UNIVERSITY OF PIRAEUS
DEPARTMENT OF INDUSTRIAL MANAGEMENT AND TECHNOLOGY
MSC IN PROJECT MANAGEMENT AND PRODUCT DEVELOPMENT

A Fuzzy Logic DSS for Scope Optimization in Industrial Maintenance Projects based on Reliability Targets

Mitrofani Ioanna
(tmd1611)

Supervisor: Prof. Dimitrios Emiris

Piraeus 2018

Abstract

The aim of this research is to build a Decision Support System (DSS) for scope optimization in large maintenance projects using fuzzy logic concepts. This thesis investigates the maintenance and reliability considerations of industrial systems and builds on basic fuzzy logic strategies to develop an agile and easy-to-use, fuzzy logic DSS for scope definition. The system, once built, is further improved and fine-tuned after examination of the initial results; furthermore, the proposed DSS is contrasted and compared to other systems that use conventional, crisp logic methods that are used to determine the maintenance project scope. The thesis culminates with the evaluation of the system through four illustrative and realistic cases.

Fuzzy Logic was selected as the foundation of our approach as it provides an answer about the need to maintain an item based on a group of criteria. These reliability-based criteria are: the Mean Time Between Failures (MTBF), the Criticality of the item, its Reliability, the Mean Time To Repair (MTTR), the Total Operation Cost (TOC) and the Value of the equipment. The combination of these criteria using fuzzy logic techniques enables the proposed DSS to extract meaningful results on the necessity to maintain an item and hence, assists decision makers to shape the maintenance project scope. The results are presented both as numbers as well as classes and are visually supported by 3D plots.

The comparison of the proposed system with other traditional approaches of the problem, adds robustness to the DSS and helps fine-tune fuzzy decision rules and parameters of the system. The comparison is rich, as it compares results for thirty (30) pragmatic cases, using data obtained from the industry. It is shown, that our DSS generates trustworthy, comparable results, and for certain cases, even more improved ones, thus justifying its use in industrial, large-scale environments.

Our analysis and approach gives important insight on maintenance techniques and sheds new light on alternative scope definition and optimization approaches. The exposed results may well lead to efficient planning of maintenance, especially in complex industrial projects, without being affected by the large data size.

Acknowledgements

I would like to thank all those who directly or indirectly helped me to complete this research. First and foremost, I would like to express my sincere thanks to my professor, Mr. Dimitrios Emiris, who supported me, showed confidence to my personality and skills, guided me constantly throughout our cooperation. Finally, I warmly thank my parents, who have supported me in every possible way during those years, giving me great supplies, part of which were my studies.

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Chapter 1. Introduction

The study and evaluation of the reliability of the equipment is of major importance in the operation of industrial plants. Damage and/or failure of equipment may turn to one of the biggest problems in the manufacturing process in industries, which due to their nature seems to reduce the useful life of the equipment components. The result of equipment failure is often the generation of a variety of problems in production and the increase of maintenance costs; furthermore, several industrial accidents have occurred due to the equipment malfunction, endangering the staff working on the premises.

In industrial sites, wear of the equipment is almost unavoidable, since, in most cases it is installed outdoors and is exposed to corrosive environment. The control and repair of breakdowns takes up most of the equipment maintenance. Repairs (damage, wear, replacements) take up most of the staff time available while diagnostic tools are used to locate the equipment failure mechanism at the early stage of its occurrence. For example, in a large refinery plant, corrective maintenance covered 55% of working hours, while 45% corresponded to preventive maintenance work. Additionally, special care must be shifted to the equipment that is characterized as critical, that is, when it fails, it causes a breakdown in the production process. Such equipment is included in preventive and predictive maintenance programs to minimize instances of failure.

The availability and reliability of the various components in industry, is thus an important area for the industrial plant operation as well as for the equipment operation. Over the years, this subject has evolved and developed to a large extent now becoming a necessary tool for industry, a key instrument for enhancing production quality and for preventing accidents.

In the business world, maintenance has traditionally been tied to the actions and practices of corrective maintenance (unplanned or breakdown or on-failure maintenance) and preventive maintenance (fixed-time or planned maintenance). Over the last decades, predictive (condition-based) maintenance has been on rise. Nowadays, there exist six categories of maintenance:

1. Preventive Maintenance
2. Predictive Maintenance
3. Proactive Maintenance
4. Run-to-Failure or Breakdown Maintenance
5. Reliability Centered Maintenance
6. Total Productive Maintenance

Focusing on preventive maintenance, it is crucial to emphasize that it is composed of regularly scheduled inspections, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment and it is performed regardless of equipment condition. Thus, the condition of each system complies with the manufacturer’s specifications and its availability is maximized, the life of the equipment will be extended, closer to design and the system runs more efficiently. Preventive maintenance, frequently, constitutes an independent project of an industry.

Due to the above concerns, the role of Project Management in industrial maintenance arises as a key necessity. According to the Project Management Institute (PMI®), a project is "*a temporary endeavour undertaken to produce a unique product, service or result*"; furthermore, Project Management is "*the application of knowledge, skills, tools and techniques to project activities to meet the project requirements*". Based on the PMBOK® guide [1], project management is composed of multiple areas that must be managed at the same time. These areas are:

- Project integration management
- Project scope management
- Project time management
- Project cost management
- Project Quality management
- Project Human resource management
- Project Communication management
- Project Procurement management
- Project Risk management
- Project Stakeholder management [1]

The definition of the scope of a project is crucial for its success, because if scope is not well-defined several problems arise and targets are difficult to meet. The project scope is the set of tasks that needs to be performed to deliver a product, service or result with the specified features and functions. The size of a project and the precise determination of its scope is a complex yet necessary task. Therefore, we must take the necessary actions to ensure that all work required has been planned and only the necessary work is executed to achieve the success of the project.

The subject of project management has become one of the most common themes nowadays. In recent years, the number of mega projects worldwide is increased and there is a rapid growth in all areas of knowledge, which requires new methods of project management. One of the biggest and common seen contemporary problems in the project area, in recent years, is the management of a huge scope. This research deals with the problem of upper and lower limitation of the scope of a project. Its purpose is the scope optimization in industrial maintenance projects, including regulations and concepts of reliability. Thus, a solution, to one of the biggest contemporary problems in the project management area, is offered.

In order to better illustrate our approach, this thesis is structured as follows. Chapter 2 describes the concepts of maintenance and reliability. It is about basic principles which, by extension are part of our system. Chapter 3 presents the fuzzy logic theory, the whole system and our development approach. Chapter 4 presents our system, how it is built and analyses a basic version. In Chapter 5, a testing of the system takes place, an improved version is generated and the outcomes are presented. Chapter 6 contains a comparative study between an established system used in industry and our fuzzy logic system. Finally, in Chapter 7 the conclusions of the survey are presented and guidelines for future research are highlighted.

Chapter 2. Maintenance and Reliability Theory

"Production" is the reason organisations exist. Systems used in the production of goods are subject to deterioration with usage and age. Most of them are maintained or repairable systems. Thus, applying maintenance on them may be necessary since it can improve reliability, prevent the occurrence of system failures, and reduce maintenance costs of deteriorating systems [1] [2].

Maintenance often includes major machine components changes or upgrades. “Reliability” of a machine measures whether it does what it is manufactured to do whenever it is required to do it. Statistically, reliability is the probability that a machine will remain on line producing as required for a desired time period [1]. These two notions are not strictly connected by their definition, but they use one another, in order to maximize the machine-hours and minimize the costs.

2.1 Maintenance

Maintenance in the manufacturing environment is one of the most complicated types of maintenance. Manufacturing has a highly competitive environment, with extremely high pressure in reducing cost and increasing value of assets and improving the quality of outcomes. These factors enforce the manufacturing business put maintenance in a great pressure on developing more effective and efficient operations.

Additionally, maintenance in manufacturing deals with highly technical equipment that needs special types of expertise. As such maintenance in manufacturing requires highly sophisticated level of planning and operations more than any other business environment.

Taking all the above into account, it is obvious why several maintenance concepts and types were developed within the passage of time and the growth of technology. Some of these concepts and types are summarized below. [3]

2.1.1 Types and concepts of maintenance

In the business world, maintenance has traditionally been tied to the actions and practices of corrective maintenance (unplanned or breakdown or on-failure maintenance) and preventive maintenance (Fixed time or planned maintenance). Over the last decades, predictive (condition-based) maintenance has been on rise. [4] The following figure incorporates the most common types of maintenance:

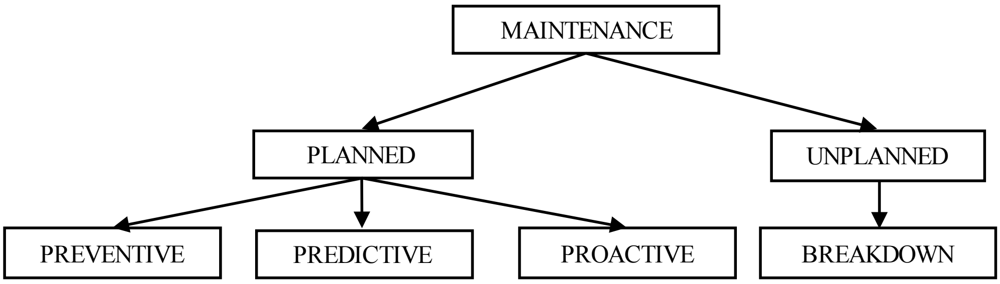

Figure 1 Types of maintenance

Preventive Maintenance: consists of regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. PM schedules periodic inspection and maintenance at pre-defined intervals (time, operating hours, or cycles) in an attempt to reduce equipment failure. It is performed regardless of equipment condition. By performing the preventive maintenance based on designer's specifications, the life of the equipment will be extended, closer to design and the system runs more efficiently. While PM prevents equipment from catastrophic failures, the number of failures is decreased. Minimizing failures translate into maximizing the system's availability and cost reduction.

Advantages

- Cost effective.
- Flexibility allows for the adjustment of maintenance periodicity.
- Increased component life cycle.
- Energy savings.
- Reduced equipment or process failure.

Disadvantages

- Includes performance of unneeded maintenance.
- Potential for incidental damage to components in conducting unneeded maintenance.

Predictive Maintenance: uses primarily non-intrusive testing techniques, visual inspection, and performance data to assess machinery condition. Predictive maintenance replaces the timed maintenance tasks with maintenance that is scheduled only when warranted by equipment condition. Continuing analysis of equipment condition-monitoring data allows planning and scheduling of maintenance or repairs in advance of catastrophic and functional failure. A well-organized predictive maintenance eliminates catastrophic equipment failures, minimizes (or deletes) the overtime cost (through optimal scheduling) and minimizes the inventory of the parts required.

Advantages

- Increased component operational life/availability.
- Allows corrective actions.
- Decrease equipment or process downtime.
- Improved worker and environmental safety.
- Energy savings

Disadvantages

- Increased investment in diagnostic equipment.
- Increased investment in staff training.
- Savings potential not readily seen by management.

Proactive Maintenance: concentrates to identifying and correcting abnormal causes of failure that create unstable operating conditions. One of the best features of a proactive approach is that the techniques are natural extensions of those used in a predictive maintenance program, and they are easily added to existing programs. A successful proactive maintenance extends machine life, reduce down time, and expands production capacity. [5] [6]

Advantages

- Increased component operational life/availability.
- Allows corrective actions.
- Decrease equipment or process downtime.
- Avoids unnecessary disruptions
- Identify improvement opportunities

Disadvantages

- Increased investment in diagnostic equipment.
- Increased investment in staff training.
- Savings potential not readily seen by management.

Run-to-Failure or **Breakdown Maintenance:** allows the failure to appear without preventive action. The failure of a component or a system is unpredictable and the cost of performing run-to-failure activities, in some cases, is lower than other types of maintenance.

In addition, varied maintenance concepts were developed around the world and this encompasses other strategies and technologies of maintenance. Some of these concepts are presented below:

Reliability Centered Maintenance (RCM)

It is commonly said “don’t fix it until it breaks” or “don’t break it by trying to fix it”. There is a grain of truth to these maxims, but they interpret a very trivial approach if it is tried to achieve reliability levels for a facility. RCM is a logical way of identifying what equipment in a facility is required to be maintained on a preventive maintenance basis rather than a run-to-failure (RTF) basis. It is an industrial improvement approach that focuses on identifying and establishing the operational and maintenance improvement policies that will manage the risks of equipment failure most effectively. Within the manufacturing conditions, RCM is an approach for understanding the function of the manufacturing system and the failure modes of its components, and choosing the most advantageous action that would prevent the failure modes from occurring or to identify them before occurring.

There are a lot of ways to maintain facilities and equipment in order to prevent failures and the reliability centered maintenance is probably the best path to get as close as possible to that 100 percent reliability threshold. A very important notion of RCM analysis is that also considers the fact that maintenance budgets are not unlimited, and thus some stable basis exists for deciding what to do and where to dispense the effort Thus, RCM takes into account safety, economics and uses a logic tree to present maintenance tasks. RCM is very simple in concept but also very complex in its application and develops maintenance standards for ensuring that a system meets its designed reliability or availability. It is function oriented, group focused and reliability centred. It uses statistics in order to look at the relationship between operating age and the failures.

There are a lot of benefits from RCM efficient implementation, some of them are presented below:

1. Increased reliability and availability.
2. Reduction in total maintenance cost.
3. Increasing efficiency and productivity.
4. Reducing lifecycle costs including acquisition phase and operation phase since decisions made early in the acquisition cycle profoundly affect the life-cycle cost.
5. Improving maintenance sustainability as RCM planning includes decisions made at all phases of equipment life cycle. [3] [7]

Additionally, reliability centered maintenance is one of the classical concepts of maintenance and the most commonly used. On the other side, there is a modern concept of maintenance, frequently named as Total Productive Maintenance, which nowadays is not applicable widenly, but in some countries and industries has emerged. This is one of the new trends in maintenance implementation.

Total Productive Maintenance

TPM is a philosophy of penetrating all the operations of a business and affects workers at all levels. It is a collection of techniques and practices that are applied in order to maximize plant efficiency and increase worker's participation and morale. The clue of this theory is that TPM is not the actual maintenance activities but setting up and sustaining an effective program of maintenance. That depends on everything that supports those activities: collection of accurate data, clearly defined responsibilities for everyone involved, and procedures that provide for ongoing support of TPM efforts.

Total: all-encompassing by maintenance and production individuals working together.

Productive: production goods and services that meet or exceed customers' expectations. Some researchers strongly believe that “Productive” means “People”. When a total productive maintenance program (TPM) is implemented, the managers usually talk about how it helps company make the workplace cleaner and reduces downtime.

Maintenance: keeping equipment and plant in as a good as or better than the original conditions at all times.

There are five (basic) pillars to support the TPM philosophy:

1. Autonomous Maintenance
2. Training and Skill Development
3. Early Equipment Management (EEM) and Maintenance Prevention (MP) design
4. Maintenance Process Improvement (MPI)
5. Planned, scheduled maintenance system

However, the plurality of analysts extends that list consisting of the traditional five TPM pillars with Quality Maintenance, Administrative Systems, and Environmental/ Safety/Health Systems (eight pillars of TPM).

Management and employees such as the operators, conservators, engineers treat the equipment as if it belonged to them. Maintenance, in TPM philosophy, is not just the work of conservators. Autonomous maintenance is a critical element of TPM and its basic idea is to provide operators with more responsibility and allow them to carry out preventive maintenance work. [4] [8] On top of that, Michael Woolbert (quality team leader, Phillips Petroleum) said: “*focusing on machines or the eight or five “pillars” of TPM is “not enough” to have a successful implementation. People are the focus and benefactors of TPM and when they feel successful and respected they are motivated to participate in continuous improvement efforts”*. [8] In addition, Rich Soderquist said: “*Morale seems to be one of the huge benefits and probably one of the main benefits is instantaneous recognition for employees. They know their work order is going to get recognized now. Everybody’s pet peeve is people who don’t follow through. They’re seeing a lot of follow-through, and that encourages them*.” [8] Nevertheless, operators and conservators must be “equipped” with training and skills which are necessary for the smooth execution of the activities in order to TPM be applied efficiently.

A fundamental difference between TPM and other maintenance programs is that the operators are those who maintain against to failures, rework, scrap etc. However, there are some experts who claim that total productive maintenance becomes more effective if it is accompanied by reliability centered maintenance

(RCM). That's the view of managers at Whirlpool, Richard Word, who said: "*RCM is a tool that a TPM team can utilize to do more proactive work. It helps TPM to just do a better job.*" [8]

Pairing the two approaches usually produces momentous benefits, such as:

- Increased equipment productivity and plant capacity.
- Approaching zero equipment downtime.
- Lower maintenance and production costs.
- Enhanced job satisfaction and morale.

2.2 Reliability

Reliable is a component that complies with the design specifications and functions without failures for a finite time in specific conditions. The definition of reliability includes a number of external variables. For example, the same machines may have different operating rate requirements, such as continuous operation or frequent stops and different environmental conditions, such as excessive dust. [4] [9]

In other words, reliability is a characteristic of an item (a system composed from parts) expressed by the probability that the item will perform its required function under finite time and given conditions. The important factors associated with reliability are probability, time period and working conditions. In order to understand, in depth, the meaning of reliability, there are two notions under analysis, the qualitative and the quantitative point of view. In a qualitative way, reliability is the ability of an item to remain functional. On the other hand, in a quantitative way, reliability specifies the probability that operational interruption will occur during a stated time. Alongside, the redundant parts may not fail and these parts can "downgrade" and be repaired without breach at item level. Thus, reliability can be applied to repairable as well as to non-repairable items. [9] [10] [11]

At this point, it is critical to mention and introduce three other terms associated with reliability, in order to define what repairable and non-repairable items are:

Total Up Time: It is the period for which an equipment remains operational without any failure.

Mean Time to Failure (MTTF): It is the time period between the failures of equipment (time of first failure to the next one).

Mean Failure Rate: expresses the failures that can be occurred over a time interval. If there are N components in service for time T, then failure rate is N/T.

Non-repairable Items

In this case the item that fails must be replaced.

It is considered that there are N items in service (down) with a test interval T and the i-th failure takes place at time T_i. So:

$$\text{Total Up Time} = \sum_{i=1}^{N} T_i$$

$$MTTF = \frac{\sum_{i=1}^{N} T_i}{N}$$

or

$$MTTF = \int_0^{\infty} R_t(dt), \text{ where } R_t(dt) \text{ is reliability}$$

In this case the Mean Failure Rate is called $\bar{\lambda}$ and it is expressed as:

$$\bar{\lambda} = \frac{Number\ of\ failures}{Total\ Up\ Time}$$

so,

$$\bar{\lambda} = \frac{N}{\sum_{i=1}^{N} T_i}$$

Therefore, $\bar{\lambda} = \frac{1}{MTTF}$ and respectively $MTTF = \frac{1}{\bar{\lambda}}$.

Repairable Items

Contrariwise, in this case items can be repaired. This involves a down time of an item as a time to repair is needed. The down time is indicated as T_{D_j} and it is associated with j-th failure. This down time refers to the total time between the appearance of the failure and the time that is needed till the repaired item being put back into operation. So the total down time for N_f failures is:

$$Total\ Down\ Time = \sum_{j=1}^{N} T_{D_j}$$

Therefore, the Mean Down Time is described as:

$$\text{Mean Down Time} = \frac{\sum_{j=1}^{N_f} T_{D_j}}{N}$$

The Total Up Time is calculated by the equation:

$$Total\ Up\ Time = Total\ Time - \sum_{j=1}^{N_f} T_{D_j}$$

Availability and Reliability

Additionally, the availability of a system quantifies its reliability, in other words, how long the system is available to function normally. The basic relationship model for availability is:

$$Availibility = \frac{Up\ Time}{Total\ Time} = \frac{Up\ Time}{Up\ Time + Down\ Time}$$

The definitions of availability are qualitative in distinction and indicate important differences. There are three types of availability: inherent, achieved and operational.

The inherent availability is dependent on mean time between failures and mean time to repair, but it excludes preventive maintenance down time, logistic time and waiting, administrative down time. Achieved availability depends on mean time between maintenance and mean maintenance time, but ignores logistics time and waiting administrative time and includes active preventive and corrective maintenance down time. The operational availability depends on mean time between maintenance, mean down time.

As it is already mentioned, reliability is the probability that the unit performs its intended functions for a given period of time under the stated operating conditions or environment. Therefore, reliability is a function of time and also depends on environmental conditions which may or may not be function of time. It is evident that, directly or not, availability and reliability are related. If the availability of the equipment/system is high its reliability will be high. [10] [12]

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Chapter 3. Fuzzy Logic

3.1 Description of Fuzzy Logic

The term "fuzzy logic" has been used for decades and at first it had the meaning of any logic possessing more than two truth values. Afterwards, L. Zadeh [13] was the first to introduce two other meanings of fuzzy logic, namely the theory of approximate reasoning and the theory of linguistic logic. Generally, fuzzy logic can be characterized as the many-valued logic with special properties. By contrast with Boolean logic, in which the truth values of variables must be the integer values 0 or 1, in Fuzzy logic the truth values of variables may be a real number between 0 and 1. [14]

Fuzzy logic generalizes the familiar “yes-no” Boolean logic. If you give true the numerical value of 1 and false the numerical value 0, the fuzzy logic permits in between values like 0,3 and 0,85. For example, if the question is “Is Saturday a weekend day?”, the answer is 1 (true). If the question is “Is Thursday a weekend day?”, the answer is 0 (false). If the question is “Is Friday a weekend day?”, for some people the answer is “for the most part yes but not completely” and in fuzzy logic this is “translated” as 0,8. In fuzzy logic, unlike standard conditional logic, the truth of any statement is a matter of degree.

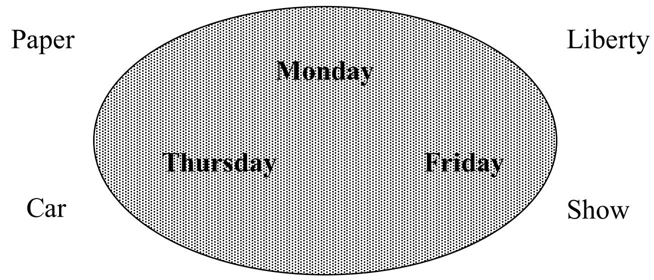
Fuzzy logic builds on a set of human language rules and converts these rules to their mathematical equivalents. The scope of this logic is to outline an output with the help of an input. A fuzzy system can be created to match any set of input-output data. Fuzzy inference systems are the models of the Fuzzy logic and they are a sequence of "if-then" rules. The way the models are built is analyzed in detail in next chapter.

To summarize, Fuzzy logic is a rule-based approach and a membership function scheme which simplify the design of systems and ensure that can be easily updated over time. The additional benefit of this type of logic, except from the simplicity and flexibility, is that clarifies the job of the system designer and the results are in much more detailed representations of the way systems behave in the real world. The major advantage that fuzzy reasoning offers is the ability to reply to a yes-no question with a not-quite-yes-or-no answer. [15] [16]

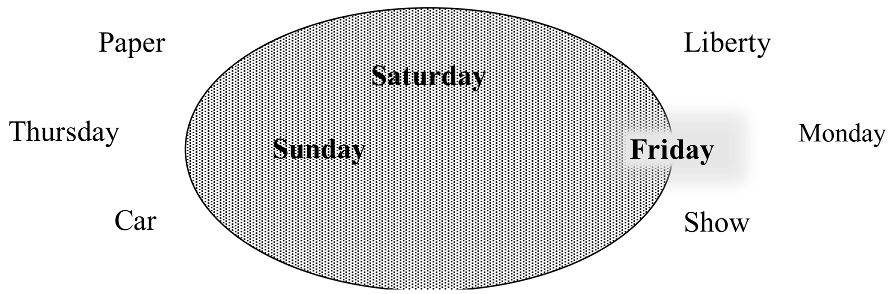
3.1.1 Fuzzy sets

A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership. In order to understand what a fuzzy set is, first we have to consider the definition of a classical set. A classical set is a container that wholly includes or excludes any given element. In a classical set, one thing must be either asserted or denied and thus there are two categories: A and not-A. Let's analyze the previous example:

- Monday, Thursday and Friday are definitely part of the set "days of the week".
- Paper, Car, Show and Liberty are definitely not a part of the set "days of the week".



In this case the values are crisp. Now, if we try to classify the days of the weekend, the set will be like:



As mentioned above, it is commonly accepted that Saturday and Sunday belong to the set "days of weekend". On the other hand, Friday feels like a part of the weekend, but technically should be excluded. Classical sets would not permit this kind of classification, but this representation is more realistic and shows the way systems behave in the real world.

At that point we attempt to represent the truth values for “days of weekend”, if you are forced to respond with an absolute yes or no response (first diagram), or if you are allowed to respond with fuzzy in-between values (multivalued logic).

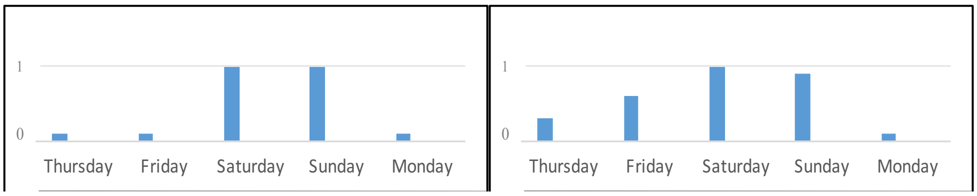


Figure 2 Scale time plot of “days of weekend”

To return to the example, if we consider a continuous scale time plot of “days of weekend”, the results are shown in the following plots. By making the plot continuous, it is defined the degree to which any given instant belongs in the weekend rather than an entire day. In the plot on the left, at midnight on Friday, just as the second hand sweeps past 12, the truth value “jumps” discontinuously from 0 to 1. The plot on the right shows a smoothly varying curve that accounts for the fact that all of Friday, and, to a small degree, parts of Thursday, deserve partial membership in the fuzzy set of weekend moments. The plot on the right represents how things happen in the real world and is way closer to fuzzy logic.

