Fuzzy Logic-Based Environmental Criteria in Engineering Design

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Dedication

I would like to dedicate this work to my high school physics teacher, who opened my eyes to the wonders of the universe.

We must be able to live in harmony with nature, for we are a part of nature, and any damage done to nature is damage done to ourselves.

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Abstract

The environment has become one of the most important issues facing all of the population of this planet. It is everyone's responsibility to minimize the destructive effect they have upon the environment. It is especially important that design engineers attempt to minimize the effect their products have upon the environment. But, it is very difficult for engineers to foresee all of the consequences that their designs may have. Many times, the information needed to complete such an analysis is beyond the engineer's expertise and is often unquantifiable and overwhelming. A solution to this problem comes in the form of an environmental impact evaluating expert system which can evaluate designs and determine if there may be undesirable environmentally-threatening consequences from the design. This expert system will be based upon a fuzzy logic inference engine. Fuzzy logic is being used because the types of rules used in environmental evaluation are more amenable to fuzzy logic representation than standard Boolean logic. In the test case examined in this paper, it is shown that this methodology is valid at least in a very basic implementation.

I. Introduction

According to the Environmental Protection Agency (EPA), by the year 2000 pollution control efforts will cost the United States Government approximately $185 billion (1990 adjusted dollars) annually [1]. Much of this money will be allocated to the environmental cleanup efforts of the EPA and its Superfund program. This is a lot of money to be spent on cleaning up our past mistakes. If we continue to make these mistakes, the cost of the cleanup will only increase in the future. There needs to be a fundamental change in the way engineers look at the process of design when it concerns substances or processes that will affect the environment. Currently, the engineer, when designing a process or product, examines only short-term effects of the substances and processes which are involved in the overall design. The engineer neglects the long-term effects of the design because these effects, if known, cannot be quantified and used in the cost assessment processes currently in use. For example, a civil engineer designs a bridge with certain constraints and goals. The engineer is constrained by the type of ground material on which the bridge footings will rest, the type of structure that will be used (arch, suspension, etc.), the materials used in the construction, the immediate effect on the surrounding environment, and the cost of the project. The goals of the engineer are to have a low cost for the design, a maximum amount of safety for the end-users of the design, and a maximum life for the design. Questions such as, "What will be the effect of the corrosive products on the fragile fish spawning grounds downstream from the bridge?" or "What effect will the bridge have on the local ecology?" (e.g., will the bridge attract creatures that will affect the local ecology) are rarely considered during the initial design phase of the bridge. The knowledge needed to determine these effects are outside the scope of the design and usually outside the knowledge-base of the design engineer. These effects can not always be foreseen as well. Thus, these types of problems often manifest themselves well after the design is implemented. At that point, it is too late to make any changes and most likely much damage has already been done. Costly cleanups and repairs are then made to attempt to alleviate the problem. This is precisely the problem that is occurring now in the chemical waste disposal area. These are the types of unforeseen problems which require the Superfund program to correct. These are problems that could have been avoided if the designers had taken the possible environmental effects and costs into account when they designed the storage facilities for the dangerous chemicals. But, there is no way at the present time to deal effectively with these types of unquantifiable and unexpected effects.

The goal of this paper is to outline a method to take those unquantifiable factors into account during the early design process and thus, to avoid these types of problems with future designs. Engineering design that takes into account environmental and ethical concerns becomes very complex, perhaps an order of magnitude more complex than the standard engineering design process. The factors that must be accounted for are usually unquantifiable, outside the realm of the designer, and often are so numerous that many must be neglected to even reach a final design. A designer who looked at all of the possible ramifications of his design would only complete one design in his lifetime. This is clearly unacceptable in the current business society. Thus, the method that deals with these factors must be able to function in the time constraints given for most engineering problems.

The method suggested by this study is simply outlined as an environmentally-aware, specialized, fuzzy logic-based expert system (to be defined in subsequent sections) which can review engineering designs and give feedback to the designer. This will allow the designer to "go back to the drawing board" and correct the areas in his design which produce unacceptable results from the expert system. This expert system would be rules-based, and its rules would outline what is acceptable with respect to the environment and what is not. The system would be necessarily fuzzy logic-based because fuzzy logic allows it to reason more like a human would reason. It is also easier to develop the rules to be used in the system if they are fuzzy in nature because the human mind is fuzzy in nature, and some of the concepts important to this type of evaluation are fuzzy in nature (e.g. what is meant by "dangerous" or "harmful"). These rules will be set up in the knowledge-base in a standardized representation based on Minsky's theory of frames (to be defined in subsequent sections). This allows the system to more accurately mimic the human thought process and makes the addition of situation-specific rules to the general knowledge-base easier. These situation-specific rules would be necessary for the system to accurately evaluate designs in specific fields.

An expert system design evaluator along these lines would make it easier to design "environmentally friendly" products and processes. By allowing the engineer to foresee some of the problems that may occur before they occur, the problems can be accommodated for. This could potentially improve our future quality of life significantly and would save business and government a large amount of money.

To understand the proposed fuzzy logic-based expert (FLBE) system, one must first understand the concepts which form the foundation for it. First, one needs an understanding of the environment and the ethical problems that one encounters when dealing with concepts such as "harmful" and "dangerous." To deal with these concepts in a systematic way, though, one needs to have a mechanism to pseudo-quantify them. Fuzzy logic allows such a systematic evaluation. Thus, one needs to understand what fuzzy logic is and what fuzzy logic can accomplish. Then, there is the problem of how to implement fuzzy logic into an expert system. This is where it becomes important to examine expert system development and how to best codify a knowledge-base into a form usable by the expert system's inference engine and yet, still be understandable by the humans who develop and possess the knowledge.

The paper follows the basic outline mentioned above. Since the knowledge needed to develop the expert system, as it will be needed, is so diverse, a substantial portion of the paper is allocated towards the explanation of the basic tenets of the fields and how they were applied to create the needed solution. The first field that will be examined is that of environmental responsibility and ethics. The second area to be examined and integrated is that of fuzzy logic. The third section of the paper will outline the basic engineering design process and show how fuzzy logic can be used in it. The fourth section will explain the test case that has been chosen to serve as a simple proof-of-concept example. The next section will show how an expert system would be developed and used to evaluate the test case chosen. The last section will outline what other work needs to be done on this solution to actually implement it in a real world design situation.

II. Environmental Concerns

The first step in developing an expert system is the development of the knowledge base that the system will use to make decisions. The system being created here is one which will evaluate the impact of designs on the environment, so it will need to have a coherent set of rules concerning the environment and the effect of certain processes and products on the environment.

Any rules that deal with environmental concerns have their foundations rooted in the fundamental belief that the environment is sacred and that humankind must respect the rights of all living creatures and the rights of the Earth. This belief is the foundation of many of the environmental activist groups and is the motivation for much recent legislation. The belief that nature has rights and humans must protect it was first and best stated in the National Environmental Policy Act (NEPA) in 1969. NEPA states that there should be a national policy which "will encourage productive and enjoyable harmony between man and nature"[2]. The NEPA also established the requirement for the filing of environmental impact statements for all systems which will effect the environment. Since the passage of this act, environmental law has evolved and many other environmental acts have been passed (e.g. Clean Water Act of 1972, 1977, and 1986, the Clean Air Act, and the Resource Conservation and Recovery Act of 1976). These acts establish guidelines for the discharge, transportation and storage of non-natural and possibly toxic substances. Unfortunately, these acts seem to many businesses to be a direct attack on their bottom line [3]. This is unfortunate because the resulting adversarial relationship between business and government hinders the development of environmental laws which would benefit everyone, including businesses in the long term.

Engineers are especially affected by these laws because engineers are beholden to their professional code which requires that engineers do not break the law when dealing with professional matters. Also, these codes also require that engineers hold the public safety as their utmost concern. The Accreditation Board for Engineering and Technology (ABET) code states that engineers shall "hold paramount the safety, health, and welfare of the public in the performance of their professional duties" [4]. This requirement can be construed to implicitly protect the environment as well, since a safe, clean environment is necessary for the health and safety of the public. Therefore, it is implicitly stated in the codes that engineers should not pollute or corrupt the environment. It is important to realize then that a design cannot be considered complete or proper until an estimate of the danger it will pose to the environment has been determined.

Explicitly, the engineering codes state that an engineer must hold the public safety to be of utmost concern. Problems that affect the environment most likely affect the people living in that environment as well. Environmental problems often involve threats to the health and well-being of the public. Consequences of a design which lead to major loss of life or property are often the subject of expensive legal action. Also, the designing engineer can be considered liable for all of the damage that has occurred due to the consequences of his/her design. Thus, it is important that a designer take into account all of the possible effects that his design may have on the environment. This evaluation is very time-consuming, and it is almost impossible to be totally thorough and complete.

The primary problem that arises in this evaluation is that the potential environmental effects and costs are difficult to determine when the component or design is in the conceptual phases when changes in the design can be made. The information that will be required to make the design environmentally sound may currently not be available, it may be unquantifiable and thus not amenable to inclusion into a cost/benefit analysis, it may be impractical or impossible to evaluate or foresee all of the possible consequences that may result from the design, and often the information and expertise needed for the evaluation may not be possessed by the designer. Thus, there is a need for a system which can at least identify the potentially pertinent information and can evaluate prospective designs in their conceptual phases to predict what problems may occur if they are implemented.

The major roadblock in creating such an evaluating system is the lack of a coherent and logical knowledge base. Most of the knowledge about the environment used in the design process is in the form of "rules of thumb." These are not explicitly outlined rules that are easily quantifiable. They take the form of such statements:

> "Chloroflourocarbons destroy ozone in the ozone layer, and thus any emission of these substances is extremely dangerous."
>
> "Non-degradable emissions are extremely harmful to the environment."
>
> "Organics dissolved by bacteria use up oxygen in the rivers and lakes, and thus are harmful to the indigenous species of aquatic life." [5]

These statements all rely on key words like "harmful" or "dangerous." There is no easy way to quantify these terms into a form usable in a standard cost/benefit analysis.

Currently, governmental bodies, like the EPA and the Occupational Safety and Health Act (OSHA), avoid these terms by creating a system of arbitrarily chosen levels of accepted release for materials. Often the levels are different depending on which body publishes the guidelines. For example, OSHA has a permissible exposure limit on lead dusts at a concentration of 0.5 mg/m^3 of lead, the National Institute for Occupational Safety and Health (NIOSH) recommends that this level be set at <0.1 mg/m^3 of lead [6]. These two standards display the problem with establishing these types of limits. Both are designed to decrease the chance of physical problems caused by exposure to these levels of lead dust. There is no way to determine which level is correct. There is also not a clear demarcation at these limit levels of the effects of the different concentrations of lead dust on different people. That is, someone who has been exposed to a concentration of 0.08 mg/m^3 of lead dust may develop physical problems due to this exposure which are just as severe as someone else who has been subjected to a concentration of 0.15 mg/m^3 of lead dust. Therefore, these limits can only be used as basic estimates for what should be safe. Current regulations and punishments are based on these limits, which do not actually guarantee the safety of all employees. Although such a system of limits is the most practical way to develop a system of regulations concerning such matters, it is not necessarily the most accurate method for representing the range of danger. A much more accurate way of representing such a range is to develop a fuzzy logic membership function based on "safety", "hazard", and "danger" (these will be defined in a subsequent section). This is the type of system which will be explained and implemented in later sections of the paper.

To develop a fuzzy logic representation of this type of safety and hazard information, there first must be usable definitions of "harmful" and "dangerous." In Webster's Dictionary, 'harmful' is defined as "causing physical or material injury" and 'dangerous' is defined as "beset with liability to injury, pain, damage." These will be the definitions that will be used in this project. The realm of danger will be broken down into three overlapping categories; Low, Medium, and High. These quantities can be represented easily by fuzzy logic membership functions (this will be explained further in the next section). The output from the system will include a quantity known as a danger rating. A danger rating is a numerical quantity that must be taken in reference to the possible range of danger ratings. This is best represented by a percentage, where 100% represents the state of ultimate, immediate danger. A danger rating of 0% would represent the state of absolutely no danger. This type of range is also amenable to fuzzy logic representation. This range can serve as a simple "domain of discourse" (to be explained in subsequent section) for a fuzzy logic representation using the Low, Medium, and High quantifiers.

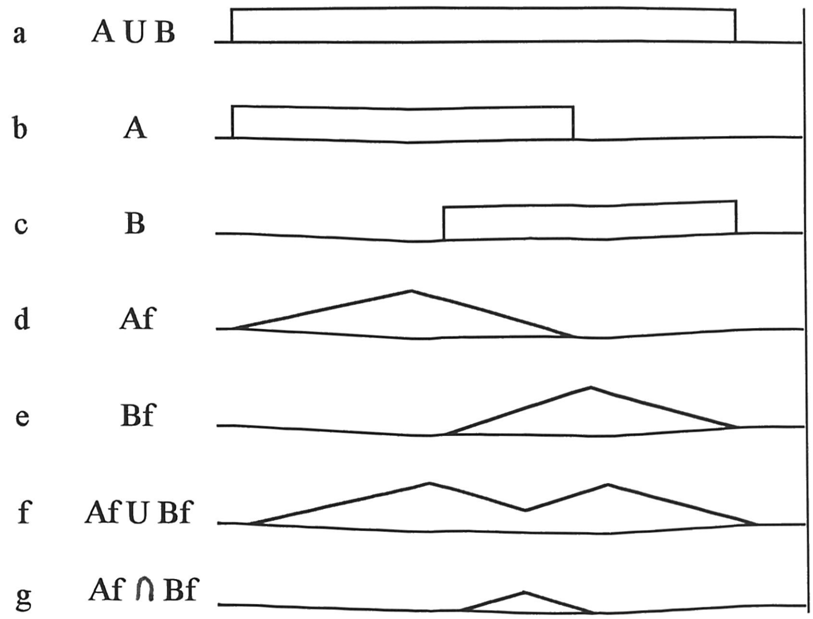
The reasons for developing this type of representation for this information will be examined in more detail in the discussion of knowledge representation and fuzzy logic. It is important to understand how such a system is developed though, because this paper serves as an outline for further work in this area.

