resolved among the experts.

6.3. REASONING EXPLANATION

The KBS built following the proposed methodology contains the ability to explain the decision process. The reasoning behind the rejection or establishment of nodes is expressed in the matchers and comment windows. The decomposition is exposed for examination by critics, and the point of discrepancy can be isolated. Often the expert would not be able to verbalize this distinction. When asked to explain his reasoning, the response is often "I just know". They cannot describe how they know. This knowledge acquisition technique allows for this distinction due to the explicit decomposition of the problem.

6.4. AUTOMATION

Automation of this method will greatly improve the quality of knowledge acquisition and representation. The expert will be able to view the decomposition of knowledge and make adjustments during the building process. Conflicts will be resolved, and gaps filled which exist in the examples included here. Experts have trouble verbalizing the decomposition, however, they are able to examine parts of a problem and reassemble components in an intelligent fashion. The skill of pattern recognition is called upon in the building or knowledge representation phase. The expert will quickly identify nonsensical relationships and conflicts which may not have been realized in the knowledge acquisition phase.

Re-evaluation of the grid results through the automation of the methodology will provide the expert with a hindsight view of their expertise. They will not be able to ignore the "noise" from irrelevant conclusions inferred from their decision tree and CBR results (Wright & Bolger, 1992).

7.0. ENGINEERING SIGNIFICANCE

The search for innovative techniques is motivated when conventional technologies fail or are too expensive. The incentive to stay with conventional techniques for regulatory approval is overwhelming in the United States today. According to the Michigan Department of Natural Resource employees interviewed in the development of the commercialization plan (Appendix A), only by addressing the regulatory community and their strict adherence to the tried and true methods will these new scientific technologies be implemented.

The hesitancy to approve innovative technologies is justified by the lack of reliable performance and specification data. Often these data exist, but not in a readily accessible format. A knowledge-based system could assist regulators by providing a resource database which includes information about new technologies. Classifying cases would direct attention toward these new methods, where the relationship between waste and treatment may not otherwise be recognized.

A knowledge based system to assist in the conceptual design process for environmental systems could expand the implementation of new technologies which are not well known or understood. The KBS applies reasoning free from regulatory biases, therefore the applicability of these treatment regimes is more visible. The knowledge acquisition process delineates the criteria important in the decision process. The performance data required to adequately place the new technology in the internal decision tree will be specified. Therefore, the developers of these technologies will have guidance as to the testing required for their design to gain acceptance and implementation. Incorporating an innovative technology into an existing KBS will clarify what information is needed to objectively compare the innovation to conventional competitive technologies. Limitations and expectations will be evaluated on the same criteria and scale. Perhaps if a technology is indicated as a potential remedy for a problem by the KBS, the regulators and consultants will have more confidence in recommending its implementation.

8.0. CONCLUSIONS

Knowledge is the key to ease the gridlock faced by the scientific and regulatory communities. The applicable knowledge is expansive and continually growing. The extent of regulations from all governmental levels is also increasing in complexity. Therefore, a computerized tool is required in environmental conceptual design to ensure the incorporation of all of this knowledge into the very important decisions being made today and tomorrow.

As a result of these factors, together with the extreme time constraints under which consultants and regulators are obliged to operate, conceptual design decisions are frequently made in a far from optimal manner. We cannot expect the experts who recommend and approve remediation solutions to keep up with this new knowledge, and incorporate all into their heuristic vocabulary. Experts compare to a wastewater to one they have seen before, take the treatment regime which worked before and apply it to the new wastewater. With modeling and estimating techniques, they judge whether it will work again. There is tendency to design around the restrictions, weed out any rejection criteria, and use scientific or risk analysis to verify their judgement. A more efficient manner could involve the assistance of a KBS as a decision support tool. This would allow a broader scope of potential technologies to choose from, thus resulting in optimized effective conceptual design.

Computer-aided tools can assist incorporating new rules which establish the scientific paradigm used when performing the search through the alternatives. Once these have been determined, the consultant can invoke their experience regarding cost, regulatory approval and design expertise. Consultants can apply their clever presentation and negotiating skills to a well-designed innovative treatment alternative to gain approval from regulators.

Although a tool which only assists in the decision making process may be helpful to the engineer or regulator, there is reason to believe that the use of this tool will not alone promote the implementation of new technologies. Choosing the appropriate technology is important, but a need was identified for a tool which would assist in the costing and final design of the selected method of treatment. A costing and/or design tool is the product which will best promote the implementation of new technologies. If the regulatory community would adopt such as KBS tool as guidance or policy in the conceptual design process, perhaps the implementation of innovative technologies would increase.

In spite of the numerous environmental software products available, the market is not growing as quickly as in other domains. Lack of standards and buyer skepticism are noted for the lack of acceptance of these new products. Gregory B. Baecher, CEO of ConSolve, the Lexington, Mass., vendor of SitePlanner software is quoted saying "Engineers and geologists still tend to work with 79 cents worth of colored pencils. The consulting industry needs to get into the 20th century." (Rubin, 1992) This applies not only to the modeling software, but to decision tools as well. The bulk of the cost of new software is the expense of demonstrating to customers that they need the system. Vice president of CM2H Hill, Inc. says "It's hard for many to make the paradigm shift." The conceptual design tool described in this paper will surely face the same battle.

From this methodology, the potential of developing new design strategies exists. A user may classify a waste from this representation and arrive at a goal state which has not been identified by the expert as a specific technology. According to the rules derived from the grid and CBR, this combination of the design criteria indicates possible remediation success. This goal state may also represent a known technology which is not apparently part of this user's paradigm. The conceptual design tool may direct users to designs which they may not otherwise consider, but may indeed be most appropriate for the situation.

9.0. FUTURE RESEARCH

9.1. AUTOMATION

Automation of this methodology could greatly enhance and improve the implementation of knowledge acquisition. When the expert can view the changes in tree structure resulting from different responses in the grid and CBR, he can develop a more accurate representation of his search space. With multiple experts, automation would provide timely feedback when resolving conflicts in expertise.

9.2. EXPANDING THE HIERARCHY

Two examples from this study were applied to the design of activated sludge processes. The methodology should be executed with experts in other areas of environmental engineering processes. Matchers need to be developed for each node in the hierarchy, regardless of the level, to complete the HC tool. The theory is that whether the process be physical, chemical or biological, the method should apply. However, this has not been tested.

9.3. ASSEMBLER

The proposed methodology is designed for knowledge acquisition and knowledge representation within the Hierarchial Classifier only. Recall that the proposed computer-aided conceptual design tool is comprised of two components - the Classifier and an Assembler. The assembler would be responsible for sequencing the technologies should more than one be required to meet regulatory standards. Many times pretreatment is necessary for effective remediation. The knowledge and decision support for both of these very important aspects of conceptual design must be developed to be incorporated with the HC for a complete system.

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Appendix A

Excerpt from

COMMERCIALIZATION PLAN

prepared by
Lori Schutz-Riley
MTA 810
Summer 1992

APPENDIX A

Excerpt from COMMERCIALIZATION PLAN

Summary of competitive products.

Environmental software is available to assist in the tasks of modeling, completing forms for governmental agencies, design, costing and decision-making. Some are available free of charge from the Environmental Protection Agency (EPA) and other branches of the United States Government. Others are commercial endeavors where prices range from a few hundred into the thousands. Pollution Engineering magazine reviews environmental software each year the January issue. They site the prime concerns for users of environmental software are flexibility, compatibility and maintainability.