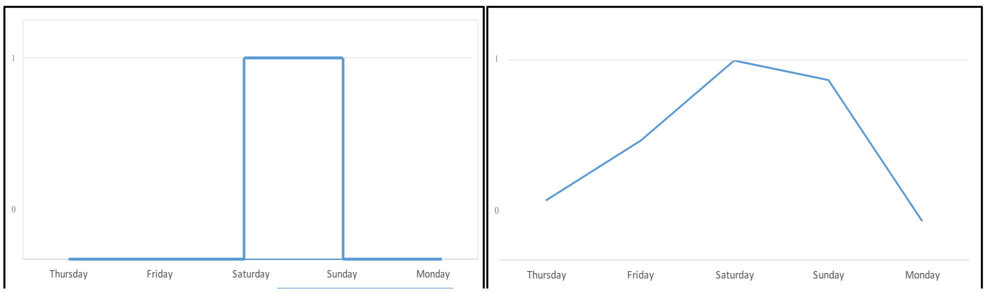


Figure 3 Scale time-continuous plot of “days of weekend”

To summarize, in fuzzy logic the truth of any statement becomes a matter of degree and membership functions, which will be analysed below, help that to be defined.

3.1.2 Membership Functions

A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is referred as the universe of discourse.

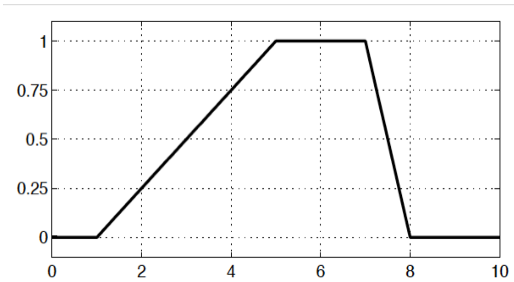
One of the most commonly used examples of a fuzzy set is the set of tall people. In this case, the universe of discourse is all potential heights, from 140cm to 200cm. The word "tall" would correspond to a curve that defines the degree to which any person is tall. If the set of "tall people" is given the defined boundary of a classical set, it is said that all people that they are taller than 165cm are tall. However, such a distinction is unreliable and does not reflect to reality.

If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs:

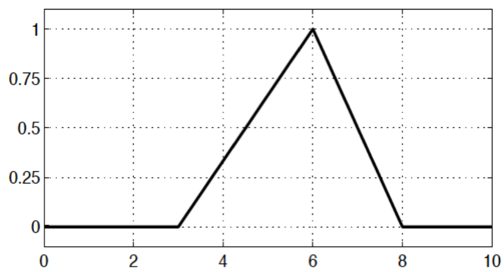
$$A = \{x \,, \mu_A(x) \mid x \in X\}$$

$\mu_A(x)$ is called the membership function of x in A

The only condition a membership function has to satisfy is that must range between 0 and 1. There are many types of curves for membership functions. The simplest membership functions are formed by straight lines. Two of them are the trapezoidal membership function and triangular membership function, as you can see respectively below:

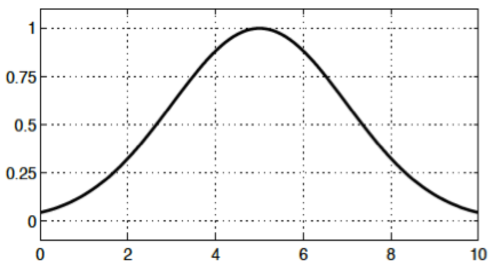


Trapezoidal

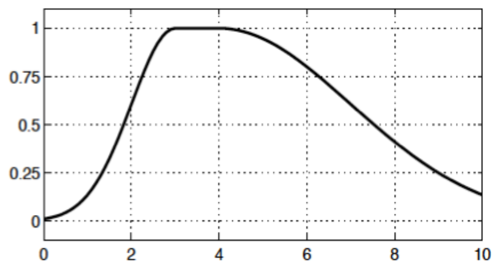


Triangular

There are also two membership functions based on Gaussian distribution, the simple Gaussian curve and the two-sided Gaussian curve (composite of two different Gaussian curves).

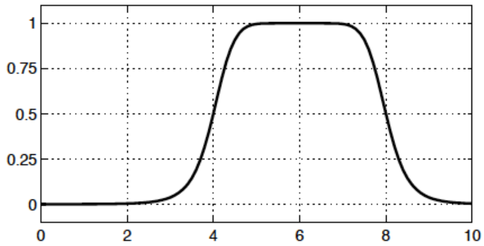


Simple Gaussian Curve



Two-Sided Gaussian Curve

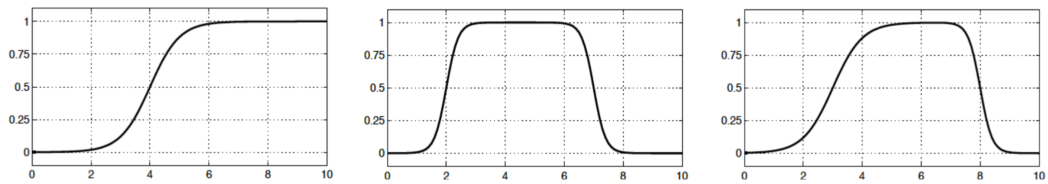
Excluding the two-sided Gaussian membership function, all the other membership function that had been referred are symmetrical. Additionally, there is the generalized bell membership function which is defined by three (3) parameters. That means that it has one more parameter than the simple Gaussian membership function. The generalized membership function can be used for non-fuzzy sets analysis and looks like the graph below:



Generalized Bell Curve

In addition, the generalized bell membership function and all the curves that are arising from Gaussian membership functions are commonly used for determining fuzzy sets because of the achieving smoothness. The same functions are unable to follow and identify asymmetric membership functions.

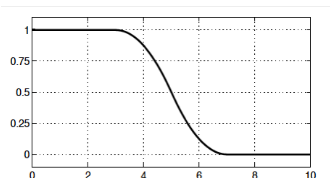
All the above membership functions are closed (not open to left or right). Contrariwise, sigmoidal membership function is open left or right. At this point it is critical to mention that asymmetric and closed membership function can be synthesized by using two sigmoidal functions. This methodology leads to different types of sigmoidal curves, as the curves presented below:



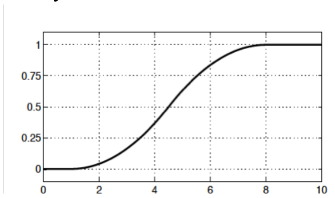
Types of Curves based on Sigmoidal Membership Functions

Also there are three polynomial-based curves, named z, s and pi. Their name arises from their shape as you can see below. The first one is an asymmetrical polynomial curve open to left. The second one is a mirror-image function that opens to right and the third one is zero in both extremes with a rise in the middle.

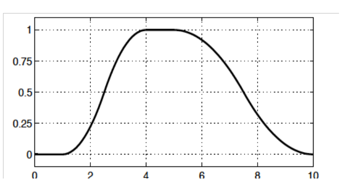
Polynomial-Based Curves



z



s



pi

To sum up, fuzzy sets describe vague concepts (fast runner, hot weather etc.) and admit the possibility of partial membership in it. The degree an object belongs to a fuzzy set is denoted by a membership value between 0 and 1. A membership function and a given fuzzy set, map an input value to a membership value. [15] [17]

3.1.3 Fuzzy Operators

The most important thing to know about fuzzy logic is the fact that it is a superset of basic Boolean logic. In other words, if we keep the fuzzy values at their extremes of 1 and 0 (completely true/false), standard logical operations will remain the same. Let us appose an example in order to understand the differences between classical and fuzzy operations. The basic operators are AND, OR, NOT and they function like in the matrixes below (based on classical theory):

AND			**OR**			**NOT**	
A	B	A and B	A	B	A or B	A	not A
0	0	0	0	0	0	0	1
0	1	0	0	1	1	1	0
1	0	0	1	0	1	B	not B
1	1	1	1	1	1	0	1
						1	0

Figure 4 Operators

In fuzzy logic the truth of a statement is a matter of degree. The input values can be real numbers between (0,1) and the operation that preserves the AND truth table and resolves the statement A AND B, is $\min(A, B)$. Let A and B are fuzzy subsets of a nonempty set X. The intersection of A and B is defined as:

$$(A \cap B)(t) = \min\{A(t), B(t)\} = A(t) \wedge B(t), \text{ for all } t \in X.$$

Using the same reasoning, the OR operation can be replaced with the max function, so that A OR B becomes equivalent to $\max(A, B)$. The union of A and B is defined as:

$$(A \cup B)(t) = \max\{A(t), B(t)\} = A(t) \vee B(t), \text{ for all } t \in X.$$

The complement of a fuzzy set A is defined as: $(-A)(t) = 1 - A(t)$.

Taking all the above into account, we can define the truth tables AND, OR, NOT for fuzzy sets as:

AND			OR		
A	B	min(A,B)	A	B	max(A,B)
0	0	0	0	0	0
0	1	0	0	1	1
1	0	0	1	0	1
1	1	1	1	1	1

NOT	
A	1-A
0	1
1	0
B	1-B
0	1
1	0

Figure 5 Fuzzy operators

As you can notice the previous table is completely unchanged compared with the first one. In order to fully understand the way those operations work we can convert the truth tables into graphs, as they are presented in the figures below. The first figure refers to a two-valued truth tables while the second figure displays how the operations work over a continuously varying range of truth values A and B.

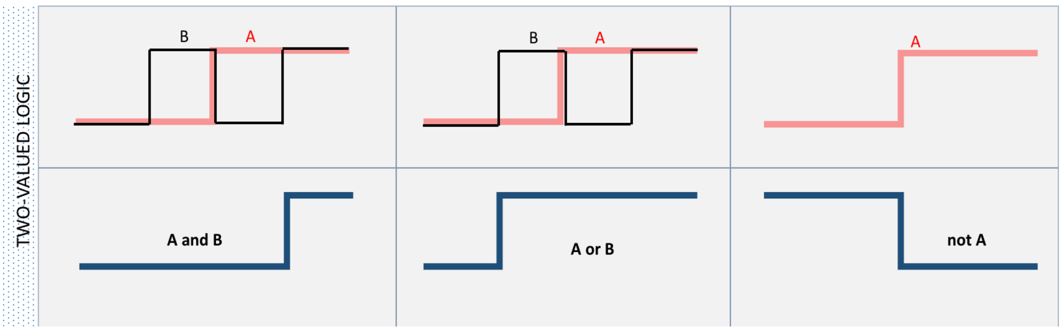


Figure 6 Two-valued logic

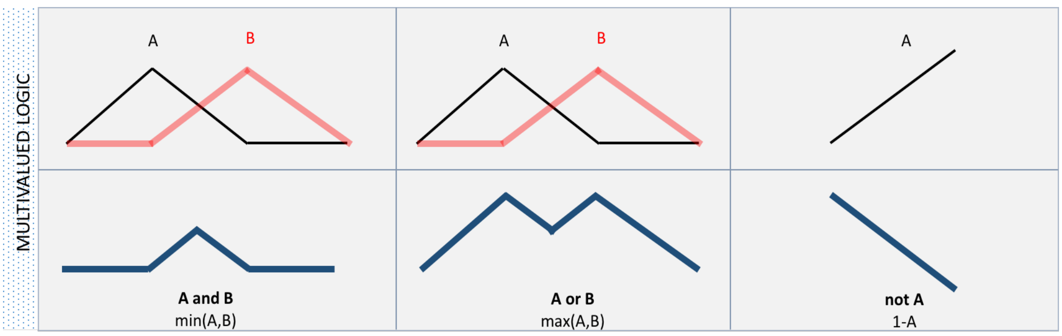


Figure 7 Multivalued logic

Combining fuzzy sets and fuzzy logical operations (AND, OR, NOT), any construction can be solved. [15] [18]

3.1.4 Rules

Fuzzy sets and fuzzy operators are for fuzzy logic what subjects and verbs are for a sentence. These if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic.

A single fuzzy if-then rule assumes the form:

if x is A then y is B

where A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y. The if-part of the rule "x is A" is called the antecedent or premise, while the then-part of the rule "y is B" is called the consequent or conclusion.

A common example might be the typical tipping problem. In this case the rule could be:

If service is good, then tip is average

The concept good is expressed as a number between 0 and 1, and so the antecedent returns a single number between 0 and 1.

Generally, the input to an if-then rule is the current value for the input variable (service) and the output is an entire fuzzy set (average). This set will be defuzzified assigning one value to the output. Interpreting an if-then rule involves distinct parts: first evaluating the antecedent and second applying that result to the consequent (known as implication). At this point is critical to note that if the antecedent is true to some degree of membership, then the consequent is also true to that same degree.

Multi-part antecedents/premises

The antecedent of a rule can have multiple parts:

If the sky is grey (1) and wind is strong (2) then (...)

All parts (1, 2) are calculated simultaneously and resolved to a single number using the logical operators described in preceding section.

Multi-part consequents/conclusions

Respectively, the consequent of a rule can have multiple parts:

If temperature is cold, then the hot water valve is open (1) and the cold water valve is closed (2).

All consequents are affected equally. The consequent specifies a fuzzy set be assigned to an output. The implication function modifies_that fuzzy set to the degree specified by the antecedent.

Interpreting if-then rules is a three-part process and it will be analysed in next section:

1. Fuzzify inputs: Resolve all fuzzy statements in the antecedent to a degree of membership between 0 and 1.
2. Apply fuzzy operator to multiple part antecedents: If there are multiple parts to the antecedent, apply fuzzy logic operators and resolve the antecedent to a single number between 0 and 1.
3. Apply implication method: Use the degree of support for the entire rule to shape the output fuzzy set. The consequent of a fuzzy rule assigns an entire fuzzy set to the output. This fuzzy set is represented by a membership function that is chosen to indicate the qualities of the consequent. [15] [19] [20]

3.2 Fuzzy Inference Process

This section refers to the mapping of the path from input to output using fuzzy logic, in other words, using member functions, logical operations, if-then rules etc. In order to understand how inference process is applied, we will examine an example of two-input, one-output, three-rule, the basic tipping problem.

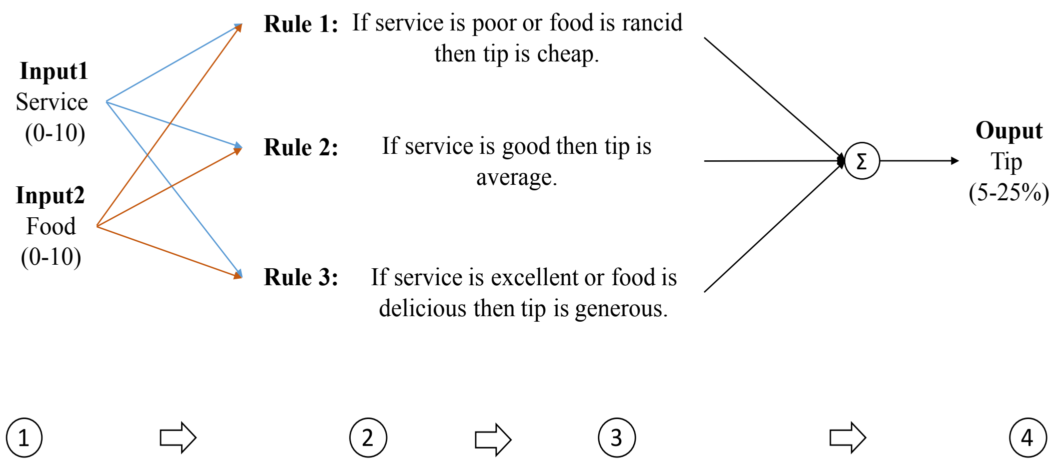


Figure 8 Inference process example

The first stage represents the inputs, which are crisp (non-fuzzy) numbers, limited to a specific range (0-10). In the second stage, all rules are evaluated in parallel using fuzzy reasoning. The parallel nature of rules is one of the most important aspects of fuzzy logic systems. Afterwards, the results of the rules are combined and distilled (defuzzified). The third stage refers to the result, which is always a crisp number. Information flows from left to right, from two inputs to a single output. Instead of sharp switching between modes based on breakpoints, logic flows smoothly from regions where the system's behaviour is dominated by either one rule or another. Fuzzy inference process comprises of five parts that are analysed in chapter 3.2.2.

In addition, there are two types of inference systems and vary in the way outputs are determined.: Mamdani and Sugeno. These types are analysed in the paragraph below. [15] [19] [20]

3.2.1 Types of Fuzzy Inference Systems

3.2.1.1 Mamdani

Mamdani is the commonly seen fuzzy methodology and expects the output membership functions to be fuzzy sets, the output need defuzzification. Sometimes is more efficient to use a single spice than a fuzzy set. This type of output is known as singleton output membership function.

Singleton output membership function maximizes the efficiency of the defuzzification process because it simplifies the computation required by the general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across two-dimensional function to find the centroid you use weighted average of a few data points.

3.2.1.2 Sugeno

Sugeno-type systems can support this model. That kind of systems can be used to model any inference system in which the output membership functions are linear or constant. The most crucial difference between Mamdani-type systems and Sugeno-type systems is the way the crisp output is generated from the fuzzy inputs. While Mamdani uses the technique of defuzzification of a fuzzy output, Sugeno uses weighted average to compute the crisp output. Mamdani systems have the “power” of consequents of the rules that are not fuzzy, on the other hand Sugeno has better processing time because the weighted average replaces the time consuming defuzzification process. Other differences between these systems are that Mamdani has output membership functions where Sugeno has no output membership functions. [15] [21] [22]

3.2.2 Steps of Fuzzy Inference Process

In furtherance of understanding the information flow during the inference process a figure is built below. This figure is a composition of other diagrams which are analysed by steps beneath this chapter.

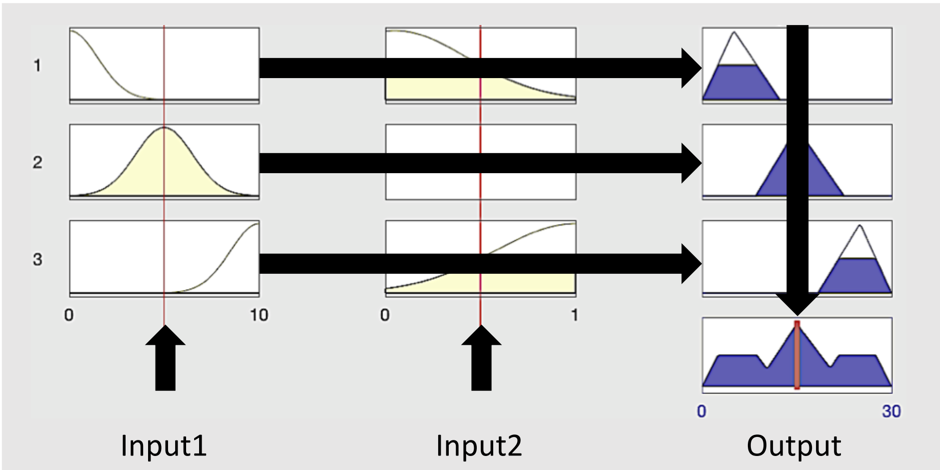


Figure 9 Fuzzy inference process

The flow proceeds up from the inputs in the left side to the lower right as the rows are showing. This compact figure shows everything at once, from linguistic variable fuzzification all the way through to defuzzification of the aggregated output. In actual full-size inference diagram there is a lot of information about the system which is under analysis, thus we will build an example and see diagrammatically the inference process step-by-step and cumulatively. The example which is used is called “The Basic Tipping Problem” and it is a simple example of two-input, one-output, three-rule tipping problem (the rules of it have been presented above this chapter).

In the next table you can see all the steps of fuzzy inference process that will get analysed.

Step 1 :	Fuzzify Inputs	→	Fuzzification of the input variables
Step 2 :	Apply Fuzzy Operator	→	Application of the fuzzy operator (AND, OR) in the antecedent
Step 3 :	Apply Implication Method	→	Implication for the antecedent to the consequent
Step 4:	Aggregate All outputs	→	Aggregation of the consequents across the rules
Step 5 :	Defuzzify	→	Defuzzification

STEP 1

- Take inputs and determine the degree they belong to each of the appropriate fuzzy sets via membership function.

This is a three-rule example and each rule depends on determining the inputs into a number of different fuzzy linguistic sets such as service is poor, service is good etc. The inputs must be fuzzified according to each of these linguist sets. For example, the following figure shows how well the food at the restaurant, rated on a scale of 0 to 10, certifies, via its membership function, as the linguistic variable delicious.

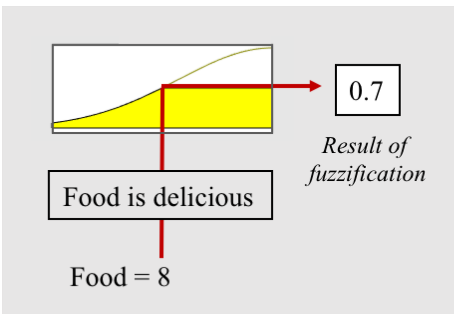


Figure 10 Result of fuzzification

In this case, we rate the food as an 8, which corresponds (from the graph) to $\mu = 0.7$ for the delicious membership function. Thus, all the inputs are fuzzified according to the rules and the membership functions.

STEP 2

- If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. The input of this step is two (or more) membership values from the first step and the output is a single number.

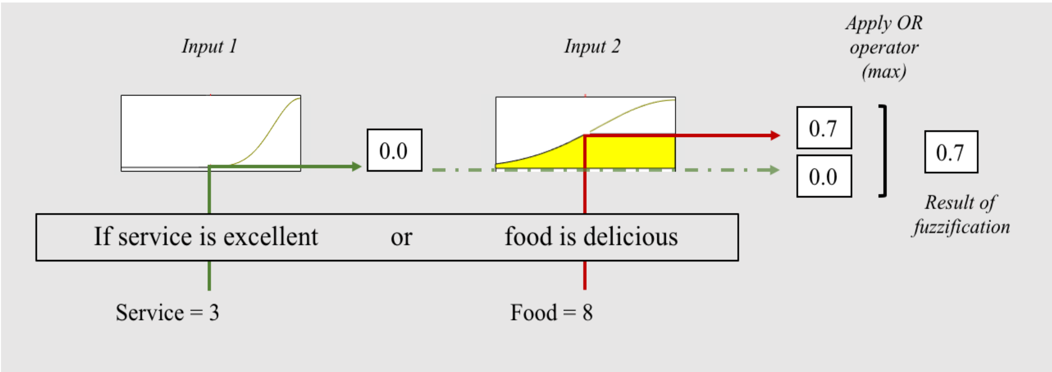


Figure 11 Application of fuzzy operator

This figure shows how practically OR operators works (logic operators are analyzed in chapter 3.1.3). The two different pieces of the antecedent, "*service is excellent*" and "*food is delicious*" return respectively the fuzzy membership values 0.0 and 0.7 (from the graph). The fuzzy OR operator, as it was known from previous chapter, selects the maximum of the two values (0.0 and 0.7). The result is 0.7.

STEP 3

- First of all, we have to determine the rule's weight. This will be applied to the number given by the antecedent. After weighting has been assigned to each rule, the implication method is implemented.

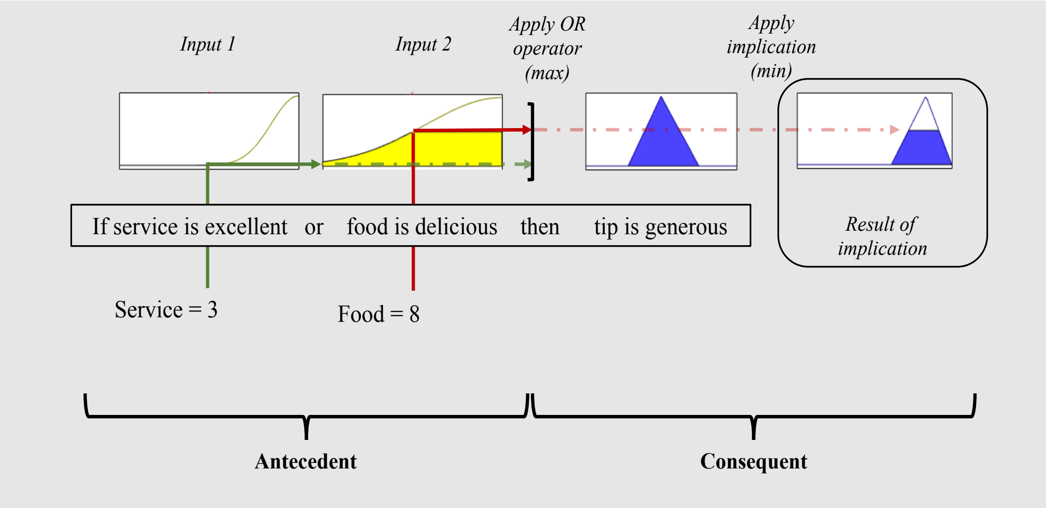


Figure 12 Result of implication

Every rule has a weight, a number between 0 and 1. In this case, the weight is 1 and thus does not effect at all on the implication process, but, generally, we can weight one rule to something other than 1. After this, the implication method is implemented. A consequent is a fuzzy set represented by a membership function, which weights appropriately the linguistic characteristics that are associated to it. The consequent is reshaped using a function attributed with the antecedent with a single number (0.7 for this example) and the output is a fuzzy set. In this manner, the implication is applied for each rule.

STEP 4

- Rules must have combined in same manner in order to make decision. In Aggregation Process the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set.

Aggregation is a preparatory step in order to an outgrowth can be exported in the next step. The input of this process are the output functions of the implication method (step3) and the output is one fuzzy set, ready to be defuzzified to the final step. In the following diagram, all rules have been implanted together to show how all the outputs are combined (aggregated) into a single fuzzy set.