III. Fuzzy Logic Fundamentals

Fuzzy logic was developed by Lotfi Zadeh in 1965 to deal with language paradoxes that could not be dealt with using normal Boolean logic. In Boolean logic, there are only two values; ON/OFF, True/False, 0/1, etc. There are only two states, and everything must fall into those two states. This is an idealized version of the real world. This is reflected in the design of machines which are in themselves idealized by the humans who design them. A computer functions on the binary system because it was straightforward to implement a switch which had two states. This is an idealized state which is not present in nature. In fact, whenever computers have to deal with outside signals, the continuous (analog) signals present in the world must be discretized (digitized) to allow the 'ideal' computer to work with them. In any case, there is substantial error and signal loss in this discretization. This is the same kind of error which occurs when a continuous world is forced into the two classifications which are given to us in Boolean logic.

Fuzzy logic is the solution to this problem. Instead of having only two groupings of which you are either in or out, fuzzy logic uses continuous membership functions which allow something to have a varying degree of membership in a group. This may seem to be a foreign concept, but we, as humans, use it almost continuously. For example, everyone has said "That person is tall," at one time or another. In a Boolean world, that forces people into two groups; Tall (T) and Not Tall (~T). The question is where do we draw the line of demarcation. At what height is a person no longer Tall (T)? Can you say that everyone over 6 feet 0 inches is Tall (T)? This actually could be done (although it would probably vary with each individual), but this is not the what is meant when "That person is tall," is said. Tall (T) is a very general category, subject to much interpretation. In fuzzy logic, Tall (T) becomes a membership function. Using a statistical distribution of heights of people who most people consider tall, we can develop a function, $\mu_t(x)$, which assigns a membership function to a person depending on his height. Thus, many people can be called tall and have the statement be deemed true. In effect, different people would just have different membership values in the group of tall people (e.g. a person who is 5'9" would have a membership of 0.65 in the group of tall people, while a 7'2" person would have a membership value of 0.95). This is what is more truly meant in our language when, "That person is tall," is spoken. We identify the person as having a membership score in a group. This allows us to say things like "That person is taller than that other person." What is being said in this statement is that the latter person has a lesser membership in the Tall (T) group than the former person (i.e. $\mu_{t1} > \mu_{t2}$). The comparison operator of the form "a is more x than b" is only possible in a system such as fuzzy logic, where there are different levels of membership in a category. For a graphical representation of this see Figure 2.

Figure 2: Fuzzy Sets and Boolean Sets



[7]

Figure 2 shows the difference between a fuzzy set and a Boolean set. The first graphic (a) shows the union of two Boolean sets, A and B which are shown in (b) and (c). The height of the graph indicates the membership value of the different locations on the line. Notice in the Boolean distribution, the height is constant throughout the set. This is because there is only one membership value in a Boolean set (the value is always 1). Graphs (d) and (e) show fuzzy versions of the sets A and B (subscripted to Af and Bf to show that they are fuzzy). Notice the membership functions are sloped lines that have varying values throughout their set space. These functions indicate that the membership in the function is dependent upon where you are in the domain of discourse. Graph (f) shows the union of the two fuzzy sets Af and Bf. In fuzzy logic, when two or more sets are joined in union a new formula must be used to determine the membership of the elements of Af and Bf in the new set Af∪Bf. The formula is

$$\mu(A \cup B) = \max(\mu(A), \mu(B)) \qquad \text{(III, 1)}.$$

Graph (g) shows the intersection of the two fuzzy sets Af and Bf. Again, a new formula is needed to determine the membership function of a member of the new set Af∩Bf. The equation used to calculate the new membership is

$$\mu(A \cap B) = \min(\mu(A), \mu(B)) \qquad \text{(III, 2)}.$$

This basically states that the membership in the new set is equal to the minimum of their past membership values in the previous sets. For example, if we examine a point near the right end of the line graph, just inside the far right hand edge of set Bf, its membership in set Bf is approximately 0.1, while its membership in Af is 0. In the intersection of the two sets, this point would not even be close to being included. The intersection formula (III,2) concurs, and thus assigns the point a new membership value of 0. These are the basics of fuzzy set theory. The next section of this part deals with special fuzzy operators.

There are several special operators which occur only in fuzzy logic. These operators are defined the best in *Foundations of Fuzzy Reasoning* by B.R.Gaines. The first operator that will be examined is the 'not' operator (~). The 'not' operator can be used in a fuzzy logic statement the same way it is used in the Boolean sense. The only difference is that there needs to be a formula to determine the membership value in the ~A set from the membership value of the original A set. The formula for determining the membership value of a point in set A in the set ~A is

$$\mu(\sim A) = 1 - \mu(A) \qquad \text{(III, 3)}.$$

Thus, a point with a membership in set A of 0.6 has a membership of 0.4 in the set of ~A.

The second operator that will be examined is what is known as the 'very' operator (γ). This operator is applied whenever the word very is used in a linguistic statement of fuzzy logic (i.e. "That person(p) is very tall (T)."). This operator has a direct effect upon the membership function. The symbolic restatement of "That person is very tall" looks like this:

$$p = \gamma T \qquad \text{(III, 4).}$$

The membership of the person in the set of very tall people can be determined from this formula:

$$\mu(\gamma T) = (\mu(T))^2 \qquad \text{(III, 5).}$$

This formula would give a person with a membership of 0.6 in the set of tall people (T), a 0.36 membership in the set of very tall people (γT). This operator can be used repeatedly to create statements such as, "This person is very, very, very tall." The membership of the previous person in this new set of very, very, very tall ($\gamma\gamma\gamma$T) would be $(0.6)^8$ or 0.017.

The third operator that is used in fuzzy logic is that of dilation (δ). This operator is used in place of the terms 'more or less' in the linguistic representation of fuzzy logic. The effect of the dilation operator is opposite the effect of the 'very' operator(also known as the concentration operator). The formula for the dilation operator is

$$\mu(\delta A) = (\mu(A))^{0.5} \qquad \text{(III, 6).}$$

This operation gives a higher membership value in the set of 'more or less' A than it had in the original set of A. For example, a person with a membership value of 0.6 in the group of very tall (γT) people, would have a membership of 0.775 ($0.6^{0.5}$) in the group of tall (T) people. This operator appears to be intuitively correct because a person who is considered very tall to a slight degree can also be considered to be tall to a greater degree. That is, he has a greater degree of membership in the tall group than he had in the very tall group.

The fourth operator that is used is the normalization operator (ν). This operator makes sure that the set is bounded by the upper limit of 1. Its formula looks like this

$$\mu_{\nu}(A) = \mu(A)/(\sup(\mu(A)) \qquad \text{(III, 7)}.$$

The meaning of this formula is that the new membership value is equal to the old membership value divided by the maximum possible membership value under the old membership function.

The last operator is the hedge 'sort of.' This hedge can be created by using several of the other operators. The symbolic representation of the 'sort of' hedge is

$$\mu(B) = \nu(\gamma\gamma\mu(A) \wedge \delta\mu(A)) \qquad \text{(III, 8)}$$

where A = "The x is sort of y"

B = "The x is y".

This is just a sample of the types of linguistically-based combinations that can be created with fuzzy logic operators. As one can see, it allows one to express very normal language constructs in a symbolic fashion. And further, it allows the mathematical assessment of the symbolic expression. The mathematical assessment ability of these constructs is where the power of fuzzy logic appears.

An equally important function of fuzzy logic is what is known as defuzzification. Defuzzification is the conversion of fuzzy quantities into crisp numbers. A crisp number is an exact number, such as an integer. There are several methods for converting a fuzzified number into a crisp number. The two primary methods are by centroid calculation and by the mean-of-maximum method. The centroid calculation method uses the value in the set which corresponds to the centroid of the area enclosed by the membership function as the crisp representation of the membership function. The centroid is chosen because its value best represents the fuzzy set [8]. The other method is the mean-of-maximum method. In this method, the maximum value of the membership function is found and the center of the region with the maximum membership value is used as the crisp result [9]. The preferred method for defuzzification is the centroid method because it most accurately represents the set shape and size.

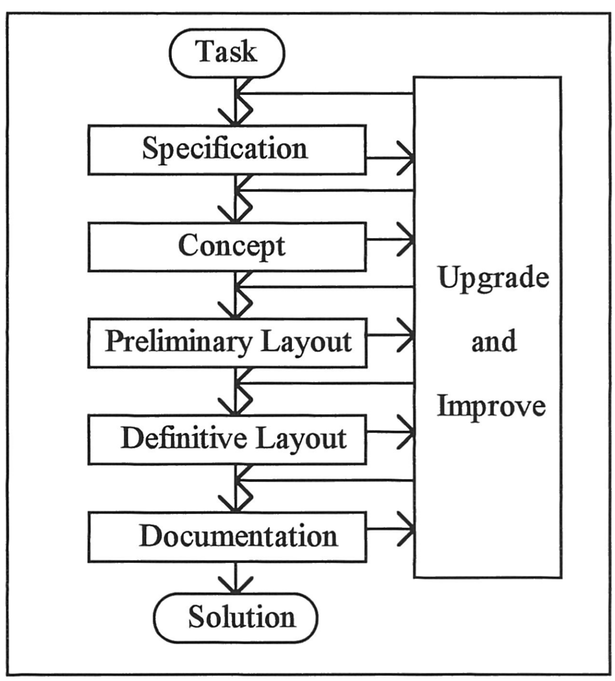
The fuzzy logic that will be used in the system outlined by this paper is a fundamental part of the FuzzyCLIPS expert system inference engine. FuzzyCLIPS allows the development of membership functions over certain domains of discourse. It then allows the user to develop "if...then" type rules that use the fuzzy membership functions to determine fuzzy or crisp outputs from a collection of the fuzzy consequents of the rules. This subject will be delved into in the later section discussing rules-based expert systems.

IV. Implementations

This research project began as a search for a method by which to use fuzzy logic to help engineers deal with unquantifiable environmental information in their design optimization calculations. Two methods of implementation were examined for this purpose. First, linear programming was examined as a viable vehicle for insinuating fuzzy logic environmental evaluative techniques into the design process. Second, a rule-based expert system was examined to achieve the same goal. Both implementations were evaluated and were required to meet several criteria.

The process that was chosen had to be able to be done in the early phases of the standard design process. The standard design process follows a simple structure outlined in *Engineering Design* by G. Pahl and W. Beitz. The basic structure of this process, which is described below, is outlined in Figure 3 [10].

Figure 3: The Design Process



The standard design process begins with a task which is outlined by the customer. The task contains a problem statement and a stated customer need. Using this task statement or need statement, the designer develops what is known as a *function structure*. A function structure is a tree-shaped structure with the need statement at the root. The structure branches out based on decreasing levels of function complexity. At the "leaf" end of the tree structure are the basic functions which need to be accomplished for the upper level functions to be carried out.

From the "leaf" ends of the function structure, one can develop a list of requirements. These requirements are pieces of information that need to be known about each of the basic functions in the "leaves." The requirements are used to verify that any components that are chosen in the later stages of the design process are able to meet the parameters outlined in the need statement. In Figure 3, the establishment of the function structure and requirements falls under the specification block.

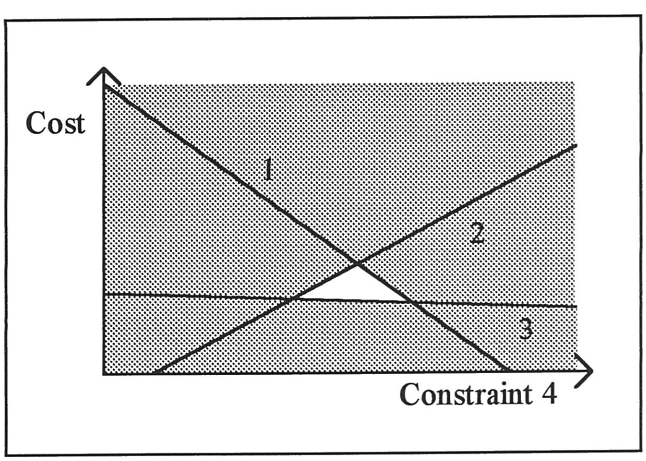
The engineer then develops several conceptual designs which meet the requirements outlined in the previous step. These conceptual designs are then evaluated using criteria based on the original problem statement. It is at this phase in the design process where the evaluation of environmental costs and benefits should be done. Either method, linear programming or an expert evaluation system, could be used. The conceptual designs would be rated and if all of the designs produced unacceptable consequences then the designer could loop back around to the conceptual design phase. The designer would be able to take the knowledge gained from the failed attempts for assistance in restructuring a design which failed. These new designs should be better able to achieve an acceptable level of environmental consequences. Once these designs have passed the evaluation, the designer could then complete the design process and take one of the approved conceptual designs to completion.