This investigation was limited to software useful in the conceptual design task. A list of features compares and contrasts five tools to the MSU (Michigan State University) tool presented in Table 29. The distinguishing features of the MSU tool are that it is an expert system with decision making capability, it draws knowledge from interfaced databases, and includes innovative technologies. Unique to the MSU tool is the portability of the Smalltalk 80 language to all major PC's, although RAAS will be portable to PC-DOS soon.

Two of the software tools, RREL and VISITT, are databases developed by the EPA. RREL is compound oriented, while VISITT is technology oriented. VISITT, according to developer Linda Fiedler, is not intended to be a decision making tool. By design, the decision of which technology to use is dependent upon the expert judgement of the user. VISITT was released in June 1992, and annual updates are scheduled. Only seven weeks after release circulation exceeded 1,500 copies. This indicates a demand for such a product is real. The product is delivered at no cost and only contains vendor information supplied by the vendors themselves. In other words, this is not a comprehensive, unbiased compilation of technologies. A customer survey was executed as orders were taken, and a copy will be sent to us in the next month. The customer base at this time appears to be a mix of the groups we interviewed.

The RREL database contains relevant data about contaminants necessary to make such decisions. A few of the consultants we interviewed were familiar with RREL, and used it when they encountered a compound new to them. This tool is especially useful to the inexperienced who are performing the conceptual design task.

Neither RREL or VISITT share the distinguishing features of the MSU system outlined at the beginning of this discussion. Their initial purpose and function are different from the MSU system as they do not make decisions. However, they do address innovative technologies. They are accepted by their audience; the success is yet to be seen. Both will be helpful tools in building the MSU conceptual design tool, however do not occupy the same marketing niche.

CORA is an expert system combined with a costing tool. The primary goal in development of CORA was to assist in developing cost estimates in the pre-feasibility stage of site analysis at Superfund Sites. The 42 technologies included in the database are conventional methods only, so that accurate costing could be performed, and approval was certain. The last update was in 1990, and there are no plans for future development.

NETAC's ETAP program uses a database of only innovative technologies. The heuristic search is manual, performed by trained technicians. A weakness of NETAC is that the possibility of the same biases seen in consultants' recommendations could develop in the technicians performing these searches. A strength is that the database is continually updated with new technologies and support data for technologies already included. Preliminary cost and design information is included with the recommendation of the appropriate technology when available.

The RAAS system is the closest to the proposed MSU system we found as shown in Table 29. RAAS is an object oriented expert system which includes 90 conventional and innovative technologies. Although the initial goal was to address Superfund and Hazardous sites, the program is applicable to industrial wastes as well. RAAS is in the final alpha testing stage, and will begin beta testing soon. This project is years ahead of MSU in development of a total conceptual design tool.

RAAS system mimics the process of the RI/FS phases of remedial action. Included in the system are site, compound and technology databases, a modeling module, the capacity to construct treatment trains and address side streams produced from the original treatment technology. Whatever the defined goal, the search through technology objects within the RAAS application will attempt to construct treatment trains to satisfy that goal. RAAS is expandable to include technologies developed in the future. A costing tool to compliment RAAS is under development at this time.

Table 29. Environmental software for conceptual design.

Feature / Software	MSU	RAAS	RREL	VISITT	CORA	NETAC
interactive	*	*			*	*
user-friendly	*	*		*	*	*
expert system	*	*			*	
database			*	*		*
based on waste	*	*	*		*	*
based on site	*	*		*		*
based on technology	*	*		*		*
explained reasoning	*	*			*	
decision making	*	*			*	
cost evaluation		*		*	*	*
multi-constituent waste	*	*		*		
Superfund sites		*			*	
Hazardous waste only					*	
domain : air		*		*		*
wastewater	*	*	*			*
groundwater	*	*	*	*	*	*
soil/sediment		*		*	*	*
sludge		*				
portable	*	*				

Potential Users

One goal of the MSU conceptual design tool is to promote the implementation of innovative technologies in environmental engineering systems. By using an unbiased, decision making computer program, the conceptual designer will recognize opportunities to implement new strategies which otherwise would be overlooked and not considered. Based on interviews with consultants, regulators and environmental lawyers, awareness was not the primary reason that these innovative methods were not being used. The reason is that there is not enough supportive costing and design data available to ensure competent design, permit approval and eventual success in the implementation.

The more experienced consulting firms did not feel that this tool would be useful. Consultants with 10 to 15 years of experience use their judgement to make technology choices. They spend very little time in the conceptual design phase. Cost is the driving force to motivate engineers to search beyond their personal knowledge base for innovative solutions. Small, inexperienced consulting firms, however, could use the expert system to make technology decisions as they lack the experience to make decisions based on their own judgement. Consultants tend not to select new technologies over conventional methods because the DNR (Department of Natural Resources) and other regulatory agencies take more time to approve permits. The cost of fixing or replacing a faulty system is also motivation to only recommend conventional methods. Consultants hesitate to use new technologies unless the government will pay for the efforts made to correct the problem if the new technology does not work.

The regulatory agencies do not perform the conceptual design task. However, they are responsible for reviewing the environmental systems recommended by consultants and industry who do perform this task. When a new or innovative technology method is involved, the review period is extended due to the research required to evaluate the design and technology selection. With a conventional choice, past experience expedites the process. Often with a new technology choice, data is incomplete and unclear, resulting in the request for additional information. Only through experience is the DNR acquainted with new methods, and this is a very slow process. A tool such as this could verify and validate the decision to implement innovative methods, however, this process would need to be mandated by a higher authority before use would be guaranteed.

The expertise of lawyers is first with the law and the process of law. The priority of environmental engineering is secondary, therefore a knowledge tool would be a asset to second guess and verify a recommendation. A large company with an in-house environmental department expressed interest in this tool. The knowledge base is useful in that they often employ inexperienced engineers to make the technology selection, and rarely go outside the company for advise.

Appendix B

KNOWLEDGE ACQUISITION FROM EXPERT # 1

Appendix B

KNOWLEDGE ACQUISITION FROM EXPERT # 1

ANALYSIS OF REPERTORY GRID OF EXPERT # 1

ORIGINAL GRID

ELEMENTS / CONSTRUCTS	1	2	3	4	5	6	CONSTRUCTS
1	0	1	1	-1	1	-1	1 High cost of construction
2	0	0	0	0	0	0	2 Low power input for aeration
3	1	-1	1	0	0	1	3 Low risk of short circuiting flow
4	0	-1	-1	-1	1	0	4 High operational costs
5	0	0	1	0	1	0	5 Low space requirement
6	1	-1	-1	0	1	1	6 Tolerates fluctuating flow
7	-1	-1	-1	-1	-1	-1	7 Sludge bulking/foaming problems
8	1	-1	-1	0	1	1	8 Tolerates shock loading, toxics
9	1	-1	-1	0	-1	1	9 High recycle rate
10	-1	-1	-1	-1	-1	-1	10 Biodegrades suspended solids
11	0	0	0	0	0	1	11 High oxygen transfer rate
12	-1	-1	-1	-1	-1	-1	12 Tolerates intermittent flow
13	-1	-1	-1	-1	-1	-1	13 SVI > 100, poor sludge settlability
14	1	1	1	1	-1	1	14 Sludge easily dewatered
15	0	0	0	0	0	0	15 High biological solids production
16	-1	1	1	1	-1	1	16 High MLSS concentration
17	1	-1	-1	1	-1	1	17 Long sludge age, > 15 days
18	1	-1	1	1	1	1	18 Dissolved oxygen > 4 mg/l
19	1	-1	1	1	1	1	19 Soluble BOD removal > 90 %
20	1	-1	-1	1	1	0	20 Complete mix flow regime
21	-1	1	1	1	-1	1	21 Plug flow regime
22	1	-1	-1	-1	-1	1	22 Long hydraulic retention time, > 10 hours
23	1	-1	-1	1	-1	1	23 Nitrification occurs
24	-1	-1	-1	1	-1	1	24 Denitrification occurs
25	1	1	1	1	1	1	25 Primary settling tank required