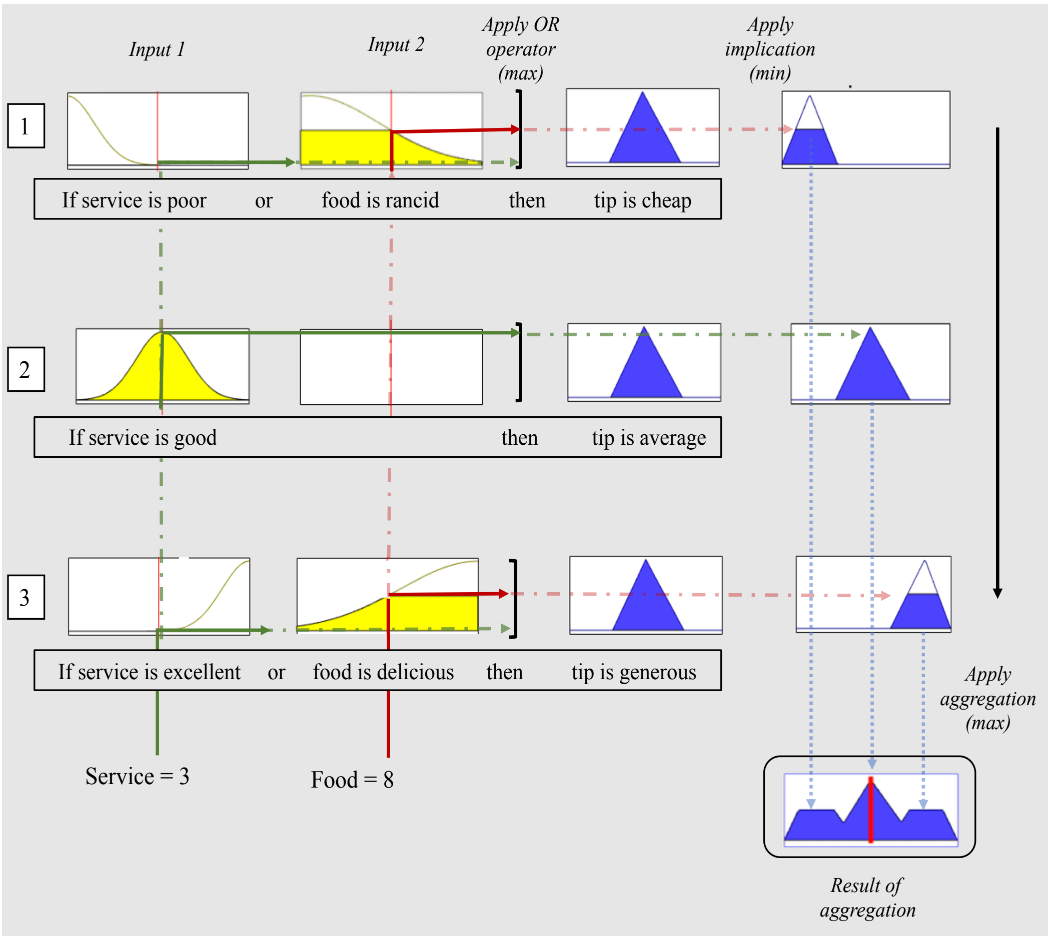


Figure 13 Aggregation of outputs

STEP 5

- This is the final step and delivers the final result. The input for the defuzzification process is a fuzzy set and the output is a single number.

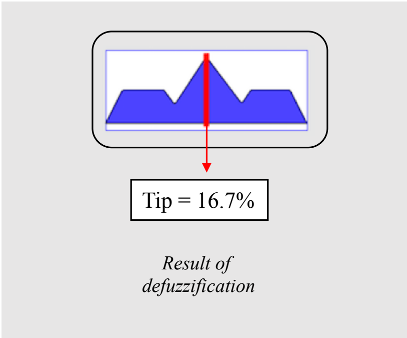


Figure 14 Result of defuzzification

All the above graphs were based on results of the Matlab tool. Using the same tool can produced the following graph that is a solid decision surface. That gives the opportunity to see the full range of output values according to service and food prices (inputs). This is a very user-friendly option, even if it is not a user or a knowledgeable of these tools. [15]

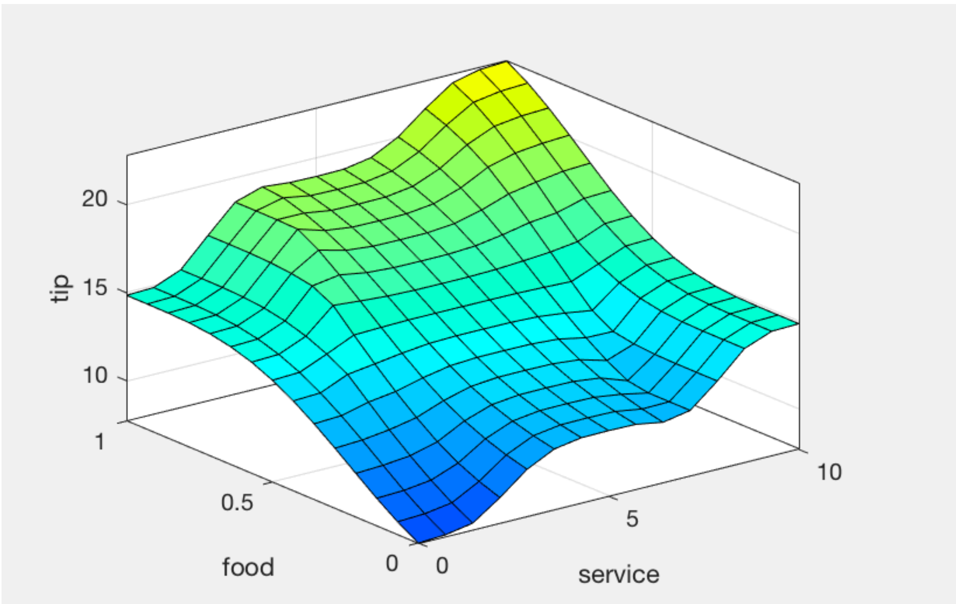


Figure 15 Decision surface

In next chapters we will present and analyse a complex example, which actually touches and solves complex realistic issues, such as a scope optimization in big projects with big scope.

Chapter 4. The system

4.1 System description

The system which is under analysis in the context of this thesis, refers to industrial maintenance projects driven by reliability targets. In the ordinary way, these projects raise the concern of the specialists about their scope. Considering that in such businesses there is a plethora of “maintainable” systems and it is a really common phenomenon to maintain the majority of them even if there is no immediate need. Thus, time and money are spent that could be used in other functions or projects of the business. On the other hand, there are cases that because of the limited budgeting or bad time management, that maintenance is skipped and the result is a conflux of failures.

The purview of this thesis is the scope optimization of projects with big scope so that will be maintained that number of systems in such a way that no time or money will be spent with no reason, or crucial systems will not be out of maintenance. The system that is analyzed in this section is a decision making system that is based on some criteria, which are analyzed below. These criteria are paired with the help of some rules. Those rules arise from empirical rules, based on the theory of maintenance as well as on practical implementation of maintenance as it is applied nowadays in industrial area.

This is a full adaptive and customizable system. Every engineer can adapt criteria, rules or the weighting part, depending on the information and needs an engineer can notice on the system which is under observation. Finally, there are some tools, like Matlab, where with their help this system becomes really user friendly, firstly because of its adaptiveness plus for the reason that the outputs are presented in such a way that the managers can easily read and decode them and make decisions.

4.2 Initial implementation

4.2.1 Criteria

Criteria are presented in the table below. As it is said above, the collection of them is based on the theory of maintenance as well as on practical implementation of maintenance as it is applied nowadays. Their analysis is in theoretical level.

	CRITERIA	ANALYSIS
1	**Mean Time Between Failures (MTBF)**	Is the mean elapsed time between failures of a system while the system operates normally. Describes the expected time between two failures for a repairable system with constant failure rate and it can be calculated as the arithmetic mean (average):

		$$MTBF = \frac{\sum(downtime - uptime)}{number\ of\ failures}$$ Alternatively, MTBF can be calculated as a reliability function: $$MTBF = \int_0^\infty t \cdot f(t)dt$$ *where,* *t, is the time of failure* *f(t), the density function of time until failure* MTBF helps out to estimate the rate of reliability of a system. The higher the MTBF, the more reliable the component is. [23] [24] [25]
2	**Criticality**	Equipment critically is used to identify the equipment priority in order of the importance to incessantness operation of a facility. This priority ranking depends on the risk of the equipment failure. Thus, those components or equipment items that will stop the production if they fail (the whole system is down) are identified as critical. Typically, the equipment's criticality ranking is performed by groups of people (expert's judgment) who analyze and categorize each equipment of a plant. There are two types of **Criticality Decision Methods**, the Standard Criticality Decision Methods and the True Cost of Failure Based Criticality Methods (Activity Based Costing-ABC). [26]
3	**Reliability**	Reliable is a component that complies with the design specifications and functions without failures for a finite time in specific conditions. Mechanical reliability (R(t)) is the probability that an item works properly, without failures for a finite time (t). $$R(t) = P(T \geq t) = 1 - P(T < t),\ t \geq 0$$ It is obvious that the more complex a system is, the more susceptible to damage it is and the overall

		function of that complex system depends on the function of the individual components. Especially in systems involving human factors, such as production systems, the chances of harm are growing and the overall reliability of the system decreases. [4]
4	**Total Operational Cost**	When a failure of a component occurs, the system is down, a corrective maintenance is performed and cost is created. In order to define that cost and which component failure affects it more, we use the Total Operational Cost (TOC): $TOC = \sum_{i=1}^{n} Ck_i \cdot \pi_i$ [9] where: Ck_i, the cost of each component π_i, stationary distribution
5	**Maintainability**	Maintainability is the probability that a failed item will be restored to operational effectiveness within a given period of time when the repair action is performed in accordance with prescribed procedures. It can be paraphrased as 'The probability of repair in a given time'. Maintainability has a relevance to maintenance in such way that takes into account the downtime of the systems. The mean time to repair (MTTR) is an indicator of maintainability, determines the repairable condition of equipment and it is usually established through corrective maintenance action. [27] [28] $MTTR = \frac{\sum t}{N}$ [29] where, $\sum t$ = summation of repair time N = total number of repairs
6	**Value of equipment**	The maintenance of equipment is the technological intervention made in order to maximize the

		production capacity for as long as possible. Repairing the equipment is to replace or repair parts of it that have been destroyed or damaged in order to restore its production capacity or improve the operating conditions. The extensions, additions and improvements of equipment increases the value of the equipment. There are several methods to evaluate the value of equipment. Both valuing the value of the equipment and maximizing it, are very important steps for the business and add value to the assets of the company. [30]

Table 1 Criteria

4.2.2 Fuzzy Rules

This section refers to rules that have been created for the example of scope optimization in an industrial maintenance project. The rules are the “backbone” of the system. As it said above, in the chapter 3, all the parts (antecedent) of one rule are connected with operators (AND, OR) in a way that is already analysed in the same chapter.

In order to be presented distinctly, easier to explain, and to explain the usefulness of each rule, the rules are categorized. The following table lists four categories of rules according to the criteria they combine.

In category A, the proportion of these two parameters, Total Operational Cost and maintainability (MTTR), is extremely useful because as long as the system is down and we expect to be repaired, extra costs are generated, like non-operation costs, replacement costs (if there is no stock available) etc. The MTTR index calculates the time which is required from the repair statement to when the system complies with the manufacturer's specifications. Consequently, it is interesting to see MTTR and TOC combined in one bunch of rules. Similarly, it's interesting to see what happens in the system by combining repair times (MTTR) and system reliability, as it appears at category C. Following the same though-flow, it is crucial to notice what is happening with the repair when there are these two parameters: Reliability and Criticality (as it appears in category B), for example what if a part of a system is unreliable and also has high criticality (may it affects the whole system). Finally, in the last category there is a combination of three parameters, MTBF, criticality, Value of equipment. That refers to an indicator that calculates the mean time between failures, one that shows whether the system which is under consideration is critical or not and all these are combined with another indicator, the value of the equipment. The combination of time, criticality and value makes this set of rules distinctive and useful for this research.

Afterwards, a part of these rules will be explained and analysed so that it is clear why are these rules useful in a practical way, in a way that a manager/engineer thinks when he faces these issues.

A	1. If Total Operational Cost is high and (maintainability) MTTR (Mean Time To Repair) is high, then the repair is DO. 2. If Total Operational Cost is high and MTTR is average, then the repair is WEAKLY CONSIDER. 3. If Total Operational Cost is high and MTTR is low, then the repair is WEAKLY CONSIDER. 4. If Total Operational Cost is average and MTTR is average, then the repair is STRONGLY CONSIDER. 5. If Total Operational Cost is low and MTTR is high, then the repair is STRONGLY CONSIDER. 6. If Total Operational Cost is low and MTTR is low, then the repair is DO NOT. 7. If Total Operational Cost is low and MTTR is average, then the repair is WEAKLY CONSIDER.
B	8. If Criticality is high and Reliability is high, then the repair is STRONGLY CONSIDER. 9. If Criticality is high and Reliability is low, then the repair is DO. 10. If Criticality is average and Reliability is high, then the repair is WEAKLY CONSIDER. 11. If Criticality is average and Reliability is low, then the repair is STRONGLY CONSIDER. 12. If Criticality is low and Reliability is high, then the repair is DO NOT. 13. If Criticality is low and Reliability is low, then the repair is WEAKLY CONSIDER.
C	14. If MTTR is high and Reliability is high, then the repair is WEAKLY CONSIDER. 15. If MTTR is high and Reliability is low, then the repair is DO. 16. If MTTR is average and Reliability is high, then the repair is DO NOT. 17. If MTTR is average and Reliability is low, then the repair is STRONGLY CONSIDER. 18. If MTTR is low and Reliability is high, then the repair is DO NOT. 19. If MTTR is low and Reliability is low, then the repair is STRONGLY CONSIDER.

D	20. If MTBF is high and criticality is low and Value of equipment is low, then the repair is DO NOT. 21. If MTBF is low and criticality is high and Value of equipment is high, then the repair is DO. 22. If MTBF is high and criticality is average and Value of equipment is high, then the repair is STRONGLY CONSIDER. 23. If MTBF is high and criticality is average and Value of equipment is average, then the repair is WEAKLY CONSIDER. 24. If MTBF is high and criticality is average and Value of equipment is low, then the repair is DO NOT. 25. If MTBF is high and criticality is low and Value of equipment is high, then the repair is WEAKLY CONSIDER. 26. If MTBF is high and criticality is low and Value of equipment is average, then the repair is DO NOT. 27. If MTBF is low and criticality is average and Value of equipment is high, then the repair is DO. 28. If MTBF is low and criticality is average and Value of equipment is average, then the repair is STRONGLY CONSIDER. 29. If MTBF is low and criticality is average and Value of equipment is low, then the repair is WEAKLY CONSIDER. 30. If MTBF is low and criticality is low and Value of equipment is high, then the repair is STRONGLY CONSIDER. 31. If MTBF is low and criticality is low and Value of equipment is average, then the repair is WEAKLY CONSIDER. 32. If MTBF is average and criticality is high and Value of equipment is high, then the repair is DO. 33. If MTBF is average and criticality is high and Value of equipment is average, then the repair is DO. 34. If MTBF is average and criticality is high and Value of equipment is low, then the repair is STRONGLY CONSIDER. 35. If MTBF is average and criticality is average and Value of equipment is high, then the repair is STRONGLY CONSIDER. 36. If MTBF is average and criticality is average and Value of equipment is average, then the repair is WEAKLY CONSIDER. 37. If MTBF is average and criticality is average and Value of equipment is low, then the repair is STRONGLY CONSIDER. 38. If MTBF is average and criticality is low and Value of equipment is high, then the repair is STRONGLY CONSIDER. 39. If MTBF is average and criticality is low and Value of equipment is average, then the repair is WEAKLY CONSIDER. 40. If MTBF is average and criticality is low and Value of equipment is low, then the repair is DO NOT.

Table 2 Rules

In the context of a thorough analysis, a verbal justification for a representative set of rules is referred. The categorization will be same as above. In category A, there is the rule number (1) "*If Total Operational Cost is high and (maintainability) MTTR (Mean Time To Repair) is high, then the repair is DO.*". The reasoning behind this rule is that getting started from the second part of the antecedent, a system which has high mean time to be repaired is a system that it is not worth to be repaired and much better be maintained, especially when the total operational cost of it is high. That practically means that if this system will not be maintained, then a failure occurs and it will take a lot time and money so this be functional again. Precisely with the same reasoning, but vice versa, the next rule is formed: "*If Total Operational Cost is low and MTTR is low, then the repair is DO NOT.*" (rule number 6).

Continuing on category B, there is another pair of rules, rule number 9 and 12, compared with rule number 13: "*If Criticality is high and Reliability is low, then the repair is DO.*" ***[9]***, "*If Criticality is low and Reliability is high, then the repair is DO NOT.*"***[12]***, "*If Criticality is low and Reliability is low, then the repair is WEAKLY CONSIDER.*"***[13]***. The comparison of these occurs with the main purpose of understanding both extreme decisions, but above all the intermediate values such as "weakly consider". When a system has small reliability and its criticality is high, means respectively that this system has immense possibility to fail and if it fails, will enormously affect the whole system, because of its criticality. In order to avoid these bad impacts if we are under concern to maintain a system like this, or not, we have to answer that we must maintain it. Correspondingly, if a system has high reliability and its criticality is low, it is unnecessary to maintain it and if we include it in the scope we are under the danger of over-grow the scope of the project and being out of budget and time. In case of rule 13, the criteria are loose because it is truly that is "dangerous" the fact that the reliability is low, so, overwhelmingly, it is like a bomb ready to explode, but the criticality is also low so if a failure occurs, it will not be a big deal. For those reasons the answer for the issue of the maintaining is weakly consider.

Additionally, when a device has high Mean Time To Repair (MTTR) means that it has low maintainability, practically it takes a big amount of time so this be repaired. What really happens when a system has big time to be repaired, combined with low reliability? This is definitely a bad scenario because if this system will not be maintained, because of low reliability, it is very possible a failure to be occurred and because of high MTTR, the repair will take a respectable amount of time. A case like this is described in rule number 15 and conversely in rule number 18. "*If MTTR is high and Reliability is low, then the repair is DO.*"***[15]***, "*If MTTR is low and Reliability is high, then the repair is DO NOT.*"***[18]***. The rule 17, (*"If MTTR is average and Reliability is low, then the repair is STRONGLY CONSIDER."*[17]) is identified with the rules above just in the part of the low reliability. This is a dangerous assumption and combined with an average mean time to repair, the decision becomes really difficult. It cannot be ignored the bad condition of the system but those information are not a necessary arrangement to definitely set the system under maintain. This is exactly what the option "strongly consider" comprehend.

Finally, in category D, the antecedent of each rule has three parts and this makes the decision complex. As an example, the rule number 26 is going to be analyzed: *"If MTBF is high and criticality is low and Value of equipment is average, then the repair is DO NOT."*[26]. If a system has high Mean Time Between Failures means that the it takes a lot time from one failure till the next failure to be occurred and that practically means that this is system is kind of reliable. If the same system is not critical (does not extremely affect the whole system) and the value of it is not extremely important, then if we choose to maintain it, is really possible to maintain something unnecessary. Because of its high MTBF, it has small chances to fail. The corresponding extreme case of having a system with average MTBF, high criticality and average value of equipment (rule number 33: *"If MTBF is average and criticality is high and Value of equipment is average, then the repair is DO"*), contributes to degraded situation. There are a lot of chances to fail this system and if this happen the whole system will be highly affected (because of the high criticality) and a value of the equipment (a good amount) will be downgraded. In situations like this, the engineers prefer to maintain it and that is what they suggest in large industrial complexes.

4.2.3 Inference

In this section all the above information are used to set up our system. This is a six-input, one-output example. As inputs we take the criteria, where based on them, the maintenance-repair decision is taken. All the below diagrams are made with the help of Matlab tool.

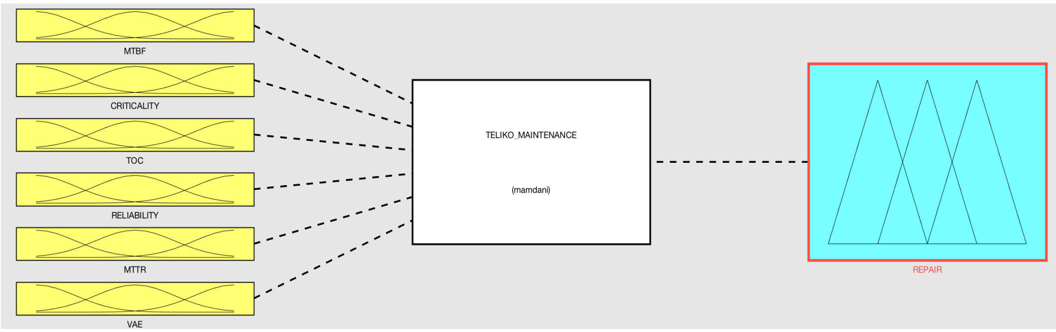


Figure 16 Six-input one-output example

A membership function is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. For each input a membership function is defined and the curves of each membership function are presented below. There are many types of curves for membership functions. The simplest membership functions are formed by straight lines, such as trapezoidal and triangular membership functions. For this study, we made the assumption that all the membership functions are trapezoidal. The trapezoidal membership function is a piecewise-linear function. It is described by a quadrant of parameters, which define its active core region, and provide the coordinates of the four peaks of the trapezoid:

$$
trapezoidal_{mf} = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases}
$$

Practically, this function turns into a compact-form function, as it is implemented in Matlab:

$$
trapMF(x; a, b, c, d) = max\left\{min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right\}
$$

This function has the simplest form of membership functions and requires a small computing effort to implement it. For this reason, it is usually preferred to real-time fuzzy systems. These are the reasons we chose for our system that the functions are bankers.