The fuzzy logic-based evaluation system would best fit in this design process in the "Update and Improve" step (Figure 5) which provides all of the feedback between the major design steps. An evaluation system located in this area would help in selecting concepts to proceed with or in providing advice to the designer to help in the redesign. The evaluation system would be a very useful tool in this step of the design.

IV.A. Linear Programming

Linear programming is a mathematical/graphical method for optimizing a system with multiple constraints. In a two dimensional analysis, all but two of the constraining factors (usually cost and some other important constraint) are used to develop constraint functions. These constraint functions are then plotted onto a graph where the two axes are the left over two constraints. Figure 4 shows an example of several constraining

Figure 4: Linear Programming



functions plotted on a graph. The constraining functions limit the regions of the graph where it is possible to have a viable solution.

In Figure 4, the shaded regions are regions which have been deemed not viable by the three constraint functions (1,2, & 3). This graph can now be used to select a value for Constraint 4 to minimize the cost. This value must be inside the non-shaded region of the graph outlined by the constraining functions. The rightmost point in the triangular acceptable region is the point where cost is the least in the region. Thus, the value of Constraint 4 should be the one which corresponds to this minimum cost point. This is a basic outline of how this method can be used to optimize designs.

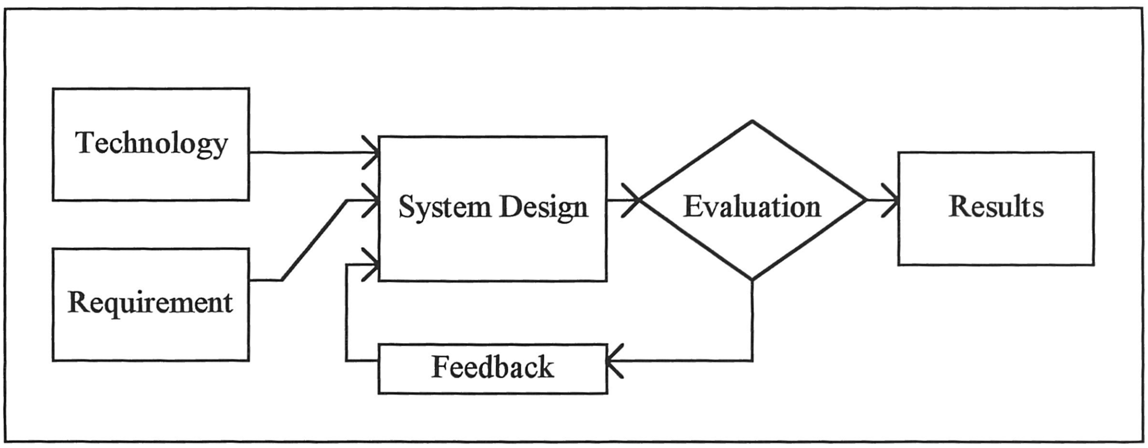
Applying fuzzy logical methodology to linear programming allows the method to be slightly more forgiving. Instead of the constraining functions being strict lines of demarcation between acceptable and unacceptable, they mark the initiation of a region with an acceptability gradient spanning it. A point just outside of the truly acceptable region would be considered "slightly less acceptable," while a point which was far from the acceptable region would be considered more unacceptable. Application of fuzzy logic would essentially allow the designer to have more flexibility in his optimization because it would allow the engineer to bend the rules (the constraints) if he thought that the benefit from doing so would far outweigh the small amount of design unacceptability that would be introduced by crossing into the region that had previously been excluded by the constraint curves.

It was decided that while this technique is useful for optimizing the design process and evaluation of different concepts, it would not be the best method for achieving the goal that was outlined in the problem statement. The goal was to be able to introduce "fuzzy" environmental concerns into the design methodology in a way which would ensure that resulting designs were environmentally sound. This was to be accomplished by introducing extra constraints into the evaluation. In a linear programming methodology, this would just increase the number of constraint functions. It is known that introducing more constraint functions makes the linear programming method more difficult. To add a whole set of extra constraint functions into the process and then try to implement the changes in the method required by the use of fuzzy logic would be more trouble than it is worth. Thus, this line of thought was abandoned early in the project, and the rule-based expert system method was chosen as a preferable method of attack.

IV.B. Rule-based system

A rule-based expert system is the most practical and most easily implementable way to incorporate fuzzy logic methodology into the evaluation of a design with respect to fuzzy environmental constraints. The primary function of an expert system is the interpretation and evaluation of complex input and that is exactly what is called for in this case. The evaluation system must be capable of interpreting the input from the design process and must be able to develop important feedback which can then be used by the engineer to redesign a more acceptable design. A rule-based evaluation system also fits almost perfectly into the design process as outlined by B. Blanchard and W. Fabrycky in *Systems Engineering and Analysis* (shown in Figure 5). This design process is a refinement of the one shown earlier in Figure 3. It incorporates the same steps, but places them in a more systematically-oriented manner. The Evaluation function is where the rule-based expert system fits into the methodology. It takes the results from the design process, interprets and evaluates, and then outputs feedback recommendations to the designer to assist in the redesign and to make the process iterative.

Figure 5: The Systems Engineering Approach to Design



[11]

The expert system can be implemented easier than the linear programming method, as well. There are several commercially-available software packages which allow the development of rule-based expert systems. The one that will be used in this project for the actual implementation of the test system is FuzzyCLIPS from Togai Infralogic. This development system allows for the specification of fuzzy logic membership functions and fuzzy conditional rules which operate over the values of the membership functions.

IV.B.1. FuzzyCLIPS System Development

The FuzzyCLIPS fuzzy logic rule-based expert system is composed of two main parts; the inference engine and the rules base. The inference engine is the software which interprets the membership functions and the rules base and provides the output in crisp or fuzzy form. The inference engine uses a weighted combined output of all of the consequents (right hand sides) of rules that executed (fired) when the rules were evaluated. It then defuzzifies the resulting combination if it is sufficient enough to exceed a threshold value. The crisp result is then produced by the system and output along with any other user-specified information. In the implementation of the environmental evaluation system, it would be necessary to output recommendations to the engineer to help with the redesign effort. The recommendations will stem from the specific rules which failed the evaluation and will alert the designer to the problem spots in the design.

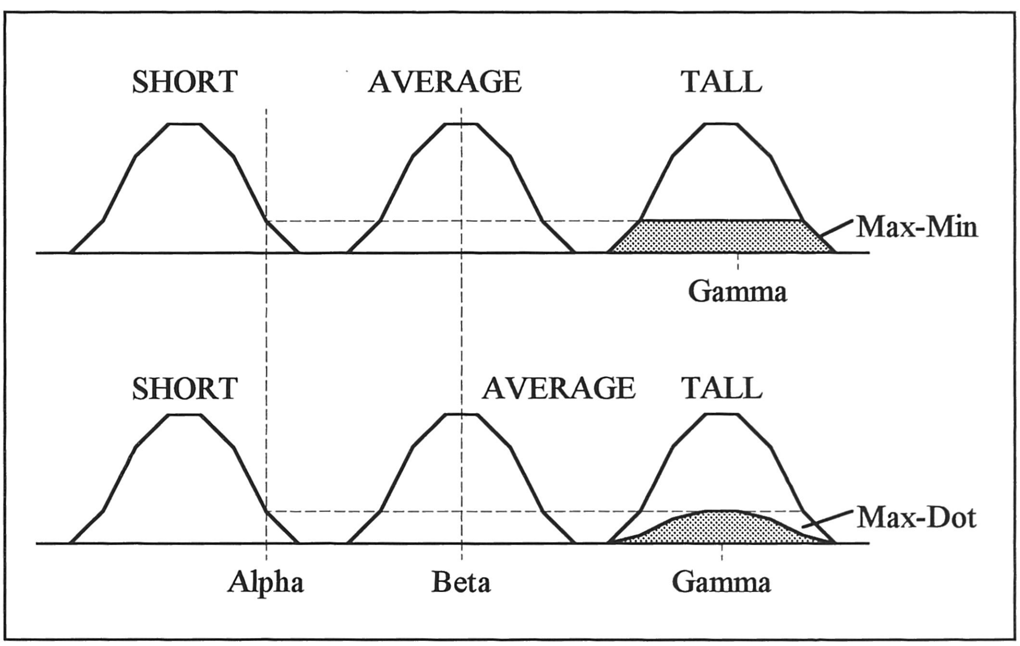
The inference engine uses several inference techniques which should be explained at this point in the discussion. In the fuzzy logic-based expert system inference engine, any rule whose antecedent has a non-zero truth membership value will execute (i.e. the right hand side of the conditional statement will be executed by the computer) [12]. Its results will be weighted by the membership value of the truth of the antecedent. In this way, all of the rules that execute contribute to the output of the system. In a traditional expert system, the rule executes if the antecedent is TRUE and the inference engine performs a conflict resolution scheme to determine whether the rule's execution will conflict with the execution of rules with higher priority. In the fuzzy expert system, such conflict resolution is unneeded because the output of the most important rules will outweigh the output of the rules of lesser priority due to the way the inference engine weights the results [13].

The method by which the FuzzyCLIPS system performs inferences is shown in the following example. The example rule is

IF (Alpha is SHORT) AND (Beta is AVERAGE) THEN Gamma is TALL

This rule uses the variables Alpha, Beta, and Gamma all of which are in the same universe of discourse (all deal with the quantity defined as height). There are three membership functions in the domain; SHORT, AVERAGE and TALL. Figure 6 shows the universe of discourse and the three membership functions and the location of Alpha, Beta and Gamma. The membership function of Gamma is determined by the Max-Min Inference method (explained below) in the top case and determined by the Max-Dot Inference method (explained below) in the bottom case.

Figure 6: Fuzzy Inference Techniques



[14]

It can be seen that the Max-Min Inference method uses the minimum membership value of the antecedents to "clip" the membership function of the consequent output. The Max-Dot inference technique uses the minimum membership value of the antecedents to scale the consequent's membership function to make the maximum possible output value attainable equal to the minimum of the antecedents' membership values.

The inferencing is done for each of the rules in the rules-base. The outputs, which are all in the same domain of discourse, are then aggregated and defuzzified. The aggregation techniques available include the union method and the summation method. The union method follows the union method outlined in the Section II of this paper. The new membership function is equivalent to the maximum membership of a point in both sets being unioned. The equation representing this function is

$$\mu(A \cup B)_{union} = \max(\mu(A), \mu(B)) \qquad \text{(IV, 1).}$$

The second method is the summation method. In this method of aggregation, the membership values of the point in each of the two functions is summed together to create the new membership function. The equation representing this function is

$$\mu(A \cup B)_{summation} = \mu(A) + \mu(B) \qquad \text{(IV,2).}$$

Once all of the rules which deal with a certain domain of discourse are inferenced, they are aggregated using one of the above techniques. Once they have been aggregated, they are then defuzzified and the crisp result is output.

The inference engine needs two other things to make the system function. First, the membership functions are need to be determined. The input into the system is in crisp form. This input must be fuzzified. This is done by applying a membership function to the values of the input. The input must fall into the domain of discourse of the membership function for this to be possible. Thus, there must be a domain of discourse for all of the input information and there must also be membership functions to divide up the domains of discourse. Once the information is converted to fuzzy logical membership values, it can then be used in evaluating the truth state of the antecedents of the rules. The membership functions can be of any shape. FuzzyCLIPS contains several primitives that can be used in creating custom membership functions. The primitives available include a linear function, an S function, a PI function, a gaussian function, a monotonic function of Tsukamoto, a threshold function, a hyperbolic function, and an inverse form function. It is possible to make any custom function out of any combination of these, or by just using short length linear functions to approximate the curve [15].

Second, the system needs a coherent and complete rules-base which can deal with any combination of input. The rules must be fuzzy in nature and must use the membership functions and domain of discourse outlined earlier. The rules take the form of this:

IF ((input variable) is (membership function)) THEN (output function)

The antecedent contains a reference to an input variable, and a membership function. The membership function implicitly signifies which domain of discourse is being used. The input variable is fuzzified and its membership value in the membership function listed after the keyword "is" is determined. This value is then used in one of the inferencing schemes and the output is then aggregated with the other outputs from the other rules which output into the same domain of discourse.

The rules can also have certain properties such as a threshold level for the antecedent value to meet to execute the rule and also it can have a tuning factor which can modify the alpha factor (the output clipping or scaling factor) and allow the output functions from some rules to be weighted on top of the natural weighting which occurs when the inference operations are used. The rules must also follow some sort of coherent hierarchical order to make the process of expanding the rules-base simple. Also, an ordering scheme is needed to prevent a rule in a very large rules-base from being repeated. The method of ordering the rules and determining how to execute them seems simple, but it is not. There is much research being done in the artificial intelligence field on finding the best way to organize and represent information in an expert system. This is made even more complicated in this project because fuzzy logical processes and concepts are included.

