CHAPTER 3

FUZZY LOGIC

3.1 INTRODUCTION

Requirements Engineering is a human-centered process. Software development has been described by Nuseibeh as one full of descriptions, such as requirements, specification, documentation, of data, of operating instructions, etc. The problem with descriptions is that they are often subjective, ambiguous and prone to different interpretations. Added to this is the fact that a lot of requirements are informal and are often vague and imprecise. Secondly, requirements may conflict with each other. Lastly, existing methods for prioritizing conflicting requirements are limited in their scope and in identifying the impact of a requirement change on the system. This is the ideal situation for use of Fuzzy Logic, and a number of studies and research work have been made in this area. (Example: Fuzzy Logic has been used to trade-off and prioritizes between conflicting, imprecise requirements).

Understanding others requirements has always been a challenge, the very nature of the human thinking process is such Neurology has now came to accept that our basic brain function can be similar to the neural networks. Neural Networks are a different paradigm for computing. Neural networks are a form of multiprocessor computer system, with simple processing elements. A neural network is a powerful data modeling tool that is able to capture and represent complex input/output relationships. The motivation for the development of neural network technology stemmed from
the desire to develop an artificial system that could perform "intelligent" tasks similar to those performed by the human brain. Neural networks resemble the human brain in the following two ways. A neural network acquires knowledge through learning. A neural network's knowledge is stored within inter-neuron connection strengths known as synaptic weights. A good requirements specification should consider cost, quality feasibility, speed of completion, risk profiles, data availability, robustness, reliability, simplicity, manpower availability, maintainability among others.

Digital Logic works on the basis of known discovered and calculated formulae. So all new thinking has to be clouded by previous knowledge. Fuzzy Logic, it works on real world data acquired by sensors, actual interactions and rules formulated by involuntary behavior of the various experts in the project. The current methodology and why it has not been able to represent the information contained in the inexact, imprecise and conflicting human language of the client or domain expert are discussed. The problems faced in requirement engineering in Pollution forecasting are examined. Few processes using Fuzzy logic, which can be applied to solve the problems are presented.

EVOLUTION

Fuzzy logic is derived from fuzzy set theory dealing with reasoning that is approximate rather than precisely deduced from classical predicate logic. It can be thought of as the application side of fuzzy set theory dealing with well thought out real world expert values for a complex problem (Klir 1997).

Degrees of truth are often confused with probabilities. However, they are distinct conceptually; fuzzy truth represents membership in vaguely
defined sets, not likelihood of some event or condition. For example, if a 100 ml glass contains 30 ml of water, then, for two fuzzy sets, Empty and Full, one might define the glass as being 0.7 empty and 0.3 full. Note that the concept of emptiness would be subjective and thus would depend on the observer or designer. Another designer might equally well design a set membership function where the glass would be considered full for all values down to 50 ml. A probabilistic setting would first define a scalar variable for the fullness of the glass, and second, conditional distributions describing the probability that someone would call the glass full given a specific fullness level. Note that the conditioning can be achieved by having a specific observer that randomly selects the label for the glass, a distribution over deterministic observers, or both. While fuzzy logic avoids talking about randomness in this context, this simplification at the same time obscures what is exactly meant by the statement the 'glass is 0.3 full'.

Fuzzy logic allows for set membership values to range (inclusively) between 0 and 1, and in its linguistic form, imprecise concepts like "slightly", "quite" and "very". Specifically, it allows partial membership in a set. It is related to fuzzy sets and possibility theory. It was introduced in 1965 by Lotfi Zadeh at the University of California, Berkeley.

Fuzzy logic is controversial in some circles and is rejected by some control engineers and by most statisticians who hold that probability is the only rigorous mathematical description of uncertainty. Critics also argue that it cannot be a superset of ordinary set theory since membership functions are defined in terms of conventional sets.
3.3 THE BASE ON WHICH FUZZY LOGIC IS BUILT

As the complexity of a system increases, it becomes more difficult and eventually impossible to make a precise statement about its behavior, eventually arriving at a point of complexity where the fuzzy logic method born in humans is the only way to get at the problem (Originally identified and set forth by Lotfi A. Zadeh, Ph.D., University of California, Berkeley). Fuzzy logic is used in system control and analysis design, because it shortens the time for engineering development and sometimes, in the case of highly complex systems, is the only way to solve the problem.

Although most of the time we think of "control" as having to do with controlling a physical system, there is no such limitation in the concept as initially presented by Dr. Zadeh. Fuzzy logic can apply also to economics, psychology, marketing, weather forecasting, biology, politics ...... to any large complex system.