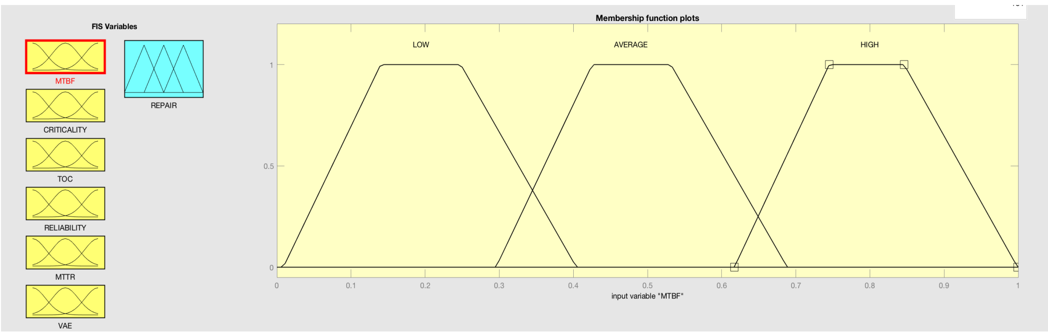


Figure 17 MTBF membership function curve

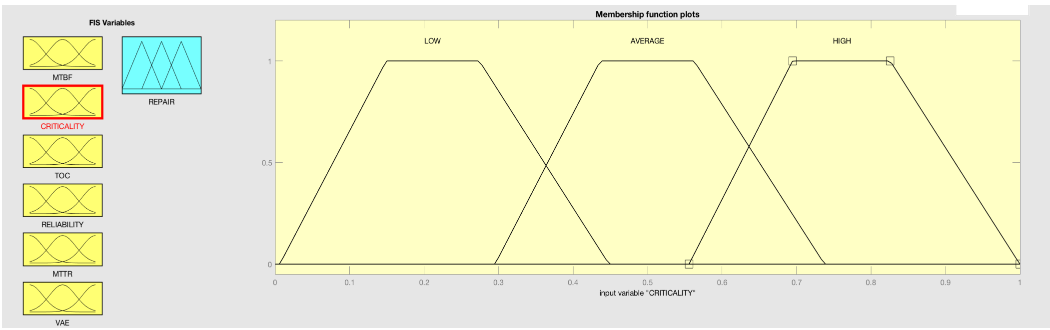


Figure 18 Criticality membership function curve

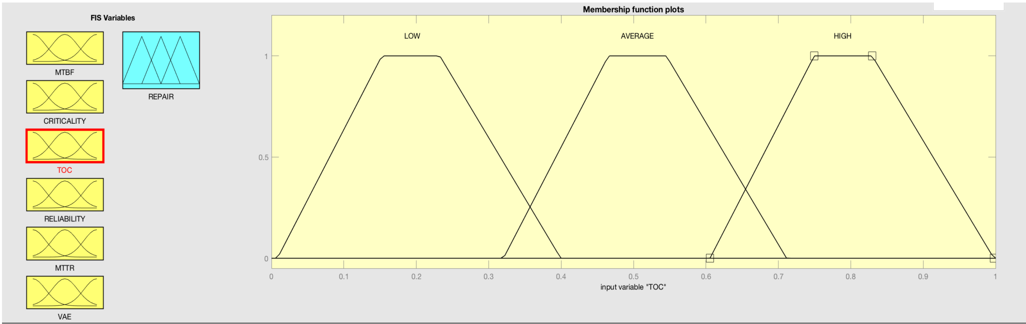


Figure 19 TOC membership function curve

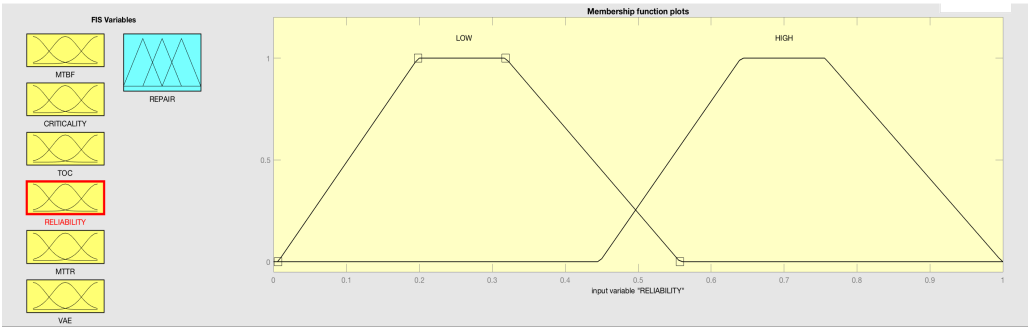


Figure 20 Reliability membership function curve

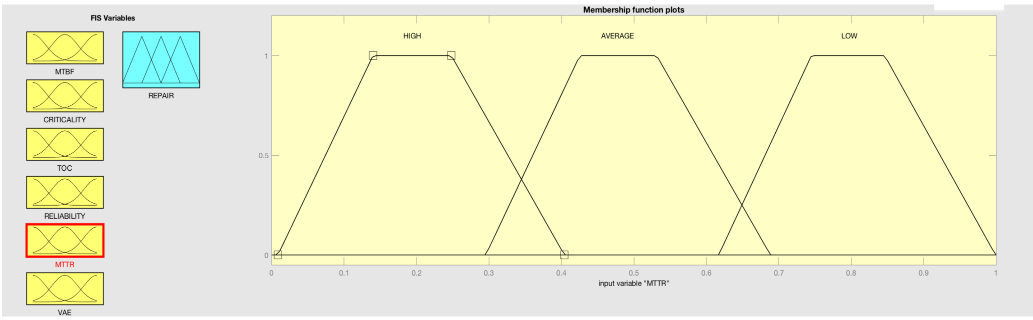


Figure 21 MTTR membership function curve

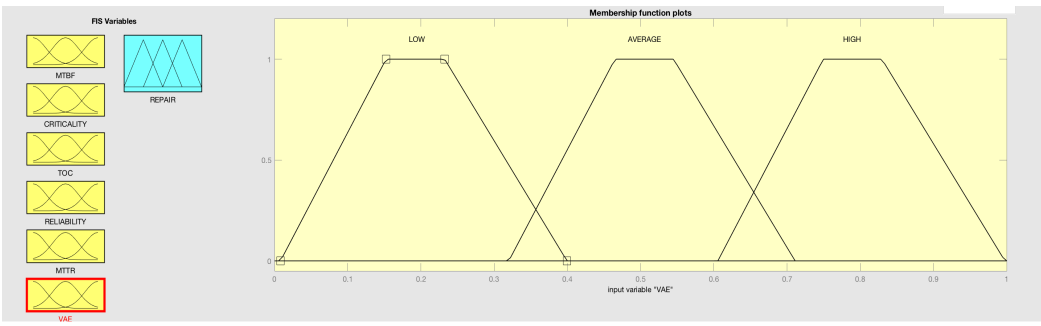


Figure 22 Value of equipment membership function curve

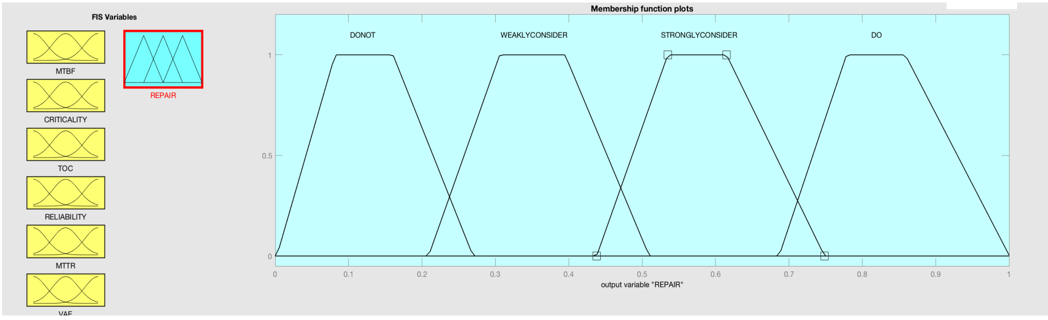


Figure 23 Repair membership function curve

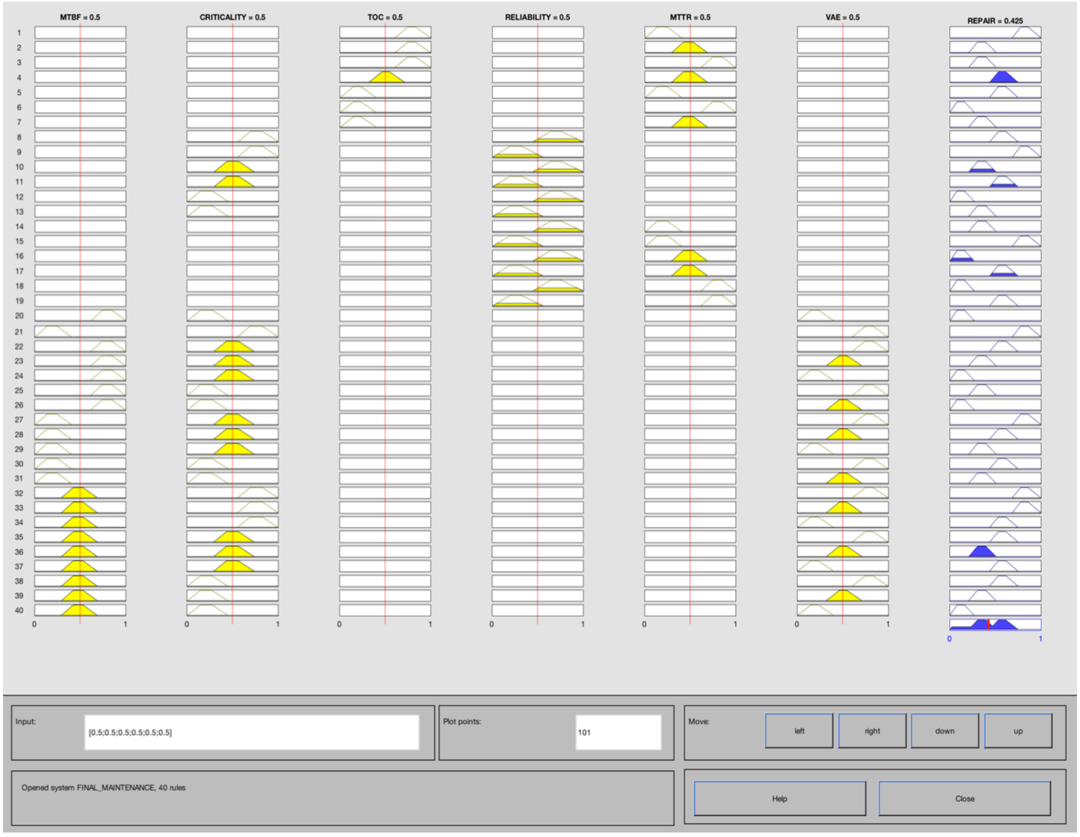
Referring to figure 23, trapezoidal curve fits exactly to the type of membership function of the output, except from the correspondence to real systems that type offers a “resting” area to our decision. The peak values of each curve is the “rest area”, there, for several values , the decision is the same. That gives to the output area a smoothness and corresponds to reality.

The next step includes the extracting expertise and creation of fuzzy rules base. Fuzzy rules base is a set of "if-then" rules which is considered as the heart of system because the rest of fuzzy system components are used effectively and efficiently for implementation of these rules. In the same step, a weigh is attached to all rules. The weigh is an indicator about how each rule takes part to the final decision. For this example, all rules have the same weigh, in order to remain simple.

1. If (TOC is HIGH) and (MTTR is HIGH) then (REPAIR is DO) (1)
2. If (TOC is HIGH) and (MTTR is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
3. If (TOC is HIGH) and (MTTR is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
4. If (TOC is AVERAGE) and (MTTR is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
5. If (TOC is LOW) and (MTTR is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
6. If (TOC is LOW) and (MTTR is LOW) then (REPAIR is DONOT) (1)
7. If (TOC is LOW) and (MTTR is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
8. If (CRITICALITY is HIGH) and (RELIABILITY is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
9. If (CRITICALITY is HIGH) and (RELIABILITY is LOW) then (REPAIR is DO) (1)
10. If (CRITICALITY is AVERAGE) and (RELIABILITY is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
11. If (CRITICALITY is AVERAGE) and (RELIABILITY is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
12. If (CRITICALITY is LOW) and (RELIABILITY is HIGH) then (REPAIR is DONOT) (1)
13. If (CRITICALITY is LOW) and (RELIABILITY is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
14. If (RELIABILITY is HIGH) and (MTTR is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
15. If (RELIABILITY is LOW) and (MTTR is HIGH) then (REPAIR is DO) (1)
16. If (RELIABILITY is HIGH) and (MTTR is AVERAGE) then (REPAIR is DONOT) (1)
17. If (RELIABILITY is LOW) and (MTTR is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
18. If (RELIABILITY is HIGH) and (MTTR is LOW) then (REPAIR is DONOT) (1)
19. If (RELIABILITY is LOW) and (MTTR is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
20. If (MTBF is HIGH) and (CRITICALITY is LOW) and (VAE is LOW) then (REPAIR is DONOT) (1)
21. If (MTBF is LOW) and (CRITICALITY is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
22. If (MTBF is HIGH) and (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
23. If (MTBF is HIGH) and (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
24. If (MTBF is HIGH) and (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is DONOT) (1)
25. If (MTBF is HIGH) and (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
26. If (MTBF is HIGH) and (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is DONOT) (1)
27. If (MTBF is LOW) and (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is DO) (1)
28. If (MTBF is LOW) and (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
29. If (MTBF is LOW) and (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
30. If (MTBF is LOW) and (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
31. If (MTBF is LOW) and (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
32. If (MTBF is AVERAGE) and (CRITICALITY is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
33. If (MTBF is AVERAGE) and (CRITICALITY is HIGH) and (VAE is AVERAGE) then (REPAIR is DO) (1)
34. If (MTBF is AVERAGE) and (CRITICALITY is HIGH) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
35. If (MTBF is AVERAGE) and (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
36. If (MTBF is AVERAGE) and (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
37. If (MTBF is AVERAGE) and (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
38. If (MTBF is AVERAGE) and (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
39. If (MTBF is AVERAGE) and (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
40. If (MTBF is AVERAGE) and (CRITICALITY is LOW) and (VAE is LOW) then (REPAIR is DONOT) (1)

Figure 24 Aggregate depiction and weighing of rules

Afterwards, central method is used by MATLAB software in defuzzification because this method of defuzzification reduces the complexity of the problem and leads to less time for calculations. Here, we select "Sum" aggregation method for fuzzy rules due to connected fuzzy rules due to AND operator. The way the operations are carried out has already been analysed in a previous chapter. The next figure shows the output and the way the system "arrived" to it.



This picture displays a roadmap of the whole fuzzy inference process and it is based on the fuzzy inference diagram described in the previous chapter. This is a single figure with 281 plots nested in it. The first 7 plots across the top of the figure represent the antecedent and consequent of the first rule, and so goes for all the rules. The final plot on the bottom of the figure represent the output. The variables and their current values are displayed on top of the columns and in the lower left, there is a text field "Input" in which we can enter specific input values. For this example we enter 0.5 for each input, in next chapter we will test the system by giving other number to the inputs.

As it is already said, the aggregation occurs down the 41column, and the resultant aggregate plot is shown in the single plot appearing in the lower right corner of the plot field. The defuzzified output value is shown by the thick line passing through the aggregate fuzzy set and the "crisp" value of the output appears on the top of the output column.

This figure allows to interpret the entire fuzzy inference process at once, shows one calculation at a time, in great detail and alongside, shows the shape of certain membership functions and they influence the overall result. In this sense, it presents a micro-view of the fuzzy inference system but if we desire to see the entire output surface of the system, the next figures show all the decision-making surface.

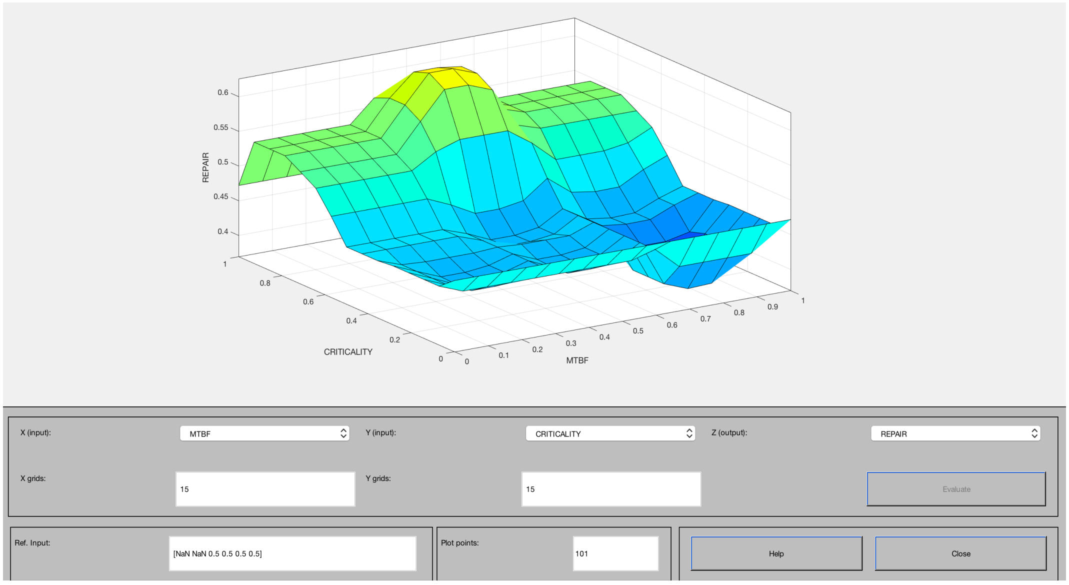


Figure 25 Surface MTBF-CRITICALITY-REPAIR

This surface is a three-dimensional curve that represents the mapping from MTBF and Criticality to Repair. That kind of view is very helpful in cases with two inputs and one output. The Surface Viewer of Matlab, which is used in order to make those plots, can generate a three-dimensional output surface. Computer monitors cannot display a six-dimensional shape, so any two of the inputs vary, but the other inputs must be held constant. In such a cases, the input is a six-dimensional vector with NaNs (is the IEEE symbol for Not a Number) holding the place of the varying inputs while numerical values indicates those values that remain fixed. In figure 9, the numbers are presented on the bottom-left of the figure and so it goes for the next figures. The next figures present all the possible combinations of the inputs.

