# POLITECNICO DI TORINO

Automotive Engineering

**Master degree**

**in Methodology for testing the risk of deferred maintenance**

Master thesis

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**Abstract**: maintenance activity to equipment is very important for production process and safety. It has a vital role to play in reducing the risk associated with some workplace hazards and providing safer and healthier working conditions. However the maintenance activity is an disadvantage for improving production rate, and it`s not good for economic budget. So sometimes the company decide to defer the maintenance activity.

In this paper we will talk about the methodology for testing the risk of deferred maintenance. With respect to risk assessment analysis, fuzzy logic is a more efficient methodology. With the help of professional experts, we can define the membership function and precise rule for every considerable variable and every possible condition. To define every possible rule, we can have a total rule as a base rule, and we can define the relative importance and value to make some mathematical calculations.

We can use average weighted method to define the precise value of output and the relative risk level. It`s possible to acknowledge the risk of deferred maintenance, and this will help the company to make decisions.

**Key words**: deferred maintenance, risk, fuzzy logic, membership function, average weighted method.

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# 1 Introduction

## 1.1 The risk of deferred maintenance

By definition, deferred maintenance is maintenance, system upgrades, or repairs that are deferred to a future budget cycle or postponed until funding becomes available. It causes the ageing of equipment.【1】

The term ageing does not refer to how old equipment is, but it is related to its condition and how it is changing over time. 【2】 Ageing of a component is revealed as some form of material deterioration and damage, usually associated with time in service, and causes an increasing probability of failure over the lifetime. It has been shown to be an important factor of incidents and accidents.

If regular maintenance is postponed or deferred, a relative minor project could potentially escalate into a complex and costly problem. Additionally, the deferred maintenance reduces the equipment`s efficiency, which is not good to energy savings and extended equipment lifespan.

The risk of deferred maintenance is high, but sometimes the company have to defer the maintenance activities. The primary reason is the lack of money. If budget planning does not allocate adequate funding or the budget is cut mid-year, the decision-maker have no choice but to defer the maintenance. Then the possible reason is that there is not enough manpower. What`s more, sometimes maintenance would interrupt or interfere with business operations for example the maintenance is canceled because of the need to boost production.

According to ‘ Geaslin’s Inverse-Square Rule for Deferred Maintenance Effort ’, when an organization attempts to reduce maintenance costs by reducing maintenance spending, maintenance costs will be reduced until spending falls below the minimum needs of the machines. 【3】

The relationship is not linear. The risk and possible repair fee is arising with time. When maintenance spending falls below the minimum level of funding required and the machines are operated to failure, the results will be an exponential cost increase that is inverse to the expected savings.

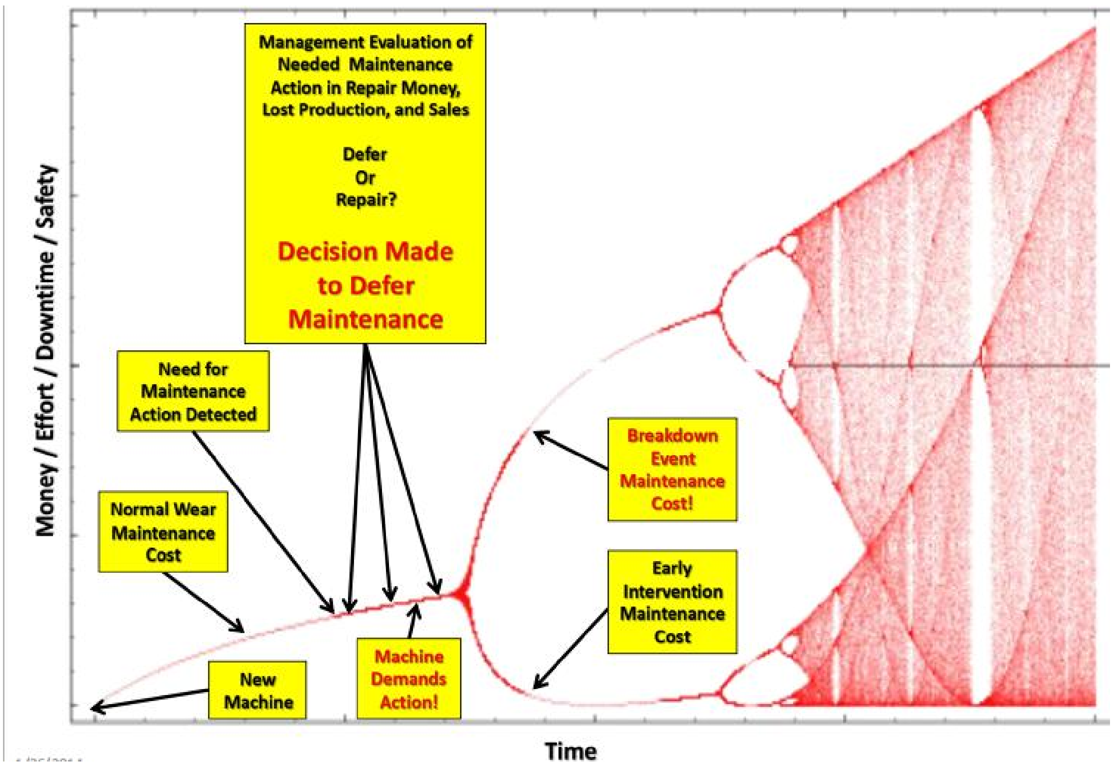



***Figure 1:*** *Geaslin’s inverse-square rule for deferred maintenance effort, we can see that when the scheduled maintenance time is coming, you can have two actions: Repair or Defer. The early repair intervention just need little cost, in the contrast, deferring will induce large amount of cost finally.*

## 1.2 research background

Regular maintenance of equipment is an important and necessary activity. The term 'maintenance' covers many activities, including inspection, testing, measurement, replacement and adjustment, and is carried out in all sectors and workplaces. It has a vital role to play in reducing the risk associated with some workplace hazards and providing safer and healthier working conditions. Insufficient maintenance can cause serious (and potentially deadly) accidents or health problems.

All equipment should be checked regularly and repaired immediately if it has some problems. Maintenance needs to be kept up to date and maintenance operations need to be carried out safely. There are two types of maintenance: routine maintenance is planned and focuses on preventing future problems, while corrective maintenance is reactive and happens when equipment goes wrong and needs to be fixed.

However, not every maintenance activity is needed so urgently. If the equipment works in good working environment and it works less time than expected, the risk of going into malfunction is lower. We can defer the maintenance activity if we don`t have enough maintenance budget. Or we can reduce the maintenance frequency, which can reduce the maintenance cost. The maintenance activity is an disadvantage for improving production rate, because we should stop the production activity when the maintenance activity occurs, which will reduce the competitive ability.

What`s more, the maintenance activity can be a high-risk activity. According to Healthy Working Lives, it is estimated that 25-30% of all manufacturing industry deaths in Britain result from maintenance activity. This activity is also associated with exposure to hazards that cause health problems such as respiratory diseases, musculoskeletal disorders and skin diseases. 【4】

Maintenance is also heavily subcontracted by organizations that consider maintenance to be a specialized activity which does not belong to their core business or which requires expertise not present in the company. In some environments, this may increase risk as the outsourced workers may be unfamiliar with the working environment.

So if the equipment works in good working condition, we can defer the maintenance activity. But it does have some risks, we need a methodology to test the risks of deferred maintenance.

## 1.3 Research purpose and significance

Deferred maintenance is the practice of postponing maintenance activities on both real property (i.e. infrastructure) and personal property (i.e. machinery) in order to save costs, meet budget funding levels, or realign available budget monies. The failure to perform needed repairs could lead to asset deterioration and ultimately asset impairment. In some cases it may cause higher cost and health and safety implications. 【5】

The technical community has different opinion with accountants. The engineers, facilities managers, and logisticians always regard the maintenance activity as capital improvements that become capitalized and depreciated over some future time period. However, the accountants typically look at maintenance and repairs as period costs requiring immediate expensing.【6】 We need a methodology to test the risk of deferred maintenance to please both technical community and the accountants.

In theory, the methodology can help the decision-maker to decide whether the maintenance activity can be deferred and how long it can be deferred. Additionally, this methodology can give us the standard when we make decision about deferring maintenance or not.

In practice, a company can reduce cost and relating maintenance time if the maintenance activity is deferred. But at the same time, the company must overtake the risk if something bad happens. According to this theory, the company can decide whether to defer the maintenance activity.

The company should evaluate the equipment condition from several aspects. At first, the company should evaluate if the equipment works more or less time than expected, if the equipment works more time than expected, the management staff should reduce the deferring time or not defer the maintenance activity. And vice versa.

Then what`s important is the equipment working condition. We can classify the working condition as protective, neutral or critical condition. Once the specification is defined according to the working temperature and working fluid condition and so on, the company can recognize the actual working condition so as to decide whether to defer the maintenance activity and how long it should be deferred.

The equipment monitoring quality is another important issue to be considered. If the monitor activities are able to find all the faults at the beginning, we can call the monitoring quality ‘proof’, and we can also define ‘medium’ or ‘superficial’ monitoring quality if the monitoring activities are not so effective.

What`s more, we should acknowledge the expected level of risk severity if failures occur. If the severity is high, which means the consequence is catastrophic and the repairing activity will cost a lot of money, the company should treat the deferred maintenance with caution.

And there are many other important considerations to be accounted according the actual situations. The question to be solved is that how to recognize the condition and make the decisions in the best way. In this paper we will talk about the methodology to test the risks of deferred maintenance. It can be a reference when people meet this kind of situation.

# 2 Risk assessment analysis

The purpose is that we need to define whether to defer the maintenance activities and how long we can defer. In actual cases, there are many different conditions that we should consider. We need a method to help us deal with each condition, which is sufficient enough at any cases.

In the following, we will talk about different methods to help us decide whether to defer the maintenance activities and how long we can defer. It should be noticed that we want to save human power and maintenance fees by deferring the maintenance activities but we don`t want to increase the failure probability, which will interfere the production line and will cost much more money to repair the equipment. So the methodology should be chosen carefully.

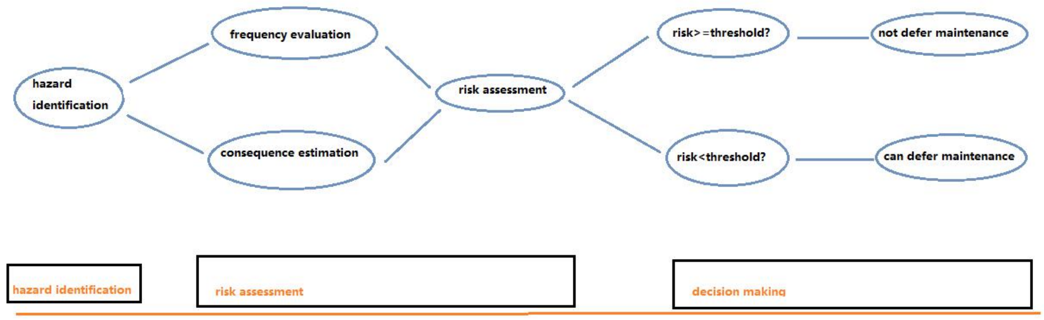



***Figure 2:*** *Risk assessment analysis procedure, usually it`s divided into three sections: Hazard identification, Risk assessment and Decision making.*

Risk is the undesired consequence of a particular activity in relation to its likelihood of occurrence. Which clearly means:

$$R = f(F, M) \qquad (2\text{-}1)$$

Where:

- F is the probability that an event could occur within a given time interval (in practice, the frequency of occurrence)

- M is the severity of the consequences (Magnitude).

From the Rasmussen Report (1975) we have the logical link within the two parameters:

$$R = F \cdot M \qquad (2\text{-}2)$$

Risk assessment procedure can be divided into three steps. Hazard identification, risk assessment and decision making. From this standard procedure, one company can decide whether to defer the maintenance activities. About how long it can defer the maintenance activities, we will talk about from the frequency point of view later.

The first step is hazard identification, which means the identification of components and degradation to be organized into a hierarchy. Hazard is not the same concept as risk, often the concept of ‘risk’ is confused with the concept of “hazard” or with the consequences a ‘risk’ may pose to individuals.【7】 During the production processes, there are many kinds of hazards. The equipment may fail, it will interfere the production process and it will stop the production activity. The workers may get injured, which is a huge problem with respect to the damage to company reputation. And hazards may cause the waste of original materials which is a direct waste of money. The company should check every possible hazard and make a list. But it must be noticed that some hazards are due to the same reason, it should not be counted twice.

The second step is risk assessment, which depends on the state of the structure and the potential failure modes. When the decision-maker considers about probability and consequences, some compensation factors should be introduced to account for specific aspects such as the process, equipment, fluid characteristics, organization (including management system) and performed inspection type.

At this step the company should evaluate the frequency and relative consequence of each hazard. The frequency is not so easy to evaluate, we can use the past data as a reference, and the world-class company data can be used as a reference too. The company should consider the real working condition of their equipment, to reduce or improve the frequency. As for the relative consequence, we need the past experience and opinions from professional experts. Then according to formula (2-2), the company can evaluate the risk.

Generally speaking, the higher the severity of the consequences, the lower the frequency. About the severity, we can define it from two aspects. The choice depends on the core interests of the company. On the one hand, the company can define the severity of consequences from money point of view. So the relative consequence is higher if company will pay a lot of money when hazard occurs. On the other hand, the company can evaluate the severity of consequences from safety point of view, which the severity level is evaluated higher if more workers will get injured when an accident occurs.