ELEMENTS

1 Conventional completely mixed reactor
2 Step feed, plug flow reactor
3 Deep shaft
4 Sequencing batch reactor
5 Pure oxygen complete mix reactor
6 Oxidation ditch, extended aeration

dij CALCULATIONS

E / C	1/2	1/3	1/4	1/5	1/6	2/3	2/4	2/5	2/6	3/4	3/5	3/6	4/5	4/6	5/6
1	1	1	1	1	1	0	2	0	2	2	0	2	2	0	2
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	0	1	1	0	2	1	1	2	1	1	0	0	1	1
4	1	1	1	1	0	0	0	2	1	0	2	1	2	1	1
5	0	1	0	1	0	1	0	1	0	1	0	1	1	0	1
6	2	2	1	0	0	0	1	2	2	1	2	2	1	1	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	2	2	1	0	0	0	1	2	2	1	2	2	1	1	0
9	2	2	1	2	0	0	1	0	2	1	0	2	1	1	2
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	1	0	0	0	1	0	0	1	0	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	2	0	0	0	2	0	0	2	0	2	0	2
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	2	2	2	0	2	0	0	2	0	0	2	0	2	0	2
17	2	2	0	2	0	0	2	0	2	2	0	2	2	0	2
18	2	0	0	0	0	2	2	2	2	0	0	0	0	0	0
19	2	0	0	0	0	2	2	2	2	0	0	0	0	0	0
20	2	2	0	0	1	0	2	2	1	2	2	1	0	1	1
21	2	2	2	0	2	0	0	2	0	0	2	0	2	0	2
22	2	2	2	2	0	0	0	0	2	0	0	2	0	2	2
23	2	2	0	2	0	0	2	0	2	2	0	2	2	0	2
24	0	0	2	0	2	0	2	0	2	2	0	2	2	0	2
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dij	26	21	14	14	9	7	18	20	25	15	15	20	20	9	23

FOCUS OF THE ELEMENTS

GRID # 1

DIFFERENCE MEASURES (dij)

ELEMENTS	2	3	4	5	6
1	26	21	14	14	9
2		7	18	20	25
3			15	15	20
4				20	9
5					23

SIMILARITY VALUES (SV)

ELEMENTS	2	3	4	5	6
1	48	58	72	72	82
2		86	64	60	50
3			70	70	60
4				60	82
5					54

FUSED GRID # 2

ELEMENTS / CONSTRUCTS	5	7	8
1	1	1	-1
2	0	0	0
3	0		1
4	1	-1	-1
5	1	1	0
6	1	-1	1
7	-1	-1	-1
8	1	-1	1
9	-1	-1	1
10	-1	-1	-1
11	0	0	1
12	-1	-1	-1
13	-1	-1	-1
14	-1	1	1
15	0	0	0
16	-1	1	
17	-1	-1	1
18	1		1
19	1		1
20	1	-1	1
21	-1	1	
22	-1	-1	
23	-1	-1	1
24	-1	-1	
25	1	1	1

dij CALCULATION

E / C	5 / 7	5 / 8	7 / 8
1	0	2	2
2	0	0	0
3		1	
4	2	2	0
5	0	1	1
6	2	0	2
7	0	0	0
8	2	0	2
9	0	2	2
10	0	0	0
11	0	1	1
12	0	0	0
13	0	0	0
14	2	2	0
15	0	0	0
16	2		
17	0	2	2
18		0	
19		0	
20	2	0	2
21	2		
22	0		
23	0	2	2
24	0		
25	0	0	0
dij	14	15	16

DIFFERENCE MEASURES (dij)

ELEMENTS	7	8
5	14	15
7		16

SIMILARITY VALUES (SV)

ELEMENTS	7	8
5	68	64
7		56

FUSED GRID # 3

ELEMENTS / CONSTRUCTS	9	8
1	1	-1
2	0	0
3		1
4		-1
5	1	0
6		1
7	-1	-1
8		1
9	-1	1
10	-1	-1
11	0	1
12	-1	-1
13	-1	-1
14		1
15	0	0
16		
17	-1	1
18		1
19		1
20		1
21		
22	-1	
23	-1	1
24	-1	
25	1	1

dij CALCULATION

ELEMENTS / CONSTRUCTS	8 / 9
1	2
2	0
3	
4	
5	1
6	
7	0
8	
9	2
10	0
11	1
12	0
13	0
14	
15	0
16	
17	2
18	
19	
20	
21	
22	
23	2
24	
25	0
dij	10
SV	62

FOCUS OF THE CONSTRUCTS OF EXPERT # 1

dij VALUES

CONSTRUCTS	16	17	18	19	20	21	22	23	24	25
1	7	11	7	7	8	7	9	11	11	5
2	6	6	6	6	5	6	6	6	6	6
3	6	4	2	2	5	6	4	4	6	4
4	10	6	6	6	3	10	4	6	6	8
5	6	8	4	4	5	6	8	8	8	4
6	9	3	3	3	2	9	3	3	5	5
7	8	6	10	10	7	8	4	6	4	12
8	9	3	3	3	2	9	3	3	5	5
9	7	1	5	5	4	7	1	1	3	7
10	8	6	10	10	7	8	4	6	4	12
11	5	5	5	5	6	5	5	5	5	5
12	8	6	10	10	7	8	4	6	4	12
13	8	6	10	10	7	8	4	6	4	12
14	2	4	4	4	7	2	6	4	6	2
15	6	6	6	6	5	6	6	6	6	6

SV VALUES OVER 60 FOR EXPERT # 1

CONSTRUCTS	16	17	18	19	20	21	22	23	24	25
1										
2										
3		67	83	83			67	67		67
4					75		67			
5			67	67						67
6		75	75	75	83		75	75		
7							67		67	
8		75	75	75	83		75	75		
9		92			67		92	92	75	
10							67		67	
11										
12							67		67	
13							67		67	
14	83	67	67	67		83				
15										

Table 30. Primary matcher for Element 1 from Expert # 1 - Conventional completely mixed reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days		+1	-1		
Nitrification occurs		+1	-1		
Plug flow regime		-1	+1		
HRT > 10 hours		+1	-1		
Denitrification occurs		-1	+1		
High MLSS concentration		-1	+1		
Dissolved O_2 > 4 mg/l		+1	-1		
Soluble BOD removal > 90 %		+1	-1		
DEGREE OF MATCH					

Table 31. Primary matcher for element 2 from Expert # 1 - Step feed, plug flow reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days		-1	+1		
Nitrification occurs		-1	+1		
Plug flow regime		+1	-1		
HRT > 10 hours		-1	+1		
Denitrification occurs		-1	+1		
High MLSS concentration		+1	-1		
Dissolved O_2 > 4 mg/l		-1	+1		
Soluble BOD removal > 90 %		-1	+1		
DEGREE OF MATCH					