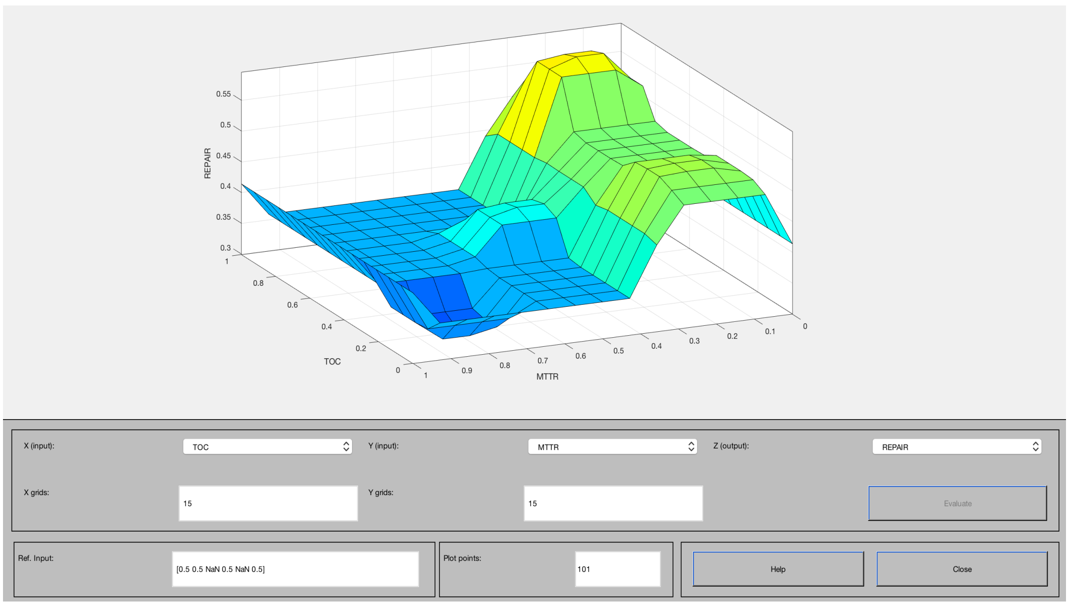


Figure 26 Surface TOC-MTTR-REPAIR

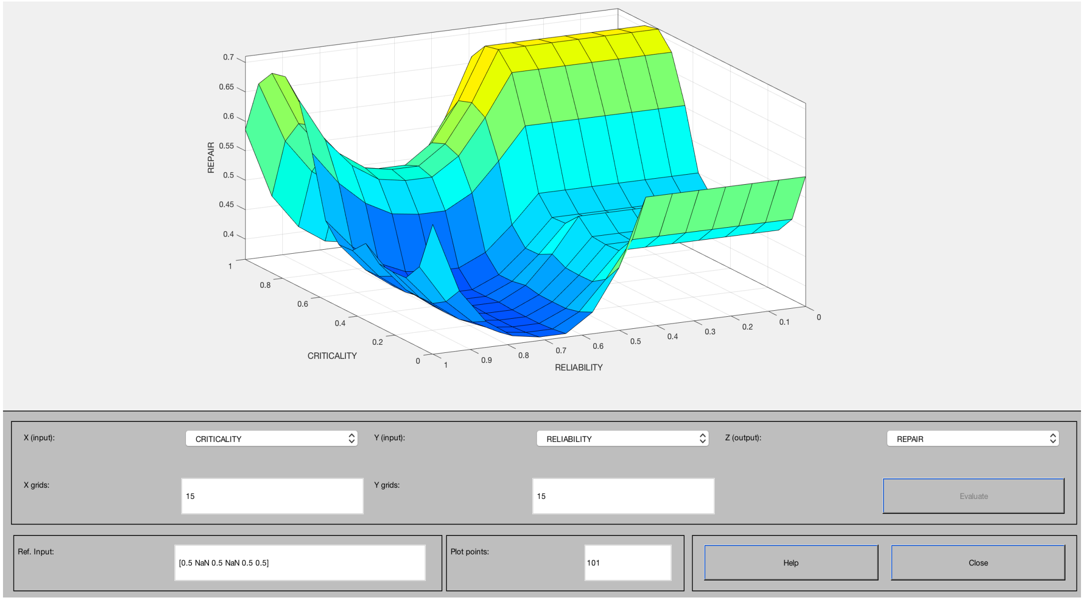


Figure 27 Surface CRITICALITY-RELIABILITY-REPAIR

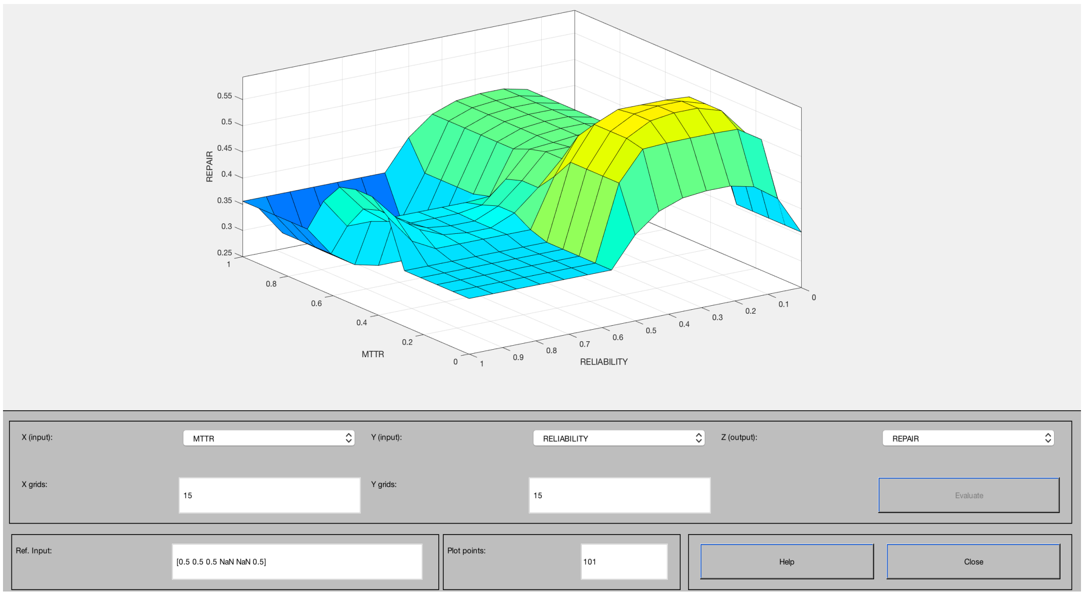


Figure 28 Surface MTTR-RELIABILITY-REPAIR

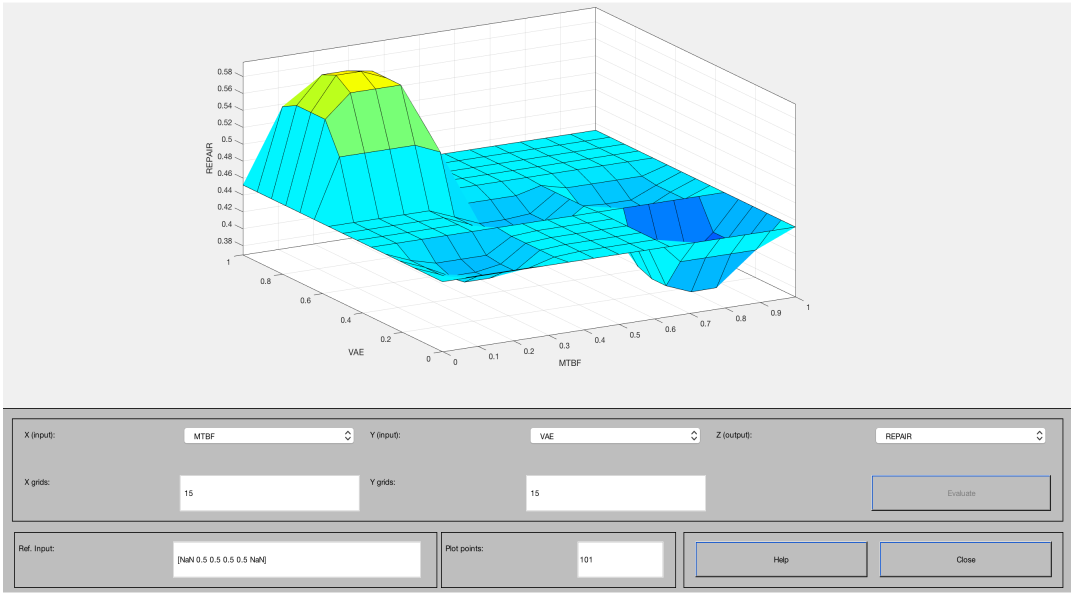


Figure 29 Surface MTBF-VAE-REPAIR

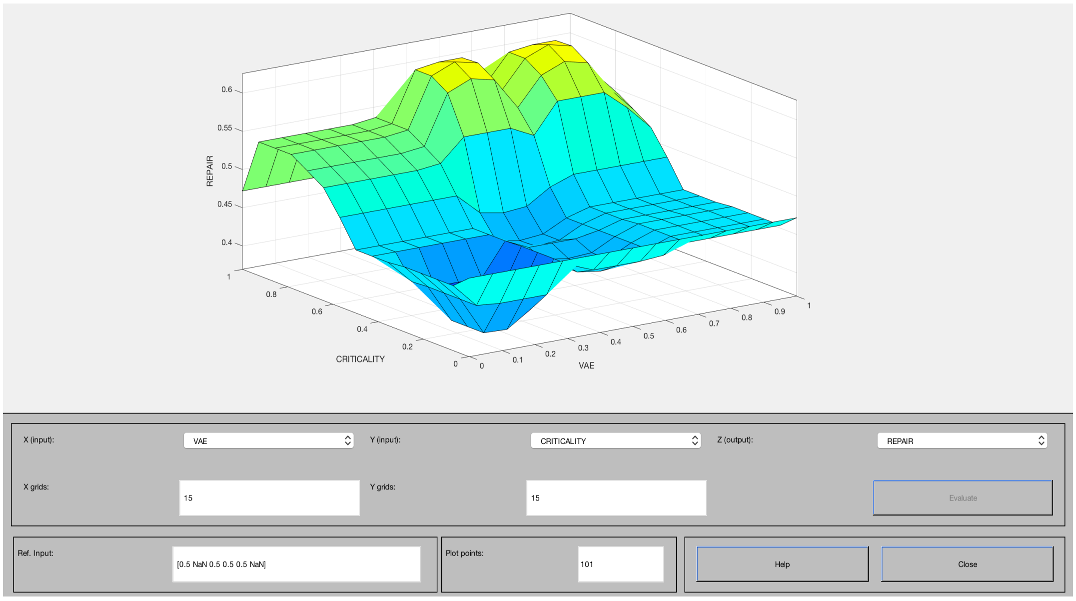


Figure 30 Surface VAE-CRITICALITY-REPAIR

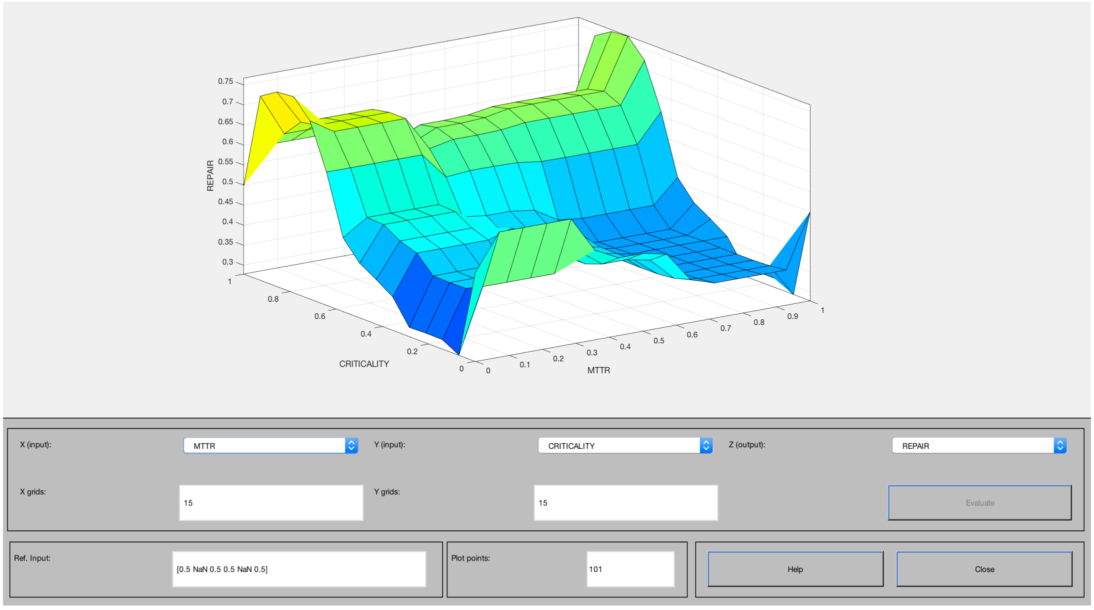


Figure 31 Surface MTTR-CRITICALITY-REPAIR

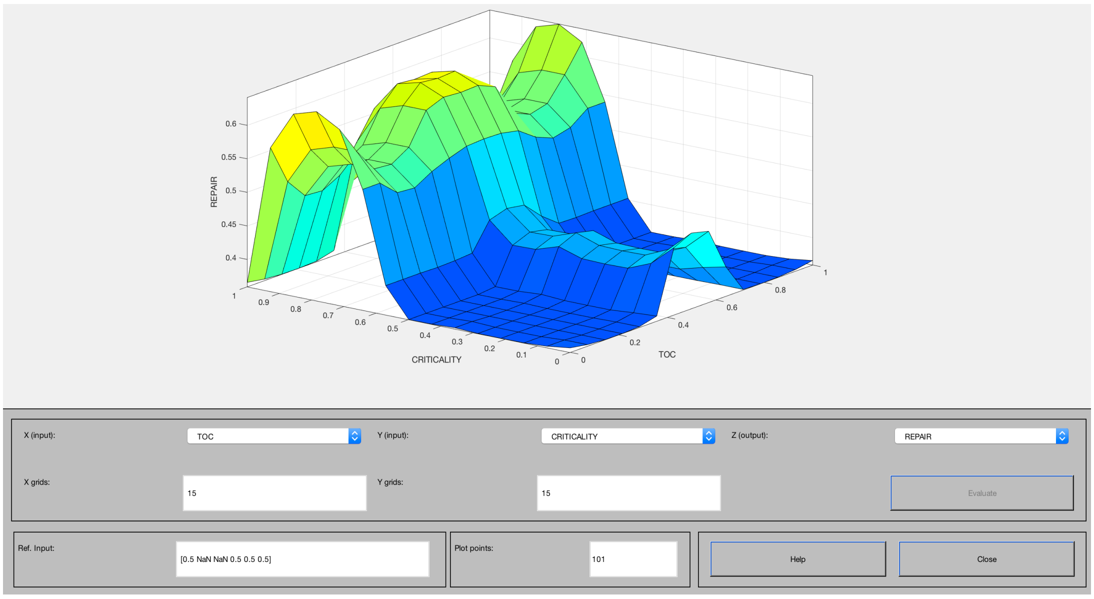


Figure 32 Surface TOC-CRITICALITY-REPAIR

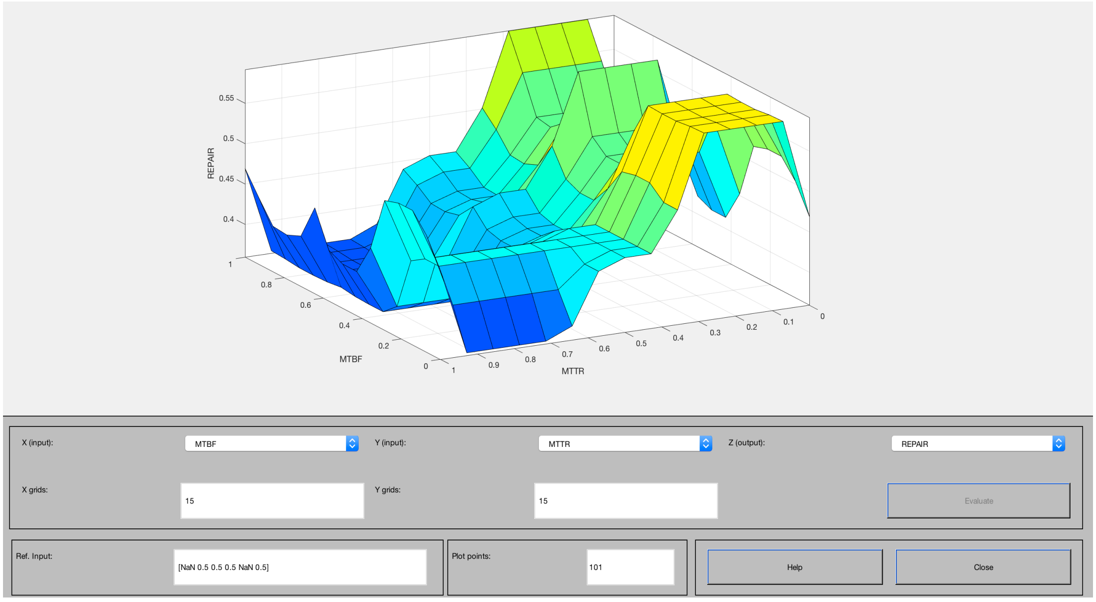


Figure 33 Surface MTBF-MTTR-REPAIR

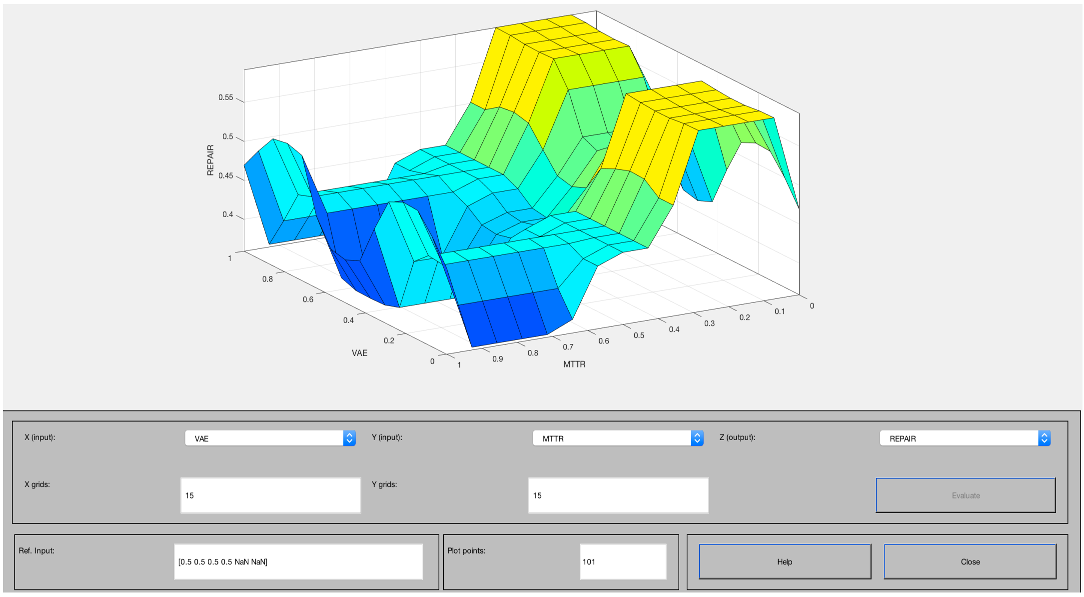


Figure 34 Surface VAE-MTTR-REPAIR

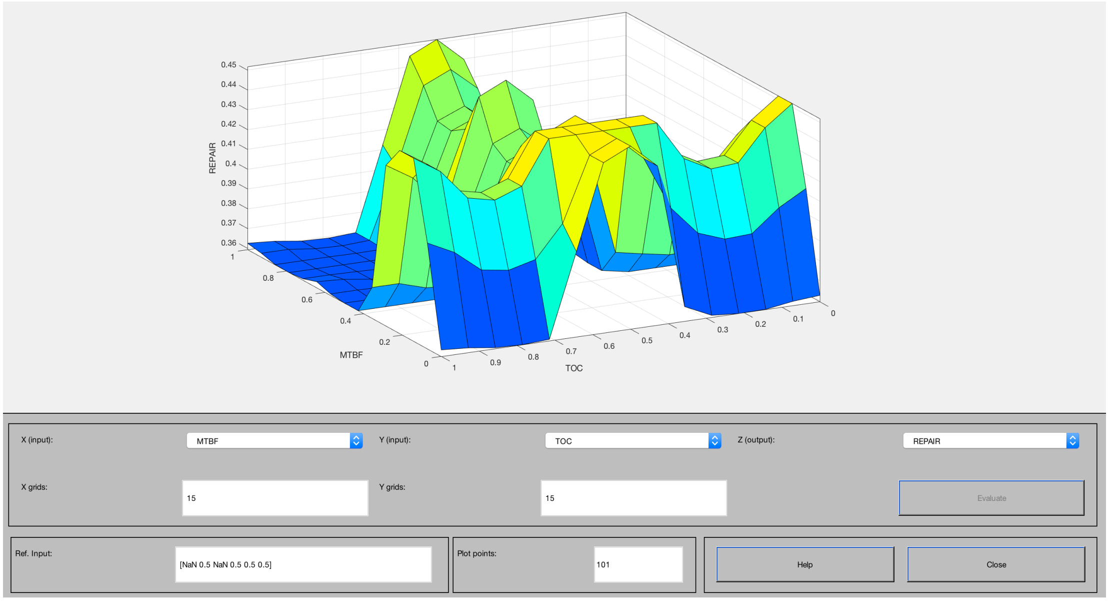


Figure 35 Surface MTBF-TOC-REPAIR

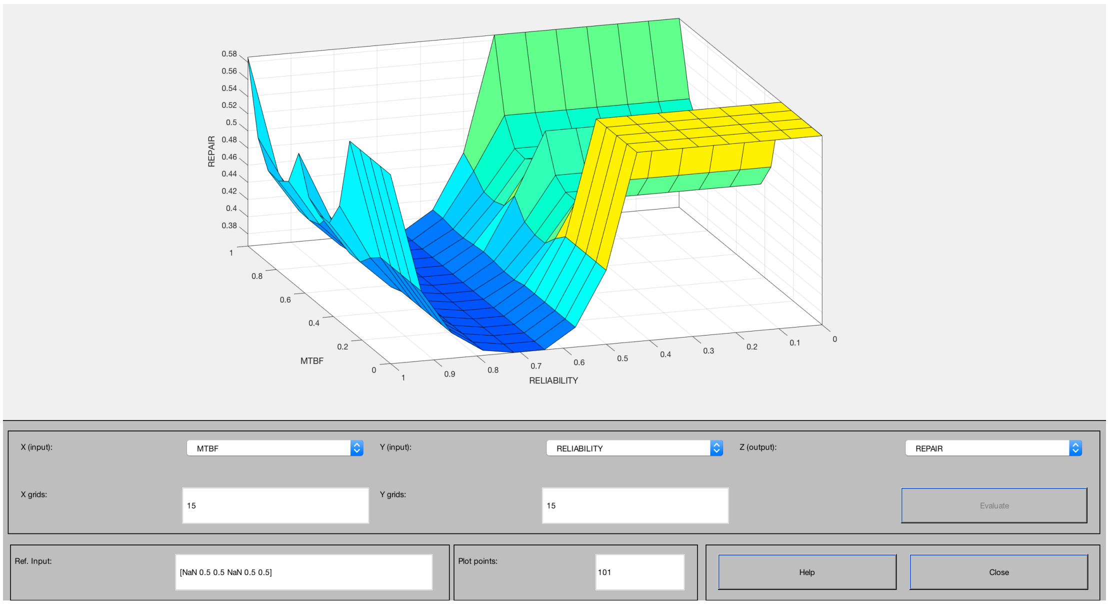


Figure 36 Surface MTBF-RELIABILITY-REPAIR

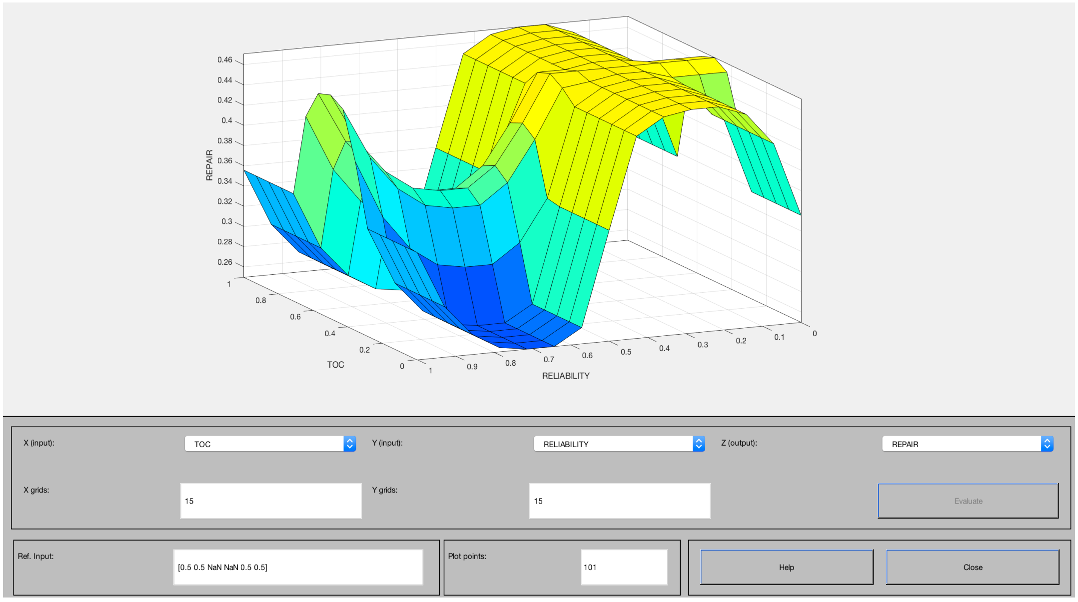


Figure 37 Surface TOC-RELIABILITY-REPAIR

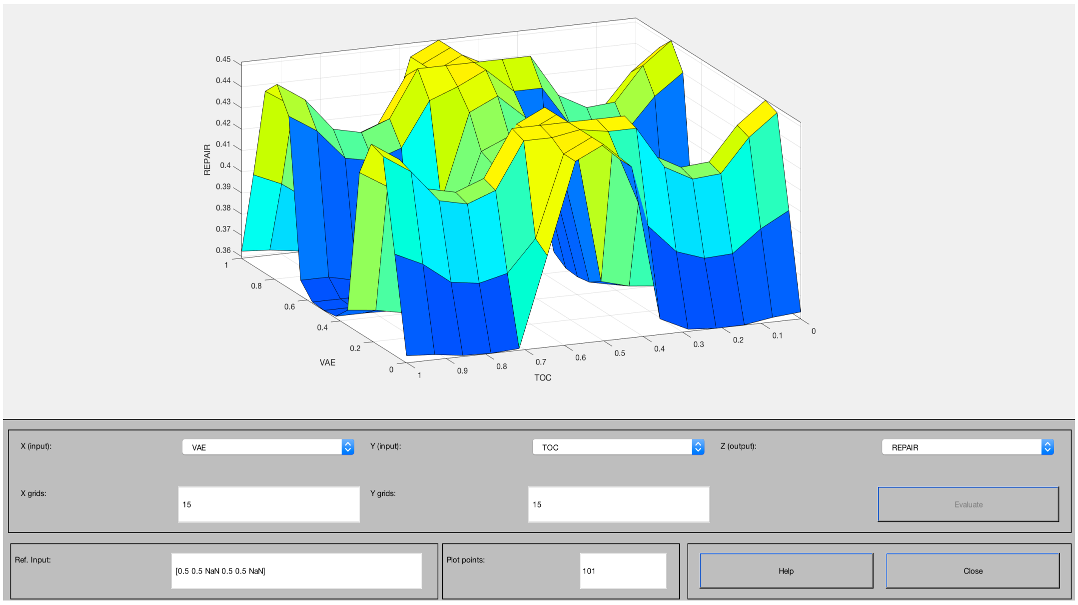


Figure 38 Surface VAE-TOC-REPAIR

All the plots that are presented above are decision surfaces. Thus, we expect to be smooth in order to be a good "simulation" of a realistic manner of thinking. Observing the results, we notice that the majority of them is not as smooth as they can be, so we decided to improve our system. One of the reasons that led us to this decision are the sudden changes of the slope of the surface. That is, for a slight change of the input there is a large change in the output, keeping all the other factors stable. On several occasions we noticed that the edges of the surface display a sharp rise or a steep descent. That was a sigh that concerned us in a way of logic, since the closer one of the factors reaches the limits, the output should not take extreme value changes. Taking under examination the figure 36 (Surface of MTBF-RELIABILITY), if we keep reliability closer to 0, a change of 0.2 of MTBF, from 0.4 to 0.6, the decision ranges from 0.56 to 0.44. This is a major change and there is also an inconsistency in this change in relation to intervals that the MTBF changes from 0 to 0.2 and from 0.2 to 0.4. Thus, in order to cure those problems, we decided to change the limits of membership functions and add more rules. Therefore, the improved system will have more data so that the results could be closer to reality, valid and the decision surfaces could be smoother. In next chapter the improved system and the changes will be analytically presented.

4.3 Improved implementation

In this system we keep the criteria exactly same, we just spilled the rules. Therefore, in this section we will not analyse them again, we just briefly remind them:

- Mean Time Between Failures (MTBF)
- Criticality
- Reliability
- Total Operational Cost (TOC)
- Maintainability (Mean Time To Repair-MTTR)
- Value of Equipment (VAE)

Afterwards, in chapter 4.3.1, all the rules of the new system are presented. As it said above, all the parts (antecedent) of one rule are connected with operators (AND, OR) in a way that is already analysed.

4.3.1 Rules

In order to be presented, distinctly, the rules are categorized in the same way that they were categorised above. The following table lists nine categories of rules according to the criteria they combine. The first four sets of rules are using the same criteria as in the first system: Category A combines TOC-MTTR, Category B combines Criticality-Reliability, Category C combines Reliability-MTTR and Category D combines MTBF-Criticality-VAE. The justification of those categories has already been presented in chapter 4.2.2. Additionally, Category E combines TOC-VAE, Category F combines MTBF-TOC, Category G MTBF-RELIABILITY, Category H MTBF-MTTR and Category I CRITICALITY-VAE. All extra categories have been included in order to fortify the system with more data so to produce more affective results and solve all problems that have been presented above. However this addendum increases the complexity of the system the resolution time. Nevertheless all of the adds information to the system in order to be completed.

A	1. If TOC is high and MTTR is high then the repair is do. 2. If TOC is high and MTTR is average then the repair is strongly consider. 3. If TOC is high and MTTR is low then the repair is strongly consider. 4. If TOC is average and MTTR is high then the repair is weakly consider. 5. If TOC is average and MTTR is average then the repair is weakly consider. 6. If TOC is average and MTTR is low then the repair is do not. 7. If TOC is low and MTTR is high then the repair is strongly consider. 8. If TOC is low and MTTR is average then the repair is weakly consider. 9. If TOC is low and MTTR is low then the repair is do not.
B	10. If criticality is high and reliability is high then the repair is strongly consider. 11. If criticality is high and reliability is low then the repair is do. 12. If criticality is average and reliability is high then the repair is weakly consider. 13. If criticality is average and reliability is low then the repair is strongly consider. 14. If criticality is low and reliability is high then the repair is do not. 15. If criticality is low and reliability is low then the repair is weakly consider.
C	16. If reliability is high and MTTR is high then the repair is weakly consider. 17. If reliability is low and MTTR is high then the repair is do. 18. If reliability is high and MTTR is average then the repair is weakly consider. 19. If reliability is low and MTTR is average then the repair is strongly consider. 20. If reliability is high and MTTR is low then the repair is do not. 21. If reliability is low and MTTR is low then the repair is strongly consider.

D	22. If MTBF is high and criticality is low and VAE is low then the repair is do not. 23. If MTBF is high and criticality is low and VAE is average then the repair is do not. 24. If MTBF is high and criticality is low and VAE is high then the repair is weakly consider. 25. If MTBF is high and criticality is average and VAE is high then the repair is strongly consider. 26. If MTBF is high and criticality is average and VAE is average then the repair is weakly consider. 27. If MTBF is high and criticality is average and VAE is low then the repair is weakly consider. 28. If MTBF is high and criticality is high and VAE is high then the repair is do. 29. If MTBF is high and criticality is high and VAE is average then the repair is strongly consider. 30. If MTBF is high and criticality is high and VAE is low then the repair is strongly consider. 31. If MTBF is average and criticality is low and VAE is high then the repair is weakly consider. 32. If MTBF is average and criticality is low and VAE is average then the repair is weakly consider. 33. If MTBF is average and criticality is low and VAE is low then the repair is do not. 34. If MTBF is average and criticality is average and VAE is high then the repair is strongly consider. 35. If MTBF is average and criticality is average and VAE is average then the repair is weakly consider. 36. If MTBF is average and criticality is average and VAE is low then the repair is weakly consider. 37. If MTBF is average and criticality is high and VAE is high then the repair is do. 38. If MTBF is average and criticality is high and VAE is average then the repair is do. 39. If MTBF is average and criticality is high and VAE is low then the repair is strongly consider. 40. If MTBF is low and criticality is low and VAE is high then the repair is do. 41. If MTBF is low and criticality is low and VAE is average then the repair is strongly consider. 42. If MTBF is low and criticality is low and VAE is low then the repair is do not. 43. If MTBF is low and criticality is average and VAE is high then the repair is do. 44. If MTBF is low and criticality is average and VAE is average then the repair is strongly consider. 45. If MTBF is low and criticality is average and VAE is low then the repair is strongly consider.

	46. If MTBF is low and criticality is high and VAE is high then the repair is do. 47. If MTBF is low and criticality is high and VAE is average then the repair is do. 48. If MTBF is low and criticality is high and VAE is low then the repair is strongly consider.
E	49. If TOC is high and VAE is high then the repair is do. 50. If TOC is average and VAE is high then the repair is strongly consider. 51. If TOC is low and VAE is high then the repair is strongly consider. 52. If TOC is high and VAE is average then the repair is strongly consider. 53. If TOC is average and VAE is average then the repair is weakly consider. 54. If TOC is low and VAE is average then the repair is weakly consider. 55. If TOC is high and VAE is low then the repair is do not. 56. If TOC is average and VAE is low then the repair is do not. 57. If TOC is low and VAE is low then the repair is do not.
F	58. If MTBF is high and TOC is high then the repair is strongly consider. 59. If MTBF is high and TOC is average then the repair is weakly consider. 60. If MTBF is high and TOC is low then the repair is do not. 61. If MTBF is average and TOC is high then the repair is strongly consider. 62. If MTBF is average and TOC is average then the repair is strongly consider. 63. If MTBF is average and TOC is low then the repair is weakly consider. 64. If MTBF is low and TOC is high then the repair is do. 65. If MTBF is low and TOC is average then the repair is strongly consider. 66. If MTBF is low and TOC is low then the repair is weakly consider.
G	67. If MTBF is high and reliability is high then the repair is do not. 68. If MTBF is average and reliability is high then the repair is weakly consider. 69. If MTBF is average and reliability is low then the repair is do. 70. If MTBF is low and reliability is low then the repair is do. 71. If MTBF is high and reliability is low then the repair is strongly consider. 72. If MTBF is low and reliability is high then the repair is weakly consider.

H	73. If MTBF is high and MTTR is high then the repair is strongly consider. 74. If MTBF is high and MTTR is average then the repair is weakly consider. 75. If MTBF is high and MTTR is low then the repair is do not. 76. If MTBF is average and MTTR is high then the repair is strongly consider. 77. If MTBF is average and MTTR is average then the repair is strongly consider. 78. If MTBF is average and MTTR is low then the repair is weakly consider. 79. If MTBF is low and MTTR is high then the repair is do. 80. If MTBF is low and MTTR is average then the repair is do. 81. If MTBF is low and MTTR is low then the repair is weakly consider.
I	82. If criticality is high and VAE is high then the repair is do. 83. If criticality is high and VAE is average then the repair is strongly consider. 84. If criticality is high and VAE is low then the repair is strongly consider. 85. If criticality is average and VAE is high then the repair is strongly consider. 86. If criticality is average and VAE is average then the repair is weakly consider. 87. If criticality is average and VAE is low then the repair is weakly consider. 88. If criticality is low and VAE is high then the repair is weakly consider. 89. If criticality is low and VAE is average then the repair is do not. 90. If criticality is low and VAE is low then the repair is do not.