IV.B.2 Knowledge Representation

One of the prime areas of focus in the artificial intelligence and knowledge engineering fields is the problem surrounding knowledge representation in artificial intelligence projects. The question is not just about what information to include, it is about how to link the information together to allow the system to make judgments on and associations between the information provided to the system. Oftentimes, how the information is arranged is much more crucial than the information itself. This is due to the fact that if the information is in a structure, the intelligent system can not only use the information that is present in the system, but it can be aware of what information is not present and make judgments based on that fact. Thus, it is very important to structure the information in the system in a reliable and coherent way. There are several methods that can be used to achieve this goal. The method that will be used to represent the information in this project is Minsky's method of frames (also known as the method of holons [16]).

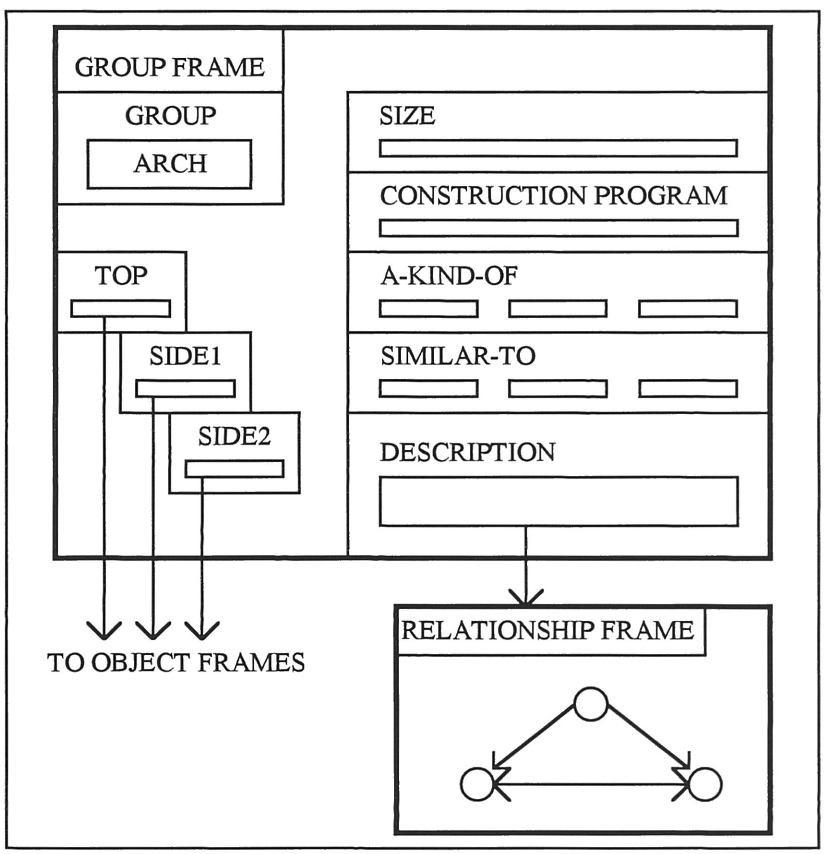
In 1974, Marvin Minsky defined "frames" as "a data-structure for representing a stereotyped situation like being in a certain kind of living room or going to a child's birthday party" [17]. He goes on to refine the concept,

> The 'top' levels of a frame are fixed, and represent things that are always true about the supposed situation. The lower levels have many terminals- 'slots' that must be filled by specific instances or data. Each terminal can specify conditions its assignments must meet. (The assignments themselves are usually smaller 'sub-frames.') Simple conditions are specified by markers that might require a terminal assignment to be a person or object of sufficient value, or a pointer to a sub-frame of a certain type. More complex conditions can specify relations among the things assigned to several terminals [18].

The power of the frame representation hinges on "the inclusion of expectations and other kinds of presumptions" [19]. The frame's slots are usually filled with default values which are based on the standard situation. These default values represent general information and creates a way for the system to make generalizations and associations which may not have been made otherwise. The application of the theory will be demonstrated in an example. Figure 7 outlines a basic frame describing a simple arch made out of three bricks.

The bricks are labeled TOP, SIDE1, and SIDE2 and each brick is represented by an object frame. The arch itself is made of the three bricks. Note that the arch frame refers to the three object sub-frames that represent the bricks. The other slots in the arch frame refer to other pertinent information about the arch. Also, it is possible to add default values for all of the slots. One could specify that the default size is medium and that value would be present until better information dislodges it.

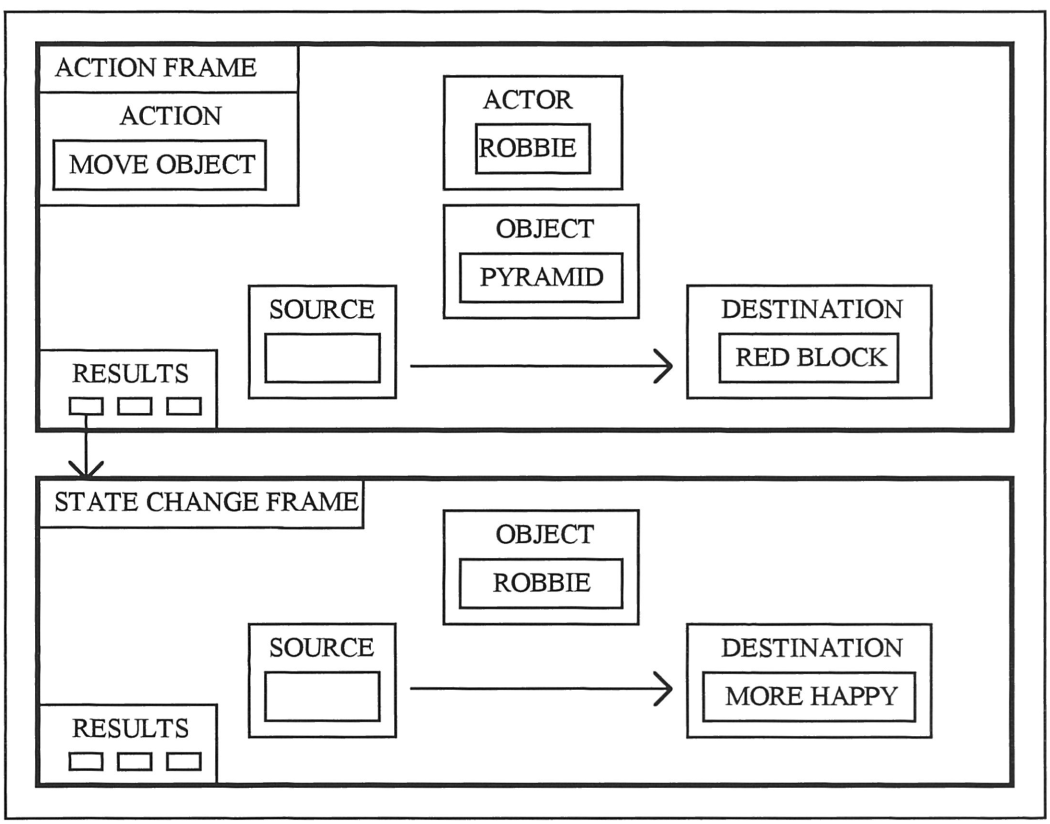
Figure 7: Frame Representation of an Arch



[20]

The frame gives the system knowledge above and beyond what needs to be supplied to the system. It knows that if it encounters an arch, that there are three objects that comprise it. It knows the relationship between those objects, and it knows that it is similar to something (assuming the similar-to slot is default-filled). Also, each of the slots can refer to another frame. In this way, the system can discover links between objects. These links are found when it finds a slot assignment that is common between the frames. The system will also be able to make connections that may be useful. For example, if in its interaction with the world, it encounters an arch, then it assumes that there are three parts to it. Conversely, if the system encounters a brick, it can make the connection that this brick could be a part of an arch by examining the links between the frames.

Figure 8: Frame Representation of Action



The frame representation is very useful in representing actions as well as objects. There are a few simple action primitives that can be combined to make more complex action sequences. This is illustrated in Figure 8 and its representation of the statement, "Robbie enjoyed putting the pyramid onto a red block" [21]. This example shows how easy it is to break up actions and state changes into frames and sub-frames. If the "Results" slot is changed to "Possible Results," it is possible to create an event tree and to represent contingencies. This is precisely what is needed in the evaluation system. The evaluation system needs to be able to analyze actions, event chains, synergies, and then predict the danger level of the whole system. It will be shown later (Section VI) that this is possible. Lotfi Zadeh has stated that fuzzy logic is not conducive to being represented by this sort of frame system [22], but this is in reference to the method's inability to deal with lexically imprecise language when representing language. This should not be a problem with the concepts that are being dealt with here, though. The expert system will be implemented for this system in Section VI.

V. Test Case: Gilbane Gold

The National Society of Professional Engineers' National Institute for Engineering Ethics developed a case study to highlight ethical problems faced by practicing engineers. This case study was named Gilbane Gold and it is available on a half hour videotape from the NSPE. The case study deals with a young engineer and the problems he faces when he learns that the corporation he works for is possibly violating the law by discharging wastewater with minute concentrations of hazardous materials in it into the local sewer system of the town of Gilbane. The sludge from this sewer system is known as Gilbane Gold because it is sold to local farmers as a fertilizer and is a large source of revenue for the town. Although this case is designed to highlight possible ethical problems that engineers can face, its premise provides a simple exercise in environmental damage analysis. In addition to the simplicity of the case, if it can be shown that if the proposed environmental evaluation system had been in existence so that the quandary that the young engineer finds himself in the video could have been avoided, then it would provide a compelling reason for using such an evaluation system in the real world.

The Gilbane Gold case revolves around a young engineer, David Jackson. He is an employee of Z-CORP, a major computer component manufacturer. Mr. Jackson is an engineer in the environmental relations department of the corporation. He is responsible for measuring and verifying the levels of toxic materials in the discharged wastewater from the Z-CORP plant in Gilbane. The plant has a sizable water treatment plant that treats the wastewater from the processes used in the factory, but it is apparently not capable of dealing with the amount of toxic material the plant is creating. Mr. Jackson discovers that, according to a new test that has just become available, the plant has been discharging slightly higher concentrations of lead than the local law allows into the sewer system. The old test that the city uses to enforce the law is not sensitive enough to detect the slightly higher concentrations, though. So no action has been taken against Z-CORP.

This would not be as much of a problem if the city was not selling the sludge from the city sewer system as a fertilizer to the local farmers. Mr. Jackson is afraid that the levels of lead and arsenic in his plant's discharge may increase the heavy metal levels in the sludge and may have an adverse affect on the local agricultural products. Mr. Jackson cannot prove that there will be any adverse effect, but he is still concerned that he may be placing future generations in danger.

Mr. Jackson's boss, Diane Collins, refuses to spend any more money than is needed to keep the city off of the corporation's back. She believes that since the city is unable to detect the violation, because their test is not sensitive enough, that Z-CORP should not notify them. Mr. Jackson fears that the city can not handle the extra lead and arsenic that they are discharging and feels that it is his responsibility to notify the city that there may be a problem. Diane Collins reminds Mr. Jackson that the local limits on discharge of lead are ten times more stringent than the federally mandated limits and that since the levels of lead and arsenic are so much less than the federally mandated limits that the situation is not as hazardous as Mr. Jackson believes. She is convinced that if there is a problem, the city will notify Z-CORP. Until then, no money will be spent on upgrading the wastewater treatment system. Mr. Jackson lacks reliable information on the concentration of lead and arsenic in the sludge and the danger that it may pose, so he is unable to convince his boss of the possible danger.

To complicate matters, Z-CORP has just received a new contract which is sure to increase production in the plant by 500%. This means that five times more lead and arsenic will be discharged by the plant. There is one loophole in the law establishing the discharge limits. The law sets limits on the concentration of the lead in the discharge. Thus, Z-CORP could legally put out five times the mass of lead and arsenic, if the volume of discharged water was increased five times. Mr. Jackson realizes how dangerous this could be to the public, because this means that lead and arsenic will be building up cumulatively in the sludge at a much higher rate than at the present time. This increases his fears that the public safety is in danger, particularly since the heavy metals do not decompose over time.

Thus, Mr. Jackson is forced to balance "considerations of environmental quality and human health against legitimate concerns for his own career, considerations of justice for Z-CORP, which must contend with the unusually strict environmental standards that were imposed after the plant was built, and the importance of Z-CORP's payroll for the community" [23]. He is forced to make a decision between several evils.

This decision is difficult to make because he lacks much information and has little evidence to support him. The evaluation system outlined in this paper could, if endorsed and applied by the professional societies or a governmental body, provide David with the information he so desperately needs to end his quandary. If such a standardized system of evaluation systems could be implemented, the system would benefit from an extremely large database of information and experience and it would decrease the likelihood of such cases from arising. In the next section of this paper, a rudimentary system will be outlined and applied to this case. The results will be evaluated and comments made upon how this system could be implemented on a wider scale with a greater impact.