The term "fuzzy" was first used by Dr. Lotfi Zadeh in the engineering journal, "Proceedings of the IRE" in 1962. Dr. Zadeh became, in 1963, the Chairman of the Electrical Engineering department of the University of California at Berkeley. Fuzzy logic is not the wave of the future. It is now! There are already hundreds of successful, fuzzy logic based commercial products, everything from self-focusing cameras to washing machines that adjust themselves according to how dirty the clothes are, automobile engine controls, anti-lock braking systems, color film developing systems, subway control systems and computer programs trading successfully in the financial markets.
3.4 FUZZY LOGIC ANALYSIS AND CONTROL

A major contributor to Homo sapiens success and dominance of this planet is our innate ability to exercise analysis and control based on the fuzzy logic human method. Here is an example: Suppose you are driving down a typical, two ways, 6-lane street in a large city, one mile between signal lights. The speed limit is posted at 45 Mph. It is usually optimum and safest to "drive with the traffic," which will usually be going about 48 Mph. How do you define with specific, precise instructions "driving with the traffic?" It is difficult. But, it is the kind of thing humans do every day and do well. There will be some drivers weaving in and out and going more than 48 Mph and a few drivers driving exactly the posted 45 Mph. But, most drivers will be driving 48 Mph. They do this by exercising "fuzzy logic" - receiving a large number of fuzzy inputs, somehow evaluating all the inputs in their human brains and summarizing, weighting and averaging all these inputs to yield an optimum output decision. Inputs being evaluated may include several images and considerations such as: How many cars are in front. How fast are they driving. Any "old clunkers" going real slow. Any trucks holding up one of the lanes. How about side traffic entering from side streets. Do the police ever set up radar surveillance on this stretch of road. How much leeway do the police allow over the 45 Mph limit. What do you see in the rear view mirror. Even with all this, and more, to think about, those who are driving with the traffic will all be going along together at the same speed.

The same ability you have to drive down a modern city street was used by our ancestors to successfully organize and carry out chases to drive wooly mammoths into pits, to obtain food, clothing and bone tools. Human beings have the ability to take in and evaluate all sorts of information from the physical world they are in contact with and to mentally analyze, average and summarize all this input data into an optimum course of action. All living
things do this, but humans do it more and do it better and have become the
dominant species of the planet.

If one think about it, much of the information you take in is not
very precisely defined, such as the speed of a vehicle coming up from behind.
We call this fuzzy input. However, some of your "input" is reasonably precise
and non-fuzzy such as the speedometer reading. Your processing of all this
information is not very precisely definable. This is fuzzy processing. Fuzzy
logic theorists would call it using fuzzy algorithms (algorithm is another word
for procedure or program, as in a computer program).

Fuzzy logic is the way the human brain works, and we can mimic
this in machines so they will perform somewhat like humans (not to be
confused with Artificial Intelligence, where the goal is for machines to
perform EXACTLY like humans). Fuzzy logic control and analysis systems
may be electro-mechanical in nature, or concerned only with data, for
example economic data, in all cases guided by "If-Then rules" stated in
human language.

3.5 THE FUZZY LOGIC METHOD

The fuzzy logic analysis and control method is, therefore:

1. Receiving of one, or a large number, of measurement or other
   assessment of conditions existing in some system we wish to
   analyze or control.

2. Processing all these inputs according to human based, fuzzy
   "If-Then" rules, which can be expressed in plain language
   words, in combination with traditional non-fuzzy processing.
3. Averaging and weighting the resulting outputs from all the individual rules into one single output decision or signal which decides what to do or tells a controlled system what to do. The output signal eventually arrived at is a precise appearing, defuzzified, "crisp" value. The following Fuzzy Logic Control/Analysis Method diagram shows this Figure 3.1.

![Figure 3.1 The fuzzy logic control-analysis method](image)

### 3.6 FUZZY PERCEPTION

A fuzzy perception is an assessment of a physical condition that is not measured with precision, but is assigned an intuitive value. In fact, the fuzzy logic people assert everything in the universe is a little fuzzy, no matter how good your measuring equipment is. It will be seen below that fuzzy perceptions can serve as a basis for processing and analysis in a fuzzy logic control system. Measured, non-fuzzy data is the primary input for the fuzzy logic method. Examples: temperature measured by a temperature transducer, motor speed, economic data, financial markets data, etc. It would not be usual in an electro-mechanical control system or a financial or economic analysis system, but humans with their fuzzy perceptions could also provide input. There could be a human "in-the-loop."
The term "fuzzy set" is a group of anything that cannot be precisely defined. Consider the fuzzy set of "old houses." How old is an old house? Where is the dividing line between new houses and old houses? Is a fifteen-year-old house an old house? How about 40 years? What about 39.9 years? The assessment is in the eyes of the beholder. Other examples of fuzzy sets are: tall women, short men, warm days, high pressure gas, small crowd, medium viscosity, hot shower water, etc. When humans are the basis for an analysis, we must have a way to assign some rational value to intuitive assessments of individual elements of a fuzzy set. We must translate from human fuzziness to numbers that can be used by a computer. We do this by assigning assessment of conditions a value from zero to 1.0. For "how hot the room is" the human might rate it at .2 if the temperature were below freezing, and the human might rate the room at .9, or even 1.0, if it is a hot day in summer with the air conditioner off. You can see these perceptions are fuzzy, just intuitive assessments, not precisely measured facts. By making fuzzy evaluations, with zero at the bottom of the scale and 1.0 at the top, we have a basis for analysis rules for the fuzzy logic method, and we can accomplish our analysis or control project. The results seem to turn out well for complex systems or systems where human experience is the only base from which to proceed, certainly better than doing nothing at all, which is where we would be if unwilling to proceed with fuzzy rules.