4.3.2 Inference

This system is also a six-input-one-output system. As it is said above, a membership function is a curve that defines how each point in input space is mapped to a membership value between 0 and 1. There are many types of curves for membership functions. For each input a membership function is defined and a curve is presented below. All membership curves are trapezoidal. We briefly oppose the function, which is exactly the same as in first system:

$$trapezoidal_{mf} = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases}$$

The function below is how the trapezoidal function is implemented in Matlab:

$$trapMF(x; a, b, c, d) = max\left\{min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right\}$$

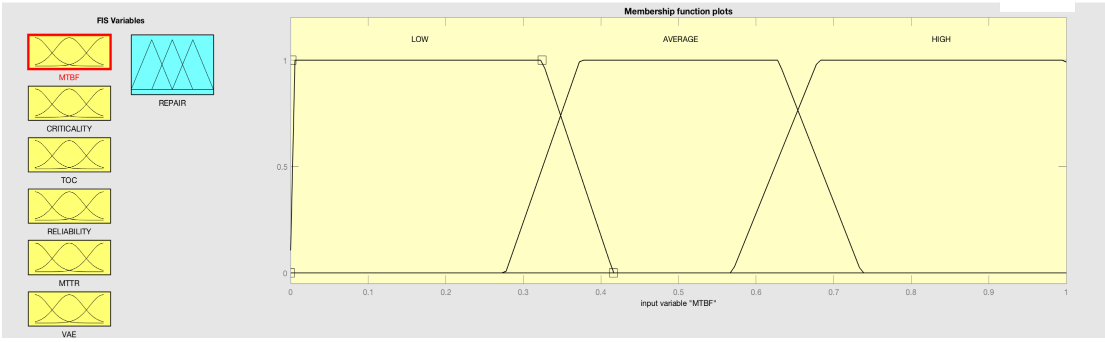


Figure 39 MTBF membership function curve

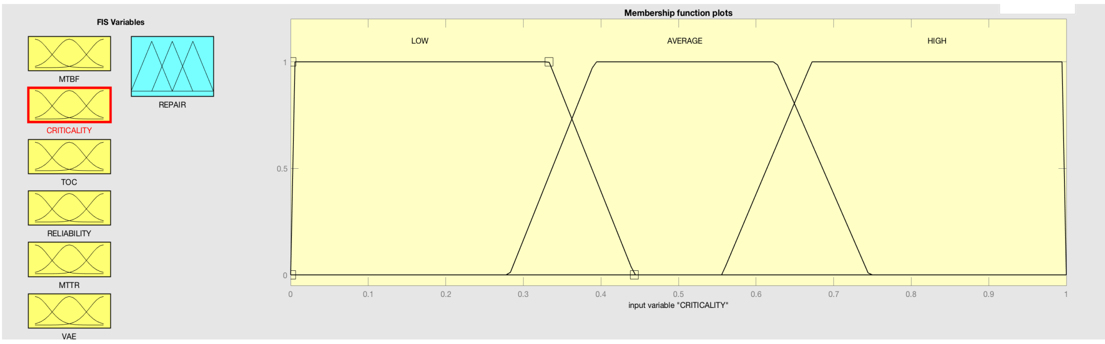


Figure 40 Criticality membership function curve

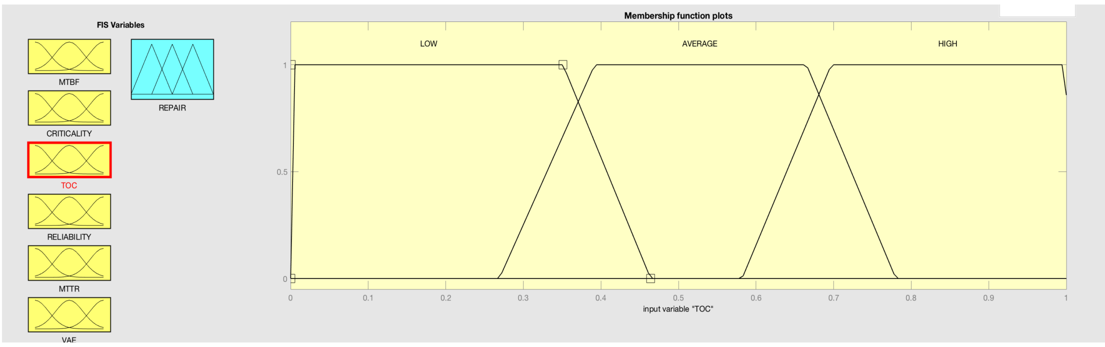


Figure 41 TOC membership function curve

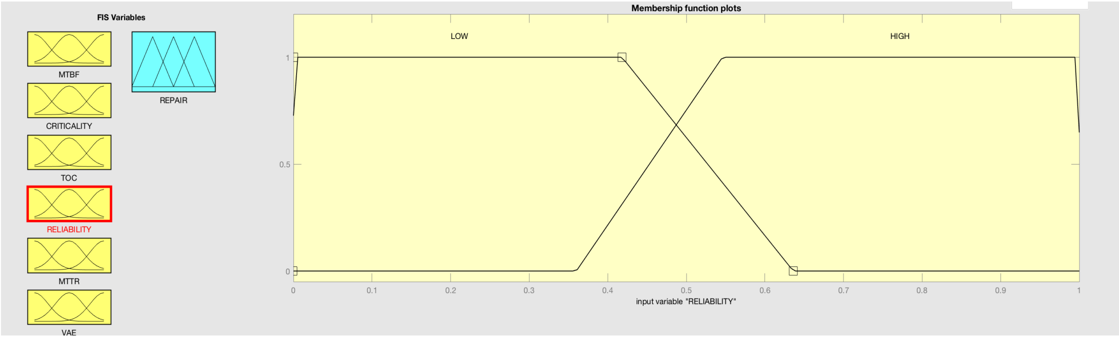


Figure 42 Reliability membership function curve

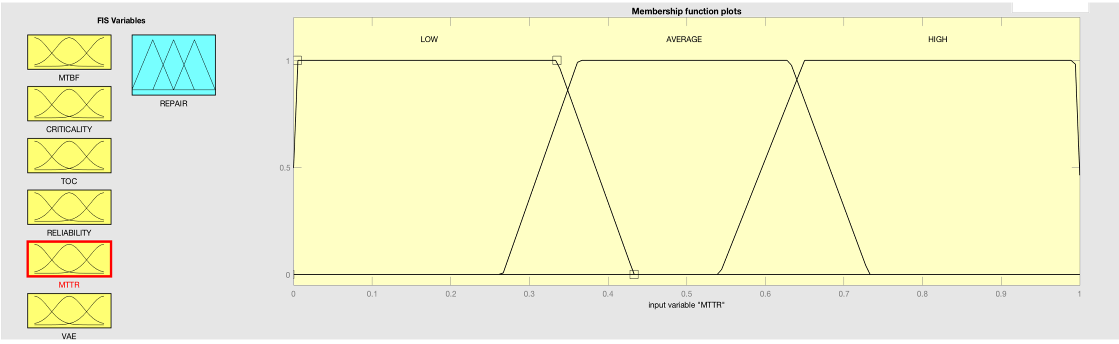


Figure 43 MTTR membership function curve

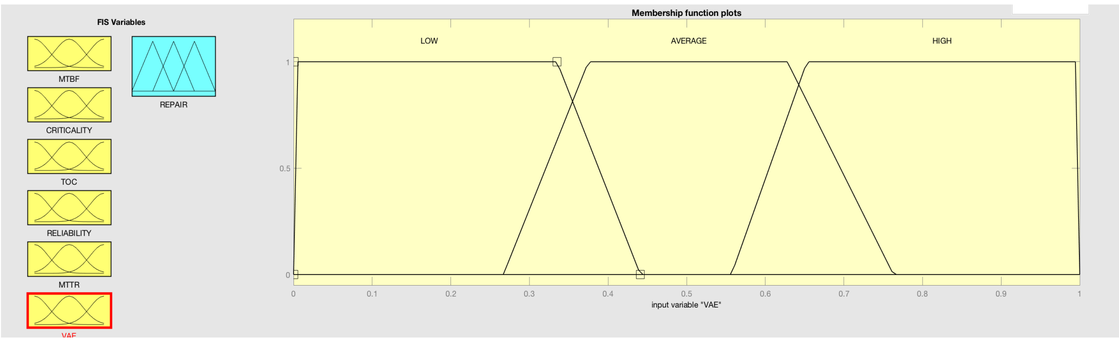


Figure 44 VAE membership function curve

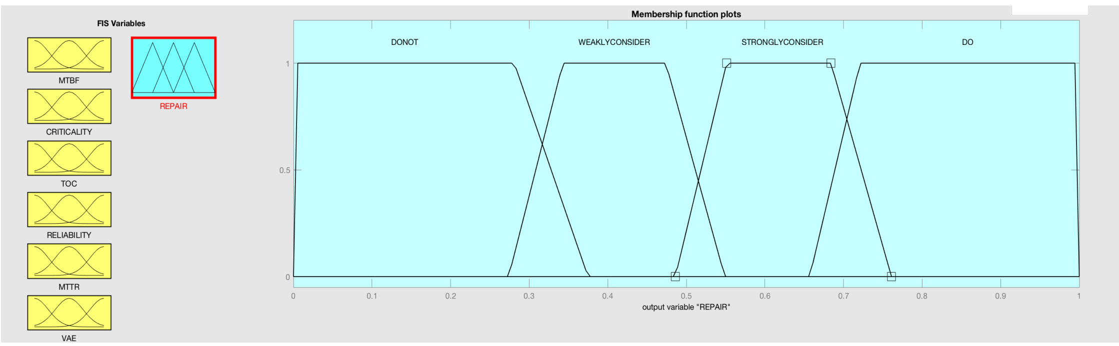


Figure 45 Repair membership function curve

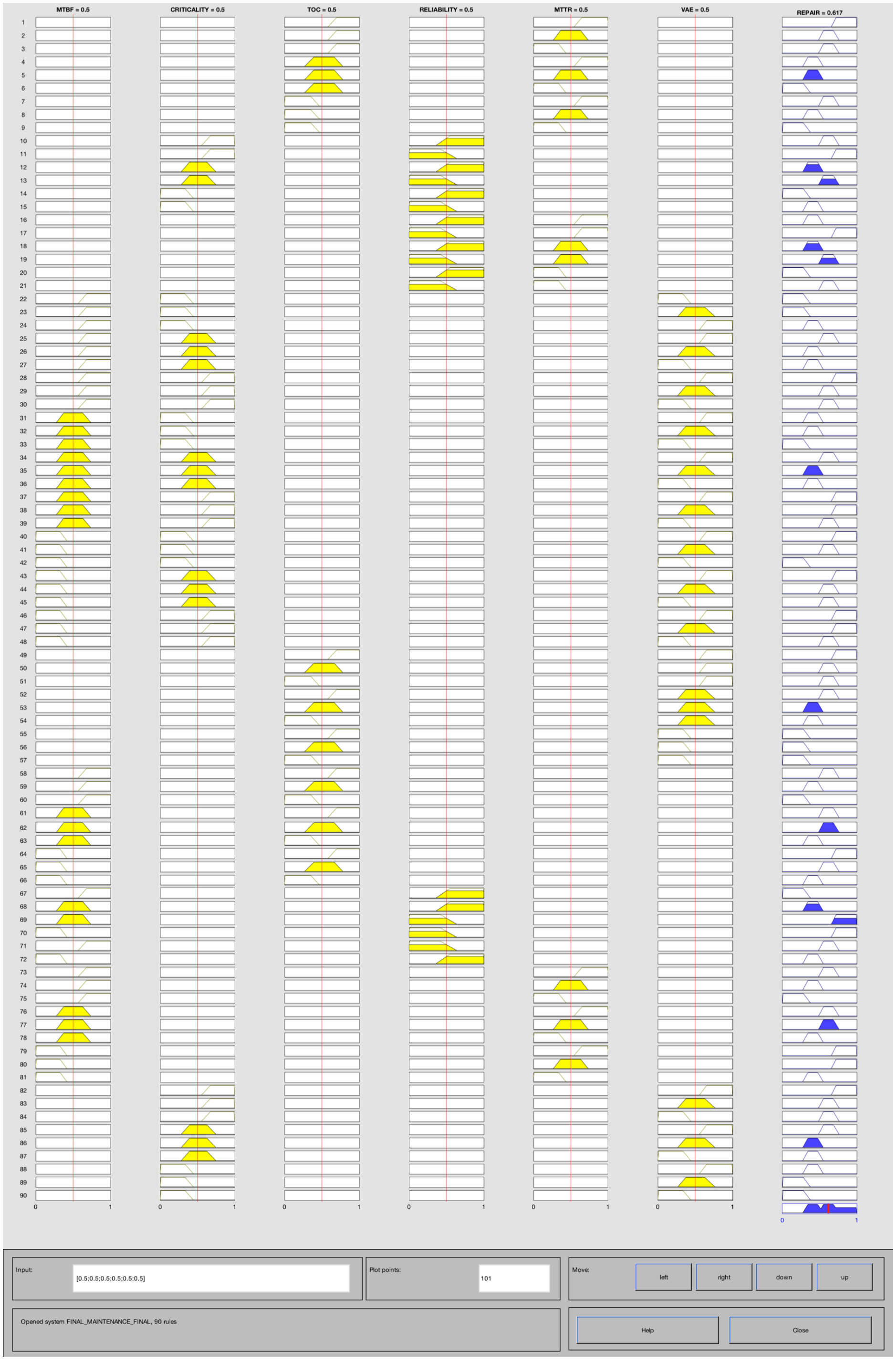
According to figure 45, there are four “stages” of output, “DO NOT”, “WEAKLY CONSIDER”, “STRONGLY CONSIDER”, “DO”. One of the most eloquent differences is the range of each stage, compared to the previous system, the spot of each peak point. In other words, we have longer peak intervals, so the rest areas are longer. That practically means that in those areas our decision takes a "rest". For several values the decision stays the same and that makes our decision-output more stable. Regarding all membership curves, there is a greater degree of overlaps amongst the stages. That condition gives to the final plots the required smoothness.

The next step includes the extracting expertise and creation of fuzzy rules base and in the same step, a weigh is attached to all rules. The weigh is an indicator about how each rule takes part to the final decision. For this example, all rules have the same weigh, in order to remain simple.

1. If (TOC is HIGH) and (MTTR is HIGH) then (REPAIR is DO) (1)
2. If (TOC is HIGH) and (MTTR is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
3. If (TOC is HIGH) and (MTTR is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
4. If (TOC is AVERAGE) and (MTTR is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
5. If (TOC is AVERAGE) and (MTTR is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
6. If (TOC is AVERAGE) and (MTTR is LOW) then (REPAIR is DONOT) (1)
7. If (TOC is LOW) and (MTTR is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
8. If (TOC is LOW) and (MTTR is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
9. If (TOC is LOW) and (MTTR is LOW) then (REPAIR is DONOT) (1)
10. If (CRITICALITY is HIGH) and (RELIABILITY is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
11. If (CRITICALITY is HIGH) and (RELIABILITY is LOW) then (REPAIR is DO) (1)
12. If (CRITICALITY is AVERAGE) and (RELIABILITY is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
13. If (CRITICALITY is AVERAGE) and (RELIABILITY is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
14. If (CRITICALITY is LOW) and (RELIABILITY is HIGH) then (REPAIR is DONOT) (1)
15. If (CRITICALITY is LOW) and (RELIABILITY is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
16. If (RELIABILITY is HIGH) and (MTTR is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
17. If (RELIABILITY is LOW) and (MTTR is HIGH) then (REPAIR is DO) (1)
18. If (RELIABILITY is HIGH) and (MTTR is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
19. If (RELIABILITY is LOW) and (MTTR is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
20. If (RELIABILITY is HIGH) and (MTTR is LOW) then (REPAIR is DONOT) (1)
21. If (RELIABILITY is LOW) and (MTTR is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
22. If (MTBF is HIGH) and (CRITICALITY is LOW) and (VAE is LOW) then (REPAIR is DONOT) (1)
23. If (MTBF is HIGH) and (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is DONOT) (1)
24. If (MTBF is HIGH) and (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
25. If (MTBF is HIGH) and (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
26. If (MTBF is HIGH) and (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
27. If (MTBF is HIGH) and (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
28. If (MTBF is HIGH) and (CRITICALITY is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
29. If (MTBF is HIGH) and (CRITICALITY is HIGH) and (VAE is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
30. If (MTBF is HIGH) and (CRITICALITY is HIGH) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
31. If (MTBF is AVERAGE) and (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
32. If (MTBF is AVERAGE) and (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
33. If (MTBF is AVERAGE) and (CRITICALITY is LOW) and (VAE is LOW) then (REPAIR is DONOT) (1)
34. If (MTBF is AVERAGE) and (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
35. If (MTBF is AVERAGE) and (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
36. If (MTBF is AVERAGE) and (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
37. If (MTBF is AVERAGE) and (CRITICALITY is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
38. If (MTBF is AVERAGE) and (CRITICALITY is HIGH) and (VAE is AVERAGE) then (REPAIR is DO) (1)
39. If (MTBF is AVERAGE) and (CRITICALITY is HIGH) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
40. If (MTBF is LOW) and (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is DO) (1)
41. If (MTBF is LOW) and (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
42. If (MTBF is LOW) and (CRITICALITY is LOW) and (VAE is LOW) then (REPAIR is DONOT) (1)
43. If (MTBF is LOW) and (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is DO) (1)
44. If (MTBF is LOW) and (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
45. If (MTBF is LOW) and (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
46. If (MTBF is LOW) and (CRITICALITY is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
47. If (MTBF is LOW) and (CRITICALITY is HIGH) and (VAE is AVERAGE) then (REPAIR is DO) (1)
48. If (MTBF is LOW) and (CRITICALITY is HIGH) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
49. If (TOC is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
50. If (TOC is AVERAGE) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
51. If (TOC is LOW) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
52. If (TOC is HIGH) and (VAE is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
53. If (TOC is AVERAGE) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
54. If (TOC is LOW) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
55. If (TOC is HIGH) and (VAE is LOW) then (REPAIR is DONOT) (1)
56. If (TOC is AVERAGE) and (VAE is LOW) then (REPAIR is DONOT) (1)
57. If (TOC is LOW) and (VAE is LOW) then (REPAIR is DONOT) (1)
58. If (MTBF is HIGH) and (TOC is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
59. If (MTBF is HIGH) and (TOC is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
60. If (MTBF is HIGH) and (TOC is LOW) then (REPAIR is DONOT) (1)
61. If (MTBF is AVERAGE) and (TOC is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
62. If (MTBF is AVERAGE) and (TOC is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
63. If (MTBF is AVERAGE) and (TOC is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
64. If (MTBF is LOW) and (TOC is HIGH) then (REPAIR is DO) (1)
65. If (MTBF is LOW) and (TOC is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
66. If (MTBF is LOW) and (TOC is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
67. If (MTBF is HIGH) and (RELIABILITY is HIGH) then (REPAIR is DONOT) (1)
68. If (MTBF is AVERAGE) and (RELIABILITY is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
69. If (MTBF is AVERAGE) and (RELIABILITY is LOW) then (REPAIR is DO) (1)
70. If (MTBF is LOW) and (RELIABILITY is LOW) then (REPAIR is DO) (1)
71. If (MTBF is HIGH) and (RELIABILITY is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
72. If (MTBF is LOW) and (RELIABILITY is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
73. If (MTBF is HIGH) and (MTTR is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
74. If (MTBF is HIGH) and (MTTR is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
75. If (MTBF is HIGH) and (MTTR is LOW) then (REPAIR is DONOT) (1)
76. If (MTBF is AVERAGE) and (MTTR is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
77. If (MTBF is AVERAGE) and (MTTR is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
78. If (MTBF is AVERAGE) and (MTTR is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
79. If (MTBF is LOW) and (MTTR is HIGH) then (REPAIR is DO) (1)
80. If (MTBF is LOW) and (MTTR is AVERAGE) then (REPAIR is DO) (1)
81. If (MTBF is LOW) and (MTTR is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
82. If (CRITICALITY is HIGH) and (VAE is HIGH) then (REPAIR is DO) (1)
83. If (CRITICALITY is HIGH) and (VAE is AVERAGE) then (REPAIR is STRONGLYCONSIDER) (1)
84. If (CRITICALITY is HIGH) and (VAE is LOW) then (REPAIR is STRONGLYCONSIDER) (1)
85. If (CRITICALITY is AVERAGE) and (VAE is HIGH) then (REPAIR is STRONGLYCONSIDER) (1)
86. If (CRITICALITY is AVERAGE) and (VAE is AVERAGE) then (REPAIR is WEAKLYCONSIDER) (1)
87. If (CRITICALITY is AVERAGE) and (VAE is LOW) then (REPAIR is WEAKLYCONSIDER) (1)
88. If (CRITICALITY is LOW) and (VAE is HIGH) then (REPAIR is WEAKLYCONSIDER) (1)
89. If (CRITICALITY is LOW) and (VAE is AVERAGE) then (REPAIR is DONOT) (1)

Figure 46 Aggregate depiction and weighing of rules

Afterwards, central method is used by MATLAB software in defuzzification because this method of defuzzification reduces the complexity of the problem and leads to less time for calculations. Here, we select, again, "Sum" aggregation method for fuzzy rules due to connected fuzzy rules due to AND operator. The way the operations are carried out has already been analysed in a previous chapter. The next figure shows the output and the way the system is led to it.



This picture displays a roadmap of the whole fuzzy inference process. This is a single figure with 630 plots nested in it. The first 7 plots across the top of the figure represent the antecedent and consequent of the first rule, and so goes for all the rules. The final plot on the bottom of the figure represent the output. The variables and their current values are displayed on top of the columns and in the lower left, there is a text field “Input” in which we can enter specific input values. For this example we enter 0.5 for each input, in next chapter we will test the system by giving other number to the inputs. As it is already said, the aggregation occurs down the 91column, and the resultant aggregate plot is shown in the single plot appearing in the lower right corner of the plot field. The defuzzified output value is shown by the thick line passing through the aggregate fuzzy set and the “crisp” value of the output appears on the top of the output column.

This figure allows to interpret the entire fuzzy inference process at once, shows one calculation at a time, in great detail and alongside, shows the shape of certain membership functions and they influence the overall result. In this sense, it presents a micro-view of the fuzzy inference system but if we desire to see the entire output surface of the system, the next figures show all the decision-making surface.