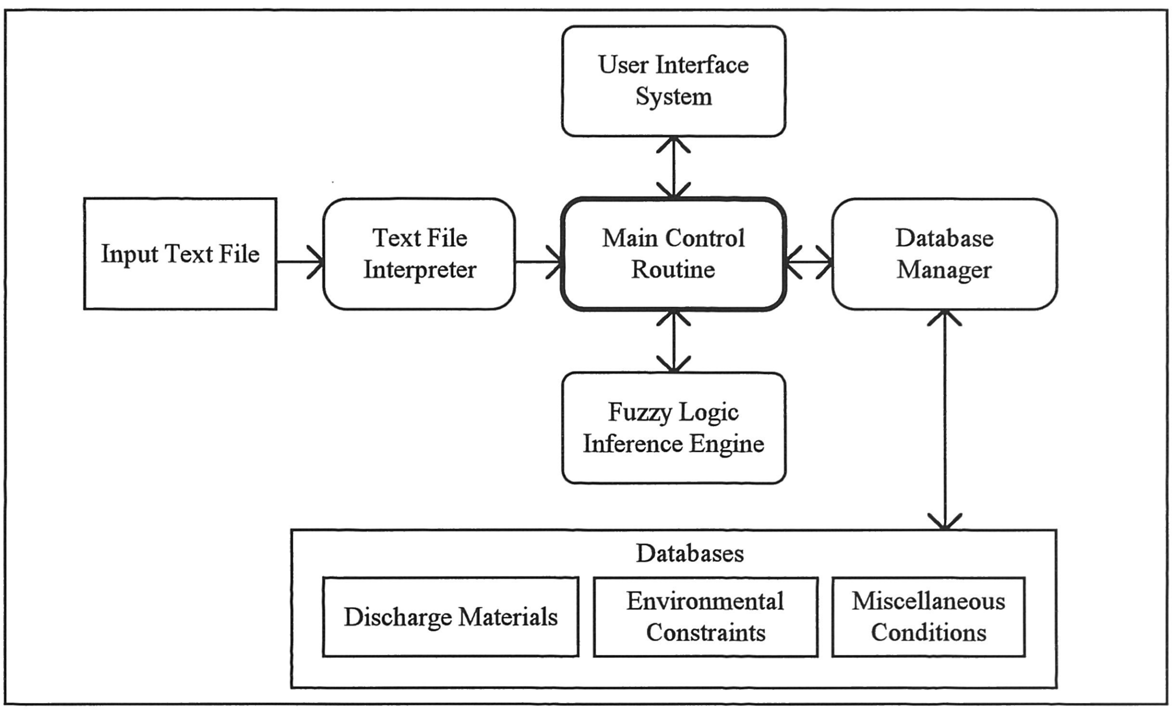
VI. Application of the Rule-based System

All of the knowledge that will be used to synthesize a solution has been covered in the previous sections. All that is left is the actual synthesis of a solution. This section outlines this process. It is the process which is the most important result from this research. The example system that will be created here is not a production system. It is a proof-of-concept example. The method by which it is created can be scaled up to create a practical and usable system, though. Thus, it is important that the method be laid out in a simple manner which is amenable to the scale-up process. There are three major concerns that are encountered in developing a system like this. The first is determining how the knowledge in the system will be represented. The second is determining how to create a system by which the knowledge can be used. The third is determining how to use the system to perform an analysis. These are the aspects that will be discussed in the rest of this section.

VI.A. Knowledge Representation

The knowledge in an expert system must be organized in a coherent hierarchical manner. This is needed to facilitate the addition of new information and to make the system more efficient and complete. The conceptual configuration of the envisioned system is shown in Figure 9. The system will be referred to in the rest of this paper as the Fuzzy Logic Environmental Analysis (FLEA) system. The system will read the input information from a text file created by the designer. The information will be parsed and each line will cause a database of information to be scanned to find any entry that has a reference to the material or process listed in the text file. For example, the first line of the input text file is, "Discharge Material: Lead, 5g/hr." The system would recognize the keyword "Discharge Material" and then read in the material and the discharge rate. The DM (Discharge Material) database would be summoned and the information would be scanned by using a keyword field. All entries in the database with the input word in their keyword field would be put into a queue to be analyzed with the fuzzy logic inference engine. Each entry would contain information to fit into a generic

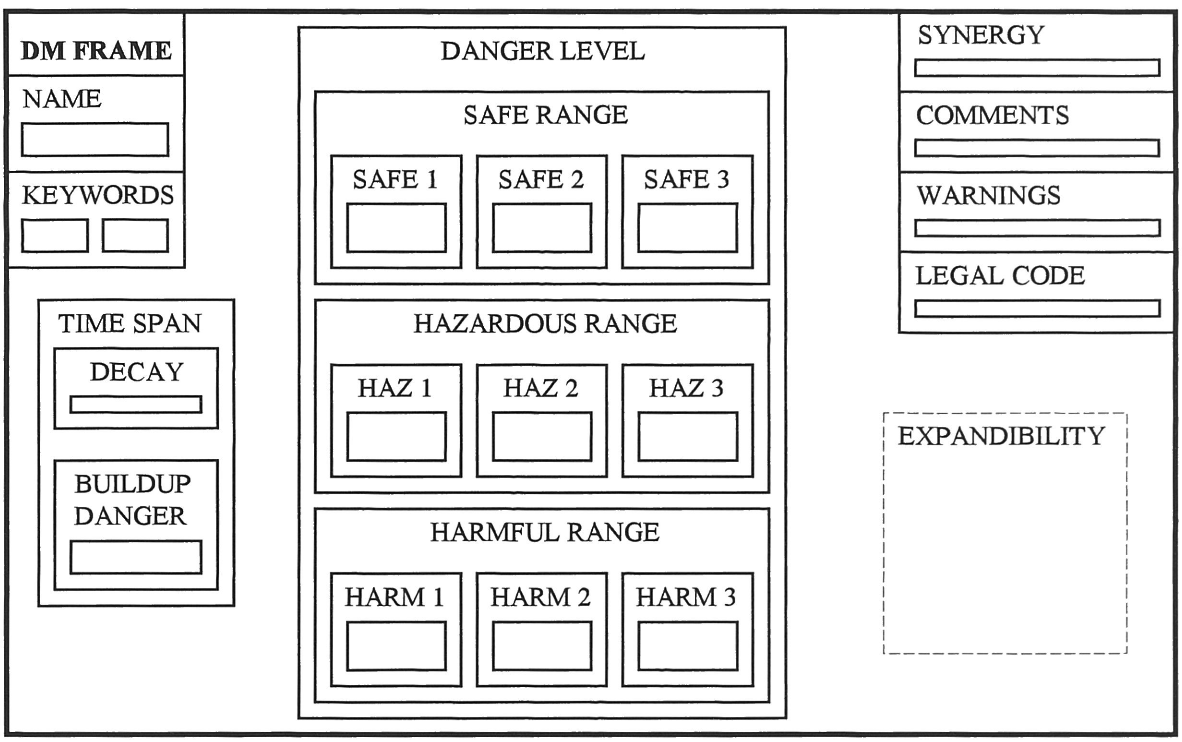
Figure 9: Conceptual Configuration of the FLEA System



inference engine rules-base. Each of the databases has a generic rules-base that goes along with that database. The database fields contain the information which can be used to fill in the needed information in the inference engine's rules. The database structures of fields and entries replicate the frame structure of slots and frames, thus allowing us to represent this information in frames and slots.

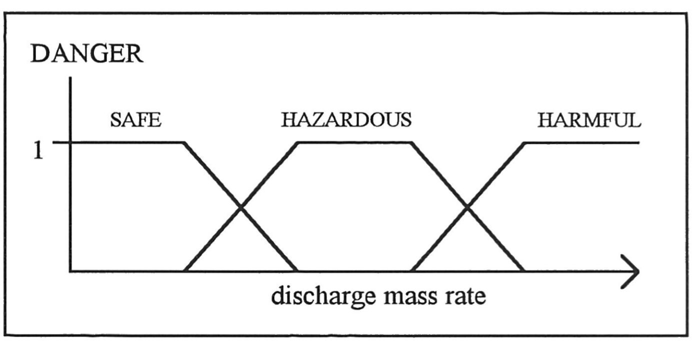
There will be three main databases; the discharge materials (DM) database, the environmental constraints (EC) database, and the miscellaneous conditions (MC) database. The standard database frame for the DM database will be of the structure of the frame shown in Figure 10.

Figure 10: Discharge Materials Database Information Frame



The DM frame has several features which need more explanation. The NAME slot will contain the common name of the discharged material. The KEYWORDS slots will contain any names which when input will require reference to this material. The TIME SPAN sub-frame contains the DECAY slot which contains a sub-frame of information dealing with the decay rate and products of the substance. The BUILDUP DANGER slot contains information dealing with long term buildup of the substance. It most likely will contain a scaling factor to multiply against the long term danger rating if the environmental conditions are correct for buildup of the substance. The DANGER LEVEL sub-frame is the most important piece of information in the DM frame. There are three sub-frames in the DANGER LEVEL sub-frame. Each of these sub-frames outlines the limits of the fuzzy membership functions for the different levels of danger. In this rudimentary system, it is assumed that all materials have a series of membership functions for the levels of danger (safe, hazardous, harmful) spanning a domain of discourse of mass rates of discharge that are all linear functions like the ones shown in Figure 11. This data will be based on the medical studies done for OSHA and NIOSH on the effects of the toxic materials.

Figure 11: Fuzzy Logic Danger Functions



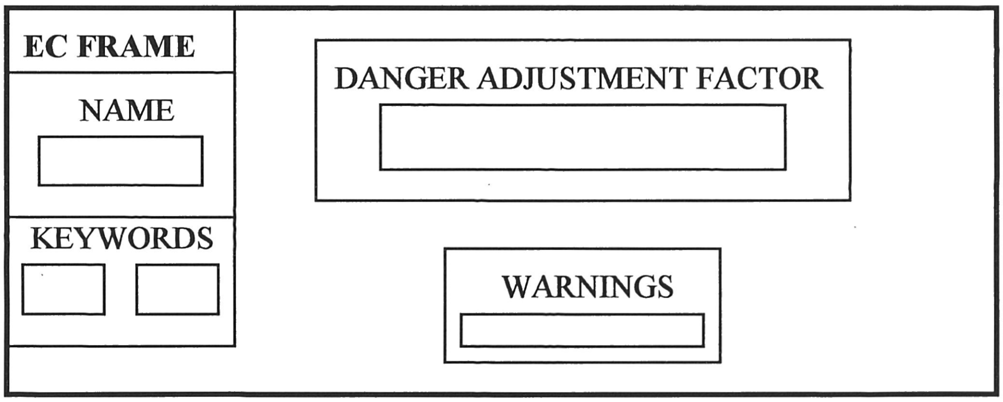
The slots of the sub-frames in the DANGER LEVEL sub-frame are filled with the mass rates that correspond to the break points in the membership function corresponding to the sub-frame's membership function (e.g. the SAFE sub-frame's slots are filled by the break points of the SAFE membership function). In this way, it is possible to specify membership functions that are specific to each material and yet fit into a generic membership function form used by the inference engine. More rigorous systems would be capable of specifying the exact type of membership function that would be used to represent the danger level.

The other slots which occur in the DM frame are the SYNERGY slot which contains information about synergistic effects that this substance may have with any other substances. It notifies the system that a problem may occur if both this material and the other material with which this material is synergistic are released. There is a COMMENTS slot which contains any comments about this substance that may be needed. The WARNINGS slot contains information that will appear in the feedback information that will be output along with the danger rating to the user. The WARNINGS slot will be output if a certain danger level is achieved. This threshold information may be included in the sub-frame that fills the WARNINGS slot. There is also a LEGAL CODE slot which can contain legal information, like legal limits on concentration that must be addressed by the system in its analysis. The system is also designed to be expandable to include any future information that may be needed by the system to complete its analysis.

The Environmental Constraints (EC) database will have its information represented by a simpler frame known as the EC frame. This frame is shown in Figure 12. The EC frame is much simpler than the DM frame. The EC frame contains the NAME and KEYWORDS slots which are exactly the same as the slots in the DM frame. The

DANGER ADJUSTMENT FACTOR (DAF) is the most important piece of information in this frame. It determines what type of impact an environmental constraint has on the

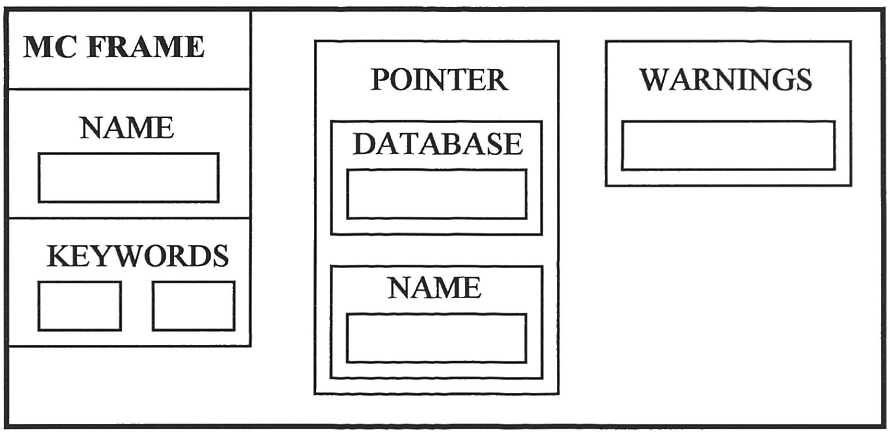
Figure 12: The Environmental Constraints Database Information Frame



danger rating of the system being analyzed. This frame is where rules-of-thumb can be added into the knowledge base. For example, the rule-of-thumb that states that higher levels of pollution are acceptable in less populated areas can be expressed by giving the DAF slot a value less than one. Thus, if in the input parameters it is revealed to the system that the design will be located in a remote area, then it will take the danger rating (which is calculated by the inference engine from operations over the DM database) and multiply it by the DAF. So, the danger rating of the design will be reduced by the fact that it will be located in a remote area. The WARNINGS slot is used to inform the user of the system that this rule-of-thumb has been used in the evaluation process.