3.7 MISCONCEPTIONS AND CONTROVERSIES

Fuzzy logic is the same as "imprecise logic": Fuzzy logic is not any less precise than any other form of logic: it is an organized and mathematical method of handling inherently imprecise concepts. The concept of "coldness" cannot be expressed in an equation, because although temperature is a quantity, "coldness" is not. However, people have an idea of what "cold" is, and agree that there is no sharp cutoff between "cold" and "not
cold", where something is "cold" at N degrees but "not cold" at N+1 degrees — a concept classical logic cannot easily handle due to the principle of bivalence. The result has no set answer so it is believed to be a 'fuzzy' answer.

**Fuzzy logic is a new way of expressing probability:** Fuzzy logic and probability are different ways of expressing uncertainty. While both fuzzy logic and probability theory can be used to represent subjective belief, fuzzy set theory uses the concept of fuzzy set membership (i.e. how much a variable is in a set), probability theory uses the concept of subjective probability (i.e. how probable do I think that a variable is in a set). While this distinction is mostly philosophical, the fuzzy-logic-derived possibility measure is inherently different from the probability measure, hence they are not directly equivalent. However, many statisticians are persuaded by the work of Bruno de Finetti that only one kind of mathematical uncertainty is needed and thus fuzzy logic is unnecessary. On the other hand, Bart Kosko argues that probability is a subtheory of fuzzy logic, as probability only handles one kind of uncertainty. He also claims to have proven a derivation of Bayes' theorem from the concept of fuzzy subsethood. Lotfi Zadeh, the creator of fuzzy logic, argues that fuzzy logic is different in character from probability, and is not a replacement for it. He has created a fuzzy alternative to probability, which he calls possibility theory. Other controversial approaches to uncertainty include Dempster-Shafer theory and rough sets.

**Fuzzy logic will be difficult to scale to larger problems:** This criticism is mainly because there exist problems with conditional possibility, the fuzzy set theory equivalent of conditional probability (see Halpen (2003), section 3.8). This makes it difficult to perform inference. However, there have not been many studies comparing fuzzy-based systems with probabilistic ones.
3.8 FUZZY LOGIC REPRESENTATION

**Formal fuzzy logic:** In mathematical logic, there are several formal systems that model the above notions of "fuzzy logic"; most of them belong among so-called t-norm fuzzy logics. Note that they use a different set of operations than above mentioned Zadeh operators.

**Prepositional fuzzy logics:** The most important propositional fuzzy logics are:

- Basic propositional fuzzy logic BL is an axiomatization of logic where conjunction is defined by a continuous t-norm, and implication is defined as the residuum of the t-norm. Its models correspond to BL-algebras.

- Łukasiewicz fuzzy logic is a special case of basic fuzzy logic where conjunction is Łukasiewicz t-norm. It has the axioms of basic logic plus an axiom of double negation (so it is not intuitionistic logic), and its models correspond to MV-algebras.

- Gödel fuzzy logic is a special case of basic fuzzy logic where conjunction is Gödel t-norm. It has the axioms of basic logic plus an axiom of idempotence of conjunction, and its models are called G-algebras.

- Product fuzzy logic is a special case of basic fuzzy logic where conjunction is product t-norm. It has the axioms of basic logic plus another axiom, and its models are called product algebras.
• Monoidal t-norm logic MTL is a generalization of basic fuzzy logic BL where conjunction is realized by a left-continuous t-norm. Its models (MTL-algebras) are prelinear commutative bounded integral residuated lattices.

• Rational Pavelka logic is a generalization of multi-valued logic. It is an extension of Łukasiewicz fuzzy logic with additional constants.

All these logics encompass the traditional propositional logic (whose models correspond to Boolean algebras).