Table 32. Primary matcher for element 3 from Expert # 1 - Deep shaft design

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days		-1	+1		
Nitrification occurs		-1	+1		
Plug flow regime		+1	-1		
HRT > 10 hours		-1	+1		
Denitrification occurs		-1	+1		
High MLSS concentration		+1	-1		
Dissolved O_2 > 4 mg/l		+1	-1		
Soluble BOD removal > 90 %		+1	-1		
DEGREE OF MATCH					

Table 33. Primary matcher for element 4 from Expert # 1 - sequencing batch reactor

DESIGN CONSTRUCTS	WEIGHT FACTORS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days		+1	-1		
Nitrification occurs		+1	-1		
Plug flow regime		+1	-1		
HRT > 10 hours		-1	+1		
Denitrification occurs		+1	-1		
High MLSS concentration		+1	-1		
Dissolved O_2 > 4 mg/l		+1	-1		
Soluble BOD removal > 90 %		+1	-1		
DEGREE OF MATCH					

Table 34. Primary matcher for element 5 from Expert # 1 - pure oxygen complete mix reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days		-1	+1		
Nitrification occurs		-1	+1		
Plug flow regime		-1	+1		
HRT > 10 hours		-1	+1		
Denitrification occurs		-1	+1		
High MLSS concentration		-1	+1		
Dissolved O_2 > 4 mg/l		+1	-1		
Soluble BOD removal > 90 %		+1	-1		
DEGREE OF MATCH					

Table 35. Primary matcher for element 6 from Expert # 1 - oxidation ditch

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days		+1	-1		
Nitrification occurs		+1	-1		
Plug flow regime		+1	-1		
HRT > 10 hours		+1	-1		
Denitrification occurs		+1	-1		
High MLSS concentration		+1	-1		
Dissolved O_2 > 4 mg/l		+1	-1		
Soluble BOD removal > 90 %		+1	-1		
DEGREE OF MATCH					

Table 36. Secondary matcher for Expert # 1 - Sludge age > 15 days

FEATURE CONSTRUCT	9	6	8	3	14
SV	+ 0.92	+ 0.75	+ 0.75	+ 0.67	+ 0.67

Table 37. Secondary matcher for Expert # 1 - Plug flow regime

FEATURE CONSTRUCT	6	8	14	4	9
SV	- 0.83	- 0.83	+ 0.83	- 0.67	- 0.67

Table 38. Secondary matcher for Expert # 1 - Hydraulic retention time > 10 hours

FEATURE CONSTRUCT	9	6	8	3	4	7	10	12	13
SV	+ 0.92	+ 0.75	+ 0.75	+ 0.67	+ 0.67	- 0.67	- 0.67	- 0.67	- 0.67

Table 39. Secondary matcher for Expert # 1 - High MLSS Concentration

FEATURE CONSTRUCT	14
SV	- 0.83

Table 40. Secondary matcher for Expert # 1 - Dissolved O_2 > 4 mg/l

FEATURE CONSTRUCT	3	6	8	5	14
SV	+ 0.83	- 0.75	- 0.75	+ 0.67	+ 0.67

Table 41. Secondary matcher for Expert # 1 - Soluble BOD removal > 90 %

FEATURE CONSTRUCT	3	6	8	5	14
SV	+ 0.83	- 0.75	- 0.75	+ 0.67	+ 0.67

Appendix C

KNOWLEDGE ACQUISITION RESULTS FROM EXPERT # 2

FOCUS OF ELEMENTS

dij CALCULATION

ELEMENTS	1							2						3					4				5			6		7
CONSTRUCTS	2	3	4	5	6	7	8	3	4	5	6	7	8	4	5	6	7	8	5	6	7	8	6	7	8	7	8	8
1	0	0	1	0	0	1	1	0	1	0	0	1	1	1	0	0	1	1	1	1	0	2	0	1	1	1	1	2
2	0	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0	2	0	2	1	2	0	1	2	1	1
3	1	1	0	1	1	0	0	0	1	0	0	1	1	1	0	0	1	1	1	1	0	0	0	1	1	1	1	0
4	0	0	1	0	0	1	1	0	1	0	0	1	1	1	0	0	1	1	1	1	0	2	0	1	1	1	1	2
5	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	2	0	0	2	0	2	2
6	1	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1	1
7	1	1	2	0	2	0	0	0	1	1	1	1	1	1	1	1	1	1	2	0	2	2	2	0	0	2	2	0
8	2	0	2	2	1	2	2	2	0	0	1	1	0	2	2	1	2	2	0	1	0	0	1	0	0	1	1	0
9	1	1	2	2	2	2	2	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
10	0	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0	2	2	0	1	0	2	1	2	1	1
11	1	0	0	1	1	0	1	1	1	2	2	1	0	0	1	1	0	1	1	1	0	1	0	1	2	1	2	1
12	0	0	1	0	0	1	0	0	1	0	0	1	0	1	0	0	1	0	1	1	0	1	0	1	0	1	0	1
13	1	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1	1
14	2	1	0	0	2	0	1	1	2	2	0	1	1	1	1	1	1	0	0	2	0	1	2	0	1	2	1	1
15	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	2	0	2	2	0	2	2	0	2
16	0	0	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	2	0	0	2	2	0
17	1	1	1	0	1	1	1	2	0	1	0	1	2	2	1	2	2	0	1	0	0	2	1	1	1	0	2	2
18	0	0	0	1	0	0	2	0	0	1	0	1	2	0	1	0	0	2	1	0	0	2	1	1	1	0	2	2
19	0	0	2	0	0	2	0	0	2	0	0	1	0	2	0	0	2	0	2	2	0	2	0	2	0	2	0	2
20	0	0	2	0	2	2	0	0	2	0	2	1	0	2	0	2	2	0	2	0	0	2	2	2	0	0	2	2
21	2	0	0	0	0	0	1	2	2	2	2	1	1	0	0	0	0	1	0	0	0	1	0	0	1	0	1	1
22	2	0	0	0	0	0	0	2	2	2	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	2	0	0	0	0	1	2	0	0	0	0	2	0	0	0	2	0	0	2	0	2	2
24	1	0	0	2	2	0	0	1	1	1	1	1	1	0	2	2	0	0	2	2	0	0	0	2	2	2	2	0
25	0	1	2	2	2	0	0	1	2	2	2	1	0	1	1	1	1	1	0	0	2	2	0	2	2	2	2	0
26	0	0	2	0	0	0	2	0	2	0	0	1	2	2	0	0	0	2	2	2	2	0	0	0	2	0	2	2
dij	16	6	22	16	21	17	21	14	28	22	21	26	21	22	16	17	21	21	22	19	9	31	15	17	25	24	32	28

dij TABLE

ELEMENTS	2	3	4	5	6	7	8
1	16	6	22	16	21	17	21
2		14	28	22	21	26	21
3			22	16	17	21	21
4				22	19	9	31
5					15	17	25
6						24	32
7							28

SIMILARITY VALUES, SV

E	2	3	4	5	6	7	8
1	69	88	58	69	60	67	60
2		73	46	58	60	50	60
3			58	69	67	60	60
4				58	63	83	40
5					71	67	52
6						54	38
7							46