The Miscellaneous Conditions (MC) database is used to find hidden dangers that may arise in the design. It includes factors such as the fact that rust results when steel construction is used. The MC database directs the evaluation system's focus back towards the DM database or EC database. For example, if the MC database includes information about iron oxide discharge if the structure is made of steel, it would tell the system to add in the effect of the discharge of the iron oxide to the danger rating evaluation, and it would warn the user that an unexpected problem has arisen and is influencing the final danger rating of the system being analyzed. The information needed in the MC database can be represented in the MC frame. The MC frame can be seen in Figure 13.

Figure 13: Miscellaneous Conditions Database Information Frame



The POINTER sub-frame contains the slots which can be used to force the system to evaluate an overlooked factor from another database. It contains the DATABASE and the NAME slots which point to a material in the DM database or to a rule-of-thumb in the EC database. It also contains a WARNINGS sub-frame which can be used to notify the engineer that a miscellaneous condition was encountered and included in the analysis.

The DM database could be standardized by the professional societies or the government, as it contains only materials properties and acceptable concentration limits.

these facts are general knowledge and can be determined and distributed by a standardizing body. The EC database can be filled with some basic rules-of-thumb, but this database is designed to be expanded upon by the users. It is designed to be adaptable to any industry and any circumstance. The rules should not be included unless there is already an established procedure surrounding the use of these rules by the organization using the evaluation system. The MC database is designed to be a catch-all database. It is the place where most of the knowledge addition will take place. This is an area where the knowledge learned through experience by the designers can be integrated into the system and used in the evaluation. If there is any doubt about where a new piece of information should be added, then it should be added to the MC database and it should point to the needed information in the other databases.

The knowledge representation method outlined here is demonstrated on a simple example in Appendix 1. Lead (Pb) is displayed as a typical DM entry and there are a few examples of the rules-of-thumb being represented in the EC database. There also is one example of a standard MC entry.

VI.B. FLEA System Operational Procedures

The FLEA system is outlined in graphical form in Figure 9 (page 38). In the previous section, the method for representing the system's knowledge was explained. This section of the paper will examine how this information is accessed and used. There are four subsystems which must be examined to understand how the system functions. These subsystems are the Text File Interpreter, the Database Manager, the Fuzzy Logic

Inference Engine, and the User Interface System. An example of the operation of the system can be found in Appendix 2.

The Text File Interpreter system is the system which reads the input file created by the designer of the system. This input file is highly structured. Each line has a prefix which allows the system to understand what information structures the line refers to. There are three prefixes; DM, EC, and MC. These prefixes refer to the three types of knowledge that have been included in the system.

The line that follows the DM-prefix will contain information about a material being discharged by the system. This information includes the name of the substance, the discharge rate, and the background concentration of the substance. The name of the substance is used to identify which database entries should be used to perform the analysis on this material. The mass discharge rate will be used to evaluate the membership values in the danger level membership functions. The background concentration can be used as a baseline for determining the effect that the discharge may have on the buildup of the substance in the environment.

The line which follows the EC-prefix will contain information in the form of antecedents of the rules-of-thumb included in the analysis. Thus, if the system is using the rule-of-thumb mentioned before (If the plant is in a remote area, a slightly higher level of pollution is acceptable) the line which would trigger this rule would mention something along the lines that the plant was located in a remote area. This input should be constrained by a standard method of input. For example, giving each user of the system a list of all of the rules-of-thumb used in the analysis would help the users to know what to place on the input line to trigger a rule.

The line which follows the MC-prefix will contain miscellaneous information that the user has entered in response to a list of what miscellaneous conditions are presently functioning in the system. The line will again be in a standard format recognizable by the system. It should be in the form of the name of the MC entry or contain the keywords which would trigger the rule to execute.

The system will parse all of the lines in the input text file and store the information in three temporary databases. One of the databases will contain a list of all of the materials that are being output by the system being evaluated. This will be the DMTEMP database. The other two databases will be named the ECTEMP and MCTEMP databases. These databases will contain the input lines which are relevant to their knowledge base (i.e. the ECTEMP system will contain the lines following the EC-prefix). These databases will be used by the Database Manager to extract the information from the databases to allow the inference engine to analyze the input data. For example, if the line, "DM: Lead, 5g/hr" is parsed out of the input text file, the corresponding entry in the DMTEMP database is "Lead" and "5 g/hr" in their respective fields. The system then uses the entry "Lead" to do an DM database search through the NAME and KEYWORDS fields (slots) to find all of the information pertaining to the discharge of Lead. It will find the DM database entry labeled "Lead" and it will invoke the inference engine with a DM-database standard configuration rules set. The information from the database entry will fit precisely into the holes that are open in the generic rules structure. The inference engine can then perform an evaluation on the input concentration which is located in the second field of the first entry in the DMTEMP database.

It then repeats this procedure until all of the materials in the DMTEMP database have been evaluated. The database manager then evaluates the ECTEMP and MCTEMP fields in the same way. The MCTEMP fields may require the system to reevaluate a material in the DM database, so it is designed to be able to implement the DM database or EC database evaluations when needed. If the system ever encounters an unknown input field it notifies the user that the system is incapable of evaluating that parameter.

The Fuzzy Logic Inference Engine functions exactly as explained in an earlier section. The inference engine does not have a large rules-base though. It contains three small generic rules-bases which have interchangeable information fields. This is possible because all of the information needed for the evaluation is represented in standard frames in the databases. Thus, it is possible to have a small set of rules that always are used when evaluating information such as materials discharges because all of the evaluations dealing with materials discharged are done in the same way. The only difference in each of the different evaluations is the information being used for comparison. This information, if stored in a modular form, can be switched in and out of a set of generic rules. This greatly simplifies the information storage technique and it ensures that all of the evaluations are being performed in a consistent manner.

The Inference Engine has only a few outputs. The inference engine keeps a running total of the danger rating (long term and short term) and it sends warnings to the User Interface System if a threshold value is reached. In the evaluation of the MCTEMP database, the danger ratings are developed from inferences between the materials and their danger levels. The long term danger rating is just the short term danger rating scaled by such factors as buildup potential and decay rate. These danger ratings are aggregated across the different discharged materials and a final danger rating (long term and short term) is developed from this aggregation. This aggregation is then scaled by the DAF factors from the EC evaluations. The final danger rating is affected by the MC evaluations as well. The MC evaluations cause the system to determine another danger rating and then scale and aggregate it with the original final danger rating. Then, after all analysis has been completed, the system outputs the overall system long term and short term danger ratings. This along with the warning information which is triggered during the analysis can help the designer redesign his product or system.

IV.C. Analysis Technique

The designer must view his system from a systems point of view. His plant or design is surrounded by a "bubble." Anything that leaves this "bubble" by any means, has the potential to harm the environment. The designer does not have to predict all of the possible problems to allow the system to perform a proper analysis. The MC database can have information in it which can cause the system to prompt the user for more information. For example, the MC database system can serve as an evaluator of the effects that any construction material or the decomposition products which may occur from chemical reactions with those construction materials may have on the environment. All that is needed in the MC system is a series of entries testing to see what materials are used in construction. This will be enough to prompt the system to go back and reanalyze the system with respect to these new substances and to see what effect these substances may have on the environment. The system can be considered to have some degree of intelligence. Unfortunately, this intelligence is limited by the foresight of the people who determine what rules to add to the system. Although, over time, it should be possible for the system to acquire enough knowledge to become useful. In this way, the system is completely expandable and will grow as long as the engineers operating it continue to update and expand the materials data, the rules-of-thumb, and the rules dealing with the miscellaneous conditions.

A complete example of the application of a rudimentary implementation of the FLEA system can be found in Appendix 2.

VII. Evaluation

The FLEA System outlined in the last section achieves most of the goals of this project. It is a fuzzy-logic based system for evaluating environmental effects of designs in their early stages when changes can be made easily. It fits into a standard systems engineering approach to design and can provide useful feedback to the designer. The system has some promising features that could be used to assist in developing a complete commercially-available system for use in engineering practice. It also has some drawbacks which may need to be remedied in the future implementations of this concept.

The FLEA System has several promising features that can be used to improve the system in future versions. First, the system is completely expandable. The databases can hold any number of rules and materials data and so can be shown to be expandable. The generic rules which the materials data and rules-of-thumb fit into allow easy expandability as well. Instead of having to develop a whole new system of rules for a new material or process, it is possible for the designer just to input the relevant materials data and just use the standard rules set that fits that knowledge frame. The system can continue to improve and refine its analysis as more information is given to it.

The knowledge representation is straightforward as well. The information is divided into materials constants, design rules-of-thumb, and indirect effects (miscellaneous conditions). Each of these categories of knowledge has a standard frame which can accommodate most information and make it accessible to the evaluation system. It is easy to adapt the rules-of-thumb that are currently used to the frame representation that the evaluation system needs. It is also possible to add information to the system in the

Miscellaneous Conditions database to allow the system to make connections that may have gone unnoticed in the normal design process.

The FLEA System is also flexible. This is due to its fuzzy nature. The input concentrations of the discharged materials need not be unrealistically accurate. Since the system is fuzzy in nature, and fuzzifies all input, it can accept input that is not truly accurate. As long as the input data is reasonably close to the true values, it will return values which are reasonable. The rules-of-thumb in the EC database allow designers to specify concepts that cannot be quantified per se. The way that the rules-of-thumb are applied allows the designer to tune the system to an optimum state for their design environment.

The FLEA system also provides useful feedback to the designer. As the evaluation procedure is executed, warning text appears on the user's screen to notify him/her that there is a specific problem in the system. These warnings will only appear because of the information in the system. So, in effect, the system is only as good as the information input into it. This problem is discussed later in this section.

This warning text not only includes a notification of a problem, but it outlines what state of the system was responsible for the problem. It also lets the designer know what rules-of-thumb are being applied to the design and what miscellaneous or unforeseen factors have been triggered by the design. All of this information makes the redesign process much easier, since the designer now knows where the trouble spots are in his design. The system also provides a way to compare various designs on an unbiased scale. The danger ratings (long term and short term) provide crisp numerical ratings of the safety of any design. Any system design evaluated on a standardized FLEA system can be compared to any other system by way of the danger rating. This danger rating provides an easy way to discriminate between competing designs. Thus, the system can be shown to provide useful information to the designers.

The FLEA system relies on standard software packages which can be linked together through the common basis of the C-language. The database constructs are rooted in the C-language and the FuzzyCLIPS fuzzy logic expert system engine can be implemented in C-language calls to the fuzzy logic inference engine. Also, the system should be able to deal with the dynamic data exchange (DDE) concept. All that is needed is to convert the Text Interpretation System from text file-based to a protocol which is compatible with the DDE standards.

There are some disadvantages to the system, though. The system is unable to predict problems which have not been experienced. All of the data and knowledge that the system has must be input by someone. This would make it seem that little has been gained by implementing this system. This is an incorrect assumption, though. The system will serve as a "living library" for the knowledge it contains. The "library" will be continually updated and the system will continue to improve. This is the basic premise behind an expert system. An expert system is essentially an expert in its field because it contains all of the experience that the expert who entered the data has gained. Thus, the system will be limited by the amount of information the expert can enter. But, as time passes and the system is updated, the system will become more and more useful and knowledgeable. The system will serve as both a repository for knowledge and as a user of this knowledge in its evaluation function. Therefore, it can be shown that this system will provide some benefit after its implementation.

The most glaring flaw of the system is the method of the input of the system parameters. The designer must know all of the discharge materials that are leaving the plant. This is often not the case, though. The FLEA System does have the ability to make connections to some unforeseen consequences, but again the system is forced to wait for a human to input the link between the problem and the cause. The system can not discover this link on its own. But, this problem can be alleviated by providing the documentation for the rules-of-thumb and materials databases. The designer should come to understand how the system works and what its limitations are as he/she gains experience at using it. This increased understanding should allow the designer to better understand what the system needs to function accurately.

The system will also require quite a bit of knowledge to even come close to accurately evaluating a real system. It will take several years of actual implementation to develop a truly usable system. Also, the ease of modification of the system may cause the system to not be used because all of the value of the system could be destroyed by groundless or inappropriate rules. It is possible for an unscrupulous person to falsify his results by manipulating the knowledge of the system and creating rules which are made to make the design look safer than it actually is. This problem can be avoided by certification and standardization of the rules and knowledge that are used in the various implementations of this concept system.

VIII. Conclusion

Since the beginning of human history, the world has been viewed as an unlimited resource that should be plundered by humankind. Various religions emphasized this fact by declaring that the earth and its creatures were created for humans to use. It has not been until recently that humankind has realized that the earth and the other inhabitants of it have rights as well. In this new world view, all life is considered sacred and it is believed that humans should strive to live in harmony with the earth and not seek to subjugate it.

Unfortunately, the problems created by our predecessors do not disappear with their beliefs. There are many places on this planet which are so contaminated that no person will ever be allowed to live there. In many cases, this pollution is spreading. Old poisons and old wastes seep into the groundwater of the cities in which we all live. These poisons have the ability to destroy many fragile ecosystems, including our own, and all humans can do now is try to clean up and prevent any more damage. It is a disgrace that this is the legacy left to us by our ancestors. This generation must take it upon itself to ensure that this sort of destruction does not continue into the future. The destruction must end here.