The relation between frequency and severity of consequences is the following:

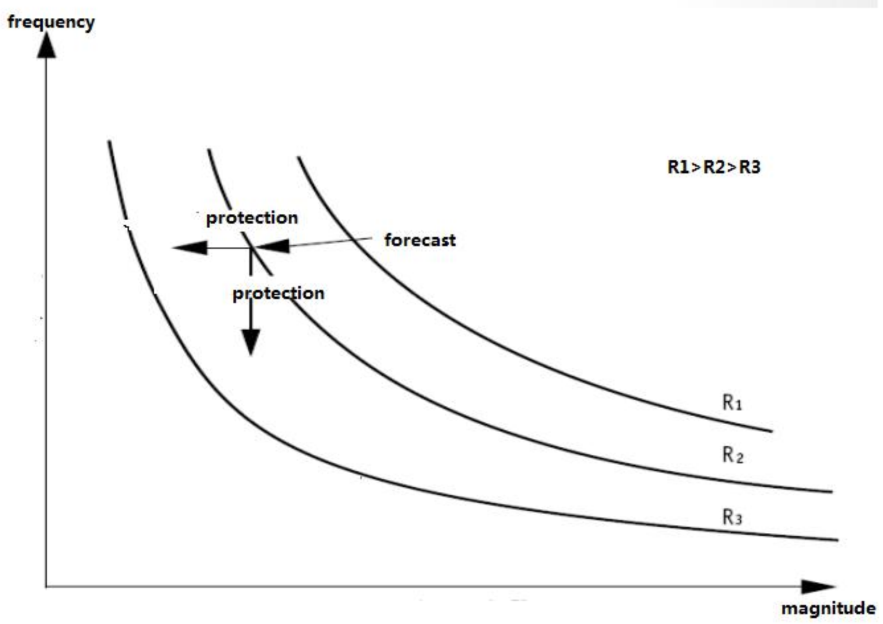


***Figure 3:*** *The relation of frequency and magnitude, we can see that at the same risk level, the higher frequency, the lower severity should be. If we do some protection process by reducing the frequency at the same severity level or reducing the severity with the same frequency, we can reduce the total risk level.*

The last step is decision making. Decisions related to actions (inspection or repairs) for ageing management. At first we need a threshold T as a reference value to define whether to defer the maintenance activities. The threshold is defined as the money we can save or the injury we can avoid. If the risk is higher than the threshold, the company should not defer the maintenance activities. Conversely, if the risk is lower, the company can defer the maintenance.

$$\begin{cases} R = F \cdot M > T, not \\ R = F \cdot M < T, yes \end{cases} \qquad (2\text{-}3)$$

As for how long the time t the company can defer the maintenance activities, we can use the following formula. Deferred time is the product of frequency difference and period. For example, the current frequency is 3 times/year, $F_1$ is 4 times/year, the company can defer 1 month.

$$\begin{cases} T = F_1 \cdot M \\ \Delta F = F_1 - F \\ t = \Delta F \cdot period \end{cases} \qquad (2\text{-}4)$$

But this kind of method has some disadvantages, and it`s not precise enough to make a decision.

Generic failure frequencies are used although it is recognized that data related to certain equipment types (including pressurized equipment) are not updated. Public databases do not take into account the ageing of materials, the newer quality systems and the different maintenance management. The lack in such data may lead to questionable decisions regarding facilities` licensing, land use and emergency planning.

And there are many uncertain parts about frequencies. The first uncertainty comes from the inadequate knowledge about the failure modes and related probabilities; further uncertainties are added at any step of the application of the method.

The possible deterioration mechanisms may include erosion, environmental corrosion, internal corrosion, mechanical fatigue, thermal fatigue. In most case the deterioration process is a slow mechanism, thus the failure probability appears constant for a sufficiently long time, before significantly increasing.【8】 The assumption of no-dependence of fault probability vs. equipment age, known as ‘bath-tube curve’.

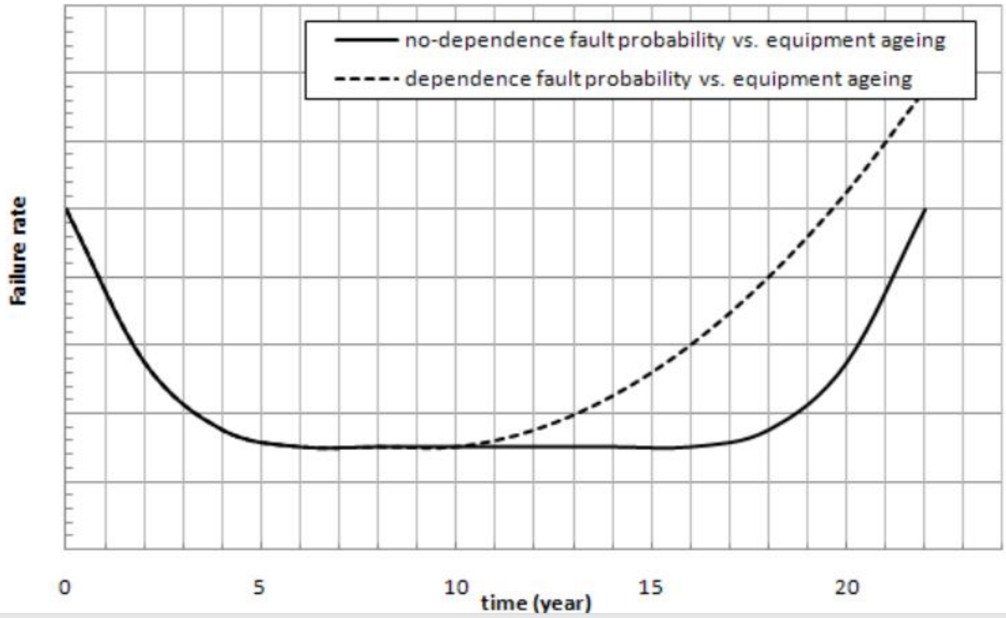



***Figure 4:*** *Bath-tube curve, widely used in reliability engineering. It describes a particular form of the hazard function which comprises three parts: The first part is a decreasing failure rate, known as early failures. The second part is a constant failure rate, known as random failures. The third part is an increasing failure rate, known as wear-out failures.*

So the company can`t have a certain value of the probability. And not every hazard can be identified, the severity of consequence almost totally depends on the opinions of experts, which is always a fuzzy information, some experts think it a big problem but others may have different opinions. The company should not just simply use the ‘minority obeying majority’ principle, which is not always right.

What`s more, the methodology to decide how long the company can defer the maintenance activities is not so proof. When time is going, the failure probability is growing, and the severity level of consequence is higher than before, which means the cost to repair the equipment or the injury severity of workers is higher. So it`s a variable which is not easy to define. In actual situations, the company will use a more scientific methodology, which is based on fuzzy logic.

# 3 Risk assessment based on fuzzy logic

When the company talk about the severity of consequence, there are some information which is not specific enough to be evaluated. The traditional mathematical method need precise information, but some data depends on opinions coming from professional experts, which is always subjective, some experts think the severity is high, some others think it`s not so high. Of course we should consider every opinion from experts. So we need a concept of degree of membership. It is more like in one state if the degree of membership is high. Just like the probability theory, but there are some differences.

To solve this kind of problems, the company needs a method more ‘emotional’, this method can think just like people.

Fuzzy logic is a form of many-valued logic in which the truth values of variables may be any real number between 0 and 1 inclusive. It`s used to handle the concept of partial truth, where the truth value may range between completely true and completely false.【9】

It is based on the observation that people make decisions based on imprecise and non-numerical information, fuzzy models or sets are mathematical means of representing vagueness and imprecise information. These models have the capability of recognizing, representing, manipulating, interpreting, and utilizing data and information that are vague and lack certainty.【10】 So we can choose fuzzy logic as our methodology.

In the following we will talk about fuzzy logic definition and the application, and we will have an actual case study from Italdesign to explain how to use fuzzy logic to deal with deferred maintenance.

## 3.1 The history of fuzzy logic

A fuzzy concept is a concept of which the boundaries of application can vary considerably according to context or conditions, instead of being fixed once and for all. This means the concept is vague in some way, lacking a fixed, precise meaning, without however being unclear or meaningless altogether.【11】 The inverse of a "fuzzy concept" is a 'crisp concept', which means precise concept.

Problems of vagueness and fuzziness have probably always existed in human experience. The boundary between different things is not so obviously, so sometimes people need to make decisions based on confused information.

The ancient Sorites paradox first raised the logical problem of how we could exactly define the threshold at which a change in quantitative gradation turns into a qualitative or categorical difference.【12】 Some thresholds are relatively easy to identify, but the point to change is much more difficult to define in some other processes. Thus, the boundaries between qualitatively different things may be not sharp: we know that there are boundaries, but we cannot define them exactly. This is the embryonic form of fuzzy logic.

The Nordic myth of Loki's wager suggested that concepts that lack precise meanings or precise boundaries of application cannot be usefully discussed at all.【13】 However, the 20th century idea of "fuzzy concepts" proposes that "somewhat vague terms" can be operated with, since we can explicate and define the variability of their application, by assigning numbers to gradations of applicability. This idea sounds simple enough, but it had large implications.

An early attempt in the post-WW2 era to create a theory of sets where set membership is a matter of degree was made by Abraham Kaplan and Hermann Schott in 1951. They intended to apply the idea to empirical research. Kaplan and Schott measured the degree of membership of empirical classes using real numbers between 0 and 1, and they defined corresponding notions of intersection, union, complementation and subset. 【14】 However, at the time, their idea "fell on stony ground". 【15】 J. Barkley Rosser Sr. published a treatise on many-valued logics in 1952, anticipating "many-valued sets".【16】 Another treatise was published in 1963 by Aleksandr A. Zinov'ev and others.【17】

In 1964, the American philosopher William Alston introduced the term "degree vagueness" to describe vagueness in an idea that results from the absence of a definite cut-off point along an implied scale.【18】.

The German mathematician Dieter Klaua published a German-language paper on fuzzy sets in 1965, but he used a different terminology (he referred to "many-valued sets", not "fuzzy sets").【19】

Two popular introductions to many-valued logic in the late 1960s were by Robert J. Ackermann and Nicholas Rescher respectively.【20】 Rescher’s book includes a bibliography on fuzzy theory up to 1965, which was extended by Robert Wolf for 1966-1974.【21】 Haack provides references to significant works after 1974. Bergmann provides a more recent (2008) introduction to fuzzy reasoning.【22】

Usually the Iranian-born American computer scientist Lotfi A. Zadeh (1921-2017) is credited with inventing the specific idea of a "fuzzy concept" in his seminal 1965 paper on fuzzy sets, because he gave a formal mathematical presentation of the phenomenon that was widely accepted by scholars.【23】 It was also Zadeh who played a decisive role in developing the field of fuzzy logic, fuzzy sets and fuzzy systems, with a large number of scholarly papers.【24】

Fuzzy logic and probability address different forms of uncertainty. Fuzzy set theory uses the concept of fuzzy set membership, how much an observation is within a vaguely defined set, and probability theory uses the concept of subjective probability, likelihood of some event or condition. The concept of fuzzy sets was developed in the mid-twentieth century at Berkeley as a response to the lacking of probability theory for jointly modelling uncertainty and vagueness.

Bart Kosko claims in Fuzziness vs. Probability that probability theory is a subtheory of fuzzy logic, as questions of degrees of belief in mutually-exclusive set membership in probability theory can be represented as certain cases of non-mutually-exclusive graded membership in fuzzy theory.【25】 In that context, he also derives Bayes' theorem from the concept of fuzzy subsethood. Lotfi A. Zadeh argues that fuzzy logic is different in character from probability, and is not a replacement for it. He fuzzified probability to fuzzy probability and also generalized it to possibility theory.

Many of the early successful applications of fuzzy logic were implemented in Japan. The first notable application was on the subway train in Sendai, in which fuzzy logic was able to improve the economy, comfort, and precision of the ride. 【26】 It has also been used in recognition of hand written symbols in Sony pocket computers, flight aid for helicopters, controlling of subway systems in order to improve driving comfort, precision of halting, and power economy, improved fuel consumption for automobiles, single-button control for washing machines, automatic motor control for vacuum cleaners with recognition of surface condition and degree of soiling, and prediction systems for early recognition of earthquakes through the Institute of Seismology Bureau of Meteorology, Japan.【27】

Now fuzzy logic has been applied to many fields, from automatic control theory , artificial intelligence, pattern recognition decision analysis and timing signal processing.

Compensatory fuzzy logic (CFL) is a branch of fuzzy logic with modified rules for conjunction and disjunction. When the truth value of one component of a conjunction or disjunction is increased or decreased, the other component is decreased or increased to compensate. This increase or decrease in truth value may be offset by the increase or decrease in another component. An offset may be blocked when certain thresholds are met.

Some scientists claim that CFL allows for better computational semantic behaviors and mimic natural language.【28】

## 3.2 The process of applying fuzzy logic

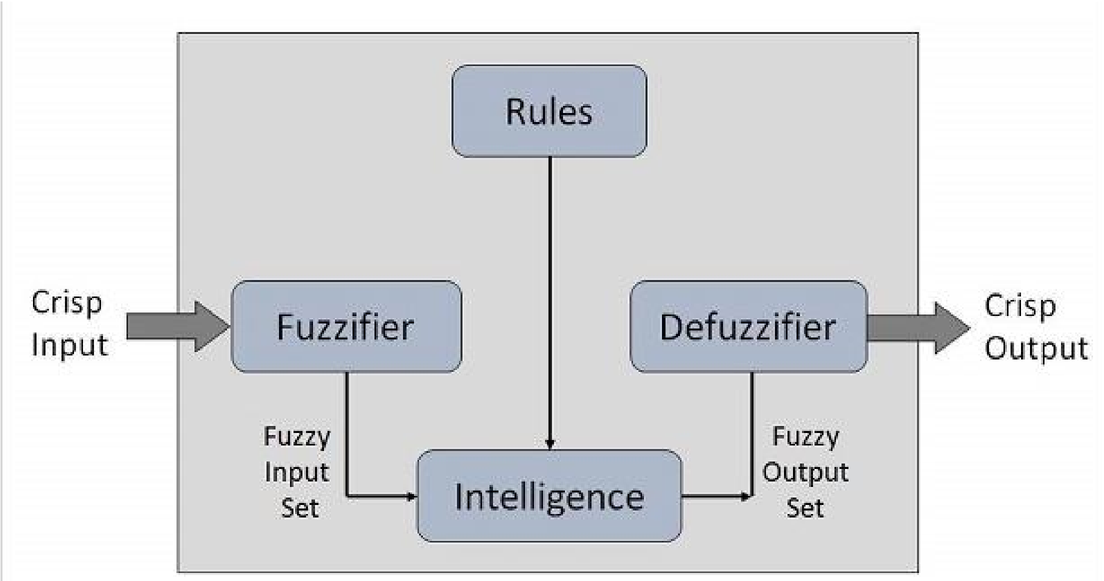



***Figure 5:*** *Fuzzy logic architecture, which reveal how we can get crisp output from the crisp input with fuzzy process. At first we need to fuzzy the input with membership function, after that we need to deal with different inputs with rules, at last we need to defuzzify the fuzzy output.*

Fuzzification is the first step of applying fuzzy logic. It`s used to fuzzify all input values into fuzzy membership functions. Fuzzy logic uses the degree of truth as a mathematical model of vagueness, which can be defined by applying truth value or linguistic variables. In fuzzy logic applications, non-numeric values are often used to facilitate the expression of rules and facts, which we called the membership function.

Then we use rules to evaluate the input variables. The fuzzy inference mechanism is the core of the fuzzy system. It is used to simulate the human decision-making mode to solve the problem. Fuzzy logic works with membership values in a way that mimics Boolean logic. And we can also use the concept of 'hedge', which is more linguistic in nature. The mostly used rule is called 'IF...THEN...'. IF-THEN rules map input or computed truth values to desired output truth values. If an output variable occur in several THEN parts, then the values from the respective IF parts are combined using the OR operator in Zadeh operator in the table 1.

***Table 1:*** *Zadeh operator as the basic rule of fuzzy logic. For TRUE/1 and FALSE/0, the fuzzy expressions produce the same result as the Boolean expressions. But the meaning of 'And' and 'Or' are different from Boolean operator.*

| Boolean | Fuzzy |
|---|---|
| AND(x,y) | MIN(x,y) |
| OR(x,y) | MAX(x,y) |
| NOT(x) | 1-x |

De-fuzzification can be used to map a fuzzy output membership functions into a "crisp" output value that can be then used for decision or control purposes. The goal is to get a continuous variable from fuzzy truth values. One has then to decide for a number that matches best the "intention" encoded in the truth value.