FUSED GRID # 2

ELEMENTS / CONSTRUCTS	2	5	6	8	9	10
1	0	0	0	-1	0	1
2	0	-1	1	0	0	
3	0	0	0	1	1	1
4	0	0	0	-1	0	1
5	0	1	1	-1	0	1
6	1	0	0	1	0	0
7	0	1	-1	1	1	
8	1	1	0	1	-1	1
9	0	1	1	1	-1	1
10	0	1	1	0	0	-1
11	-1	1	1	-1	0	0
12	0	0	0	0	0	1
13	1	0	0	1	0	0
14	-1	1	-1	0	0	1
15	0	-1	1	1	0	-1
16	0	1	-1	1	0	1
17	-1	0	-1	1	1	-1
18	-1	0	-1	1	-1	-1
19	-1	-1	-1	-1	-1	1
20	-1	-1	1	-1	-1	1
21	1	-1	-1	0	-1	-1
22	-1	1	1	1	1	1
23	-1	-1	-1	1	-1	-1
24	0	-1	-1	1	1	1
25	1	-1	-1	1	1	
26	1	1	1	-1	1	

dij CALCULATION

ELEMENTS / CONSTRUCTS	2/5	6	8	9	11	5/6	8	9	11	6/8	9	11	8/9	11	9/11
1	0	0	1	0	1	0	1	0	1	1	0	1	1	2	1
2	1	1	0	0		2	1	1		1	1		0		
3	0	0	1	1	1	0	1	1	1	1	1	1	0	0	0
4	0	0	1	0	1	0	1	0	1	1	0	1	1	2	1
5	1	1	1	0	1	0	2	1	0	2	1	0	1	2	1
6	1	1	0	1	1	0	1	0	0	1	0	0	1	1	0
7	1	1	1	1		2	0	0		2	2		0		
8	0	1	0	2	0	1	0	2	0	1	1	1	2	0	2
9	1	1	1	1	1	0	0	2	0	0	2	0	2	0	2
10	1	1	0	0	1	0	1	1	2	1	1	2	0	1	1
11	2	2	0	1	1	0	2	1	1	2	1	1	1	1	0
12	0	0	0	0	1	0	0	0	1	0	0	1	0	1	1
13	1	1	0	1	1	0	1	0	0	1	0	0	1	1	0
14	2	0	1	1	2	2	1	1	0	1	1	2	0	1	1
15	1	1	1	0	1	2	2	1	0	0	1	2	1	2	1
16	1	1	1	0	1	2	0	1	0	2	1	2	1	0	1
17	1	0	2	2	0	1	1	1	1	2	2	0	0	2	2
18	1	0	2	0	0	1	1	1	1	2	0	0	2	2	0
19	0	0	0	0	2	0	0	0	2	0	0	2	0	2	2
20	0	2	0	0	2	2	0	0	2	2	2	0	0	2	2
21	2	2	1	2	2	0	1	0	0	1	0	0	1	1	0
22	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
23	0	0	2	0	0	0	2	0	0	2	0	0	2	2	0
24	1	1	1	1	1	0	2	2	2	2	2	2	0	0	0
25	2	2	0	0		0	2	2		2	2		0		
26	0	0	2	0		0	2	0		2	0		2		
dij	22	21	21	16	23	15	25	18	15	32	21	18	19	25	18

dij TABLE

ELEMENTS	5	6	8	9	10
2	22	21	21	16	23
5		15	25	18	15
6			32	21	18
8				19	25
9					18

SIMILARITY VALUES, SV

E	5	6	8	9	10
2	58	60	60	69	48
5		71	52	65	66
6			38	60	59
8				63	43
9					59

FUSED GRID # 3

ELEMENTS / CONSTRUCTS	8	10	11	12
1	-1	1	0	0
2	0			0
3	1	1	0	1
4	-1	1	0	0
5	-1	1	1	0
6	1	0	0	1
7	1			1
8	1	1	1	
9	1	1	1	-1
10	0	-1	1	0
11	-1	0	1	-1
12	0	1	0	0
13	1	0	0	1
14	0	1		-1
15	1	-1		0
16	1	1		0
17	1	-1	-1	
18	1	-1	-1	-1
19	-1	1	-1	-1
20	-1	1		-1
21	0	-1	-1	
22	1	1	1	
23	1	-1	-1	-1
24	1	1	-1	1
25	1		-1	1
26	-1		1	1

dij CALCULATION

ELEMENTS / CONSTRUCTS	8 / 10	11	12	10 / 11	12	11 / 12
1	2	1	1	1	1	0
2			0			
3	0	1	0	1	0	1
4	2	1	1	1	1	0
5	2	2	1	0	1	1
6	1	1	0	0	1	1
7			0			
8	0	0		0		
9	0	0	2	0	2	2
10	1	1	0	2	1	1
11	1	2	0	1	1	2
12	1	0	0	1	1	0
13	1	1	0	0	1	1
14	1		1		2	
15	2		1		1	
16	0		1		1	
17	2	2		0		
18	2	2	2	0	0	0
19	2	0	0	2	2	0
20	2		0		2	
21	1	1		0		
22	0	0		0		
23	2	2	2	0	0	0
24	0	2	0	2	0	2
25		2	0			2
26		2	2			0
dij	25	23	14	11	18	13

dij TABLE

ELEMENTS	10	11	12
8	25	23	14
10		11	18
11			13

SIMILARITY VALUES, SV

E	10	11	12
8	40	39	67
10		68	47
11			57

FUSED GRID # 4

ELEMENTS / CONSTRUCTS	13	14
1	-1	1
2	0	
3	1	1
4	-1	1
5	-1	1
6	1	0
7	1	
8		1
9		1
10	0	
11	-1	1
12	0	1
13	1	0
14	-1	
15	1	
16	1	
17		-1
18		-1
19	-1	
20	-1	
21		-1
22		1
23		-1
24	1	
25	1	
26		

dij CALCULATION

ELEMENTS / CONSTRUCTS	13 / 14
1	2
2	
3	0
4	2
5	2
6	1
7	
8	
9	
10	
11	2
12	1
13	1
14	
15	
16	
17	
18	
19	
20	
21	
22	
23	
24	
25	
26	
dij	11
SV	31

FOCUS OF CONSTRUCTS

dij VALUES

CONSTRUCTS	17	18	19	20	21	22	23	24	25	26
1	9	10	5	5	10	7	11	6	8	7
2	8	9	8	6	7	8	7	8	9	9
3	8	9	8	8	11	3	10	4	4	7
4	9	10	5	5	9	7	11	6	7	6
5	11	12	7	4	12	5	12	8	9	4
6	6	7	9	8	7	7	7	7	6	9
7	6	6	10	12	8	5	7	5	2	5
8	10	6	5	6	9	6	8	8	9	10
9	10	9	7	5	10	3	9	7	8	7
10	6	6	11	9	6	7	7	11	8	5
11	9	10	9	7	10	7	11	11	10	5
12	7	8	5	5	8	5	9	5	6	7
13	5	6	9	9	8	7	7	7	6	9
14	9	10	7	9	10	5	11	5	6	7
15	4	5	10	8	5	8	4	8	5	8
16	5	6	7	9	8	5	7	5	4	10