**Predicate fuzzy logics:** These extend the above-mentioned fuzzy logics by adding universal and existential quantifiers in a manner similar to the way that predicate logic is created from propositional logic. The semantics of the universal resp. existential quantifier in t-norm fuzzy logics is the infimum resp. supremum of the truth degrees of the instances of the quantified subformula.

### 3.9 FUZZY LOGIC IS SIMPLE

Novices using personal computers and the fuzzy logic method can beat Ph.D. mathematicians using formulas and conventional programmable logic controllers. Fuzzy logic makes use of human common sense. This common sense is either applied from what seems reasonable, for a new system, or from experience, for a system that has previously had a human operator.

Here is an example of converting human experience for use in a control system: An attempt as made to automate a cement manufacturing
Cement manufacturing is a lot more difficult than one would think. Through the centuries it has evolved with human "feel" being absolutely necessary. Engineers were not able to automate with conventional control. Eventually, they translated the human "feel" into lots and lots of fuzzy logic "If then" rules based on human experience. Reasonable success was thereby obtained in automating the plant. Objects of fuzzy logic analysis and control may include: physical control, such as machine speed, or operating a cement plant; financial and economic decisions; physiological conditions; safety conditions; security conditions; production improvement and much more.

It should be noted that when Dr. Zadeh invented fuzzy logic, it appears he had in mind applying fuzzy logic in many applications in addition to controlling machines, such as economics, politics, biology, etc.

The availability of the fuzzy logic method has been made possible by the availability of the personal computer. Without personal computers, it would be difficult to use fuzzy logic to control machines and production plants, or do other analyses. Without the speed and versatility of the personal computer, we would never undertake the laborious and time consuming tasks of fuzzy logic based analyses and we could not handle the complexity, speed requirement and endurance needed for machine control.

We can do far more with a simple fuzzy logic BASIC or C++ program in a personal computer running in conjunction with a low cost input/output controller than with a whole array of expensive, conventional, programmable logic controllers.

Programmable logic controllers have their place! They are simple, reliable and keep industry operating where the application is relatively simple
and on - off in nature. For a more complicated system control application, an optimum solution may be patching things together with a personal computer and fuzzy logic rules, especially if someone who is not a professional, control systems engineer is doing the project.

3.10 FUZZY LOGIC TERMS

Following are explanations of some terms, which should help in this regard. Dr. Zadeh initially established this terminology when he originated the fuzzy logic concept.

Fuzzy - The degree of fuzziness of a system analysis rule can vary between being very precise, in which case we would not call it "fuzzy", to being based on an opinion held by a human, which would be "fuzzy." Being fuzzy or not fuzzy, therefore, has to do with the degree of precision of a system analysis rule.

A system analysis rule need not be based on human fuzzy perception. For example, you could have a rule, "If the boiler pressure rises to a danger point of 600 psi as measured by a pressure transducer, then turn everything off. That rule is not "fuzzy".

Principle of Incompatibility - As the complexity of a system increases, it becomes more difficult and eventually impossible to make a precise statement about its behavior, eventually arriving at a point of complexity where the fuzzy logic method born in humans is the only way to get at the problem.

Fuzzy Sets - A fuzzy set is almost any condition for which we have words: short men, tall women, hot, cold, new buildings, accelerator setting,
ripe bananas, high intelligence, speed, weight, spongy, etc., where the condition can be given a value between 0 and 1. Example: A woman is 6 feet, 3 inches tall. In my experience, I think she is one of the tallest women I have ever met, so I rate her height at .98. This line of reasoning can go on indefinitely rating a great number of things between 0 and 1.

Degree of Membership - The degree of membership is the placement in the transition from 0 to 1 of conditions within a fuzzy set. If a particular building's placement on the scale is a rating of .7 in its position in newness among new buildings, then we say its degree of membership in new buildings is 7.

In fuzzy logic method control systems, degree of membership is used in the following way. A measurement of speed, for example, might be found to have a degree of membership in "too fast of" .6 and a degree of membership in "no change needed" of .2. The system program would then calculate the center of mass between "too fast" and "no change needed" to determine feedback action to send to the input of the control system. This is discussed in more detail in subsequent chapters.

Summarizing Information - Human processing of information is not based on two-valued, off-on, either-or logic. It is based on fuzzy perceptions, fuzzy truths, fuzzy inferences, etc., all resulting in an averaged, summarized, normalized output, which is given by the human a precise number or decision value which he or she verbalizes, writes down or acts on. It is the goal of fuzzy logic control systems to also do this.

The input may be large masses of data, but humans can handle it. The ability to manipulate fuzzy sets and the subsequent summarizing capability to arrive at an output we can act on is one of the greatest assets of
the human brain. This characteristic is the big difference between humans and digital computers. Emulating this human ability is the challenge facing those who would create computer based artificial intelligence. It is proving very, very difficult to program a computer to have human-like intelligence.