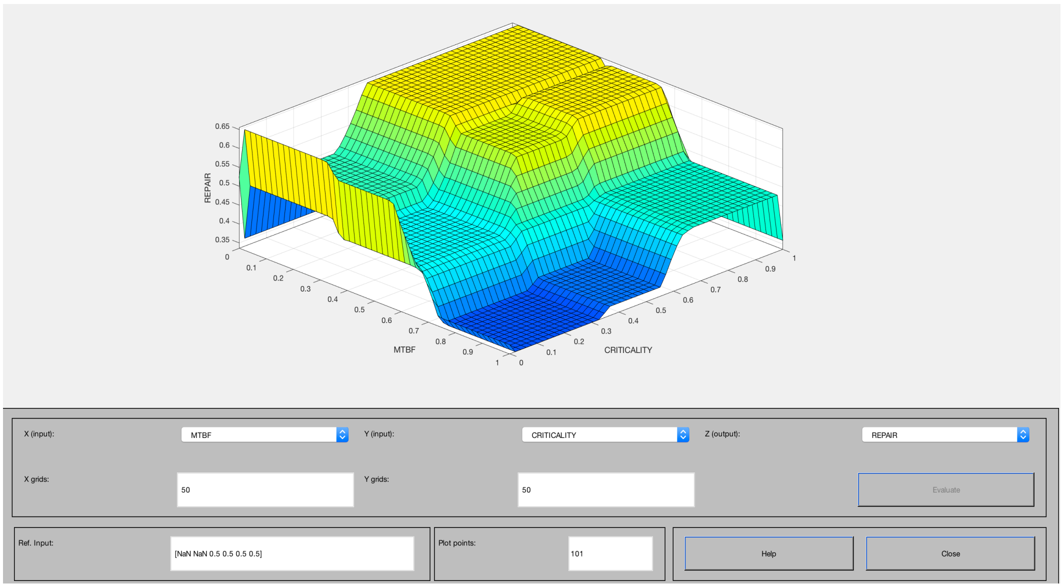


Figure 47 Surface MTBF-CRITICALITY-REPAIR, IMPROVED SYSTEM

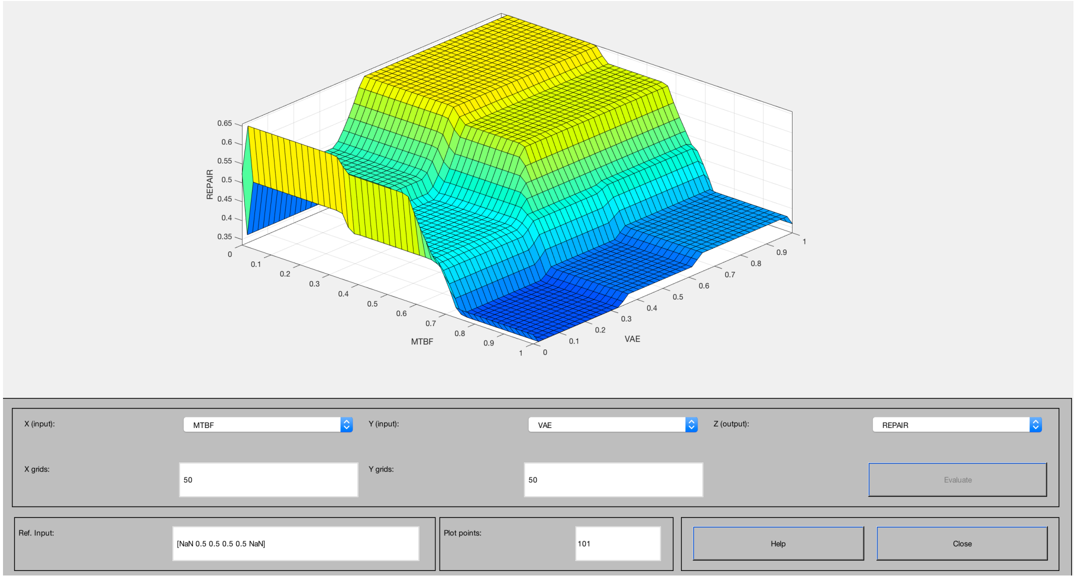


Figure 48 Surface MTBF-VAE-REPAIR, IMPROVED SYSTEM

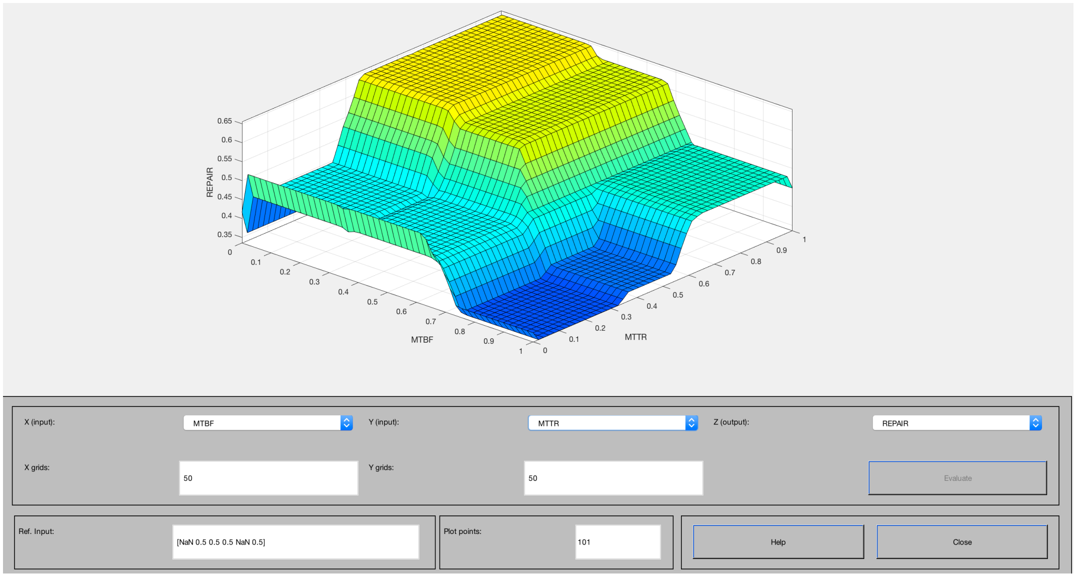


Figure 49 Surface MTBF-MTTR-REPAIR, IMPROVED SYSTEM

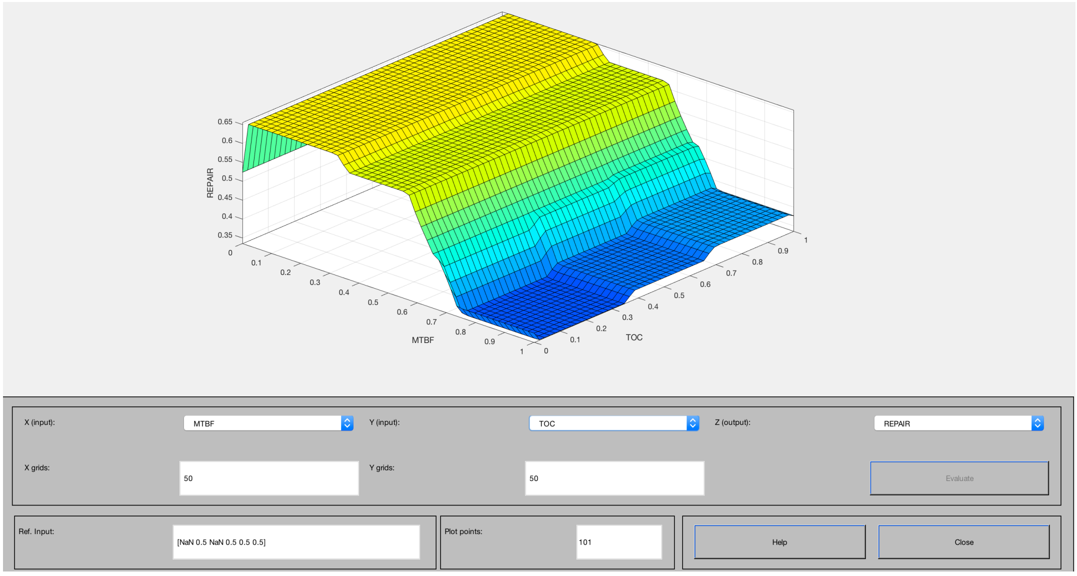


Figure 50 Surface MTBF-TOC-REPAIR, IMPROVED SYSTEM

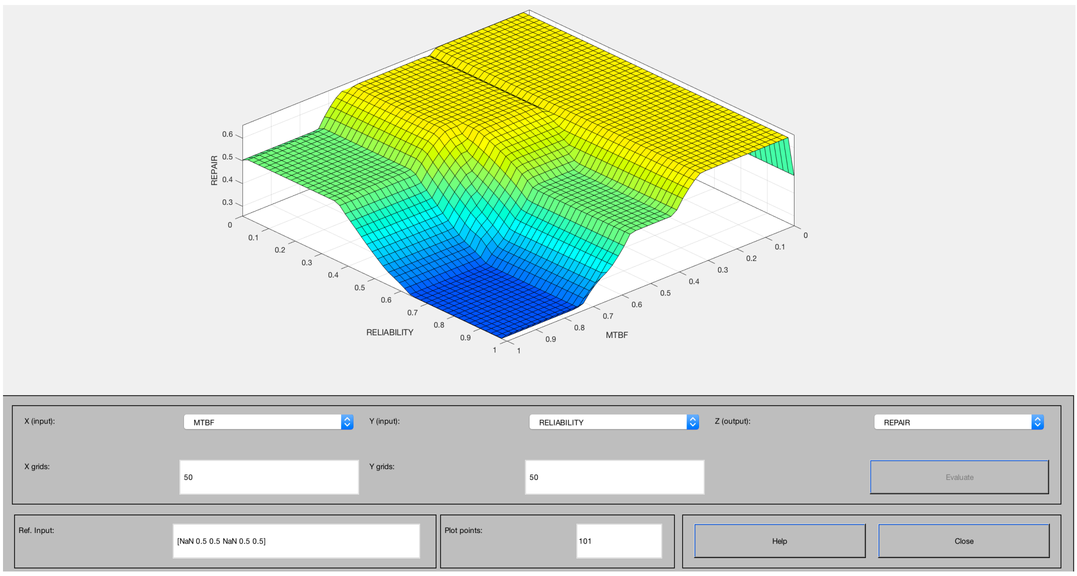


Figure 51 Surface MTBF-RELIABILITY-REPAIR, IMPROVED SYSTEM

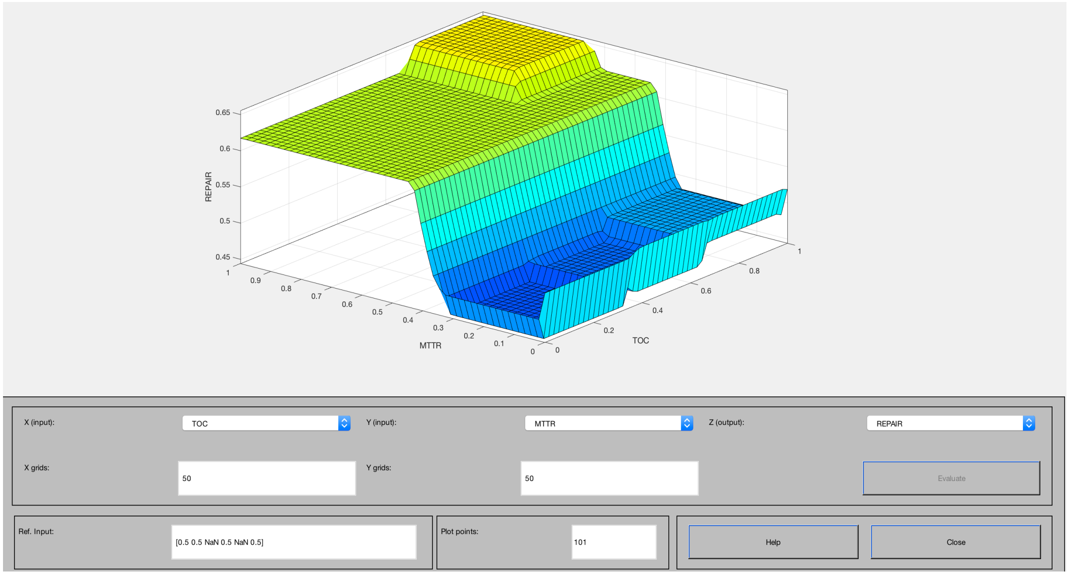


Figure 52 Surface TOC-MTTR-REPAIR, IMPROVED SYSTEM

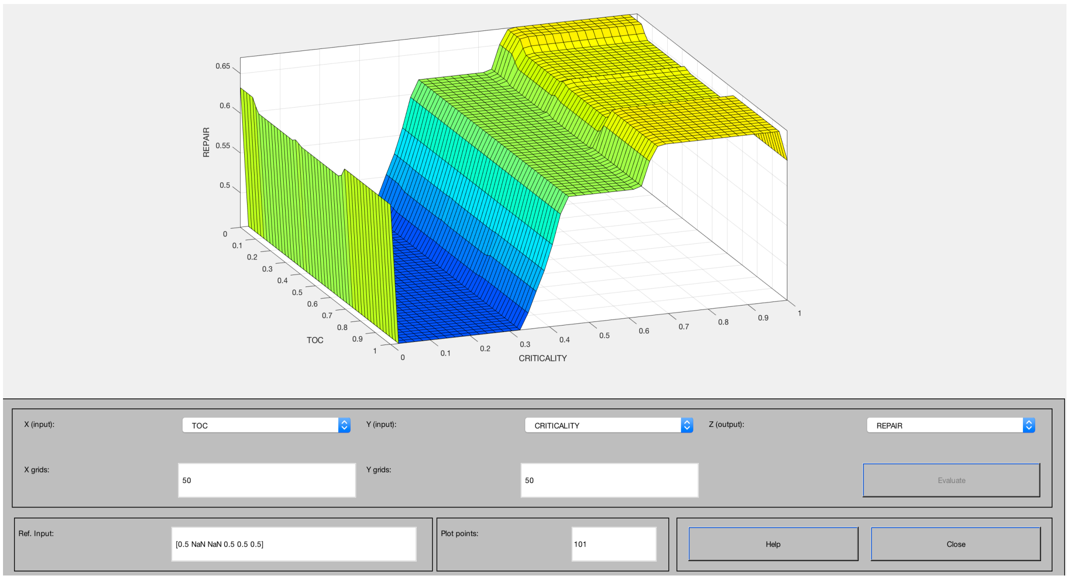


Figure 53 Surface TOC-CRITICALITY-REPAIR, IMPROVED SYSTEM

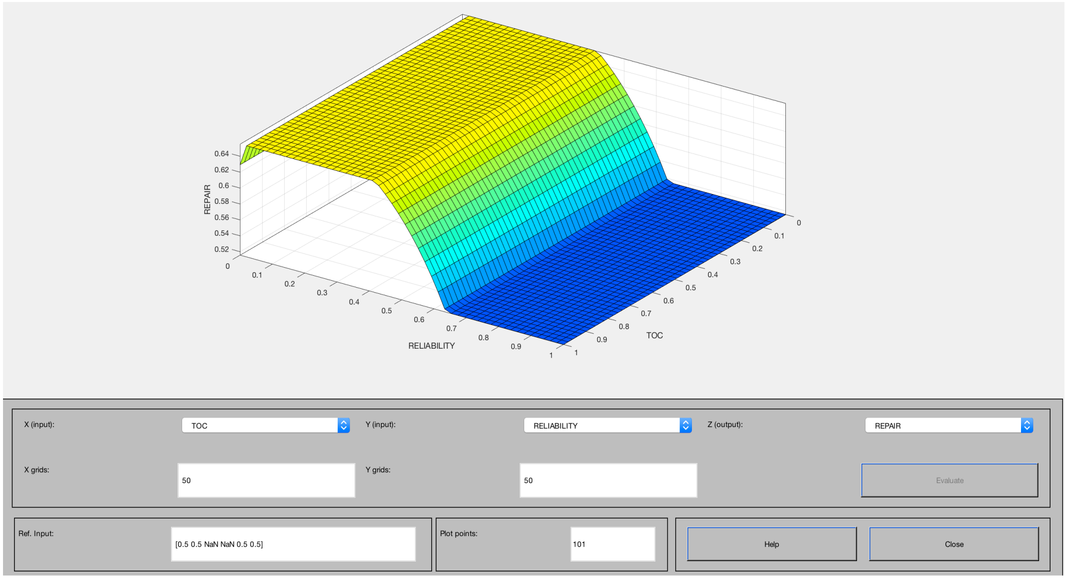


Figure 54 Surface TOC-RELIABILITY-REPAIR, IMPROVED SYSTEM

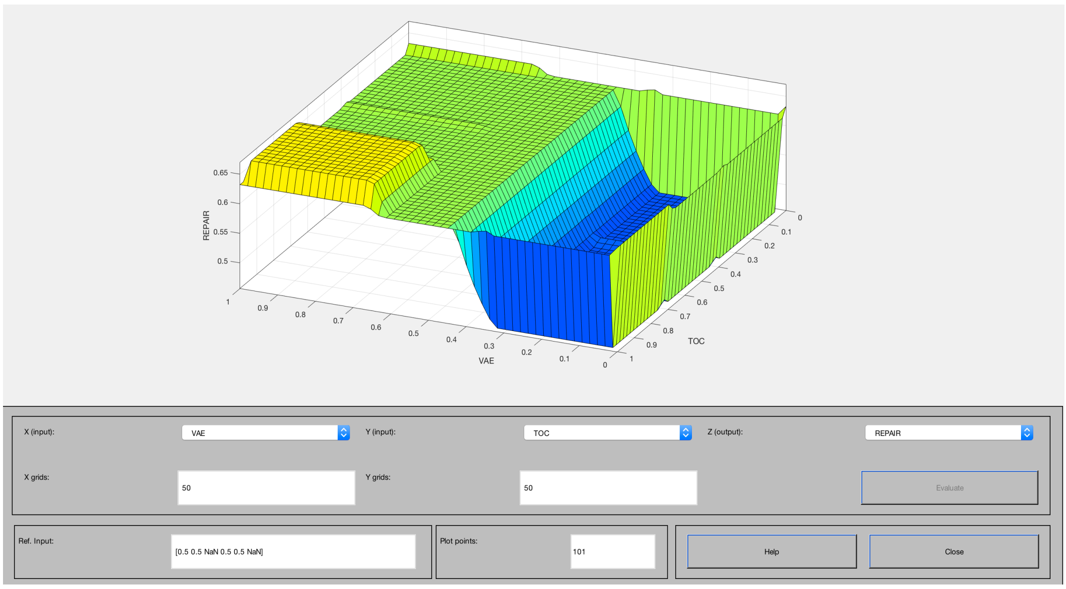


Figure 55 Surface VAE-TOC-REPAIR, IMPROVED SYSTEM

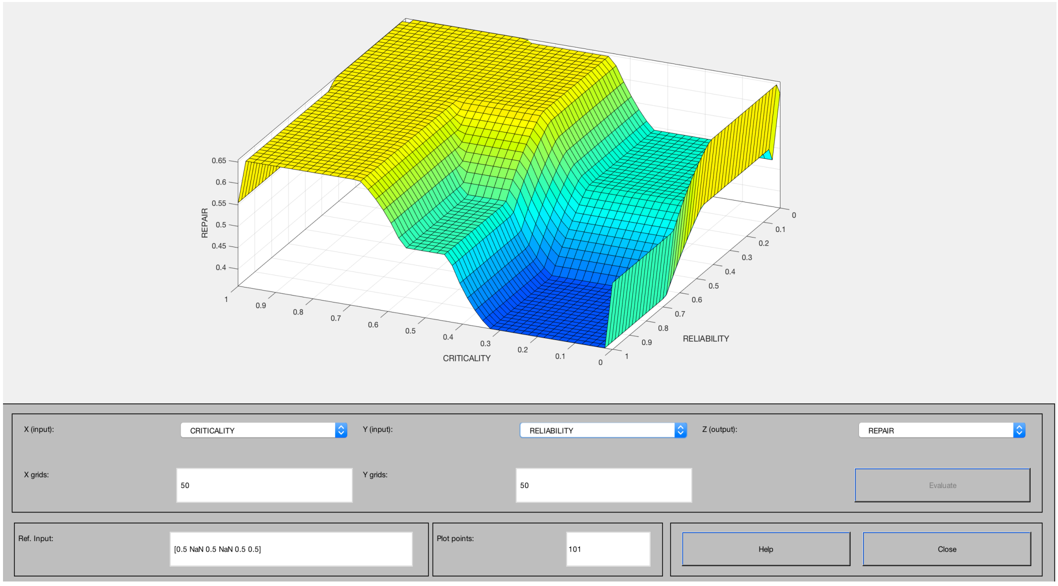


Figure 56 Surface CRITICALITY-RELIABILITY-REPAIR, IMPROVED SYSTEM

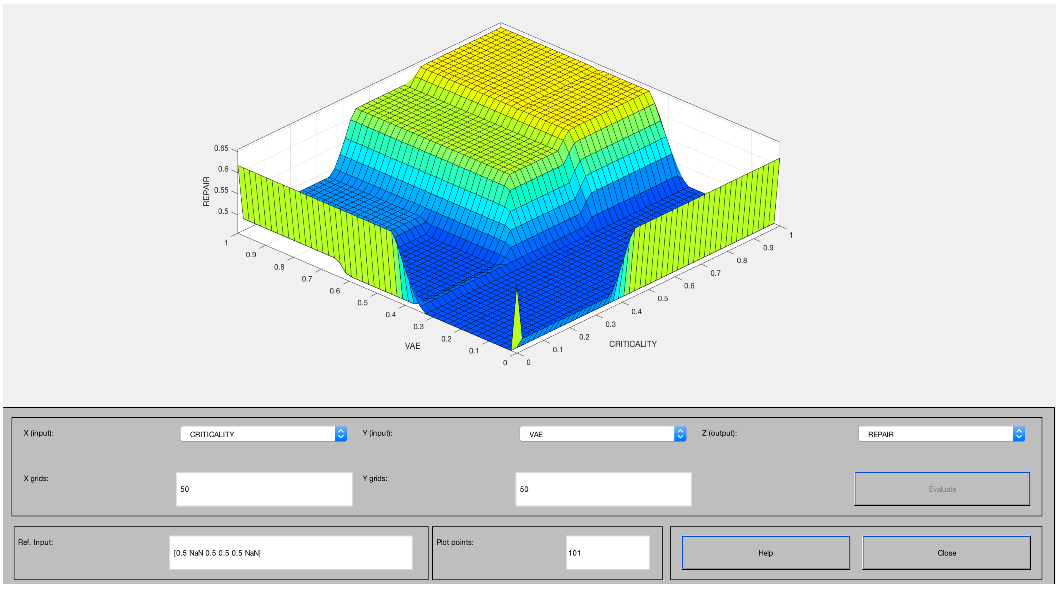


Figure 57 Surface CRITICALITY-VAE-REPAIR, IMPROVED SYSTEM

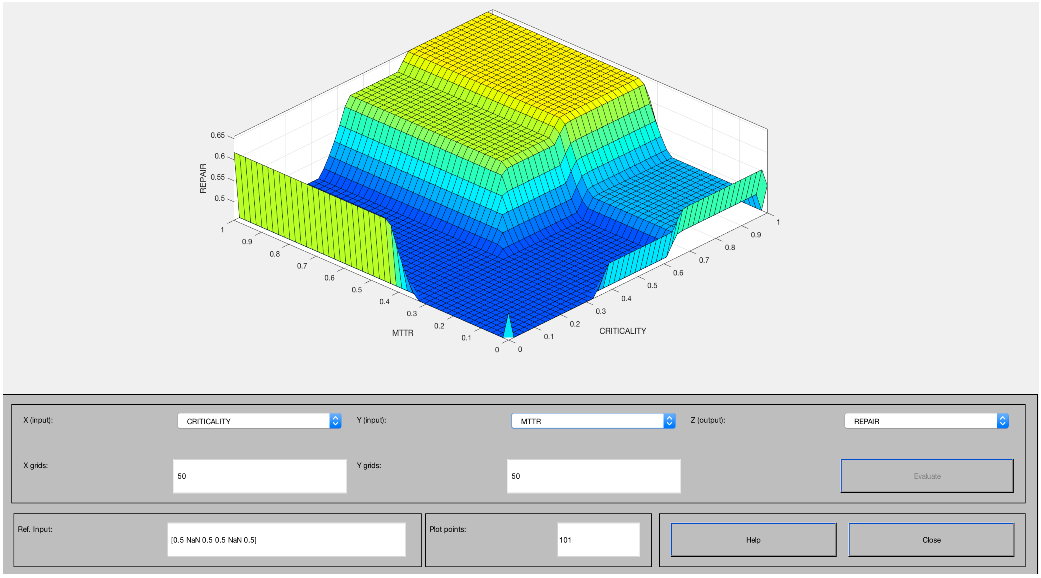


Figure 58 Surface CRITICALITY-MTTR-REPAIR, IMPROVED SYSTEM

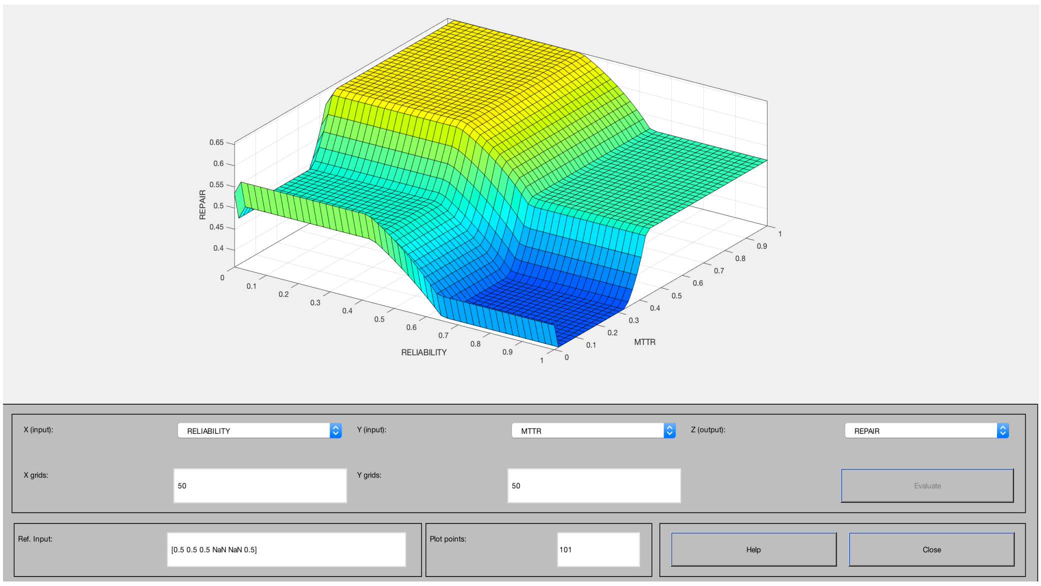


Figure 59 Surface RELIABILITY-MTTR-REPAIR, IMPROVED SYSTEM

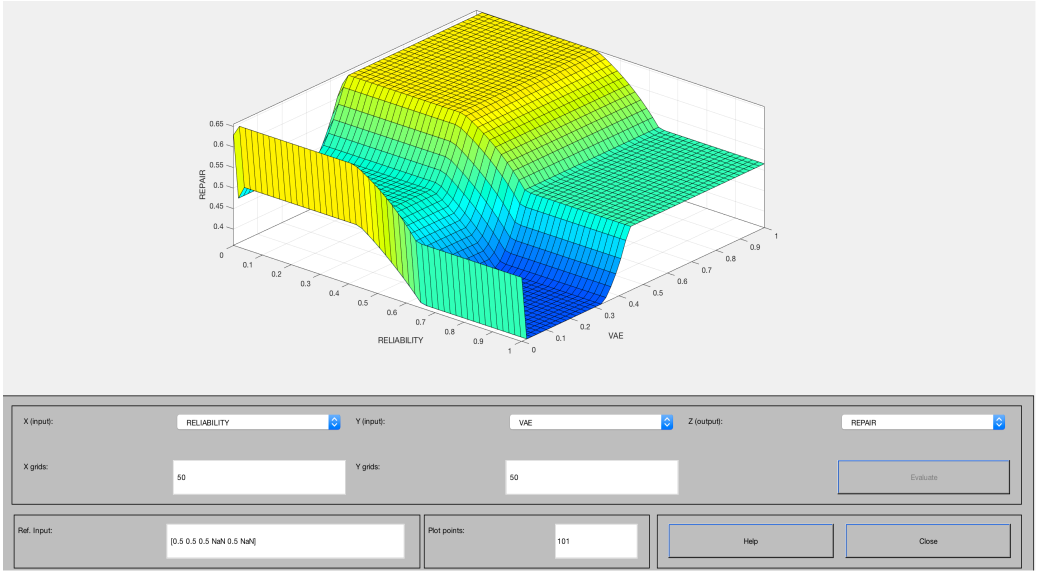


Figure 60 Surface RELIABILITY-VAE-REPAIR, IMPROVED SYSTEM

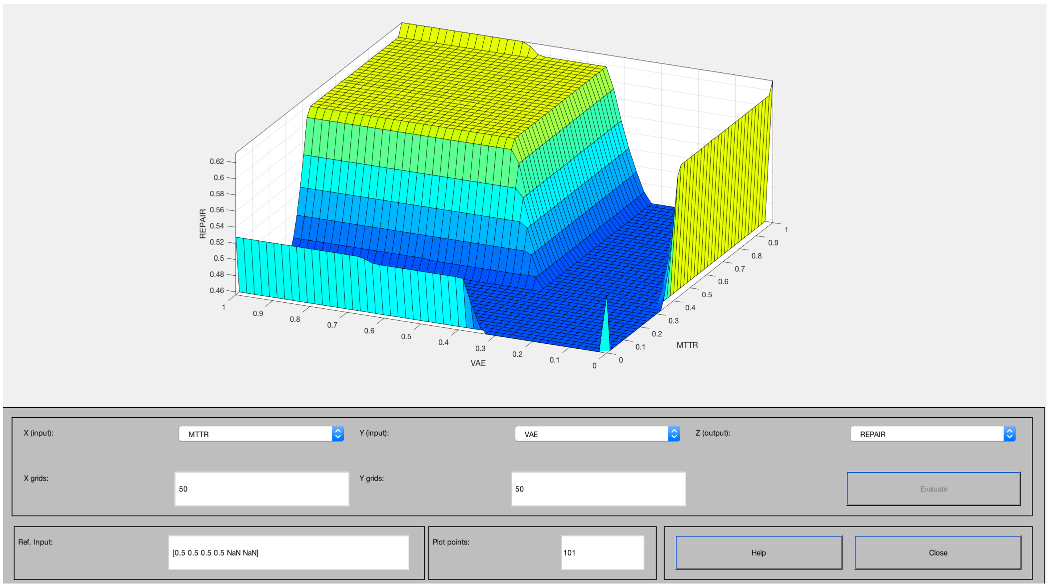


Figure 61 Surface MTTR-VAE-REPAIR, IMPROVED SYSTEM

The predominant issue was the smoothness of the plots. It is obvious that, this issue has been improved in a very large percentage after the improvement of the system. There are still cases where the result is not entirely smooth, but those cases are an exception and the only "clash" they have is only at the edges of the universe of discourse and not across the plot. We presume that the system is more efficient and the results are more realistic. This is a visibly improved system, which will be used in the consecutiveness of this research. In this chapter, the values that were given as inputs were medium values (0.5 of the universe), so that the results were representative of the total. In the next chapter, experimental trials will be carried out, covering a large range of prices in order to produce representative results, based on reality.