If the input variables are continuous, we can use 'weighted average method' to compute the output. The output can also be kind of membership function, or be a precise value. We need to make decision from the output value.

### 3.2.1 Input variables and fuzzification

At the beginning we should investigate the factors that influence individual safety behavior and productivity at work. The analysis revealed several organizational and social factors that explain why individuals engage in unsafe work practices. In fact, less than 1% of organizational and social research focuses on issues concerning occupational health and safety, which will affect productivity at the end.(Investigating factors that influence individual safety behavior at work, Jane·Mullen,2004).

According to the actual situation, we can decide some more specific factors. We decide to investigate 5 variables, which are the followings:

- The delay in the maintenance activity, this variable take into account how much the maintenance is delayed.

- The equipment working time, in this variable is taken into account if the equipment work more or lower time than expected.

- The working condition, in term of fluid severity and the working/environmental condition.

- The presence and the quality of the equipment monitoring quality.

- The expected level of severity for the fault, the severity is evaluated also for the safety than for the productivity.

In risk assessment based on fuzzy logic, we need to use membership function to represent the degree of truth in fuzzy logic. There are several important characteristics relating to membership functions, which can help us to define them for each variable considered.

Membership functions are used to characterize fuzziness, whether the elements in fuzzy sets are discrete or continuous. In another way, it`s a technique to solve practical problems by experience rather than knowledge. So we need natural language to define the variables. Sometimes different experts have different opinions, so the precise physical meaning may have two or more language variable.

The most used natural language is “low, medium, high” if the condition is divided into 3 fuzzy sets according to the habits of human. However the accurate representation can be different according to actual situations. For example, we can use “cold,warm, hot” to represent temperature, and we can use “cheap, fair, expensive” to represent the price. We can use more suitable words in actual situations. It is common to modify linguistic values with adjectives or adverbs to extend the number of language variables. For example, we can use the hedges little and more to construct the additional values.

Membership functions are represented by graphical forms. It maps the degree of membership between 0 and 1 for one variable value. To ensure the accuracy, we decide to have at least 3 membership functions for each variable. We can have more membership functions if needed.

The most used membership function shapes are triangular and trapezoidal membership functions because the calculations with triangular and trapezoidal membership are easy. We decide to use the trapezoidal shape and some variants from this shape.

Trapezoidal function is defined by a lower limit a, an upper limit d, a lower support limit b, and an upper support limit c, where $a < b < c < d$.

$$\mu_A(x) = \begin{cases} 0, & (x < a) \text{ or } (x>d) \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \end{cases}$$

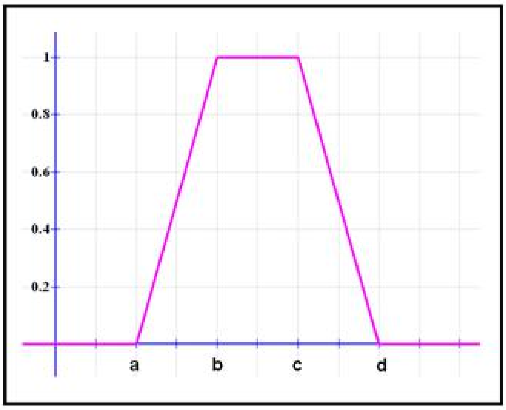



***Figure 6:*** *the mathematical representation and graph of trapezoidal function, where a,b,c,d are the characteristic points with the relative vertical sequence are 0-1-1-0.*

From the basic graph, we just to define 4 values a-b-c-d to define one trapezoidal-shape membership function fuzzy set.

For some specific cases we can use the variants form trapezoidal shape, which are called R-functions and L-functions.

R-functions: with parameters a = b = - ∞. It is trapezoidal function when value of a and b equal with the value of the first element in the universe of discourse, and sometimes this function is called Downward Slope. Elements located between b and c has a membership degree 1 while degree decrease for elements located between c and d whenever closer to the element d.

$$\mu_A(x) = \begin{cases} 0, & x > d \\ \dfrac{d - x}{d - c}, & c \le x \le d \\ 1, & x < c \end{cases}$$

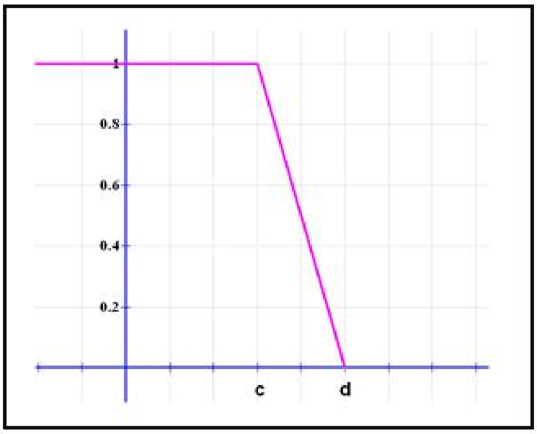



***Figure 7:*** *the mathematical representation and graph of specific R trapezoidal function with parameters a = b = - ∞, the relative vertical parameters for c and d are 1-0.*

A more specific case is that c=0, just have a down-slope. It depends on actual situation.

L-function with parameters c = d = +∞. It is trapezoidal function when value of c and d equal with the value of the last item in the universe of discourse, and sometimes a function is called Upward Slope. Elements between a and b increases its degree of membership whenever element is closer to b while elements between b and c has a membership degree 1.

$$\mu_A(x) = \begin{cases} 0, & x < a \\ \dfrac{x - a}{b - a}, & a \le x \le b \\ 1, & x > b \end{cases}$$

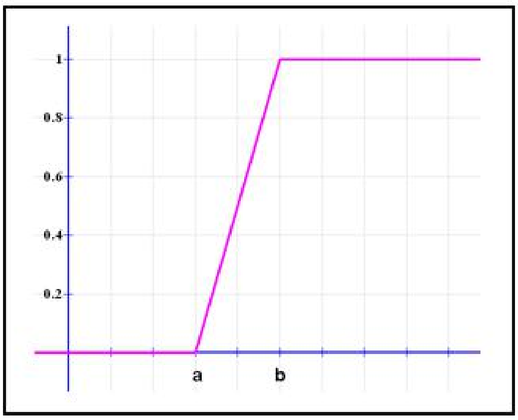


***Figure 8:*** *the mathematical representation and graph of specific L trapezoidal function with parameters c= d = - ∞, the relative vertical parameters for c and d are 0-1.*

For a basic trapezoidal shape membership function, we can define some features about it.

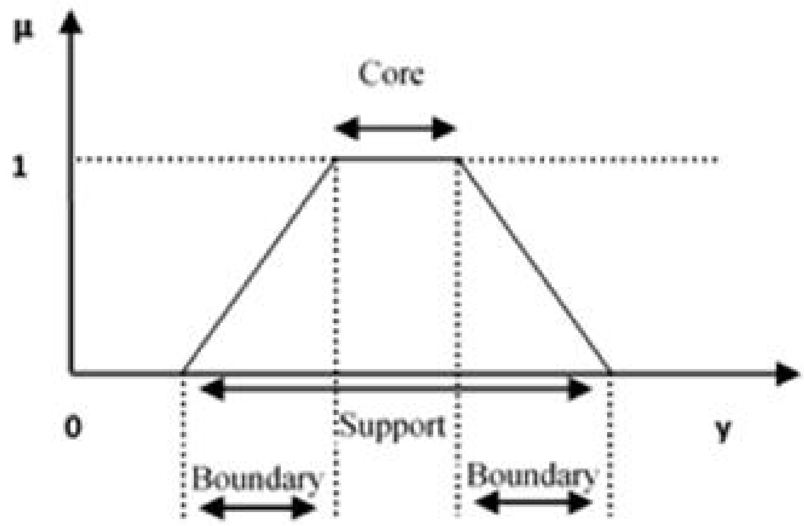



***Figure 9:*** *the main sections of trapezoidal function: core area, support area and two boundary areas. For simplicity, the figure is assumed as symmetrical with the centre line of core, and the relative length of core and boundary depends on actual situations.*

For any fuzzy set, the core of a membership function is that region of universe that is characterize by full membership 1 in the set, the support is the region of universe that is characterize by a nonzero membership in the set, and the boundary is the region of universe that is characterized by a nonzero but incomplete membership in the set.

For convenience, the figure should be symmetric, which means the left boundary and right boundary has the same area size. And the range of core and boundary can be the same or not depending the situation.

As we all know, the language description is got from the experts` opinion. For some conditions the experts have the same opinions about the description, but maybe they will have different opinions during the immediate region. It`s quiet convenient to decide the core and boundary have the same cross region.

We should notice that if there are more than one membership functions for one variable, there will be no immediate region for the left part of the first membership function, so we can use the specific case ‘R-function’. The condition is similar to the right part of the last membership function, we can use ‘L-function’ for it.

According to the above information, we can define membership functions for each variable.

The first variable is the delay in the maintenance activity, this variable take into account how much the maintenance is delayed.

$$D = \frac{delay}{t_{m0}} = \frac{t_{m1} - t_{m0}}{t_{m0}} \qquad (3\text{-}1)$$

Where $t_{m0}$ is the programmed time interval between the two maintenance activity, instead $t_{m1}$ is the real interval.

There should be no delay in the maintenance activity in theory, so we can say that the delay condition is normal only when the delay is relative much smaller with respect to the total domain. In actual engineering stress analysis cases the engineers always take s safety factor as 2~3,【29】 which means the ratio between the strength of the material and the maximum stress is 2~3. The concept is used in maintenance field similarly. Here we can decide the safety factor is 4, it can be revealed from the region of critical part and high critical part is almost 4 times as normal case.

The delay is usually not so high in actual cases, no more than twice as the scheduled maintenance period. So we can decide the delay range is [0,2]. It has no meaning to investigate longer time, a company will not defer the maintenance activity so long unless it`s bankrupt. The variable D is divided in 3 membership functions, normal, critical, high critical.

***Table 2:*** *Input 1 definition of delay. We divided this input variable into 3 groups. The maximum independent variable value is 2, and the minimum is 0.*

| Input 1 | |
|---|---|
| Name | delay |
| Group | 3 |
| Minimum | 0 |
| Maximum | 2 |

From a simple mathematical calculation, which divided the total domain into 10 pieces, we can assign the membership function for each language variable. There should be one piece for each the two cross regions, and both 4 pieces for the core regions of critical and high critical parts. If the delay is larger than 1, the condition is not completely normal, So the core region of normal part disappears.The membership function Critical and High critical represent more dangerous condition.

We can get the following table to get the membership functions of variable D.

***Table 3:*** *Groups of nodes to define the membership function D. For the first specific R trapezoidal function we just have d value. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The middle one is the normal trapezoidal function.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Normal | 0 | 0 | 0 | 0.2 |
| Critical | 0 | 0.2 | 1 | 1.2 |
| High critical | 1 | 1.2 | 2 | 2 |

We can get the figure to represent membership function for variable D as the following.

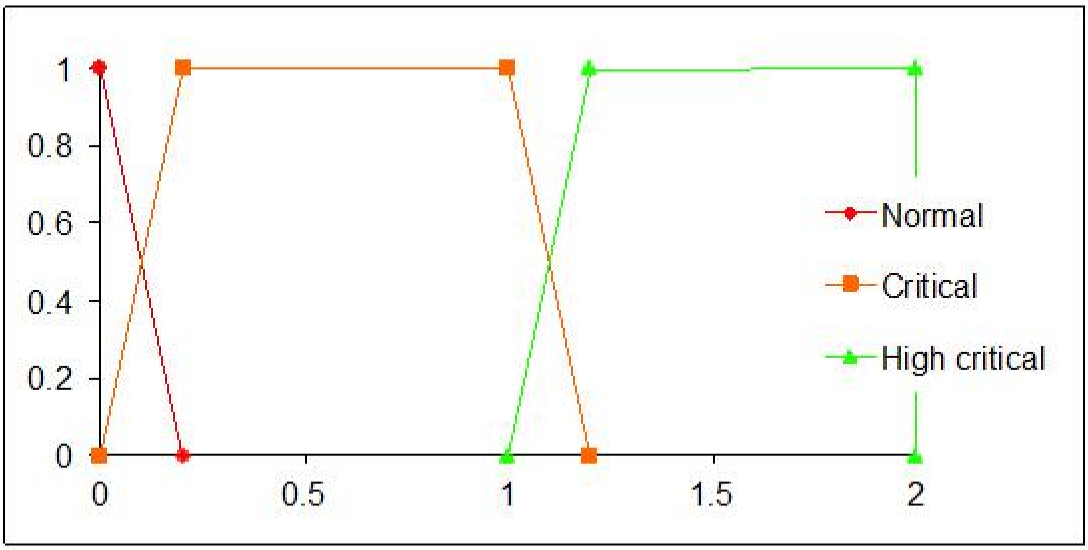


***Figure 10:*** *membership functions of the variable D. It includes three fuzzy sets with the names 'Normal, Critical, High critical'. the first fuzzy set`s shape is the more specific form of R trapezoidal function, the second is normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

And what`s more, if the delay is random, we can use the mathematical formula to calculate the degree of membership function below:

$$Normal\begin{cases}1-5D, 0<D<0.2\\ 0, D>0.2\end{cases}$$

$$Critical\begin{cases}5D, 0<D<0.2\\ 1, 0.2<D<1\\ 6-5D, 1<D<1.2\\ 0, D>1.2\end{cases}$$

$$High-critical\begin{cases}5D-5, 1<D<1.2\\ 1, D>1.2\end{cases} \quad (3\text{-}2)$$

If the scheduled maintenance period is one year, which means 12 months, we can get the following table and the relating figure.