SV VALUES

CONSTRUCTS	17	18	19	20	21	22	23	24	25	26
1	44	38	69	69	38	56	31	63	50	56
2	50	44	50	63	56	50	56	50	44	44
3	50	44	50	50	31	81	38	75	75	56
4	44	38	69	69	44	56	31	63	56	63
5	31	25	56	75	25	69	25	50	44	75
6	63	56	44	50	56	56	56	56	63	44
7	63	63	38	25	50	69	56	69	88	69
8	38	63	69	63	44	63	50	50	44	38
9	38	44	56	69	38	81	44	56	50	56
10	63	63	31	44	63	56	56	31	50	69
11	44	38	44	56	38	56	31	31	38	69
12	56	50	69	69	50	69	44	69	63	56
13	69	63	44	44	50	56	56	56	63	44
14	44	38	56	44	38	69	31	69	63	56
15	75	69	38	50	69	50	75	50	69	50
16	69	63	56	44	50	69	56	69	75	38

SV VALUES OVER 60

CONSTRUCTS	17	18	19	20	21	22	23	24	25	26
1			69	69				63		
2				63						
3						81		75	75	
4			69	69				63		63
5				75		69				75
6	63								63	
7	63	63				69		69	88	69
8		63	69	63		63				
9				69		81				
10	63	63			63					69
11										69
12			69	69		69		69	63	
13	69	63							63	
14						69		69	63	
15	75	69			69		75		69	
16	69	63				69		69	75	

Table 42. Primary matcher for element 1 from Expert # 2 - conventional plug flow

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		+1	-1		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		-1	+1		
Plug flow regime		+1	-1		
Space loading > 1.5 lbBOD/cu ft-d		-1	+1		
Nitrification single stage		+1	-1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 43. Primary matcher for element 2 from Expert # 2 - conventional completely mixed reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		0	0		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		-1	+1		
Plug flow regime		-1	+1		
Space loading > 1.5 lbBOD/cu ft-d		-1	+1		
Nitrification single stage		+1	-1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 44. Primary matcher for element 3 from Expert # 2 - step feed, plug flow

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		+1	-1		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		-1	+1		
Plug flow regime		+1	-1		
Space loading > 1.5 lbBOD/cu ft-d		-1	+1		
Nitrification single stage		0	0		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 45. Primary matcher for element 4 from Expert # 2 - deep shaft design

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		+1	-1		
Dissolved O_2 > 4 mg/l		+1	-1		
Primary settling tank required		-1	+1		
Sludge age > 15 days		-1	+1		
Plug flow regime		+1	-1		
Space loading > 1.5 lbBOD/cu ft-d		+1	-1		
Nitrification single stage		-1	+1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 46. Primary matcher for element 5 from Expert # 2 - contact stabilization

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		-1	+1		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		0	0		
Plug flow regime		+1	-1		
Space loading > 1.5 lbBOD/cu ft-d		-1	+1		
Nitrification single stage		-1	+1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 47. Primary matcher for element 6 from Expert # 2 - high rate

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		-1	+1		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		-1	+1		
Plug flow regime		+1	-1		
Space loading >1.5 lb BOD/cu ft-d		+1	-1		
Nitrification single stage		-1	+1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 48. Primary matcher for element 7 from Expert # 2 - pure oxygen

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		+1	-1		
Dissolved O_2 > 4 mg/l		+1	-1		
Primary settling tank required		+1	-1		
Sludge age > 15 days		-1	+1		
Plug flow regime		+1	-1		
Space loading > 1.5 lbBOD/cu ft-d		+1	-1		
Nitrification single stage		+1	-1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 49. Primary matcher for element 8 from Expert # 2 - extended aeration

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Cost factors, etc.		0	0		
Soluble BOD removal > 90 %		+1	-1		
Dissolved O_2 > 4 mg/l		-1	+1		
Primary settling tank required		-1	+1		
Sludge age > 15 days		+1	-1		
Plug flow regime		+1	-1		
Space loading >1.5 lb BOD/cu ft-d		-1	+1		
Nitrification single stage		+1	-1		
Suspended BOD removal, etc.		0	0		
DEGREE OF MATCH					

Table 50. Secondary matcher for expert # 2 - cost and space factors

FEATURE CONSTRUCT	1	4	5	11
SV	+ .8	+ .8	+ .8	+ .8

Table 51. Secondary matcher for Expert # 2 - Soluble BOD removal > 90 %

FEATURE CONSTRUCT	3	7	12	16	4	1
SV	+ .75	+ .69	+ .69	- .63	- .63	- .63

Table 52. Secondary matcher for Expert # 2 - Dissolved oxygen concentration > 4 mg/l

FEATURE CONSTRUCT	1	4	8	12
SV	+ .69	+ .69	+ .69	+ .69

Table 53. Secondary matcher for Expert # 2 - Primary settling tank (construct 10 omitted, 0 score)

FEATURE CONSTRUCTS	5	7	14	4
SV	+ .75	+ .69	- .69	+ .63

Table 54. Secondary matcher for Expert # 2 - Sludge age > 15 days

FEATURE CONSTRUCTS	15	16	13	10	7	8
SV	+ .69	+ .63	+ .63	- .63	+ .63	+ .63

Table 55. Secondary matcher for Expert # 2 - Plug flow regime

FEATURE CONSTRUCTS	3	9	7	14	16	8
SV	+ .81	- .81	+ .69	+ .69	+ .69	+ .63

Table 56. Secondary matcher for Expert # 2 - Space loading (constructs 1, 4 and 12 omitted, 0 score)

FEATURE CONSTRUCTS	5	9	2	8
SV	+ .75	+ .69	+ .63	- .63

Table 57. Secondary matcher for Expert # 2 - Nitrification (constructs 13 and 6 omitted, 0 score)

FEATURE CONSTRUCTS	7	3	16	15	14	12	6
SV	+ .88	+ .75	+ .75	- .69	+ .63	+ .63	+ .63

Table 58. Secondary matcher for Expert # 2 - Suspended BOD Removal, ETC.

FEATURE CONSTRUCT	1	7	14
SV	+ .8	+ .8	+ .8

Appendix D

KNOWLEDGE ACQUISITION FROM EXPERT # 3

ORIGINAL GRID FOR EXPERT # 3

ELEMENTS / CONSTRUCTS	1	2	3	4	5	
1	-1	1	1	-1	1	High maintenance requirement
2	1	-1	1	-1	-1	High power requirement
3	-1	1	1	-1	1	High operating costs
4	-1	1	1	-1	1	High chlorinated hydrodrocarbons
5	1	0	-1	0	1	Toxic by-products of biodegradation
6	-1	-1	-1	1	-1	High lead concentration
7	1	-1	-1	1	1	Low mobility of contaminant in soil
8	-1	-1	1	-1	1	High capital investment
9	1	1	-1	1	1	Not in close proximity of electricity
10	-1	1	1	-1	-1	BTEX concentration < 10 ppb
11	1	-1	-1	-1	1	BTEX concentration > 10,000 ppb
12	1	-1	-1	-1	-1	TDS > 30,000 mg/l, inorganic
13	-1	1	1	-1	1	Density of contaminant > water
14	1	-1	-1	-1	1	pH adjustment required
15	1	1	1	1	1	Iron removal required
16 *	-1	1	1	-1	-1	Removal rate to 1 ppb
17 *	-1	1	-1	1	-1	Flow rate > 15 MGD
18 *	1	0	1	0	1	Long residence time
19 *	1	-1	1	-1	1	Contaminant chemically destroyed
20 *	-1	0	0	-1	-1	Low temperature