Fuzzy variable - Words like red, blue, etc., are fuzzy and can have many shades and tints. They are just human opinions, not based on precise measurement in angstroms. These words are fuzzy variables.

If, for example, speed of a system is the attribute being evaluated by fuzzy, "fuzzy" rules, then "speed" is a fuzzy variable.

Linguistic variable - Linguistic means relating to language, in our case plain language words.

Speed is a fuzzy variable - Accelerator setting is a fuzzy variable. Examples of linguistic variables are: somewhat fast speed, very high speed, real slow speed, excessively high accelerator setting, accelerator setting about right, etc. A fuzzy variable becomes a linguistic variable when we modify it with descriptive words, such as somewhat fast, very high, real slow, etc.

The main function of linguistic variables is to provide a means of working with the complex systems mentioned above as being too complex to handle by conventional mathematics and engineering formulas. Linguistic variables appear in control systems with feedback loop control and can be related to each other with conditional, "if-then" statements. Example: If the speed is too fast, then back off on the high accelerator setting.

Universe of Discourse - Let us make women the object of our consideration. All the women everywhere would be the universe of women. If
we choose to discourse about (talk about) women, then all the women everywhere would be our Universe of Discourse.

Universe of Discourse then, is a way to say all the objects in the universe of a particular kind, usually designated by one word, that we happen to be talking about or working with in a fuzzy logic solution. A Universe of Discourse is made up of fuzzy sets. Example: The Universe of Discourse of women is made up of professional women, tall women, Asian women, short women, beautiful women, and on and on.

Fuzzy Algorithm - An algorithm is a procedure, such as the steps in a computer program. A fuzzy algorithm, then, is a procedure, usually a computer program, made up of statements relating linguistic variables.

Examples:
If "green x" is very large, then make "tall y" much smaller.
If the rate of change of temperature of the steam engine boiler is much too high then turn the heater down a lot.

3.11 PROGRESS IN FUZZY LOGIC

From a slow beginning, fuzzy logic grew in applications and importance, until now it is a significant concept worldwide. Intelligent beings on the other side of our galaxy and throughout the universe have probably noted and defined the concept. Personal computer based fuzzy logic control is amazing. It lets novices build control systems that work in places where even the best mathematicians and engineers, using conventional approaches to control, cannot define and solve the problem.
A control system is an electronic or mechanical system that causes the output of the controlled system to automatically remain at some desired output (the "set point") set by the operator. The thermostat on an air conditioner is a control system. A car's cruise control is a control system. Control may be an on-off signal or a continuous feedback loop.

In Japan, a professor built a fuzzy logic control system that will fly a helicopter with one of the rotor blades off! Human helicopter pilots cannot do that. The Japanese went further and built a fuzzy logic controlled subway that is as smooth as walking. People do not have to hang on to a strap to keep balance. If one did not look out the window at things flashing by, one would hardly know the train had started and were in motion. Elsewhere fuzzy logic control is gaining popularity, but is not as widely used as in Japan, where it is a multi-million dollar industry. Japan sells fuzzy logic controlled cameras, washing machines and more.

One search engine returns over 16,000 pages when searched on “fuzzy logic” and numbers growing fast even from outside Japan.

Personal computer based fuzzy logic control follows the pattern of human "fuzzy" activity. However, humans usually receive, process and act on more inputs than the typical computer based fuzzy logic controller. (This is not necessarily so; a computer based fuzzy logic control system in Japan trades in the financial markets and utilizes 800 inputs.)

3.12 FUZZY LOGIC CONTROL INPUT - HUMAN AND COMPUTER

Computer based fuzzy logic machine control is like human fuzzy logic control, but there is a difference when the nature of the computer's input
is considered. Humans evaluate input from their surroundings in a fuzzy manner, whereas machines/computers obtain precise appearing values, such as 112 degrees F, obtained with a transducer and an analog to digital converter. The computer input would be the computer measuring say, 112 degrees F. The human input would be a fuzzy feeling of being too warm.

The human says, "The shower water is too hot." The computer as a result of analog input measurement says, "The shower water is 112 degrees F and 'If-Then' statements in my program tell me the water is too warm." A human says, "I see two tall people and one short one." The computer says, "I measure two people, 6' 6" and 6' 9", respectively, and one person 5' 1" tall, and 'If-Then' statements in my program tell me there are two tall people and one short person. "Even though transducer derived, measured inputs for computers appear to be more precise, from the point of input forward it still is used in a fuzzy logic method approach that follows fuzzy, human approach to control.

For a human, if the shower water gets too warm, the valve handle is turned to make the temperature go down a little. For a computer, an "If-Then" statement in the program would initiate the lowering of temperature based on a human provided "If-Then" rule, with a command output operating a valve.