***Table 4:*** *Groups of nodes to define the membership function D for one year, we amplify the nodes cross value with ratio 12 with respect to the value in Table 3.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Normal | 0 | 0 | 0 | 2.4 |
| Critical | 0 | 2.4 | 12 | 14.4 |
| High critical | 12 | 14.4 | 24 | 24 |

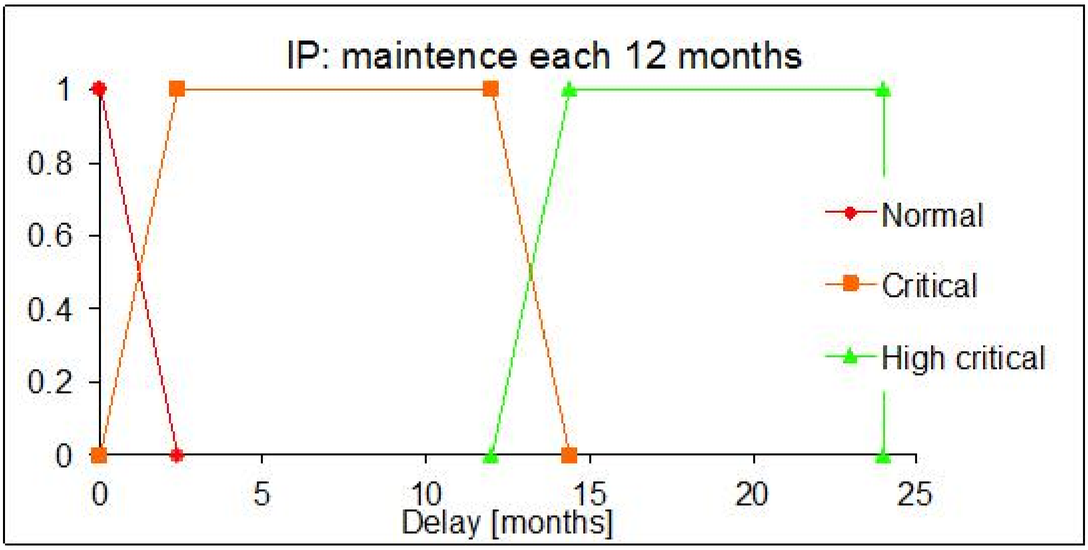



***Figure 11:*** *Membership functions of the variable D for 12 months. The cross axial value is amplified with parameter 12, while the vertical condition does not change.*

The second variable is taken into account if the equipment work more or lower time than expected.

$$W = \frac{w_1}{w_0} \qquad (3\text{-}3)$$

Where w1 is the equipment hours worked in the year, instead is w0 is the expected equipment hours worked in the year. The variable W is divided in 5 membership functions. Two membership function is consider an improvement because the equipment work less than expected, which the value is smaller than 1. At the same time two membership function is considered an worsening of the condition because the equipment work more then expected, which the value is bigger than 1. For symmetry and the consideration of actual cases, we decide the maximum of w is 2.

***Table 5:*** *Input 2 definition of working time. We divided this input variable into 5 groups. The maximum independent variable value is 2, and the minimum is 0.*

| Input 2 | |
|---|---|
| Name | Working time |
| Group | 5 |
| Minimum | 0 |
| Maximum | 2 |

For convenience as said before, the figure of membership function should be symmetry. As for the size of every fuzzy set, we have 4 parts of cross area, 5 parts of core area, normally we can divide the total range into 10 pieces for simplicity. For symmetry we can decide the core area of the middle fuzzy set is 2 pieces, and one piece for each other part. After the analysis we can get the following table and the related figures.

According to the nodes, we can get the drawing of working time membership function. The vertical value is always the sequence 0-1-1-0.

***Table 6:*** *Groups of nodes to define the membership function of working time. For the first R trapezoidal function we just have c-d values. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The three middle fuzzy sets are the normal trapezoidal functions.*

| group<br><br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Positive | 0 | 0 | 0.2 | 0.4 |
| Little positive | 0.2 | 0.4 | 0.6 | 0.8 |
| Normal | 0.6 | 0.8 | 1.2 | 1.4 |
| Critical | 1.2 | 1.4 | 1.6 | 1.8 |
| High critical | 1.6 | 1.8 | 2 | 2 |

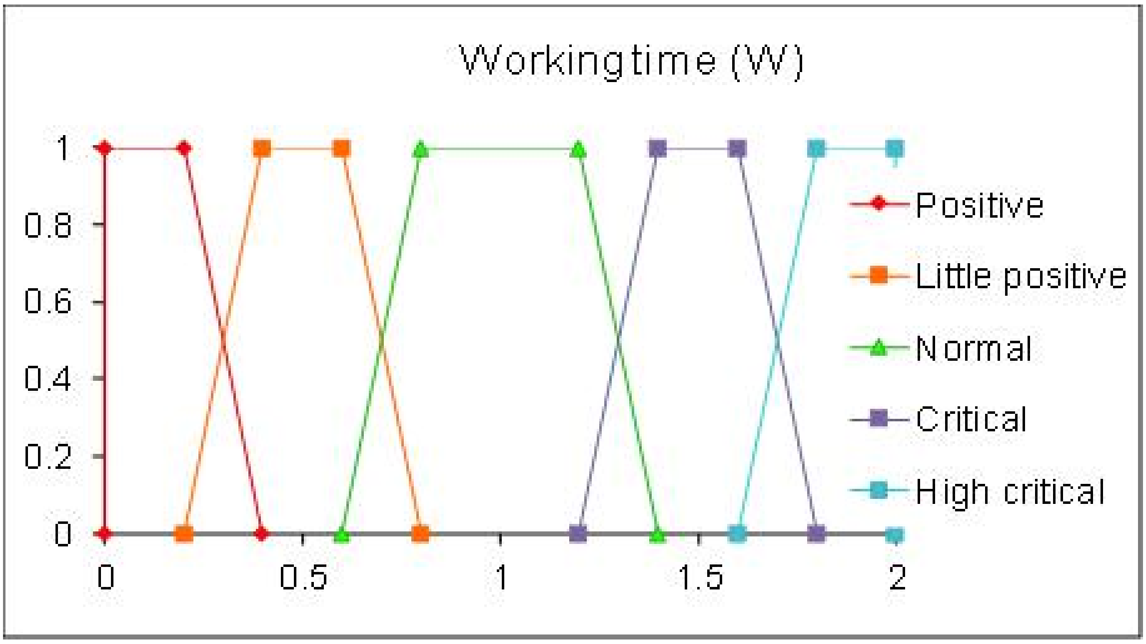



***Figure 12:*** *Membership function of the variable W, It includes five fuzzy sets with the names 'Positive, Little positive, Normal, Critical, High critical'. The first fuzzy set`s shape is the normal R trapezoidal function, the three middle fuzzy sets are normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

In the following we will see the mathematical representation of membership function for variable W. And for the special case of one year, we can simply multiply each function with 12.

$$positive\begin{cases}1,0<W<0.2\\2-5W,0.2<W<0.4\\0,W>0.4\end{cases}$$

$$Little-positive\begin{cases}0,0<W<0.2 or W>0.8\\5W-1,0.2<W<0.4\\1,0.4<W<0.6\\4-5W,0.6<W<0.8\end{cases}$$

$$Normal\begin{cases}0,0<W<0.6 or W>1.4\\5W-3,0.6<W<0.8\\1,0.8<W<1.2\\7-5W,1.2<W<1.4\end{cases}$$

$$Critical\begin{cases}0,0<W<1.2 or W>1.8\\5W-6,1.2<W<1.4\\1,1.4<W<1.6\\9-5W,1.6<W<1.8\end{cases}$$

$$High-critical\begin{cases}0,0<W<1.6\\5W-8,1.6<W<1.8\\1,1.8<W<2\end{cases} \tag{3-4}$$

In the following we will see the mathematical representation of membership function for variable W. And for the special case of one year, which the equipment expected working time is usually 2500 hours, we can simply multiply each function with 2500.

***Table 7:*** *Groups of nodes to define the membership function of working time for one year, we amplify the nodes cross value with ratio 2500 with respect to the value in Table 6.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Positive | 0 | 0 | 500 | 1000 |
| Little positive | 500 | 1000 | 1500 | 2000 |
| Normal | 1500 | 2000 | 3000 | 3500 |
| Critical | 3000 | 3500 | 4000 | 4500 |
| High critical | 4000 | 4500 | 5000 | 5000 |

According to the nodes we can get the figure 9, the membership functions of the variable W for one year. As the same as before, the vertical value for each group of nodes is sequence '0-1-1-0'.

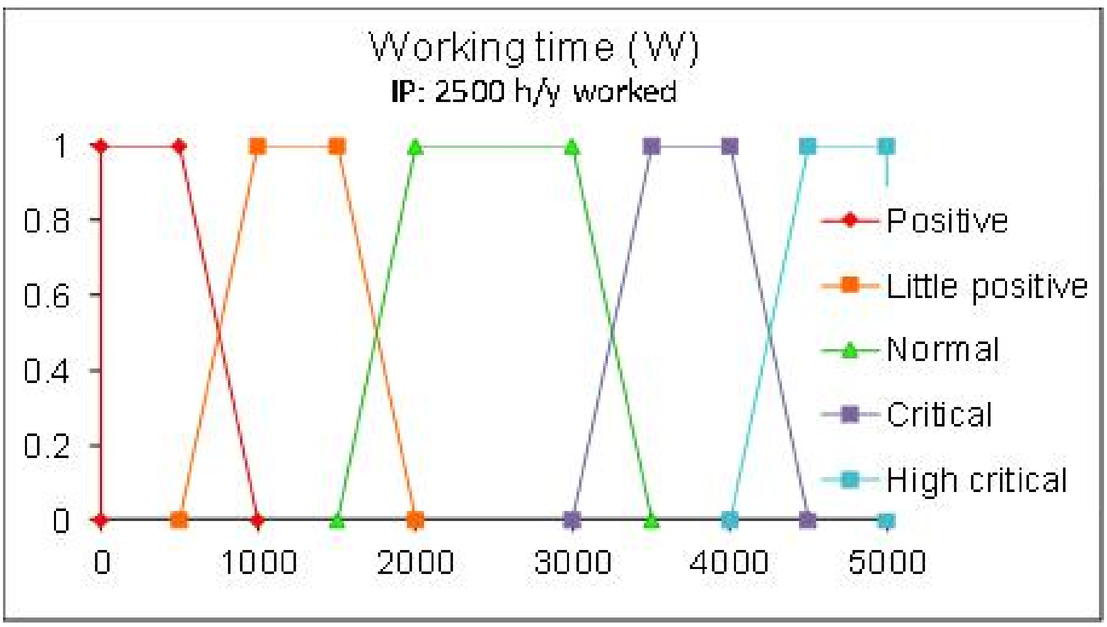


*__Figure 13:__ Membership functions of the variable W for one year. Normally the equipment works 2500 hours per year. The cross axial value is amplified with parameter 2500, while the vertical condition does not change.*

The 3rd variable C (condition) take into account the working condition, in term of fluid severity and the working/environmental condition. For this variable is more difficult to make the quantification, because it is not possible to find a miserable and unique set of parameters to describe this variable. And this variable is evaluate only throughout the management and expert opinion. The variable is divided in 3 membership function :

-Protective: if the working condition protect the equipment from the wear-out, for example if the oil contained reduce the friction more than expected during the designee phase;

-Neutral: if the working condition is similar at the condition considered during the designee phase, such as similar temperature, similar fluids or similar environmental condition;

-Critical: if the working conditions are more severe than the value hypothesized during the designee phase, for example the use of corrosive fluids, working at higher temperature, working out-side in severe condition.

The total cross axis range has no physical meaning, it`s just a qualitative expression so we can decide the range is [0,1]. For simplicity we want the figure to be symmetric and the range for core area and boundary. We use Trapezoidal R-function for the first fuzzy set and L-function for the last one. The cross area is the same area for the right boundary of last set and the left boundary of next set.

So we can assign the characteristic point of each membership function. From the table we can get the membership function figure. As the same as before, the vertical value for each group of nodes is sequence ‘0-1-1-0’.

***Table 8:*** *input 3 definition for fluid/condition/environment. We divided this input variable into 3 groups. The maximum independent variable value is 1, and the minimum is 0.*

| Input 3 | |
|---|---|
| Name | Fluid/condition/environment |
| Group | 3 |
| Minimum | 0 |
| Maximum | 1 |

***Table 9:*** *Groups of nodes to define the membership function C. For the first R trapezoidal function we just have c-d values. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The middle one is the normal trapezoidal function.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Protective | 0 | 0 | 0.2 | 0.4 |
| Neutral | 0.2 | 0.4 | 0.6 | 0.8 |
| Critical | 0.6 | 0.8 | 1 | 1 |

According to the nodes we can get the figure 10, the membership functions of the variable C. As the same as before, the vertical value for each group of nodes is sequence ‘0-1-1-0’.

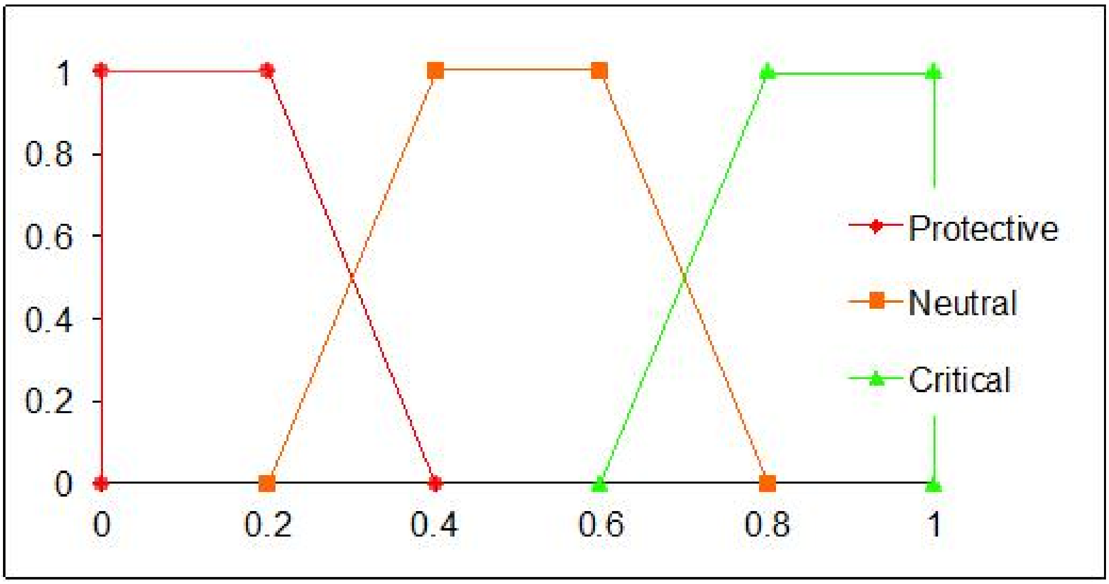



***Figure 14:*** *Membership functions of the variable C. It includes three fuzzy sets with the names 'Protective, Neutral, Critical'. The first fuzzy set`s shape is the R trapezoidal function, the second is normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

In the following we will see the mathematical representation of membership function for variable C.

$$\Pr otective\begin{cases}1,0 < C < 0.2\\2-5C,0.2 < C < 0.4\\0,0.4 < C < 1\end{cases}$$

$$Neutral\begin{cases}0,0 < C < 0.2 or 0.8 < C < 1\\5C-1,0.2 < C < 0.4\\1,0.4 < C < 0.6\\4-5C,0.6 < C < 0.8\end{cases}$$

$$Critical\begin{cases}0,0 < C < 0.6\\5C-3,0.6 < C < 0.8\\1,0.8 < C < 1\end{cases} \tag{3-5}$$

The next input variable M take into account the presence and the quality of the equipment monitoring quality. Also for this variable is difficult found some quantified variable then help the analyst and the variable M is evaluate by the management and the expert opinion. The company has a standard expert group to evaluate the monitoring quality. We can distinguish the monitoring quality to three aspects: proof, medium, superficial, which will be described in the following. The variable M is included between 0 to 1.