ELEMENTS

1 Aerobic fixed film
2 Activated carbon
3 Ultraviolet oxidation of H2O2
4 Air stripping
5 Anaerobic GAC fluidized bed

FOCUS OF ELEMENTS

dij CALCULATION

ELEMENTS	1				2			3		4
CONSTRUCTS	2	3	4	5	3	4	5	4	5	5
1	2	2	0	2	0	2	0	2	0	2
2	2	0	2	2	2	0	0	2	2	0
3	2	2	0	2	0	2	0	2	0	2
4	2	2	0	2	0	2	0	2	0	2
5	1	2	1	0	1	0	1	1	2	1
6	0	0	2	0	0	2	0	2	0	2
7	2	2	0	0	0	2	2	2	2	0
8	0	2	0	2	2	0	2	2	0	2
9	0	2	0	0	2	0	0	2	2	0
10	2	2	0	0	0	2	2	2	2	0
11	2	2	2	0	0	0	2	0	2	2
12	2	2	2	2	0	0	0	0	0	0
13	2	2	0	2	0	2	0	2	0	2
14	2	2	2	0	0	0	2	0	2	2
15	0	0	0	0	0	0	0	0	0	0
16	2	2	0	0	0	2	2	2	2	0
17	2	0	2	0	2	0	2	2	0	2
18	1	0	1	0	1	0	1	1	0	1
19	2	0	2	0	2	0	2	2	0	2
20	1	1	0	0	0	1	1	1	1	0
dij	29	27	16	14	12	17	19	29	17	22

dij TABLE

ELEMENTS	2	3	4	5
1	29	27	16	14
2		12	17	19
3			29	17
4				22
5				

SIMILARITY VALUE, SV

ELEMENTS	2	3	4	5
1	28	33	60	65
2		70	58	53
3			28	58
4				45
5				

FUSED GRID # 2

ELEMENTS / CONSTRUCTS	4	6	7
1	-1	1	
2	-1		
3	-1	1	
4	-1	1	
5	0	-1	1
6	1	-1	-1
7	1	-1	1
8	-1		
9	1		1
10	-1	1	-1
11	-1	-1	1
12	-1	-1	
13	-1	1	
14	-1	-1	1
15	1	1	1
16	-1	1	-1
17	1		-1
18	0	1	1
19	-1		1
20	-1	0	-1

dij CALCULATIONS

ELEMENTS / CONSTRUCTS	4		6
	6	7	7
1	2		
2			
3	2		
4	2		
5	1	1	2
6	2	2	0
7	2	0	2
8			
9		0	
10	2	0	2
11	0	2	2
12	0		
13	2		
14	0	2	2
15	0	0	0
16	2	0	2
17		2	
18	1	1	0
19		2	
20	1	0	1
dij	19	12	13

dij TABLE

ELEMENTS	6	7
4	19	12
6		13

SIMILARITY VALUE, SV

ELEMENTS	6	7
4	53	54
6		35

FUSED GRID # 3

ELEMENTS / CONSTRUCTS	6	8
1	1	
2		
3	1	
4	1	
5	-1	1
6	-1	
7	-1	1
8		
9		1
10	1	-1
11	-1	
12	-1	
13	1	
14	-1	
15	1	1
16	1	-1
17		
18	1	1
19		
20	0	-1

dij CALCULATIONS

ELEMENTS / CONSTRUCTS	6 / 8
1	1
2	
3	
4	
5	2
6	
7	2
8	
9	
10	2
11	
12	
13	
14	
15	0
16	2
17	
18	0
19	
20	1
dij	10
sv	38

FOCUS OF CONSTRUCTS

dij VALUES

CONSTRUCTS	16	17	18	19	20
1	2	6	4	4	4
2	4	8	4	2	4
3	2	6	4	4	4
4	2	6	4	4	4
5	8	6	2	4	6
6	6	2	8	8	4
7	10	6	4	4	8
8	4	8	4	2	4
9	8	4	4	6	8
10	0	4	6	6	2
11	8	8	4	2	6
12	6	6	6	4	4
13	2	6	4	4	4
14	8	8	4	2	6
15	6	6	2	4	8

SV VALUES

CONSTRUCTS	16	17	18	19	20
1	80		60	60	60
2	60		60	80	60
3	80		60	60	60
4	80		60	60	60
5			80	60	
6		80			60
7			60	60	
8	60		60	80	60
9		60	60		
10	100	60			80
11			60	80	
12				60	60
13	80		60	60	60
14			60	80	
15			80	60	

Table 59. Primary matcher for element 1 from Expert # 3 - aerobic fixed film

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Removal rate to 1 ppb		-1	+1		
Low temperature		-1	+1		
Contaminant destroyed		+1	-1		
Flow rate > 15 MGD		-1	+1		
Highly chlorinated hydrocarbons		-1	+1		
DEGREE OF MATCH					

Table 60. Primary matcher for element 2 from Expert # 3 - activated carbon

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Removal rate to 1 ppb		+1	-1		
Low temperature		0	0		
Contaminant destroyed		-1	+1		
Flow rate > 15 MGD		+1	-1		
Highly chlorinated hydrocarbons		+1	-1		
DEGREE OF MATCH					

Table 61. Primary matcher for element 3 from Expert # 3 - ultraviolet oxidation of H_2O_2

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Removal rate to 1 ppb		+1	-1		
Low temperature		0	0		
Contaminant destroyed		+1	-1		
Flow rate > 15 MGD		-1	+1		
Highly chlorinated hydrocarbons		+1	-1		
DEGREE OF MATCH					

Table 62. Primary matcher for element 4 from Expert # 3 - air stripping

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Removal rate to 1 ppb		-1	+1		
Low temperature		-1	+1		
Contaminant destroyed		-1	+1		
Flow rate > 15 MGD		+1	-1		
Highly chlorinated hydrocarbons		-1	+1		
DEGREE OF MATCH					

Table 63. Primary matcher for element 5 from Expert # 3 - anaerobic GAC fluidized bed

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Removal rate to 1 ppb		-1	+1		
Low temperature		-1	+1		
Contaminant destroyed		+1	-1		
Flow rate > 15 MGD		-1	+1		
Highly chlorinated hydrocarbons		+1	-1		
DEGREE OF MATCH					

Table 64. Secondary matcher for Expert # 3 - Removal rate to 1 ppb

FEATURE CONSTRUCTS	10	1	3	4	13	2	8
SV	+ 1.0	+ .80	+ .80	+ .80	- .80	- .60	- .60

Table 65. Secondary matcher for Expert # 3 - low temperature

FEATURE CONSTRUCTS	10	2	3	4	6	8	12	13
SV	+ .80	- .60	+ .60	+ .60	+ .60	+ .60	- .60	- .60

Table 66. Secondary matcher for Expert # 3 - contaminant destroyed

FEATURE CONSTRUCTS	2	8	11	14	1	3	4	5	7	12	13	15
SV	+ .80	- .80	+ .80	+ .80	- .60	- .60	- .60	+ .60	+ .60	+ .60	+ .60	+ .60

Table 67. Secondary matcher for Expert # 3 - Flow rate > 15 MGD

FEATURE CONSTRUCTS	6	9	10
SV	- .80	+ .60	+ .60

Appendix E

SAMPLE CASE CLASSIFICATION

Table 68. Primary matcher with confidence factors and degree of match for Element 1 - Conventional completely mixed reactor