Unfortunately, this goal is not easily achievable. Many of the environmental problems that currently are being dealt with were unforeseeable or easily ignored by the designers of these old systems. These are the same unquantifiable and unforeseen problems that are not being considered in today's design processes. It has been said that "Our price system fails to take into account the environmental damage that the polluter inflicts on others" [24]. This is the case in current design process as well. It is difficult to accurately assess the costs incurred by pollution originating from the design when the design is in the conceptual phase. This is unfortunate because this is where changes can most easily be made and potential problems avoided. Thus, if it is not possible to develop a process for predicting and assessing the environmental danger incurred by a design, it is not possible to prevent the possible problems that they may cause.

The system outlined here, the Fuzzy Logic Environmental Analysis System, will allow the designers to review their designs in the early phases of the design process. This evaluation will provide the engineers with a danger rating for both long term and short term effects and will provide valuable feedback information which can be used in the process of redesign. The FLEA System will not allow the designer to completely eliminate the danger posed by a design, but it will allow for a significant reduction in the danger level. Any reduction in the danger level is beneficial to society, just as any potential problem that is caught and eliminated is one less problem that will cause damage to the environment.

Engineers are bound by their code and their personal moral beliefs to protect the public safety. The public safety is directly tied to environmental safety. This is because a healthy and safe public requires a healthy and safe environment for the public to live in. Thus, it is all engineers' duty to protect the environment and to minimize the impact that their designs will have on the environment to minimize the hazard to the public. The Fuzzy Logic Environmental Analysis system will allow engineers to ensure that the danger to the public from their products and processes is minimized.

Endnotes

1. *Environmental Investments*, page xvii.
2. Harris et al, page 222.
3. Ibid.
4. Harris et al, page 225.
5. paraphrased from Nixon, page 258.
6. *Hazardous-Chemicals-on-File*, page L001.
7. Gaines, page 31.
8. *Fuzzy Logic Primer*, page 5.
9. *FuzzyCLIPS User's Guide*, page 15.
10. Pahl, page 41.
11. Blanchard, page 83.
12. *FuzzyCLIPS User's Guide*, page 13.
13. Ibid.
14. *FuzzyCLIPS User's Guide*, page 15.
15. *FuzzyCLIPS User's Guide*, page 25.
16. McFadden, page 347.
17. Winston, page 180.
18. Ibid.
19. Ibid.
20. Winston, page 185.
21. Winston, page 192.
22. Zadeh, page 89.
23. Harris et al, page 242.
24. Nixon, page 260.

APPENDIX 1

Knowledge Representation Examples

A1.1 Discharge Materials Database Frame Entry

This appendix section is provided to show a demonstration of how information concerning lead (Pb) can be included into the DM database structure. The information used to fill in the slots in the frame have been taken from *Hazardous Chemicals on File* and the *OSHA Regulated Hazardous Substances: Health, Toxicity, Economic, and Technological Data*. These are the types of sources which currently exist which can be used to fill the DM database with information for use in a generic evaluation system.

DM FRAME SLOT INFORMATION

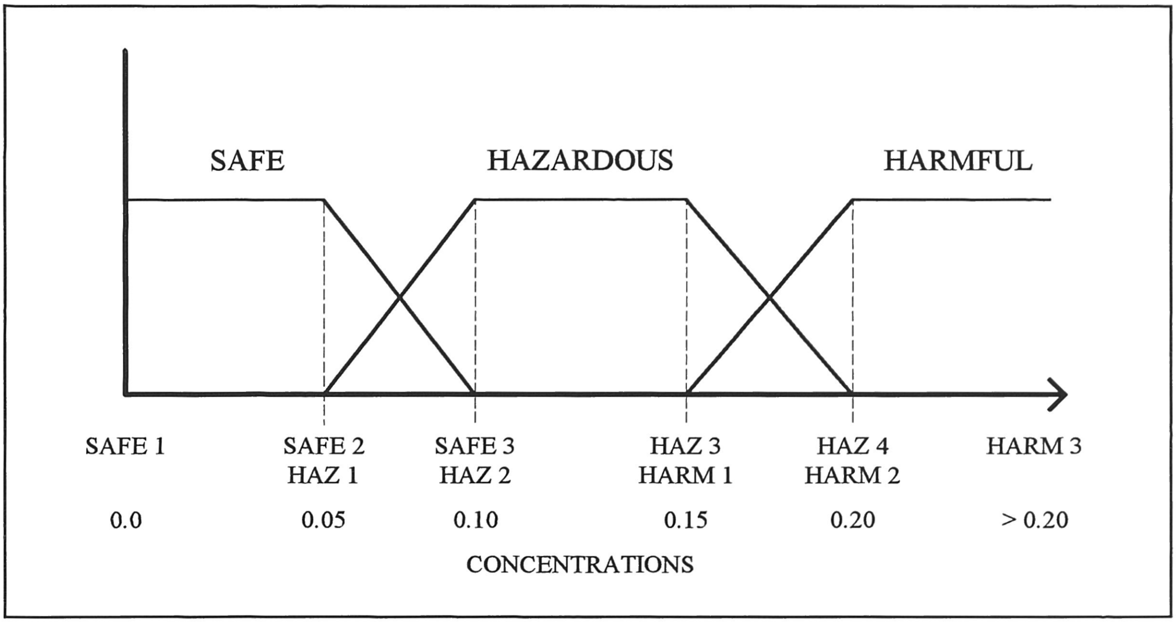
Slots	Information
NAME	Lead Dust
KEYWORDS	Lead, Lead Salts, Metallic Lead, Lead Oxides
TIME SPAN:DECAY	0.0[1]
TIME SPAN:BUILDUP DANGER	2.0[2]
DL:SR:SAFE 1	0.0 mg/m^3
DL:SR: SAFE 2	0.05 mg/m^3 [3]
DL:SR:SAFE 3	0.10 mg/m^3 [4]
DL:HR:HAZ 1	0.05 mg/m^3
DL:HR:HAZ 2	0.10 mg/m^3
DL:HR:HAZ 3	0.15 mg/m^3 [5]
DL:HR:HAZ 4	0.20 mg/m^3 [6]
DL:HMR:HARM 1	0.15 mg/m^3
DL:HMR:HARM 2	0.20 mg/m^3
DL:HMR:HARM 3	> 0.20 mg/ m^3
SYNERGY	none
COMMENTS	Lead can harm the central nervous system.
WARNINGS	Unacceptable levels of lead are present in the system and may cause long term problems!
LEGAL CODE	OSHA PEL = 0.05 mg/m^3

1. The DECAY parameter is arbitrarily chosen by the expert who enters the information into the expert system. In the rating system, a 0.0 represents that the material does not decay, while a 1.0 represents a material that decays almost immediately. A high decay rating may be beneficial or not. If the products which are created from the decay of a safe substance are dangerous, it would not be beneficial to have a high decay rating. Although, if the products were safer than the material, a high decay rating would be beneficial. NOTE: That if this material had been a decaying material, this slot would have been filled by a sub-frame which contained the decay rating and pointers to the product materials of the decay.

2. The BUILDUP DANGER slot contains a value which represents how likely this material is to build up to dangerous levels in the environment. It is determined by comparing the long term danger posed by the material compared to the danger posed by other materials. Lead is highly likely to build up to dangerous levels. This is because the lead does not decay, and it is toxic at low concentrations. The concept of danger here is derived expressly from Section I, where "danger" was defined.

This slot contains a scaling factor which will be applied to the contribution of the lead to the long term danger rating. Thus, if the lead is determined to have a fuzzy danger rating, the scaling factor will scale the distribution function by the value in the slot (2.0).

3. The fields referring to the danger level apply to this diagram:



The danger level slots are used to place the points on the family of danger membership functions. Using the information given in the slots, it is possible to develop a unique distribution for each material. The danger level slots must be filled by data that is in the domain of discourse for the family of danger membership functions.

The data used in this field, DL:SR:SAFE 2 is determined from the minimum of the lawfully allowed minimum allowances. OSHA's PEL of 0.05 mg/m^3 was chosen because it was the lowest acceptable exposure limit given by a governing body. This was an arbitrary decision and again is up to the discretion of the expert entering the knowledge. This is where the standardization procedures are useful for ensuring the data is the same for all users of the system.

4. This data point was chosen as the next concentration level for the express reason it is the next highest safe limit from a governing body. The safe range should end upon the median value of the limits given by the different governing bodies. Again this decision is

up to the expert adding the knowledge to the system. If this system is standardized, it would be useful for the governmental bodies to accept this fuzzy logic representation and to provide their safe limits in the form used in this system.

5. and 6. These values are again chosen by the expert entering the data to the system. In this example it is assumed that the minimum HARMFUL concentration should be twice the concentration of the maximum SAFE concentration.

The other information in the DM database frame is used by the system to alert the designer of the legal codes dealing with this material, any possible synergies, and allows the expert entering the information to compose warnings and comments to the user of the system which will be enacted if the level of the material is in the hazardous range.

A1.2 Environmental Constraints Database Frame Entry

The EC frame is much simpler than the DM frame. It is used to represent rules-of-thumb which can be applied to modify the overall danger rating.

EC FRAME ENTRY

for

ROT1: "Discharge into the public sewer system in a populated area is very dangerous."

Slots	Information
NAME	ROT1 [1]
KEYWORDS	"Discharge" and "public sewer system" [2]
DANGER ADJUSTMENT FACTOR	1.5 [3]
WARNINGS	It is dangerous to discharge into the public sewer system in a populated area.

1. The name of the rule-of-thumb should correspond to a standard document which outlines all of the rules-of-thumb in use in the system. This document can be used by the user to have an idea of what EC lines should be included in the input data file.

2. The rule is executed when "Discharge" and "Public sewer system" are found in an EC input line together. In this way, it is possible to ensure that the rule fires if the wording of the ROT is not exact.

3. The DAF reflects the danger level scaling factor which is assessed on the system by the rule-of-thumb when it fires. It is used to scale the overall danger rating. The higher the DAF, the higher the multiplication of the danger level.

A1.3 Miscellaneous Conditions Database Frame Entry

The MC database frame contains a rule which if it fires points to another DM database entry or an EC database entry.

MC FRAME ENTRY

for

MCRULE1: "Steel structures corrode and release iron oxide into the environment."

Slot	Information
NAME	MCRULE1[1]
KEYWORDS	Steel structure[2]
POINTER:DATABASE	DM[3]
POINTER:NAME	iron oxide[4]
WARNINGS	Steel structures will release iron oxide when they corrode.

1. The name of the miscellaneous rule should correspond to a standard document which outlines all of the miscellaneous rules in use in the system. This document can be used by the user to have an idea of what MC lines should be included in the input data file.

2. The keywords field was explained in the last section.

3. This slot contains the name of the database that this rule is pointing to.

4. This slot contains the name of the NAME of the material or rule in the DM or EC databases respectively.

APPENDIX 2

Basic FLEA System Implementation

A2.1 Test Case Information

The test case that is being used is the Gilbane Gold case outlined in the paper. The first step in analyzing the test case is to develop the FLEA System input file. This file follows the formatting convention outlined in the Applications section of the paper. Input lines which deal with the discharge materials are prefixed with a DM, lines which deal with the Environmental Conditions are prefixed with an EC, and the lines which deal with the Miscellaneous Conditions are prefixed with a MC.

This method is designed to evaluate a design though, so to use the Gilbane Gold case, it is necessary to examine the design of the plant's first water treatment system. The treatment system was to be able to treat all of the wastewater from the plant and remove toxic materials from the water. The major discharge would be lead (Pb) from the manufacturing processes done on the computer components. The plant must be examined from a systems point of view, where the plant is assumed to be in a bubble. Everything which crosses through this barrier should be included in the input file for the system.

This case will be simplified, due to the lack of other knowledge about the plant in the case. It will be assumed that there are only two outputs from the plant; lead and arsenic. They are output in levels that are slightly above the safe level (this level will be enumerated later). The design that we are looking at includes the manufacturing system and the wastewater treatment system for the plant. The wastewater treatment system can not deal with the output levels of these two materials. So, either a change in the method of manufacture or a change in the method of wastewater treatment should be enacted. The FLEA system should show that this is the case and should warn the designer that the system is dangerous and it should tell the designer how it is dangerous.