***Table 10:*** *Input 4 definition for monitor quality. We divided this input variable into 3 groups. The maximum independent variable value is 1, and the minimum is 0.*

| Input 4 | |
|---|---|
| Name | Monitor quality |
| Group | 3 |
| Minimum | 0 |
| Maximum | 1 |

The variable is divided in 3 membership functions:

-Proof: in this case the monitor activities are able to found all the faults and the monitor see the faults at the beginning;

-Medium: in this case the monitor activities found a bigger part of the fault and it see the fault with sufficient time for stop the equipment and perform the maintenance before the consequences of the fault;

-Superficial: in this case the monitor activity is not performed or it is performed rarely. And it quality is only superficial, in fact the faults are founded only after the first consequences appear.

The approach to get the membership function figure is the same as before. We use Trapezoidal R-function for the first fuzzy set and L-function for the last one. The cross area is the same area for the right boundary of last set and the left boundary of next set.

So we can assign the characteristic point of each membership function. From the table we can get the membership function figure.

***Table 11:*** *Groups of nodes to define the membership function M. For the first R trapezoidal function we just have c-d values. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The middle one is the normal trapezoidal function.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Proof | 0 | 0 | 0.2 | 0.4 |
| Medium | 0.2 | 0.4 | 0.6 | 0.8 |
| Superficial | 0.6 | 0.8 | 1 | 1 |

According to the nodes we can get the figure 11, the membership functions of the variable M. As the same as before, the vertical value for each group of nodes is sequence '0-1-1-0'.

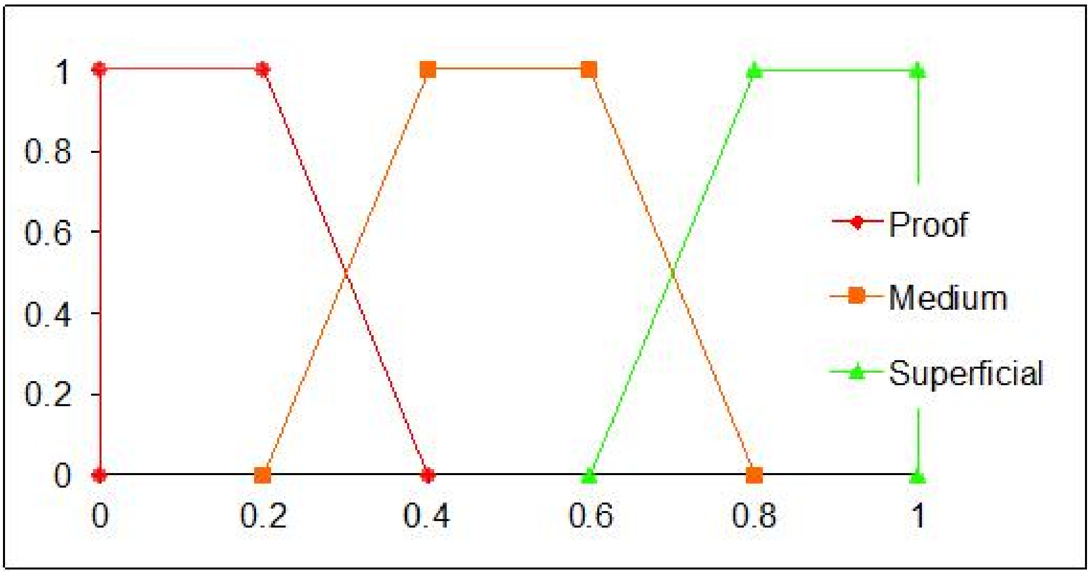



***Figure 15:*** *membership functions of the variable M. It includes three fuzzy sets with the names 'Proof, Medium, Superficial'. The first fuzzy set`s shape is the R trapezoidal function, the second is normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

And if the experts` opinion about the monitoring quality is not at the nodes, we can evaluate from the following formula.

$$\mathrm{Pr}\,oof\begin{cases}1,0<M<0.2\\2-5M,0.2<M<0.4\\0,0.4<M<1\end{cases}$$

$$Medium\begin{cases}0,0<M<0.2or0.8<M<1\\5M-1,0.2<M<0.4\\1,0.4<M<0.6\\4-5M,0.6<M<0.8\end{cases}$$

$$Superficial\begin{cases}0, 0 < M < 0.6 \\ 5M - 3, 0.6 < M < 0.8 \\ 1, 0.8 < M < 1\end{cases} \quad (3\text{-}6)$$

The last input variable is the expected level of severity for the fault, the severity is evaluated also for the safety than for the productivity. Two different value are used for the severity in this way are possible evaluate both the risk for the safety ($S_s$) and for the productivity ($S_p$). Both the severity are discretized by 3 membership function . The severity level is also a variable that is difficult to be quantitied. We can divide the severity to three levels: Low, medium, high. The value of the severity used in this variable depends of the methods used for its evaluation and the level of detail available, normalized between 0 to 1.

***Table 12:*** *Input 5-1 definition for severity for safety. We divided this input variable into 3 groups. The maximum independent variable value is 1, and the minimum is 0.*

| | |
|---|---|
| Input 5-1 | |
| Name | Severity for safety |
| Group | 3 |
| Minimum | 0 |
| Maximum | 1 |

***Table 13:*** *Input 5-2 definition for severity for productivity. We divided this input variable into 3 groups. The maximum independent variable value is 1, and the minimum is 0.*

| | |
|---|---|
| Input 5-2 | |
| Name | Severity for productivity |

| | |
|---|---|
| Group | 3 |
| Minimum | 0 |
| Maximum | 1 |

An indication of the membership function are described in Table 14. These definitions come from actual experiments and the opinions of professional experts.

***Table 14:*** *Severity input variable description. We can describe 3 different levels of severity for both safety and productivity: Low, Medium, High. These classifications derive from the opinion of experts and past experience.*

| | Severity for Safety ( $S_s$ ) | Severity for productivity ( $S_p$ ) |
|---|---|---|
| Low | No consequences or injuries without absence from work | No consequences or the equipment fault can be stopped without consequences on the plant production |
| Medium | Injuries with absence of the work, but without permanent consequences | Not classifiable in the other category |
| High | Injuries with permanent consequences or operator death | Long plant stop and domino effect on the other part of plant |

We use the same division method for the two variables. We use Trapezoidal R-function for the first fuzzy set and L-function for the last one. The cross area is the same area for the right boundary of last set and the left boundary of next set.

So we can assign the characteristic point of each membership function. From the table we can get the membership function figure.

*__Table 15:__ Groups of nodes to define the membership function* $S_s$. *For the first R trapezoidal function we just have c-d values. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The middle one is the normal trapezoidal function.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Low | 0 | 0 | 0.2 | 0.4 |
| Medium | 0.2 | 0.4 | 0.6 | 0.8 |
| High | 0.6 | 0.8 | 1 | 1 |

According to the nodes we can get the figures, the membership functions of the severity for safety and for productivity. As the same as before, the vertical value for each group of nodes is sequence '0-1-1-0'.

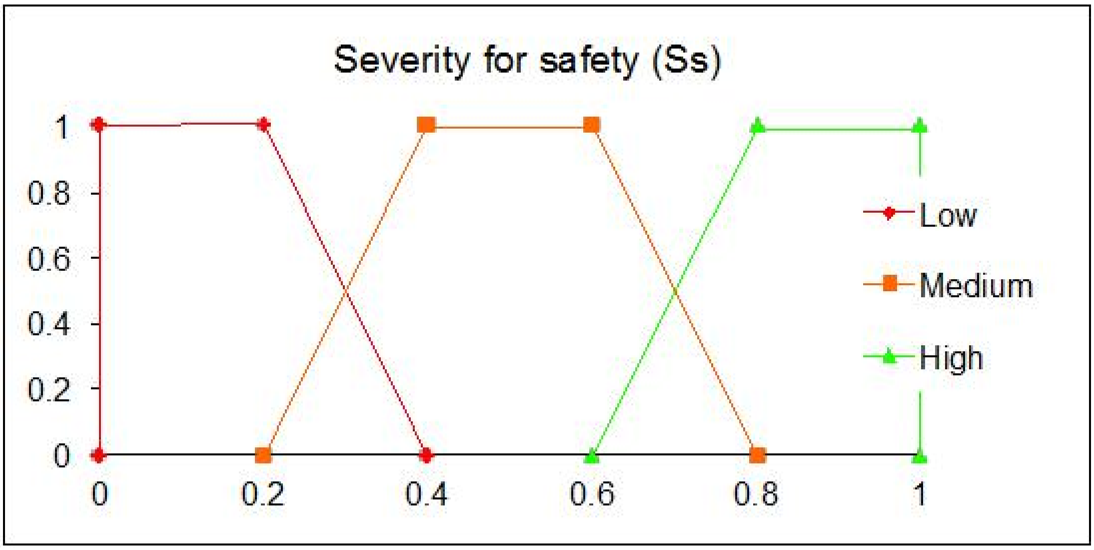



***Figure 16:** membership function of severity for safety. It includes three fuzzy sets with the names 'Low, medium, High'. The first fuzzy set`s shape is the R trapezoidal function, the second is normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

Then we can focus on the representation of membership function of severity for productivity. The process is almost the same as safety, the basic nodes are the same and the graph is the same.

***Table 16:*** *Groups of nodes to define the membership function Sp. For the first R trapezoidal function we just have c-d values. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The middle one is the normal trapezoidal function.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Low | 0 | 0 | 0.2 | 0.4 |
| Medium | 0.2 | 0.4 | 0.6 | 0.8 |
| High | 0.6 | 0.8 | 1 | 1 |

We can get the following figure using the relating nodes in table 16.

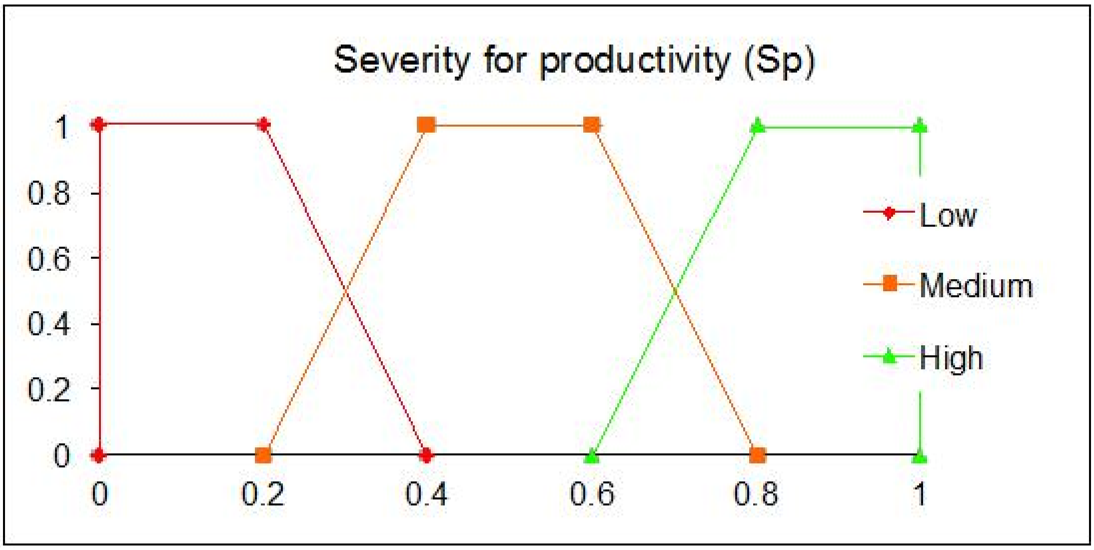



***Figure 17:*** *membership function of severity for productivity. It includes three fuzzy sets with the names 'Low, medium, High'. The first fuzzy set`s shape is the R trapezoidal function, the second is normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

If we have the random analysis results, which are not at the corners, we can use the formulas below to calculate the results.

$$Low\begin{cases}1, 0 < S < 0.2\\ 2-5S, 0.2 < S < 0.4\\ 0, 0.4 < S < 1\end{cases}$$

$$Medium\begin{cases}0, 0 < S < 0.2 or 0.8 < S < 1\\ 5S-1, 0.2 < S < 0.4\\ 1, 0.4 < S < 0.6\\ 4-5S, 0.6 < S < 0.8\end{cases}$$

$$High\begin{cases}0, 0 < \mathrm{S} < 0.6\\ 5S-3, 0.6 < S < 0.8\\ 1, 0.8 < S < 1\end{cases} \tag{3-7}$$

The value of the severity used in this variable depends of the methods used for its evaluation and the level of detail available, normalized between 0 to 1. An indication of the membership function are described in Table 14. These definitions come from actual experiments and the opinions of professional experts.

### 3.2.2 If-then rules

For the system is necessary develop 810 rules, 405 for the Risk for safety and 405 for the Risk for productivity. The rules are type 'If … Then …'.

For example: 'IF Delay is normal and Working time is positive and Fluid/condition/environment is protective and Monitor is proof and Severity for safety is low Then the Risk for safety is Low'. we can do the same to calculate the risk for productivity. But it`s too difficult to define every rule of 810 without diffusion. We can not say definitely the risk is low, medium, or high if the combination of five variables is more complex. To deal with this problem, we need a new rule as the basic to define all of the rules.

To define the rules can be used the following equation:

$$w_0 = \Sigma W_{I,i} \cdot W_{I,j} \qquad (3\text{-}8)$$

Where:

- $W_{I,i}$ is a value used for mark the relative importance of the different Input variable.

- $W_{I,j}$ is the weight of the different membership function of the input variables. The value can be lower than zero if the condition are advantageous and over than zero if the condition have negative effect on the equipment condition.

To define $W_{I,i}$ we need to discuss the relative importance.

People never accept trade-offs unless they are forced to make a Choice. 【30】 It`s the same for one company. The 5 input variables are all important for the company to make the decision. Some of them are related to each other, and some of them have the same physical meaning. For example, if we delay the maintenance activity, the equipment working time will increase proportionally at the same time.

We can use the method ‘Relative Importance Testing’ to help the company to determine what is more important for the company during the 5 input variables. As we consider the relative importance of 5 variables, we should consider all possible consequences.

The company should take one variable as standard and then analyze the others carefully. We can choose the delay in the maintenance as the standard, so we can assign the relative importance value 1.

As for the working time, we all know that the equipment should be maintained after a certain working time, if the equipment works more time than expected, we can say the company defer the maintenance. What`s more, the start-up phase has the highest damage to the equipment, 【31】 if the equipment is started and works for a long time, it reduces the potential damage to the equipment. As a conclusion, we can decide that the relative importance value of working time is 0.8, lower than 1 but not so low.

As for the working condition relating to fluid severity and environmental condition, we can consider it from a extreme point of view. If the lubrication is very poor, the friction will be so large, and the working temperature will be high due to the wasted heat from friction, which will cause failure of equipment. It`s a very dangerous condition, so the relative importance value should be larger than 1. Actually the extreme condition doesn`t exist all the time, the working condition is difficult to be kept at the optimum condition, but not so bad. We can decide that the value is 2, twice of the standard to show the importance.