To create a personal computer based fuzzy logic control system,

1. Determine the inputs.

2. Describe the cause and effect action of the system with "fuzzy rules" stated in plain English words.

3. Write a computer program to act on the inputs and determine the output, considering each input separately. The rules
become "If-Then" statements in the program (As will be seen below, where feedback loop control is involved, use of graphical triangles can help visualize and compute this input-output action.)

4. In the program, use a weighted average to merge the various actions called for by the individual inputs into one crisp output acting on the controlled system. (In the event there is only one output, then merging is not necessary, only scaling the output as needed.)

The fuzzy logic approach makes it easier to conceptualize and implement control systems. The process is reduced to a set of visualizable steps. This is a very important point. Actually implementing a control system, even a simple control system, is more difficult than it appears. Unexpected aberrations and physical anomalies inevitably occur. Getting the process working correctly ends up being a "cut and try" effort. Experienced, professional digital control engineers using conventional control might know how to proceed to fine-tune a system. But, it can be difficult for others. Fuzzy logic control makes it easier to visualize and set up a system and proceed through the cut and try process. It is only necessary to change a few plain English rules resulting in changing a few numbers in the program.

Fuzzy logic enables engineers to configure systems quickly without extensive experimentation and to make use of information from expert human operators who have been performing the task manually. Perhaps a control need is something a lot more down to earth than flying helicopters or running subways. Maybe all that is needed is to keep a small business sawmill running smoothly, with the wood changing and the blade sharpness changing or, perhaps operate a natural gas compressor for some stripper wells that are
always coming on and going off, and you need to have the compressor automatically adjust in order to stay on line and keep the suction pressure low to get optimum production. Perhaps a dream of a race car that would automatically adjust to changing conditions, the setup remaining optimum as effectively as the above mentioned helicopter adjusts to being without a rotor blade. There are a million needs and chances are, if there is something one wants to control, and are not an experienced, full time, professional control engineer financed by a big corporation, then fuzzy logic may be answer.

A conventional programmable logic controller monitors the process variable (the pressure, temperature, speed, etc., that we want to control). If it is too high, a decrease signal is sent out. If it is too low, an increase signal is sent out. This is effective up to a point. But, consider how much more effective a control system would be if we use a computer to calculate the rate of change of the process variable in addition to how far away it is from the set point. If the control system acts on both these inputs, we have a better control system. And, that could be just the beginning; we can have a large number of inputs all being analyzed according to common sense and experience rules for their contribution to the averaged crisp output controlling the system.

Further, whereas conventional control systems are usually smooth and linear in performance, we sometimes encounter aberrations or discontinuous conditions, something that does not make good scientific sense and cannot be predicted by a formula, but it's there. If this happens, the fuzzy logic method helps us visualize a solution, put the solution in words and translate to "If - Then" statements, thereby obtaining the desired result. That is a very difficult thing to do with conventional programmable logic controllers (known as PLC's). PLC's are programmable, but are far more limited than the program control available from a very simple BASIC program in a personal computer.
Fuzzy logic control is not based on mathematical formulas. This is good because it is difficult to impossible to write formulas that do what nature does. Novices using fuzzy logic can beat Ph.D. mathematicians using formulas. Fuzzy logic control makes use of human common sense. This common sense is either applied from what seems reasonable, for a new system, or from experience, for a system that has previously had a human operator. Some of the greatest minds in the technical world try to explain to others why fuzzy logic works, and other great technical minds contend that fuzzy logic is useless. The experts really "go at" each other. But, the fact is fuzzy logic does work, seems to work better than many expensive and complicated systems and is understandable and affordable.

3.13 BUILDING A FUZZY SYSTEM

The easiest and quickest way to understand fuzzy logic control is to build a fuzzy logic control system; following is one example: We explain this on because the same technique is used in our application in chapter 4. The following example system has been reduced in complexity to make it easier to understand, but the concepts are the same as those used by Prof. Mamdani at University of London. If an application is more demanding than the example, add inputs and "rules"; you do not have to learn new things or change the approach. In considering this reduced complexity example, it may be observed that control could have been effected without going through the fuzzy control exercise explained. This is correct, but only while working with a simple system, only one input and no discontinuities or aberrations requiring patching.
3.14 THE STEPS IN BUILDING A FUZZY SYSTEM

Determine the control system input - Examples: The temperature is the input for a home air conditioner control system. Speed of the car is the input for cruise control. In this case, input is the speed in RPM of the DC motor, for which we are going to regulate the speed (Figure 3.2).