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			+0.43	0.43
Nitrification occurs	+1	-1		-1.0
Plug flow regime	-1	+1		+1.0
HRT > 10 hours	+1	-1		+1.0
Denitrification occurs	-1	+1		+1.0
High MLSS concentration	-1	+1		+1.0
Dissolved O_2 > 4 mg/l			+0.38	+0.38
Soluble BOD removal > 90 %	+1	-1		+1.0
DEGREE OF MATCH				+0.60

Table 69. Primary matcher with confidence factors and degree of match for Element 2 - Step feed, plug flow reactor

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			-0.43	-0.43
Nitrification occurs	-1	+1		+1.0
Plug flow regime	+1	-1		-1.0
HRT > 10 hours	-1	+1		-1.0
Denitrification occurs	-1	+1		+1.0
High MLSS concentration	+1	-1		-1.0
Dissolved O_2 > 4 mg/l			-0.38	-0.38
Soluble BOD removal > 90 %	-1	+1		-1.0
DEGREE OF MATCH				-0.35

Table 70. Primary matcher with confidence factors and degree of match for Element 3 - Deep shaft design

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			-0.43	-0.43
Nitrification occurs	-1	+1		+1.0
Plug flow regime	+1	-1		-1.0
HRT > 10 hours	-1	+1		-1.0
Denitrification occurs	-1	+1		+1.0
High MLSS concentration	+1	-1		-1.0
Dissolved O_2 > 4 mg/l			0.38	+0.38
Soluble BOD removal > 90 %	+1	-1		+1.0
DEGREE OF MATCH				-0.06

Table 71. Primary matcher with confidence factors and degree of match for Element 4 - Sequencing batch reactor

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			0.43	+0.43
Nitrification occurs	+1	-1		-1.0
Plug flow regime	+1	-1		-1.0
HRT > 10 hours	-1	+1		-1.0
Denitrification occurs	+1	-1		-1.0
High MLSS concentration	+1	-1		-1.0
Dissolved O_2 > 4 mg/l			0.38	+0.38
Soluble BOD removal > 90 %	+1	-1		+1.0
DEGREE OF MATCH				-0.40

Table 72. Primary matcher with confidence factors and degree of match for Element 5 - Pure oxygen complete mix reactor

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			-0.43	-0.43
Nitrification occurs	-1	+1		+1.0
Plug flow regime	-1	+1		+1.0
HRT > 10 hours	-1	+1		-1.0
Denitrification occurs	-1	+1		+1.0
High MLSS concentration	-1	+1		+1.0
Dissolved O_2 > 4 mg/l			+0.38	+0.38
Soluble BOD removal > 90 %	+1	-1		+1.0
DEGREE OF MATCH				+0.50

Table 73. Primary matcher with confidence factors and degree of match for Element 6 - Oxidation ditch

DESIGN CONSTRUCTS	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days			0.43	+0.43
Nitrification occurs	+1	-1		-1.0
Plug flow regime	+1	-1		-1.0
HRT > 10 hours	+1	-1		+1.0
Denitrification occurs	+1	-1		-1.0
High MLSS concentration	+1	-1		+1.0
Dissolved O_2 > 4 mg/l			0.38	+0.38
Soluble BOD removal > 90 %	+1	-1		+1.0
DEGREE OF MATCH				0.10

Table 74. Primary matcher with weight factors, confidence factors and degree of match for Element 1 - Conventional completely mixed reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days	0.8			+0.43	0.34
Nitrification occurs	0.1	+1	-1		-0.1
Plug flow regime	1.0	-1	+1		+1.0
HRT > 10 hours	0.5	+1	-1		+0.5
Denitrification occurs	0.1	-1	+1		+0.1
High MLSS concentration	0.5	-1	+1		+0.5
Dissolved O_2 > 4 mg/l	0.5			+0.38	+0.19
Soluble BOD removal > 90 %	0.3	+1	-1		+0.3
DEGREE OF MATCH					+0.35

Table 75. Primary matcher with weight factors, confidence factors and degree of match for Element 2 - Step feed, plug flow reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days	0.5			-0.43	-0.22
Nitrification occurs	0.1	-1	+1		+0.1
Plug flow regime	1.0	+1	-1		-1.0
HRT > 10 hours	0.5	-1	+1		-0.5
Denitrification occurs	0.1	-1	+1		+0.1
High MLSS concentration	0.5	+1	-1		-0.5
Dissolved O_2 > 4 mg/l	0.8			-0.38	-0.3
Soluble BOD removal > 90 %	1.0	-1	+1		-1.0
DEGREE OF MATCH					-0.42

Table 76. Primary matcher with weight factors, confidence factors and degree of match for Element 3 - Deep shaft design

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days	0.5			-0.43	-0.22
Nitrification occurs	0.2	-1	+1		+0.2
Plug flow regime	0.5	+1	-1		-0.5
HRT > 10 hours	0.5	-1	+1		-0.5
Denitrification occurs	0.5	-1	+1		+0.5
High MLSS concentration	0.5	+1	-1		-0.5
Dissolved O_2 > 4 mg/l	0.9			0.38	+0.34
Soluble BOD removal > 90 %	0.9	+1	-1		+0.9
DEGREE OF MATCH					-0.02

Table 77. Primary matcher with weight factors, confidence factors and degree of match for Element 4 - Sequencing batch reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days	0.5			0.43	+0.22
Nitrification occurs	0.5	+1	-1		-0.5
Plug flow regime	0.5	+1	-1		-0.5
HRT > 10 hours	0.8	-1	+1		-0.8
Denitrification occurs	0.1	+1	-1		-0.1
High MLSS concentration	0.5	+1	-1		-0.5
Dissolved O_2 > 4 mg/l	0.5			0.38	+0.19
Soluble BOD removal > 90 %	0.5	+1	-1		+0.5
DEGREE OF MATCH					-0.19

Table 78. Primary matcher with weight factors, confidence factors and degree of match for Element 5 - Pure oxygen complete mix reactor

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days	0.8			-0.43	-0.34
Nitrification occurs	0.1	-1	+1		+0.1
Plug flow regime	0.9	-1	+1		+0.9
HRT > 10 hours	0.1	-1	+1		-0.1
Denitrification occurs	0.1	-1	+1		+0.1
High MLSS concentration	0.5	-1	+1		+0.5
Dissolved O_2 > 4 mg/l	0.1			+0.38	+0.38
Soluble BOD removal > 90 %	0.8	+1	-1		+0.8
DEGREE OF MATCH					**+0.21**

Table 79. Primary matcher with weight factors, confidence factors and degree of match for Element 6 - Oxidation ditch

DESIGN CONSTRUCTS	WEIGHT FACTOR	Y	N	SECONDARY MATCHER	CONFIDENCE FACTOR
Sludge Age > 15 days	1.0			0.43	+0.43
Nitrification occurs	0.4	+1	-1		-0.4
Plug flow regime	0.5	+1	-1		-0.5
HRT > 10 hours	0.5	+1	-1		+0.5
Denitrification occurs	0.4	+1	-1		-0.4
High MLSS concentration	0.5	+1	-1		+0.5
Dissolved O_2 > 4 mg/l	0.5			0.38	+0.19
Soluble BOD removal > 90 %	0.5	+1	-1		+0.5
DEGREE OF MATCH					**0.10**

Appendix A

Excerpt from

COMMERCIALIZATION PLAN

prepared by
Lori Schutz-Riley
MTA 810
Summer 1992