A2.2 Input File for the FLEA System

```
<START>
CASE: Z CORP GILBANE PLANT
DM: Lead, 12 ppm,?
DM: Arsenic, 1 ppm, .1 ppm
EC: Discharge into public sewers
EC: Solid wastes from sewer system used in agriculture
MC: Plant capable of 500% increase (curr. capacity @ 16.67%)
MC: Strict local laws
<END>
```

A2.3 Prototype DM Database for the FLEA System

DM ENTRY: LEAD

Slots	Information
NAME	Lead
KEYWORDS	Lead, Lead Salts, Metallic Lead, Lead Oxides
TIME SPAN:DECAY	0.0
TIME SPAN:BUILDUP DANGER	2.0
DL:SR:SAFE 1	0 ppm
DL:SR: SAFE 2	5 ppm
DL:SR:SAFE 3	10 ppm
DL:HR:HAZ 1	5 ppm
DL:HR:HAZ 2	10 ppm
DL:HR:HAZ 3	15 ppm
DL:HR:HAZ 4	20 ppm
DL:HMR:HARM 1	15 ppm
DL:HMR:HARM 2	20 ppm
DL:HMR:HARM 3	> 20 ppm
SYNERGY	none
COMMENTS	Lead can harm the central nervous system.
WARNINGS	Unacceptable levels of lead are present in the system and may cause long term problems!
LEGAL CODE	-

DM ENTRY: ARSENIC

Slots	Information
NAME	Arsenic
KEYWORDS	Arsenic
TIME SPAN:DECAY	0.0
TIME SPAN:BUILDUP DANGER	2.0
DL:SR:SAFE 1	0.0 ppm
DL:SR: SAFE 2	0.5 ppm
DL:SR:SAFE 3	1.0 ppm
DL:HR:HAZ 1	0.5 ppm
DL:HR:HAZ 2	1.0 ppm
DL:HR:HAZ 3	1.5 ppm
DL:HR:HAZ 4	2.0 ppm
DL:HMR:HARM 1	1.5 ppm
DL:HMR:HARM 2	2.0 ppm
DL:HMR:HARM 3	> 2.0 ppm
SYNERGY	none
COMMENTS	Arsenic is a deadly poison at 1
WARNINGS	Unacceptable levels of lead are present in the system and these pose a serious health risk.
LEGAL CODE	-

A2.4 Prototype EC Database for the FLEA System

EC FRAME ENTRY

for

ROT1: "Discharge into the public sewer system in a populated area is very dangerous."

Slots	Information
NAME	ROT1
KEYWORDS	"Discharge" and "public sewer system"
DANGER ADJUSTMENT FACTOR	1.5
WARNINGS	It is dangerous to discharge into the public sewer system in a populated area.

EC FRAME ENTRY

for

ROT2: "If the solid wastes from sewer system are used in agriculture, there is a danger of buildup."

Slots	Information
NAME	ROT2
KEYWORDS	"solid wastes" and "Agriculture"
DANGER ADJUSTMENT FACTOR	1.2
WARNINGS	There is a danger of waste buildup from the system in the agricultural sector.

EC FRAME ENTRY

for

ROT3: "If the plant's output is examined with vigor, the plant must operate well below parameters to ensure that the plant is always conforming with the law."

Slots	Information
NAME	ROT3
KEYWORDS	"Output examined with vigor"
DANGER ADJUSTMENT FACTOR	1.1
WARNINGS	The plant must operate well below the legal limit, to ensure that they do not violate the law.

EC FRAME ENTRY

for

ROT4: "An increase in production will increase the output of dangerous materials."

Slots	Information
NAME	ROT4
KEYWORDS	"increase" and "production"
DANGER ADJUSTMENT FACTOR	(1/(curr. capacity))-1

WARNINGS	An increase in output to the full capacity will cause the discharged materials to become dangerous sooner.

A2.5 Prototype the MC Database for the FLEA System

MC FRAME ENTRY

for

MCRULE1: "Strict local laws means that there is an active environmental movement which will examine the plant's output with vigor."

Slot	**Information**
NAME	MCRULE1
KEYWORDS	"strict local laws"
POINTER:DATABASE	EC
POINTER:NAME	ROT3
WARNINGS	The plant's output is regulated by strict laws, so there will be little tolerance.

MC FRAME ENTRY

for

MCRULE2: "Plant capable of 500% increase (curr. capacity @ 16.67%)."

Slot	**Information**
NAME	MCRULE2
KEYWORDS	"curr. capacity @ 16.67%"
POINTER:DATABASE	EC
POINTER:NAME	ROT4
WARNINGS	When the plant operates at the full level the discharge levels will be much higher.

A2.6 Prototype Method of Analysis for the FLEA System

The system reads the input file and uses the DM input lines to summon the DM entries from the database. The system searches the KEY WORDS slots for terms that match the name of the material in the input file. The system reads the lead (Pb) line first. This line has a concentration and a background level on it as well. the discharge concentration is at 12 ppm. The background levels are unknown and thus the designer has put a question mark there. The system default values this level to midway in the fully safe range (membership of 1).

The system applies a series of rules like those that follow to the input concentration stored in the variable m_concentration. The danger rate is stored in the variable m_danrate. The concentration variable is fuzzified over the domain of discourse for the material being examined. Thus, for each material evaluated, a new domain of discourse is used with new values for the limits of the fuzzy membership functions.

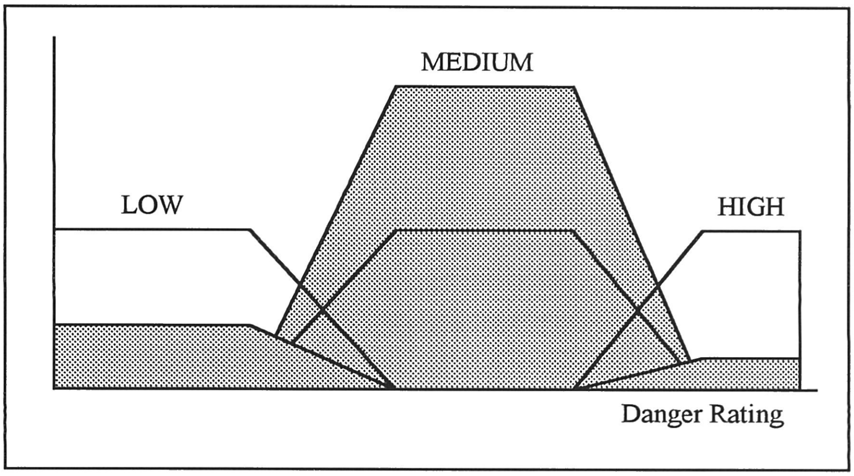
IF m_concentration IS SAFE THEN m_danrate IS LOW

IF m_concentration IS HAZARDOUS THEN (m_danrate IS MEDIUM) AND PRINT WARNING

IF m_concentration IS HARMFUL THEN (m_danrate IS HIGH) AND PRINT WARNING

IF (m_concentration + m_background) IS HAZARDOUS AND m_decay is LOW THEN m_ltdanrate = BUILDUP x m_danrate

This system assumes that the danger rate is a fuzzy quantity. The system would use Max-Dot inferencing to develop scaled membership functions for the danger rate. The rules would produce a series of scaled danger rating membership functions in a domain of discourse of the numerical danger ratings. The result would look like this:



Notice that the functions have been scaled by the truth value of the antecedent clause of the rules. Thus if the expression

m_concentration IS SAFE

has a membership value of 0.5, then the output would be a 0.5 scale version of the LOW membership function. Notice that the MEDIUM membership function is scaled greater than one. This is due to other rules, such as the EC rules which are processed once for each material. These rules scale one or more of the membership functions depending on their effect. For example, ROT1 of the EC database would scale the MEDIUM and HIGH membership functions by a factor equal to the rule's Danger Adjustment Factor (DAF).

In the rules, the variable m_ltdanrat is used to represent the fuzzy quantity of the long term danger rating. This fuzzy quantity is affected by the DECAY and BUILDUP parameters of each material. These parameters act as scaling parameters for the membership functions of the danger rating. The scaled versions become the long term danger rating. Thus, something which is a long term hazard would have its danger rating membership function scaled by the buildup danger parameter and this new scaled system would be the long term danger rating.

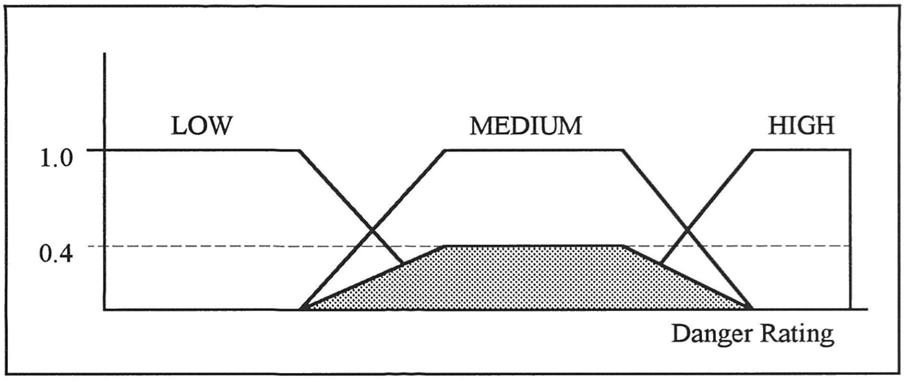
In the Gilbane Gold example, the concentration produces the following membership values in the danger functions:

μ_{safe}(m_concentration) = 0.0

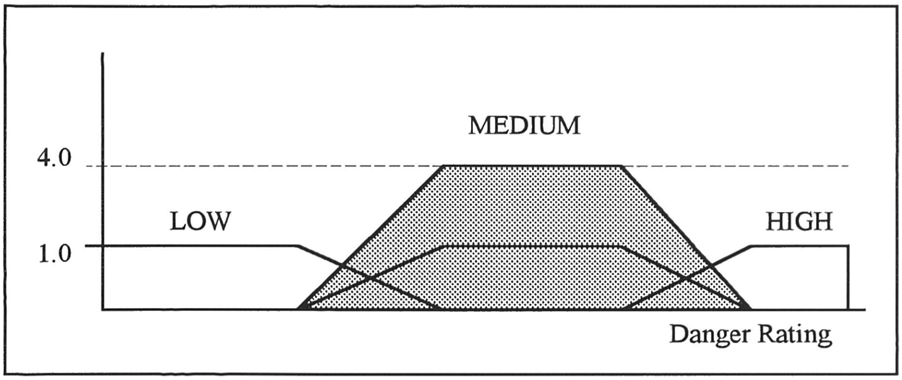
$\mu_{hazardous}$(m_concentration) = (12-10)/(15-10)x1.0 = 0.4

$\mu_{harmful}$(m_concentration) = 0.0

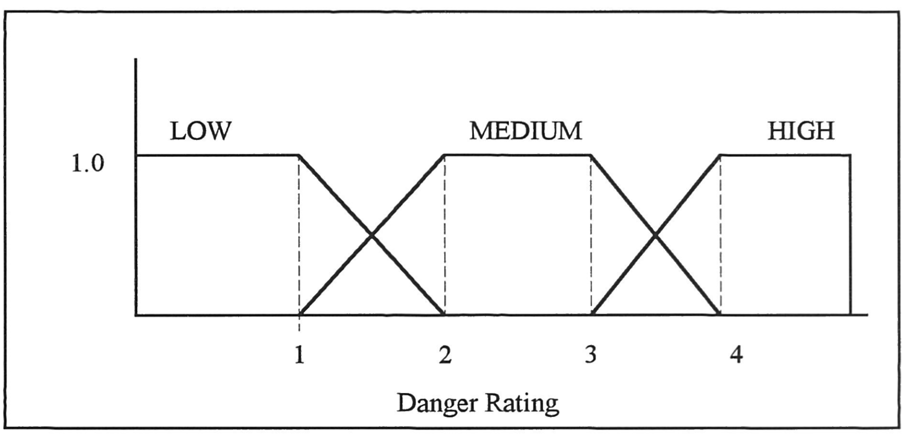
This would produce the following danger rating distribution after the application of the rules.



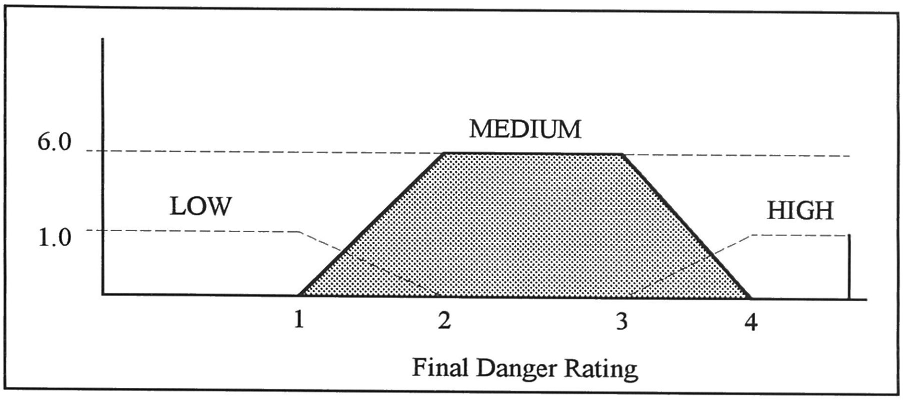
This is then evaluated with the EC and MC rules. All of the rules will fire and produce this result. The composite DAF multiplication factor is (1.5 x 1.2 x 1.1 x 5 = 9.9). This result is used to scale the danger rating membership functions to their new height.



This process is now repeated by the system for every other material present. A new danger rating distribution is developed and then all of the danger ratings are placed on top of one another and summed into one final danger rating. Then, all of the functions are aggregated and defuzzified. The defuzzification process is most likely the centroid process. The crisp value is the danger rating. This rating depends on the scale used to represent the danger rating. This scale can be changed by changing the domain of discourse over which the LOW, MEDIUM, and HIGH danger membership functions act over. I have selected a range with which looks like this:



If the arsenic case is evaluated and summed to the ratings and aggregated, the functions will now look like this:



The crisp danger rating will be 2.5, the point of the centroid of the result. This value would be output to the designer along with the various warnings which would appear during the rules evaluations. The long term danger rating will turn out to be the same because of the simplicity of the system. If the system was more complex, the result from the rules would be an oddly shaped figure where the centroid would not be in the center of the region as it is in this example. Also, the danger ratings should differ for the short term and long term evaluations.

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