![Figure 3.2 Motor speed control system](image)

Speed error between the speed measured and the target speed of 2,420 Rpm is determined in the program. Speed error may be positive or negative. We measure the DC output voltage from the generator. This voltage is proportional to speed. This speed-proportional voltage is applied to an analog input channel of our fuzzy logic controller, where it is measured by the analog to digital converter and the personal computer, including appropriate software.

Determine the control system output - For a home air conditioner, the output is the opening and closing of the switch that turns the fan and compressor on and off. For a car's cruise control, the output is the
adjustment of the throttle that causes the car to return to the target speed. In this case, we have just one control output. This is the voltage connected to the input of the transistor controlling the motor (Figure 3.2).

**Determine the target set point value** - For example 70 degrees F for your home temperature, or 60 Miles per hour for a car. In this case, the target set point is 2,420 Rpm.

**Choose word descriptions for the status of input and output** - For the steam engine project, Professor Mamdani used the following for input:

- Positive Big
- Positive Medium
- Positive Small
- Almost No Error
- Negative Small
- Negative Medium
- Negative Big

The system is much less complicated; so select only three conditions for input:

**Input Status Word Descriptions**
- Too slow
- About right
- Too fast
And, for output:

Output Action Word Descriptions

Speed up
Not much change needed
Slow down

**Rules:** Translate the above into plain English rules (called "linguistic" rules by Dr. Zadeh). These Rules will appear in the BASIC computer program as "If-Then" statements:

Rule 1: If the motor is running too slow, then speed it up.
Rule 2: If motor speed is about right, then not much change is needed.
Rule 3: If motor speed is too fast, then slow it down.

The next three steps use a charting technique which will lead to a computer program. The purpose of the computer program is to determine the voltage to send to the speed controlled motor. One function of the charting technique is to determine the "degree of membership" of the Too slow, About right and Too fast triangles, for a given speed. Further, the charting technique helps make the continuous control feedback loop easier to visualize, program and fine tune.

**Associate the above inputs and outputs** as causes and effect with a Rules Chart, as in Figure 3.3. The chart is made with triangles, the use of which is explained. Triangles are used, but other shapes, such as bell curves, could also be used. Triangles work fine and are easy to work with. Width of the triangles can vary. Narrow triangles provide tight control when operating conditions are in their area. Wide triangles provide looser control. Narrow triangles are usually used in the center, at the set point (the target speed). For
this example, there are three triangles, as can be seen in Figure 3.3 (three rules, hence three triangles).

![Figure 3.3 Cause-effect](image)

Figure 3.3 is derived from the previously discussed Rules and results in the following regarding voltage to the speed controller:

a. If speed is about right then not much change needed in voltage to the speed controller.

b. If speed is too slow then increase voltage to the speed controller to Speed up.
c. If speed is too fast then decrease voltage to the speed controller to Slow down.

**Determine the output**, that is the voltage that will be sent from the controller/signal conditioner/transistor to the speed controlled motor. This calculation is time consuming when done by hand, as we will do below, but this calculation takes only thousandths of a second when done by a computer. Assume something changes in the system causing the speed to increase from the target speed of 2,420 Rpm to 2,437.4 Rpm, 17.4 Rpm above the 'set point." Action is needed to "pull" the speed back to 2,420 Rpm. Intuitively we know, we need to reduce the voltage to the motor. The "cause" chart and vertical speed line appear as shown in Figure 3.4.

![Figure 3.4 Speed above target value](image)

The vertical line intersects the about right triangle at .4 and the Too fast triangle at 0.3. This is determined by the ratio of sides of congruent triangles from Plane Geometry:

Intersect point / 1 = 11.6/29 = .4  
Intersect point / 1 = 17.4/58 = .3
The next step is to draw "effect" (output determining) triangles with their height "h" determined by the values obtained in Step 7, above. The triangles to be drawn are determined by the rules in Step 6. Since the vertical 2,437.4 Rpm speed line does not intersect the too slow triangle, we do not draw the Speed up triangle. Draw the Not much change and the slow down triangles because the vertical speed line intersects the about right and too fast triangles. These "effect" triangles will be used to determine controller output, that is the voltage to send to the speed control transistor. The result is affected by the widths we have given the triangles and will be calculated (Figure 3.5). The Not much change triangle has a height of .4 and the Slow down triangle has a height of 3, because these were the intersect points for their matching "cause" triangles (Figure 3.4).

![Figure 3.5 Determination of control voltage to motor](image)

The output, as seen in Figure 3.5 is determined by calculating the point at which a fulcrum would balance the two triangles, as follows:

The area of the not much change triangle is: $1/2 \times \text{Base} \times \text{Height} = .5 \times .04 \times .4 = .008$. Area of the slow down triangle is $.5 \times .08 \times .3 = .012$. 
Compute the controller output voltage by finding the point on the output voltage, \( V_{dc} \), axis where the "weight" (area) of the triangles will balance. Assume all the weight of the not much change triangle is at 2.40 \( V_{dc} \) and all the weight of the Slow down triangle is at 2.36 \( V_{dc} \). We are looking for the balance point.