Then we will talk about the equipment monitoring quality. Nowadays, It is very common for the companies to use technology to a greater or lesser degree. In many cases, the good functioning of the equipment, networks and systems will be the key for the business to continue operating. 【32】 A good monitoring system is able to monitor devices, infrastructures, applications, services, and even business processes. It helps to increase productivity because It improves the use of the hardware of the company, and It prevents incidents and when these incidents happen, they are detected faster, which saves time and money. So it has almost the same importance as working condition. We can decide the value is also 2.

The severity for safety is the most important thing we concerned. If the consequence of a failure doesn`t have bad effect to the safety, maybe it just affect the aesthetic function, we can even ignore it. But if the failure of equipment can make the workers injured even died, we should pay more attention. When we analyze one hazard, we should consider the severity first. So the relative importance value for severity should be the highest. We can assign it as 3.

The condition is the same for severity for productivity. We can assign the same value for risk of productivity.

According to the information, we can get the following tables.

***Table 17:*** *Value of* $W_{I,i}$. *we use delay condition as standard value 1, then we compare other*

*variables with the standard, if it`s more important than delay, the value should be larger than 1, and vice versa. We assume the condition for safety and productivity are the same.*

| | Risk for the safety | Risk for the productivities |
|---|---|---|
| Delay (D) | 1 | 1 |
| Working time (W) | 0.8 | 0.8 |
| Working condition (C) | 2 | 2 |
| Monitor (M) | 2 | 2 |
| Severity for the safety (Ss) | 3 | |
| Severity for the productivities (Sp) | | 3 |

To define $W_{I,j}$ we should analyze the minimum and the maximum. As said before, The value can be lower than zero if the condition are advantageous and over than zero if the condition have negative effect on the equipment condition.

We find that if the working time is positive or little positive, it`s good for the equipment, so it will reduce the risk. The condition also appears for working condition and monitor quality. For this kind of variables we can define that the normal condition is 0, the positive effect is lower than 0, and the negative part is larger than 0. The total range is [-1,1], we can divide it into equal periods.

For the other variables, the effect is always bad for the equipment. So the value is always larger than 0. the total range is [0,1], and we can divide it into equal periods for simplicity.

So we can get the results in table18.

***Table 18:*** *Value of* $W_{I,j}$ *about the risk for safety. We can define that the normal condition is 0, the positive effect is lower than 0, and the negative part is larger than 0. The total range is [-1,1], we can divide it into equal periods. For some conditions there are no positive effects so the range is [0,1].*

| Delay (D) | | Working time (W) | | Working condition (C) | | Monitor (M) | | Severity for the productivity ( $S_p$ ) | |
|---|---|---|---|---|---|---|---|---|---|
| Normal | 0 | Positive | -1 | Protective | -1 | Proof | -1 | Low | 0 |
| Critical | 0.5 | Little positive | -0.5 | Neutral | 0 | Medium | 0 | Medium | 0.5 |
| High critical | 1 | Normal | 0 | Critical | 1 | Superficial | 1 | High | 1 |
| | | Critical | 0.5 | | | | | | |
| | | High critical | 1 | | | | | | |

This is the values for risk for productivity. We can use the same values for the risk for safety.

***Table 19:*** *Value of* $W_{I,j}$ *about the risk for productivity. The condition is the same as the risk for safety.*

| Delay (D) | | Working time (W) | | Working condition (C) | | Monitor (M) | | Severity for the productivity ( $S_p$ ) | |
|---|---|---|---|---|---|---|---|---|---|
| Normal | 0 | Positive | -1 | Protective | -1 | Proof | -1 | Low | 0 |
| Critical | 0.5 | Little positive | -0.5 | Neutral | 0 | Medium | 0 | Medium | 0.5 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High critical | 1 | Normal | 0 | Critical | 1 | Superficial | 1 | High | 1 |
| | | Critical | 0.5 | | | | | | |
| | | High critical | 1 | | | | | | |

$w_0$ is the threshold used for dived between the output membership functions, the values are contained in the following table. We calculate the possible maximum value and minimum value, the we divide it into 3 equal parts.

***Table 20:*** *threshold value of risk for safety and productivity. We calculate the maximum value and minimum value using formula (3-8), and then we divide it for 3 equal parts. We assign 'Low, Medium, High' risk level from low value part to high value part.*

| $w_0$ | Risk for Safety ($R_s$) | | Risk for productivity ($R_p$) | |
|---|---|---|---|---|
| | Min | Max | Min | Max |
| Low | -4.8 | -0.266667 | -4.8 | -0.266667 |
| Medium | -0.266667 | 4.266667 | -0.266667 | 4.266667 |
| High | 4.266667 | 8.8 | 4.266667 | 8.8 |

Below is the 405 rules required for risk for safety according to the FUZZY scheme, but we just represent 10 examples. The condition for risk for productivity is the same, there will be also 405 similar rules. In the following table you have to insert the variables that compose the rules according to the screen "If ... and ... then ... ..", and you can get the risk level as a result.

Sometimes we can define the rules easily, which means we can get a necessary and complete rule, but at other cases the rule requires some data to be valid.

***Table 21:*** *some examples of the rules for risk for safety. The total rules are visible after the reference as an added material.*

| | Input1 | | Input2 | | Input3 | | Input4 | | Input5 | | Risk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Normal | AND | Positive | AND | Protective | AND | Proof | AND | Low | --> | Low |
| 2 | Normal | AND | Positive | AND | Protective | AND | Proof | AND | Medium | --> | Low |
| 3 | Normal | AND | Positive | AND | Protective | AND | Proof | AND | High | --> | Low |
| 4 | Normal | AND | Positive | AND | Protective | AND | Medium | AND | Low | --> | Low |
| 5 | Normal | AND | Positive | AND | Protective | AND | Medium | AND | Medium | --> | Low |
| 6 | Normal | AND | Positive | AND | Protective | AND | Medium | AND | High | --> | Low |
| 7 | Normal | AND | Positive | AND | Protective | AND | Superficial | AND | Low | --> | Low |
| 8 | Normal | AND | Positive | AND | Protective | AND | Superficial | AND | Medium | --> | Low |
| 9 | Normal | AND | Positive | AND | Protective | AND | Superficial | AND | High | --> | Medium |
| 10 | Normal | AND | Positive | AND | Neutral | AND | Proof | AND | Low | --> | Low |

We can find that the outputs are the same even we change the delay and working time. The reason is that in fuzzy logic, we don`t use precise numerical data to make decision, it`s kind of a fuzzy concept. That`s why we can make decision to delay the maintenance activities as only if the risk level is acceptable.

### 3.2.3 Defuzzication and output variables

Defuzzification is the process of producing a quantifiable result in Crisp logic, given fuzzy sets and corresponding membership degrees. These will have a number of rules that transform a number of variables into a fuzzy result, the result is described in terms of membership in fuzzy sets.

In engineering applications, it is necessary to defuzzify the result or rather “fuzzy result” so that it must be converted to crisp result. Mathematically, the process of Defuzzification is also called “rounding it off”.

A common and useful defuzzification technique is center of gravity. First, the results of the rules must be added together in some way.Now, if this trapezoid were to be cut in a straight horizontal line somewhere between the top and the bottom, and the top portion were to be removed, the remaining portion forms a trapezoid.

In the most common technique, all of these trapezoids are then superimposed one upon another, forming a single geometric shape. Then, the centroid of this shape, called the fuzzy centroid, is calculated. The x coordinate of the centroid is the defuzzified value.

The output variable is used to define the additional risks connected with the delayed maintenance both for the operator safety and for the productivity.

Both the variables are ranged between 0 to 1. And the output variables are divided in 3 membership function (Low, Medium, High). Each membership function represents the different level of risks. For the membership functions the trapezoidal shape is used.

In the following we can define the risk details and related group nodes as before in table 22 and table 23, and we can get the relating membership function figure in figure 18, the risk level is defined according to the opinion of experts. It`s not easy to define the risk level, but we can make proper method to define them.

For the risk of safety, we can say that: the risk for the operator is low if it can be manged with appropriate protective measure; the risk is medium if ordinary protective measure are not sufficient for guaranty the safety condition; the risk is high if it`s not possible to guarantee the safety condition, the plant must be stopped.

For the risk of productivity, we can say that: the risk is low if the plant can continue at work the risk of stop and product out of specification can be managed and controlled; the risk is medium if the risk of plant stopping and product out of specification can be managed only with dedicate and extraordinary measure; the risk is high if plant stopping and product out of specification can not be managed.

***Table 22:*** *output definition for risk for safety(and for risk for productivity). We divided this input variable into 3 groups. The maximum independent variable value is 1, and the minimum is 0.*

| | |
|---|---|
| Output | |
| Name | Risk (both for safety and productivity) |
| Group | 3 |

| | |
|---|---|
| Minimum | 0 |
| Maximum | 1 |

***Table 23:*** *Groups of nodes to define the membership function. For the first specific R trapezoidal function we just have c-d values. For the last fuzzy set we have c=d= ∞, here we use the maximum value to represent infinity. The middle one is the normal trapezoidal function.*

| group<br>node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Low | 0 | 0 | 0.2 | 0.4 |
| Medium | 0.2 | 0.4 | 0.6 | 0.8 |
| High | 0.6 | 0.8 | 1 | 1 |

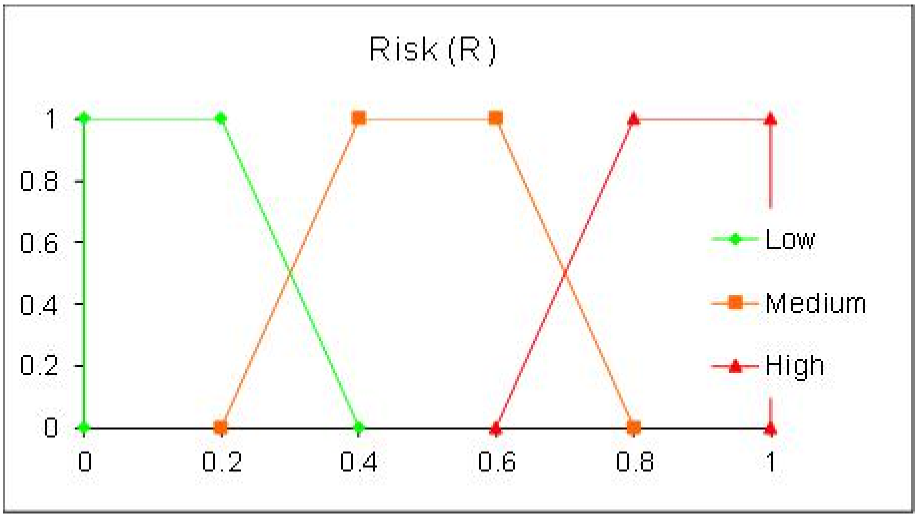



***Figure 18:*** *membership functions of the output variable. It includes three fuzzy sets with the names 'Low, medium, High'. The first fuzzy set`s shape is the R trapezoidal function, the second is normal symmetrical trapezoidal function, and the last one is L shape trapezoidal function.*

The mathematical representation of the figure is shown in the following, it can help us to get the crisp value from the fuzzy results.

$$Low\begin{cases}1, 0 < R < 0.2\\2-5R, 0.2 < R < 0.4\\0, 0.4 < R < 1\end{cases}$$

$$Medium\begin{cases}0, 0 < R < 0.2 or 0.8 < R < 1\\5R-1, 0.2 < R < 0.4\\1, 0.4 < R < 0.6\\4-5R, 0.6 < R < 0.8\end{cases}$$

$$High\begin{cases}0, 0 < R < 0.6\\5R-3, 0.6 < R < 0.8\\1, 0.8 < R < 1\end{cases} \tag{3-9}$$

***Table 24:*** *Risk output variable description. We can describe 3 different levels of severity for both safety and productivity: Low, Medium, High. These classifications derive from the opinion of experts and past experience.*

| | Risk for Safety ($R_s$) | Risk for productivity ($R_p$) |
|---|---|---|
| Low | The risk for the operator is low and it can be manged with appropriate protective measure | The plant can continue at work the risk of stop and product out of specification can be managed and controlled |
| Medium | The ordinary protective measure are not sufficient for guaranty the safety condition | The risk of plant stop and product out of specification can be managed only with dedicate and extraordinary measure |
| High | In this case is not possible guaranty the safety condition, the plant must be stopped | The risk of plant stop and product out of specification can not be managed |

# 4 Application example

Now we will have an actual case study to verify the reliability of this method. We should compare two results together to ensure the result getting from the method is not so different from the result from professional experts.

At first we should get the 5 crisp inputs from actual maintenance data. For the first and second input, we can get them from formula (3-1) and (3-3), so that we can have the precise input data. For the other three inputs we need the specific models to define the relative level, the total range is [0,1], 0 represents the lowest level and 1 represents the highest. The experts can describe how the specific condition fulfills the language representation, the company can use the average data coming from professional experts.

This case study is normal for one company relating to the vehicle limit rod near the gate of company. It rises and falls every working day when the cars want to come in the parking lot or leave from the company. If the company decide to delay the maintenance, mechanical failure maybe occurs, the vehicle limit rod will not be able to move anymore. When the staffs want to drive their cars coming into the parking lot of company, they will cause traffic jam near the company, which is a huge safety hazard. If the company decide to remove the rod by force, it`s a loss and not safe for the cars inside the company, which is not a closed space anymore.

As for the first input variable, the vehicle limit rod should be checked and maintained every 10 weeks, but there are not enough manpower during august, when almost all people are on their holiday. We can think the deferred maintenance time is 4 weeks, so we can calculate variable D using the formula (3-1).

$$D = \frac{4weeks}{10weeks} = 0.4 \qquad (4\text{-}1)$$

When we talk about about working time condition, we should consider the equivalent working time, in this case it`s number of rising and falling. According the statistical data, the actual equivalent working time of vehicle limit rod is about 0.2. The value is pretty low because there are always 2~3 cars coming together in the morning, and the condition is always the same in the afternoon. What`s more, we should consider the legal holidays and private holidays.

The vehicle limit rod is not so sensitive to the fluid working condition, because it just need to rise and fall, the electric power is sufficient to fulfill these tasks even there is not enough lubricating oil or the weather condition is not good. According to the maintenance record, the professional experts define the value is 0.45, a little smaller than 0.5.

The monitoring quality is medium. Company staff check the vehicle limit almost every because they are using it. If there are some problems they will know it immediately. But they cannot know the failure in advance, if they find the failure, there must be the actual failure. So the value for the forth variable monitoring quality is defined as 0.5.

We have said some possible severity for safety and productivity. If there is a traffic jam outside the company, as well as a safety hazard, it must influence the productivity. But the cost to replace a new vehicle limit rod is not high. In conclusion we can decide the value for the severity of safety or productivity is 0.5.