Find the position of the controller output voltage (the balance point) with the following calculation:

\[
0.008 \times D_1 = 0.012 \times D_2
\]  

(3.1)

where

- \( D_1 \) is the fulcrum distance from 2.4 \( V \)
- \( D_2 \) is the fulcrum distance from 2.36 \( V \)

\[
D_1 + D_2 = 0.04 \quad \text{(from Figure 3.4)}
\]

(3.2)

\[
D_1 = 0.04 - D_2
\]

Solving the above by substituting \((0.04-D_2)\) for \( D_1 \) in Equation (3.1) gives \( D_2 = 0.016 \) and \( D_1 = 0.024 \), therefore the balance point is a voltage of 2.376 \( V_{dc} \), and this is the voltage which we have determined should be applied to return speed to the target value (Figure 3.4).

Keep in mind that only one sample at one instant in time, with a resulting controller output voltage; the controller is sampling several times each second with a resulting "correction" output following each sample.

The above system tested with changing loads on the rotating shaft, and returned the speed of the motor to within 2 % of the 2,420 Rpm set point in less than 1.5 seconds. The accuracy with which the set point speed can be maintained is determined by the resolution of the analog to digital and digital
to analog conversion circuits in the fuzzy logic controller. Typical "low cost" resolution is "8 bit", 256 increments. Higher cost "12 bit" units provide 4,096 increments.

The above is a very effective, but much simplified, version of computer based fuzzy logic control systems actually in use commercially Kosko Bart (1993). In the Kosko method, the intersecting triangles are added, then the total area of the added triangles is determined by integration. Fulcrum location is determined by computer integration of area "under the curve" to the point of one half the total area. This sounds complicated, but only requires a few thousandths of a second for a computer, once the program is set up.

For more complex systems with additional inputs (for example, using rate of change as an input in addition to speed error), the approach is as above, but there are two or more "sub-outputs" to be considered in arriving at one crisp output to control the system. This is handled by averaging these sub-outputs with a weighting determined by the system designer and inserted in the program. This weighting may be based on theoretical prediction, previous experience with a similar manual system and/or experimentation and "tuning" of the system, once it is assembled.

3.15 SUMMARY

Words stand for sets we think in sets Thought is set play .The same word can stand for different members of the set. This does not stop with nouns. Classifying with adjectives just increases vagueness. Our language itself makes our communication fuzzy. It is rare that another thinks of the same member of the set when we speak. We structure words down to symbols to get more precision, but this causes even more confusion. Our brains group
things into loose sets and then play with the groups. These loose or fuzzy sets are expressive. The expressive power of the fuzzy set fits better with our words. As the complexity of a system increases our ability to make precise statements about its behavior diminishes. Language is sloppy and so a system to structure it is needed linguistic inventions have to be followed. They have evolved to closely represent the real world and have become communication standards. Words stand for sets of things. Sentences have many words. Sentences relate these words. In this way, we reason common sense, but what we sense is really not common to all of us. The same signals of sight, sound, feel, hit us, but to each is a unique perception. A group of sentences give a system - a fuzzy system. A system is anything that maps inputs to outputs. If knowledge can be taken from this fuzzy system to model the real world, then we can have computer systems that adjust to humans rather than reverse. Fuzzy systems allow us to model systems in words. We derive from these models and represented in symbols are approximation. However, binary logic runs our computers, it is simple, works and has served us for long. Present computers process information on binary logic, which is very different to the human thinking process. Hence, evaluation based on common sense and flexible judgment is very difficult to achieve in the computer process. Uncertainty contained in the meaning of each word makes if difficult to have an intimate relationship between man and computer. This is an attempt to use the knowledge contained in human representations using Fuzzy logic.

Traditional methods of requirements engineering has not been able to really capture the elasticity and all the information contained in requirements as expressed by clients who are only domain experienced or even experts. The system analyst, which is the first interface of requirements capture, traditionally a person recognizes the requirements from his perspective of possible computer aided solutions. From their digital background, the decisions normally are to ignore or workaround requirements
that seem imprecise or conflicting. A lot of information contained in the informal human communication is lost.

A novel process using Fuzzy Approximation Theorem and the Kosko method of intersecting triangles and the fulcrum point of area “under the curve” is used as solution in the example chosen on the following chapter. We discuss the current methodology and why it has not been able to represent the information contained in the inexact, imprecise and conflicting human language of the client or domain expert. The problems faced in requirement engineering in Pollution forecasting are examined and present processes using Fuzzy logic as a solution.