Then we will use the membership function of each variable to fuzzify them, after that we can use the "average weighted method" to get the result, at last we can defuzzify the output to get the risk level. We should compare this risk level with the opinions from experts, we can see that the risk is medium, which is similarly to the opinion from experts, so we can say that this method is acceptable.

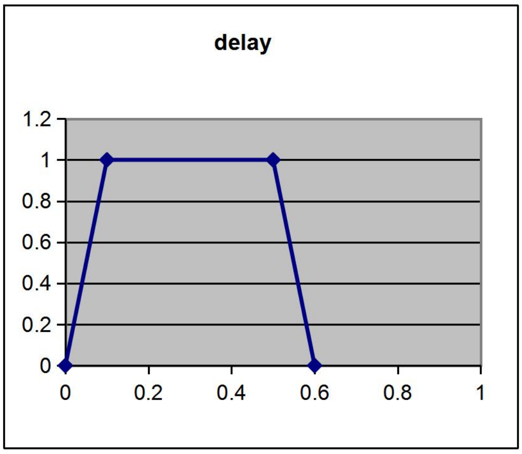
In the following table25 and figure group, we can have a look at total view of the inputs and output value.

***Table 25:*** *two groups of data, used to check the reliability of basic rule. The two group of data are the same expect of the first two input variables. Their results are the same.*

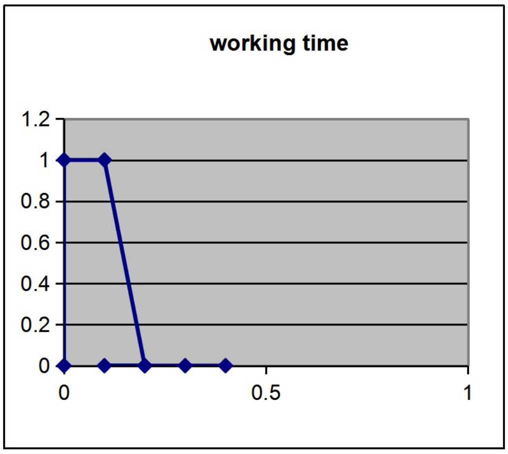
| | Value | Active part(s) |
|---|---|---|
| Delay | 0.4 | Critical |
| Working time | 0.2 | Positive |
| Fluid/condition/environment | 0.45 | Neutral |
| Monitor quality | 0.5 | Medium |
| Severity | 0.5 | Medium |
| Output | 0.5 | Medium |

Here we can check if the rules based on the basic rule are right or not. At first we have five crisp input variables, we should invert them into fuzzy parts with the help of their membership functions. After that we can use the center of gravity method to get the fuzzy result, and the related crisp result.

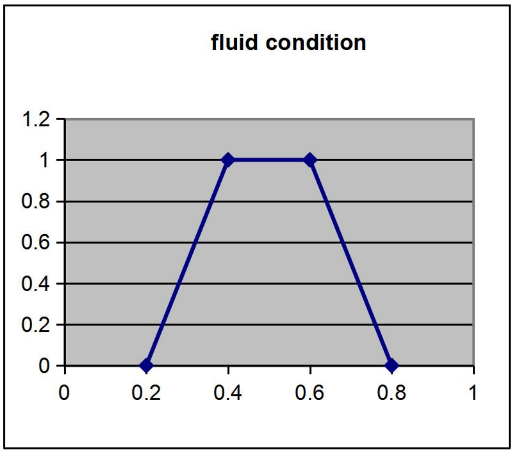
In the following figures we will see the process to get crisp results.



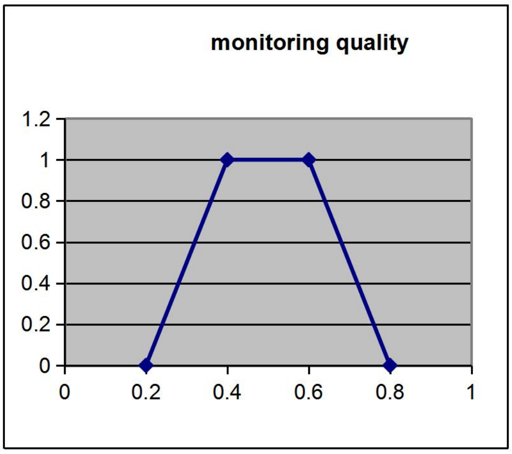

(a)



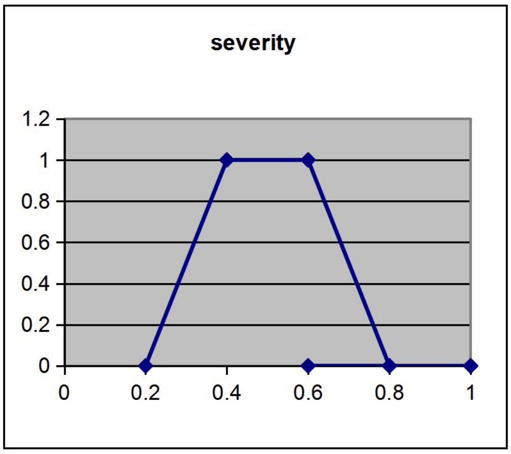

(b)



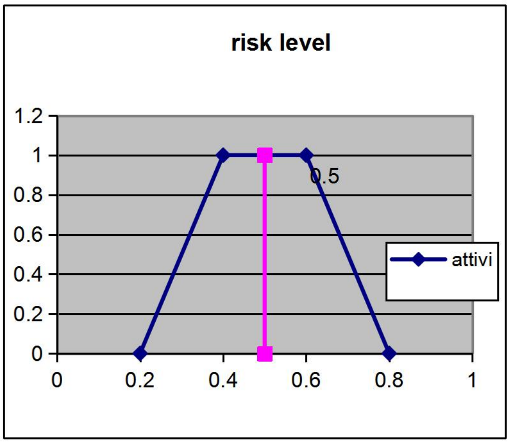

(b)




(d)




(e)




(f)

***Figure 19:*** *the five input variables figures and relating crisp output. (a) input 1, the delay is 0.4, in critical part; (b)input 2, working time. When the value is 0.2, the active part is always positive; (c)input 3, working fluid condition, the value is 0.45 which is active in neutral part; (d)input 4,*

*monitor quality, the value is 0.5 which is active in medium part; (e)input 5, severity for safety or productivity, the value is 0.5 which is active in medium part; (f)output is active in medium part, the centre line is the red one, whose crisp value is 0.5.*

We can say that if delay is critical and working time is positive and fluid condition and environment is neutral and monitor is medium and severity for safety is medium, then the risk for safety is medium. The result is acceptable so we can say the rules based on basic rule is acceptable. And although the inputs of two conditions are different, the level are almost the same, so the final risk levels are the same, which is similar to human being`s mind.

And now we should try to find some methods to reduce the risk. Here we can find it`s not useful to reduce the working time, through the vehicle limit rod works less time in August, because the active part is already in positive part, if we reduce the working time, it`s still in positive part, the risk level will not change.

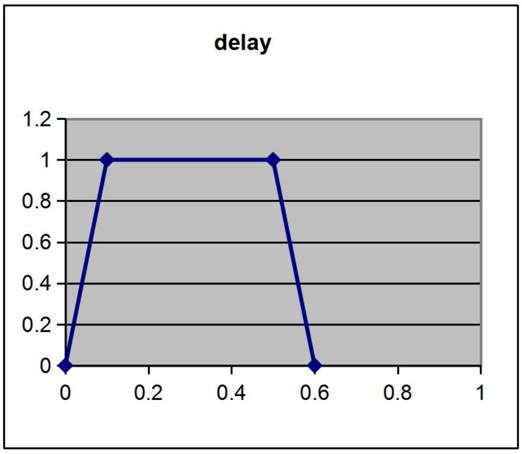
So we can try to improve the fluid condition and working environment by using lubricating oil and a cover to avoid bad weather. Image that the value of 3$^{rd}$ variable is reduced to 0.2, which is in protective part, in the mean while the other conditions don`t change, we can see if the risk is lower than before.

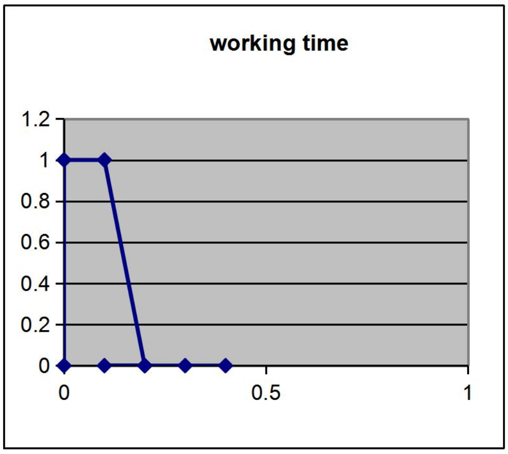
The working fluid condition and environment is 0.2 now with the help of lubricating oil and physical cover. Other conditions are the same as before. So we can have an overview of variables in the following table 26.

***Table 26:*** *the changed data group, which the fluid condition is better than before.*

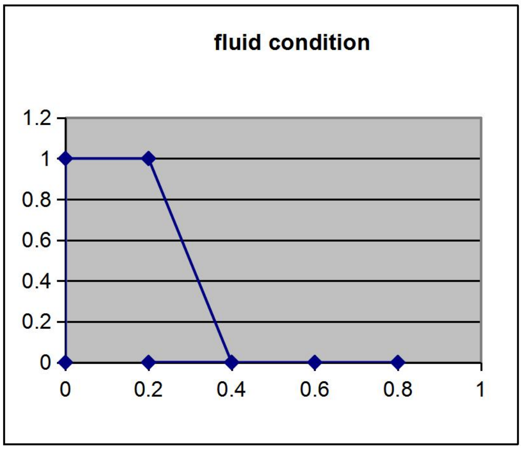
| | Value | Active part(s) |
|---|---|---|
| Delay | 0.4 | Critical |
| Working time | 0.2 | Positive |
| Fluid/condition/environment | 0.2 | Protective |
| Monitor quality | 0.5 | Medium |
| Severity | 0.5 | Medium |
| Output | 0.37 | Low / Medium |

In the following we will see the process of fuzzy logic. We will use the relative membership function to represent the five input variables condition, then we can use average weighted method to get the output value.

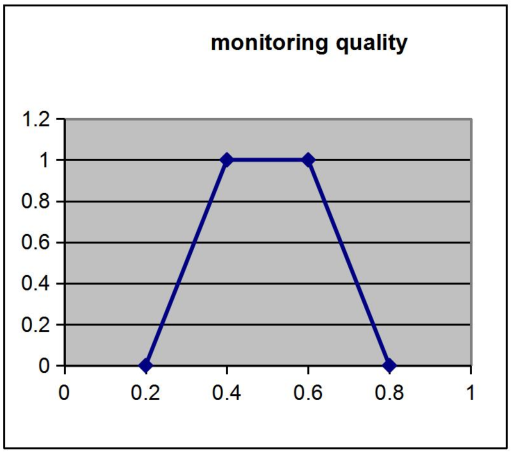


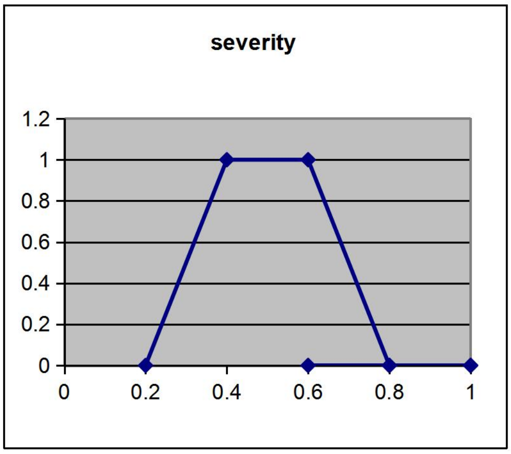

(a) (b)



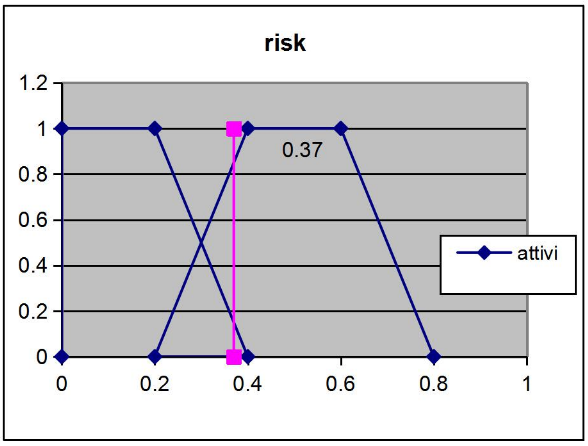

(c)




(d)




(e)




(f)

***Figure 20:*** *the five input variables figures and relating crisp output as reference condition. (a) input 1, the delay is 0.4, in critical part; (b)input 2, working time. When the value is 0.2, the active part is always positive; (c)input 3, working fluid condition, the value is 0.2 which is active in protective part; (d)input 4, monitor quality, the value is 0.5 which is active in medium part; (e)input 5, severity for safety or productivity, the value is 0.5 which is active in medium part; (f)output is active in medium part, the centre line is the red one, whose crisp value is 0.37.*

We can see that the risk level is lower if the fluid condition and working environment is better than before with the help of lubricating oil and cover. Normally if the risk level is relatively low, it means acceptable. The risk level is low but kind of medium, we can try another method to further reduce the risk.

$$risk - level \downarrow = \frac{0.5 - 0.37}{0.5} = 26\% \tag{4-2}$$

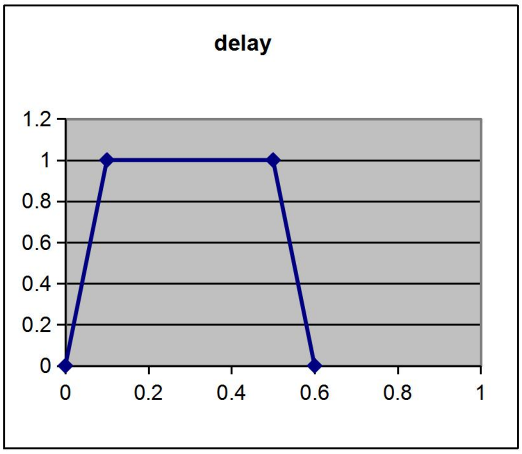
They can do some other compensation, for example they can improve the monitoring quality, they will know the problem if the company decide to use a more advanced monitoring equipment. We can image that the monitoring quality is better than before with the help of advanced automatic monitoring equipment, the value is reduced to 0.2. If we make other variables the same as before, the output value will be the same as the condition which we just modify the working fluid and environment from a mathematical point of view, because the only difference of these two conditions is the sequence of 3rd and 4th variable, the results will be the same if we use the average weighted method.

We can continue to reduce the risk level if we modify the 3rd and 4th variables together. We can image that the working fluid condition is better and the monitoring quality is better. In the following table we can see the total variables condition.

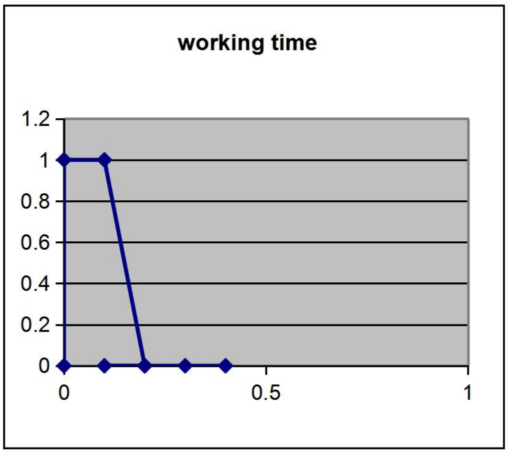
***Table 27:*** *the changed data group, which the fluid condition and monitoring quality are better than before.*

| | Value | Active part(s) |
|---|---|---|
| Delay | 0.4 | Critical |
| Working time | 0.2 | Positive |
| Fluid/condition/environment | 0.2 | Protective |
| Monitor quality | 0.2 | Proof |
| Severity | 0.5 | Medium |
| Output | 0.24 | Low / Medium |

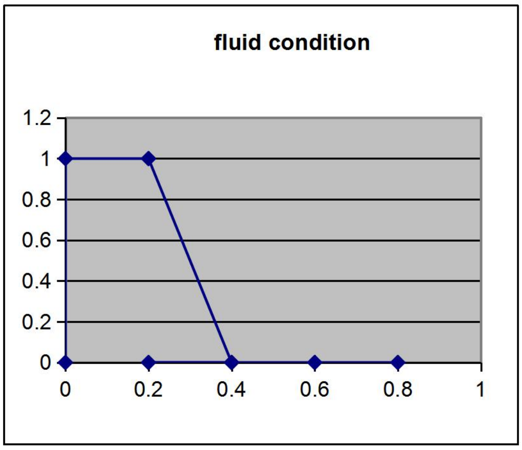
In the following we will see the process of fuzzy logic. We will use the relative membership function to represent the five input variables condition, then we can use average weighted method to get the output value.



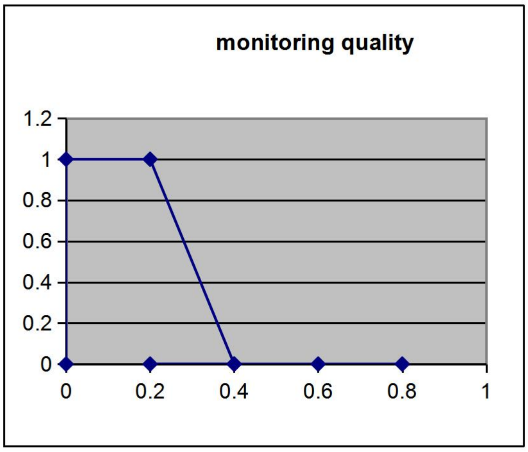

(a)



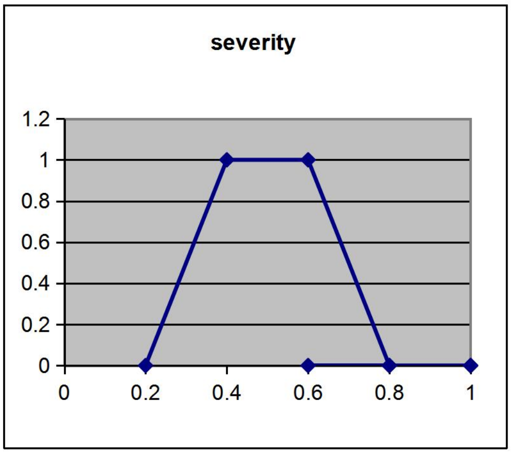

(b)

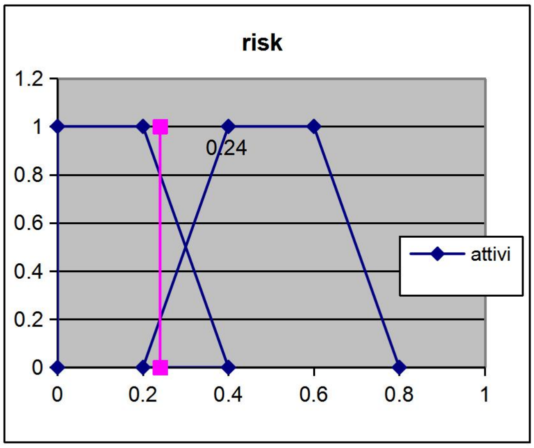



(d)




(d)




(e) (f)

***Figure 21:*** *the five input variables figures and relating crisp output as reference condition. (a) input 1, the delay is 0.4, in critical part; (b)input 2, working time. When the value is 0.2, the active part is always positive; (c)input 3, working fluid condition, the value is 0.2 which is active in protective part; (d)input 4, monitor quality, the value is 0.2 which is active in proof part; (e)input 5, severity for safety or productivity, the value is 0.5 which is active in medium part; (f)output is active in medium part, the centre line is the red one, whose crisp value is 0.24.*

We can see that the risk level is lower if the fluid condition and working environment is better than before with the help of lubricating oil and cover, and the monitoring quality is better due to a more advanced automatic monitor equipment. Normally if the risk level is relatively low, it means acceptable. The risk level is low but kind of low, we can think the risk level is acceptable.

$$risk-level \downarrow = \frac{0.5-0.24}{0.5} = 52\% \qquad (4\text{-}3)$$

In conclusion if the company can improve the working fluid condition by using the lubricating oil and the physical cover, and the company can use more advanced monitoring equipment to improve the monitoring quality, the decision-maker can decide to defer the maintenance activity for one month. But the company should do the maintenance as soon as possible when they have time.

The method can help the company to decide whether to defer the maintenance when the options occur. Based on the actual equipment working situations, the company can make the most reasonable choice. But it should be noted that the company should apply the maintenance activities as soon as possible, because we delay the maintenance without other choice at that time, we should compensate it as soon as possible. The best condition is that all equipment should be checked and maintained regularly.

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## Rules table

*The total rules for the risk assessment analysis based ob fuzzy logic. The rules for risk for safety are the same, we don`t show them for simplicity.*

| Delay | | Working time | | Fluid condition | | Monitor quality | | Severity | | Risk |
|---|---|---|---|---|---|---|---|---|---|---|
| Normal | AND | Positive | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Positive | AND | Protective | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Positive | AND | Protective | AND | Proof | AND | High | --> | Low |
| Normal | AND | Positive | AND | Protective | AND | Medium | AND | Low | --> | Low |
| Normal | AND | Positive | AND | Protective | AND | Medium | AND | Medium | --> | Low |
| Normal | AND | Positive | AND | Protective | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Positive | AND | Protective | AND | Superficial | AND | Low | --> | Low |
| Normal | AND | Positive | AND | Protective | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Positive | AND | Protective | AND | Superficial | AND | High | --> | Medium |
| Normal | AND | Positive | AND | Neutral | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Positive | AND | Neutral | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Positive | AND | Neutral | AND | Proof | AND | High | --> | Medium |
| Normal | AND | Positive | AND | Neutral | AND | Medium | AND | Low | --> | Low |
| Normal | AND | Positive | AND | Neutral | AND | Medium | AND | Medium | --> | Medium |
| Normal | AND | Positive | AND | Neutral | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Positive | AND | Neutral | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Positive | AND | Neutral | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Positive | AND | Neutral | AND | Superficial | AND | High | --> | Medium |

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| Normal | AND | Positive | AND | Critical | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Positive | AND | Critical | AND | Proof | AND | Medium | --> | Medium |
| Normal | AND | Positive | AND | Critical | AND | Proof | AND | High | --> | Medium |
| Normal | AND | Positive | AND | Critical | AND | Medium | AND | Low | --> | Medium |
| Normal | AND | Positive | AND | Critical | AND | Medium | AND | Medium | --> | Medium |
| Normal | AND | Positive | AND | Critical | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Positive | AND | Critical | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Positive | AND | Critical | AND | Superficial | AND | Medium | --> | High |
| Normal | AND | Positive | AND | Critical | AND | Superficial | AND | High | --> | High |
| Normal | AND | Litle positive | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Litle positive | AND | Protective | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Litle positive | AND | Protective | AND | Proof | AND | High | --> | Low |
| Normal | AND | Litle positive | AND | Protective | AND | Medium | AND | Low | --> | Low |
| Normal | AND | Litle positive | AND | Protective | AND | Medium | AND | Medium | --> | Low |
| Normal | AND | Litle positive | AND | Protective | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Litle positive | AND | Protective | AND | Superficial | AND | Low | --> | Low |
| Normal | AND | Litle positive | AND | Protective | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Litle positive | AND | Protective | AND | Superficial | AND | High | --> | Medium |
| Normal | AND | Litle positive | AND | Neutral | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Litle positive | AND | Neutral | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Litle positive | AND | Neutral | AND | Proof | AND | High | --> | Medium |
| Normal | AND | Litle positive | AND | Neutral | AND | Medium | AND | Low | --> | Low |
| Normal | AND | Litle positive | AND | Neutral | AND | Medium | AND | Medium | --> | Medium |

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| Normal | AND | Litle positive | AND | Neutral | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Litle positive | AND | Neutral | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Litle positive | AND | Neutral | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Litle positive | AND | Neutral | AND | Superficial | AND | High | --> | High |
| Normal | AND | Litle positive | AND | Critical | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Litle positive | AND | Critical | AND | Proof | AND | Medium | --> | Medium |
| Normal | AND | Litle positive | AND | Critical | AND | Proof | AND | High | --> | Medium |
| Normal | AND | Litle positive | AND | Critical | AND | Medium | AND | Low | --> | Medium |
| Normal | AND | Litle positive | AND | Critical | AND | Medium | AND | Medium | --> | Medium |
| Normal | AND | Litle positive | AND | Critical | AND | Medium | AND | High | --> | High |
| Normal | AND | Litle positive | AND | Critical | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Litle positive | AND | Critical | AND | Superficial | AND | Medium | --> | High |
| Normal | AND | Litle positive | AND | Critical | AND | Superficial | AND | High | --> | High |
| Normal | AND | Normal | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Normal | AND | Protective | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Normal | AND | Protective | AND | Proof | AND | High | --> | Low |
| Normal | AND | Normal | AND | Protective | AND | Medium | AND | Low | --> | Low |
| Normal | AND | Normal | AND | Protective | AND | Medium | AND | Medium | --> | Low |
| Normal | AND | Normal | AND | Protective | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Normal | AND | Protective | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Normal | AND | Protective | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Normal | AND | Protective | AND | Superficial | AND | High | --> | Medium |
| Normal | AND | Normal | AND | Neutral | AND | Proof | AND | Low | --> | Low |

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| Normal | AND | Normal | AND | Neutral | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Normal | AND | Neutral | AND | Proof | AND | High | --> | Medium |
| Normal | AND | Normal | AND | Neutral | AND | Medium | AND | Low | --> | Medium |
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| Normal | AND | Normal | AND | Neutral | AND | Medium | AND | High | --> | Medium |
| Normal | AND | Normal | AND | Neutral | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Normal | AND | Neutral | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Normal | AND | Neutral | AND | Superficial | AND | High | --> | High |
| Normal | AND | Normal | AND | Critical | AND | Proof | AND | Low | --> | Medium |
| Normal | AND | Normal | AND | Critical | AND | Proof | AND | Medium | --> | Medium |
| Normal | AND | Normal | AND | Critical | AND | Proof | AND | High | --> | Medium |
| Normal | AND | Normal | AND | Critical | AND | Medium | AND | Low | --> | Medium |
| Normal | AND | Normal | AND | Critical | AND | Medium | AND | Medium | --> | Medium |
| Normal | AND | Normal | AND | Critical | AND | Medium | AND | High | --> | High |
| Normal | AND | Normal | AND | Critical | AND | Superficial | AND | Low | --> | Medium |
| Normal | AND | Normal | AND | Critical | AND | Superficial | AND | Medium | --> | High |
| Normal | AND | Normal | AND | Critical | AND | Superficial | AND | High | --> | High |
| Normal | AND | Critical | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Normal | AND | Critical | AND | Protective | AND | Proof | AND | Medium | --> | Low |
| Normal | AND | Critical | AND | Protective | AND | Proof | AND | High | --> | Low |
| Normal | AND | Critical | AND | Protective | AND | Medium | AND | Low | --> | Low |
| Normal | AND | Critical | AND | Protective | AND | Medium | AND | Medium | --> | Medium |
| Normal | AND | Critical | AND | Protective | AND | Medium | AND | High | --> | Medium |

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| Normal | AND | Critical | AND | Protective | AND | Superficial | AND | Medium | --> | Medium |
| Normal | AND | Critical | AND | Protective | AND | Superficial | AND | High | --> | Medium |
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| Normal | AND | Critical | AND | Critical | AND | Superficial | AND | High | --> | High |
| Normal | AND | High critical | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Normal | AND | High critical | AND | Protective | AND | Proof | AND | Medium | --> | Low |

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| Critical | AND | Litle positive | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Critical | AND | Litle positive | AND | Protective | AND | Proof | AND | Medium | --> | Low |
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| Critical | AND | Normal | AND | Protective | AND | Proof | AND | Low | --> | Low |
| Critical | AND | Normal | AND | Protective | AND | Proof | AND | Medium | --> | Low |
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| Critical | AND | High critical | AND | Critical | AND | Proof | AND | Medium | --> | Medium |
| Critical | AND | High critical | AND | Critical | AND | Proof | AND | High | --> | High |
| Critical | AND | High critical | AND | Critical | AND | Medium | AND | Low | --> | Medium |
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| High critical | AND | Positive | AND | Protective | AND | Proof | AND | Low | --> | Low |

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| High critical | AND | Positive | AND | Protective | AND | Proof | AND | High | --> | Low |
| High critical | AND | Positive | AND | Protective | AND | Medium | AND | Low | --> | Low |
| High critical | AND | Positive | AND | Protective | AND | Medium | AND | Medium | --> | Low |
| High critical | AND | Positive | AND | Protective | AND | Medium | AND | High | --> | Medium |
| High critical | AND | Positive | AND | Protective | AND | Superficial | AND | Low | --> | Medium |
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| High critical | AND | Positive | AND | Neutral | AND | Proof | AND | Medium | --> | Low |
| High critical | AND | Positive | AND | Neutral | AND | Proof | AND | High | --> | Medium |
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| High critical | AND | Positive | AND | Neutral | AND | Superficial | AND | High | --> | High |
| High critical | AND | Positive | AND | Critical | AND | Proof | AND | Low | --> | Medium |
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| High critical | AND | Litle positive | AND | Protective | AND | Proof | AND | Low | --> | Low |
| High critical | AND | Litle positive | AND | Protective | AND | Proof | AND | Medium | --> | Low |
| High critical | AND | Litle positive | AND | Protective | AND | Proof | AND | High | --> | Low |
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