Chapter 5. Testing

The objective of this chapter is the test of the system in order to create a comprehensive report, as it is already said above, that is achieved by presenting 4 experiments. The first and the second one are related to the extremes of the value of margins and their results help us to reach a general output. These outputs are easy to come up with simple logic and they are an everyday-decision of experts, precisely because they are extreme cases. Nevertheless, they greatly contribute to the perception of the system and how it works by a non-specialist.

The next two experiments are more realistic. Input values are more inexplicit and as they are combined , it is really hard to make a decision about the maintenance of those systems, even if an expert tries to make this decision. Practically, the system, which is analyzed in this thesis, is designed for those cases. Thus, there may be a solution in cases where we are not sure about what should happen in terms of maintenance and size of the scope. All the outputs of the experiments are analyzed and compared each other, in order to produce safe results.

All the experiments below will be tested firstly with the initial system and then with the improved system. Afterwards the exported results will be analyzed.

5.1 Experiment 1

5.1.1 Initial Implementation

In this first test, the same value has been given for all inputs (0.9) as it is referred in the table below. Values are rendered from 0 to 1 and it has to do with a score that user gives from 0 to 1. Thus, in order to avoid any confusion, we made this assumption because some criteria have a negative connotation and some positive. Accordingly, the results which are close to 0 are those that their system does not need maintenance, while the outcome goes from 0 to 1 the system must, definitely, be maintained.

Inputs	
MTBF	0.9
Criticality	0.9
TOC	0.9
Reliability	0.9
MTTR	0.9
VAE	0.9
Output	
Repair	0.369

Table 3 Input and output values of test 1

When MTBF is 0.9, means that the system has good MTBF, there is a lot of time from one failure till the next one occurs. The failures of this system are sparse. The same system, which criticality is 0.9, is a system that the failure of it affects the whole system. Based on given numbers, the system requires a big amount of money and repair-time in case of breakdown (TOC, MTTR), it is reliable and high-valued (Reliability, Value of equipment). The next figure shows all the inference process and the result.

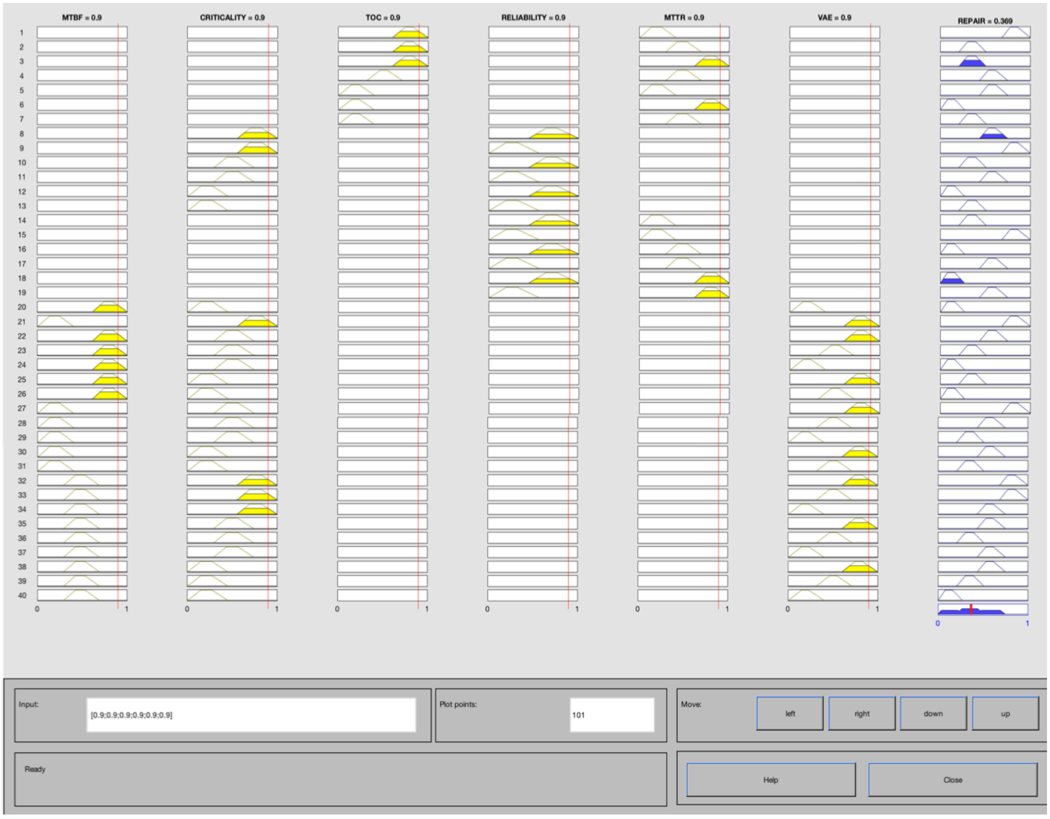


Figure 62 Experiment1-Presentation of inference system

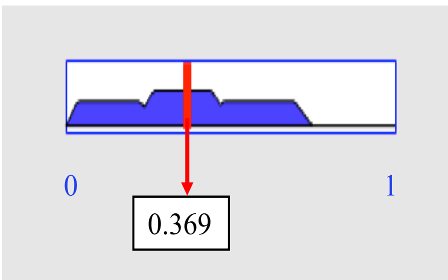
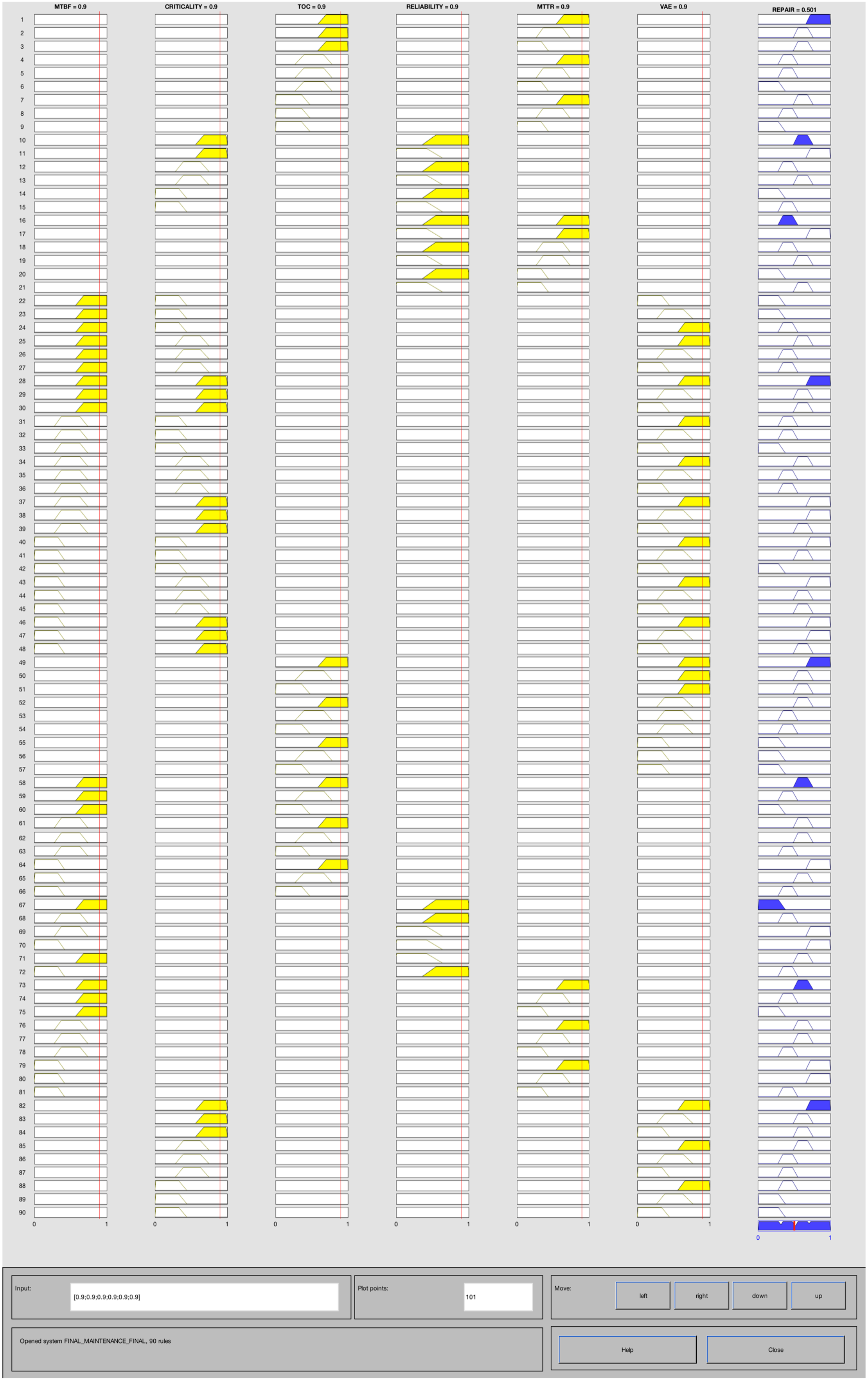
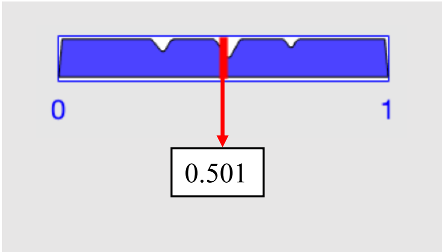


Figure 63 Result of experiment 1

The result of the system is 0.369 and that actually means that this is system does not requires maintenance. In addition, if we take a closer look at the plot of the output, it becomes obvious that, except from the "crisp" result, all the surface is located closer to 0 than 1.

5.1.2 Improved implementation





After the running of the improved system the result changed from 0.369 to 0.501, namely from “do not” or “weakly consider” to “weakly consider” or “strongly consider”. According to the data of this example the second result seems to be more realistic than the first one.

5.2 Experiment 2

5.2.1 Initial implementation

In this test, the same value has been given for all inputs (0.1) as it is referred in the table below. The ranking of values arises in same way as in experiment 1 and they are rendered from negative (0) to positive (1). Accordingly, the results which are close to 0 are those that their system does not need maintenance, while the outcome goes from 0 to 1 the system must, definitely, be maintained.

Inputs	
MTBF	0.1
Criticality	0.1
TOC	0.1
Reliability	0.1
MTTR	0.1
VAE	0.1
Output	
Repair	0.598

Table 4 Input and output values of test 2

When MTBF is 0.1, means that the system has bad MTBF and the failures of this system are frequent. The same system, which criticality is 0.1, is a system that the failure of it does not affects the whole system in big percentage. Based on given numbers, the system does not requires a lot of money and repair-time in case of breakdown (TOC, MTTR), it is unreliable and low-valued (Reliability, Value of equipment). The next figure shows all the inference process and the result.

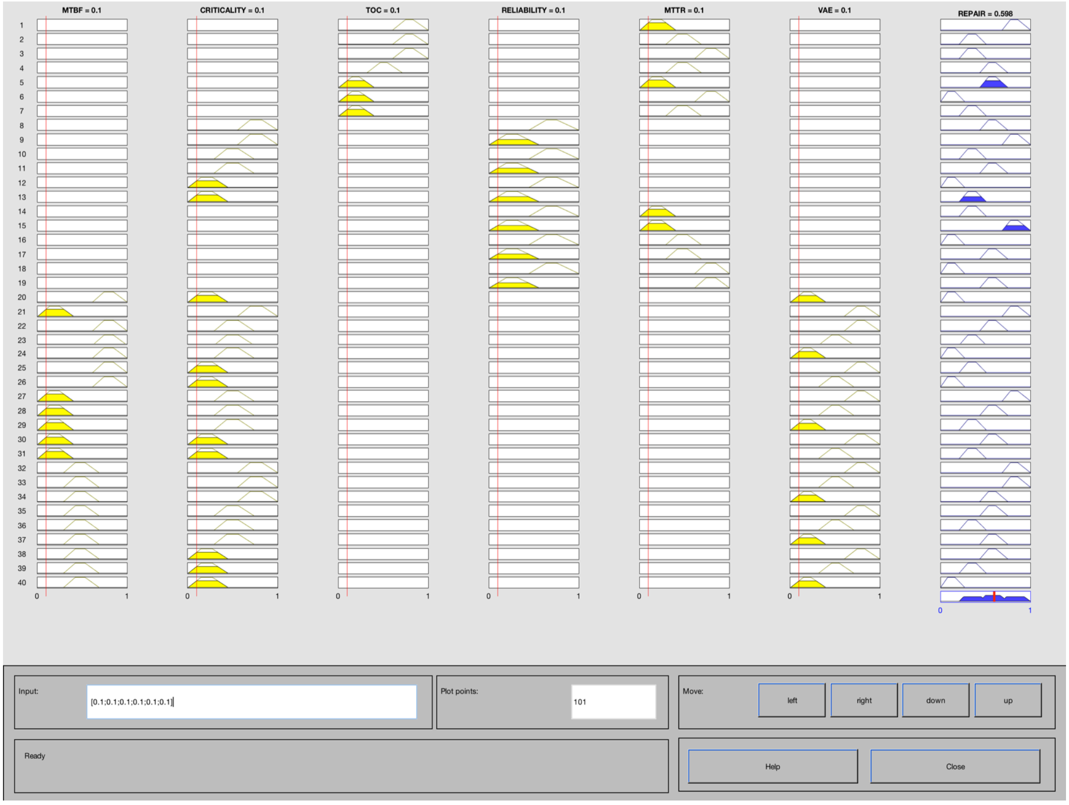


Figure 64 Experiment2-Presentation of inference system

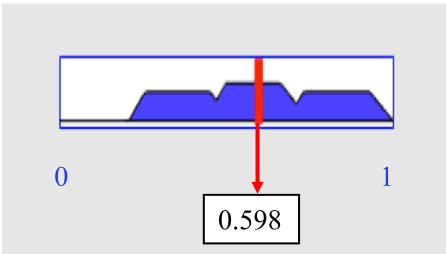
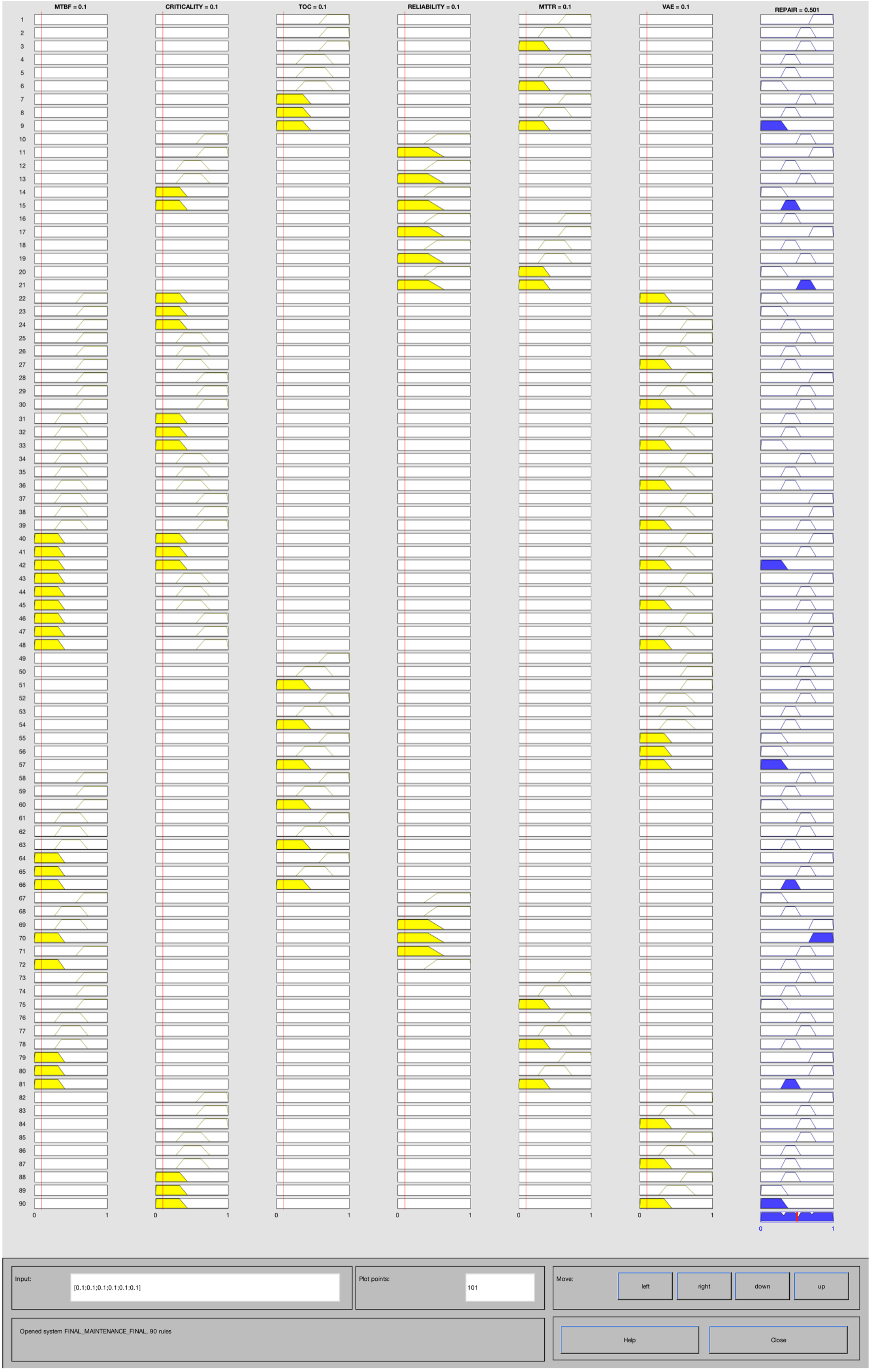
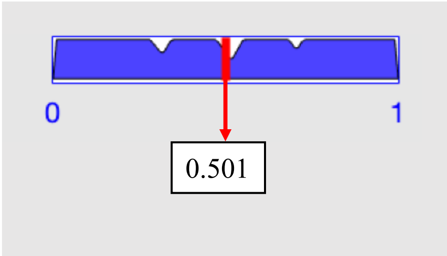


Figure 65 Result of experiment 2

The result of the system is 0.598 and that actually means that the maintenance of this system is almost necessary, as 0.595 gives the response “strongly consider”. This number is not a huge one so that maintenance is an emergency situation. Actually, it means that in 59.8% this system needs maintenance. For some researchers this percentage reflects a system that clearly needs maintenance, for others not. If we take a closer look at the plot of the output, it becomes obvious that, except from the “crisp” result, all the surface is located closer to 1 than 0. Hence, we believe that this system needs a maintenance.

5.2.2 Improved implementation





As it is obvious, the difference between the initial and the improved system, is not colossal, hence the decision about the maintenance is the same. Nevertheless, it is interesting to compare the results of the first two experiments (only by running the improved system).

In the first two cases, despite the fact that the input data are different, the result remains the same. This is a normal phenomenon, as it shows the temperament of the system. In the first experiment, the system has a high MTBF, i.e. the occurrences of damage are sparse and its reliability is high. However, it is a critical system of great value, which in an event of damage it costs a lot and requires long repair time. The combination of those elements "draws" the result to an average value.

Correspondingly, in the second example, the failures are frequent and the reliability of this system is small. However, it is a low-criticality system that requires both short time and cost in the event of a failure. These factors contribute to an average value as a result.

As to the result, the two cases seem to be very similar, even if they are different as to the data. This is one of the most transient proofs of system improvement, as the differences from the initial system to the improved system, were several (0.369-0.598, 0.501-0.501).

5.3 Experiment 3

5.3.1 Initial implementation

In this experiment, the values vary from one rule to another, but also are rendered from negative (0) to positive (1). Accordingly, the results which are close to 0 are those that their system does not need maintenance, while the outcome goes from 0 to 1 the system requires maintenance. The values of each input are presented in the table below:

Inputs	
MTBF	0.2
Criticality	0.8
TOC	0.9
Reliability	0.3
MTTR	0.8
VAE	0.7
Output	
Repair	0.71

Table 5 Input and output values of test 3

The values of the described system seem realistic. When MTBF is 0.2, means that the system has bad MTBF and the failures of this system occur with high frequency. The criticality is 0.8 and this is not a good factor because it means that once the system fails, does affects the whole system in a big percentage. Based on given numbers of TOC and VAE, there are huge financial requirements in a case of failure and this is a high-valued system. However, this system is unreliable and needs a big amount of time to be repaired after a breakdown. The next figure shows all the inference process and the result.

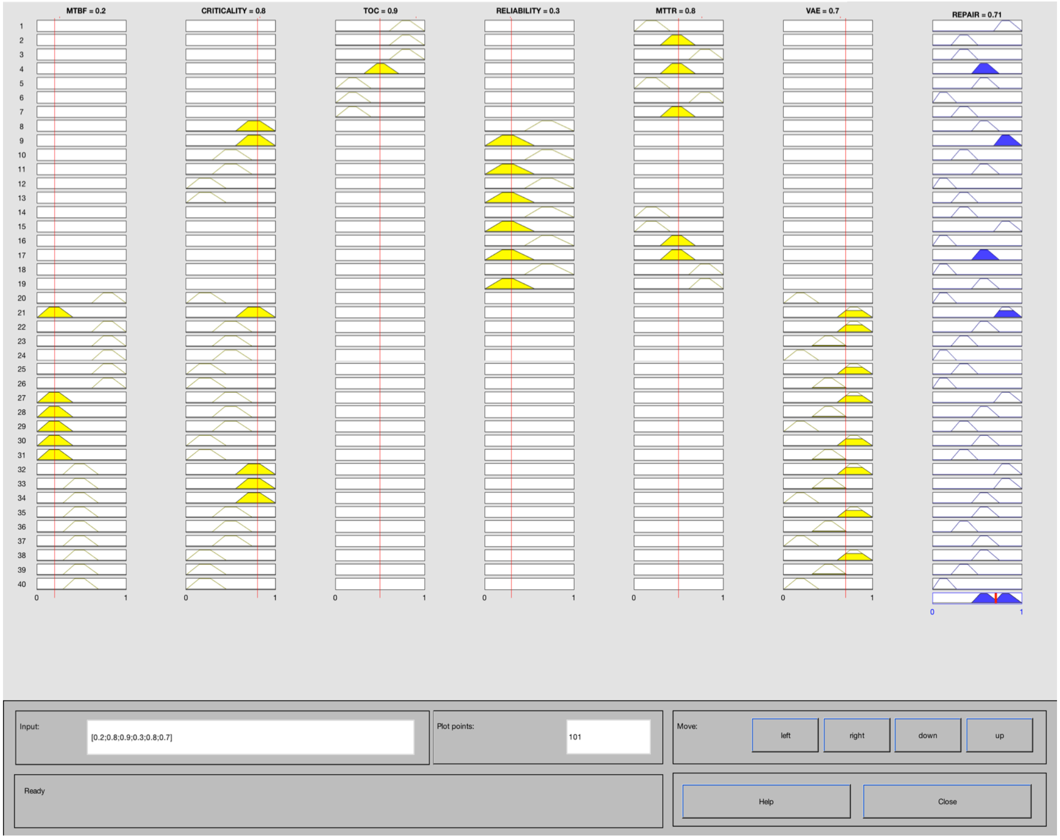


Figure 66 Experiment3-Presentation of inference system

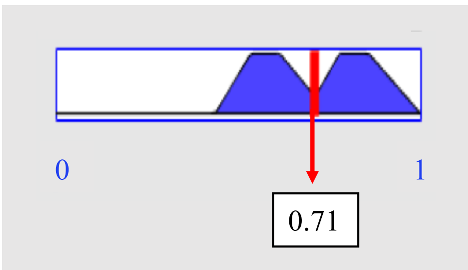
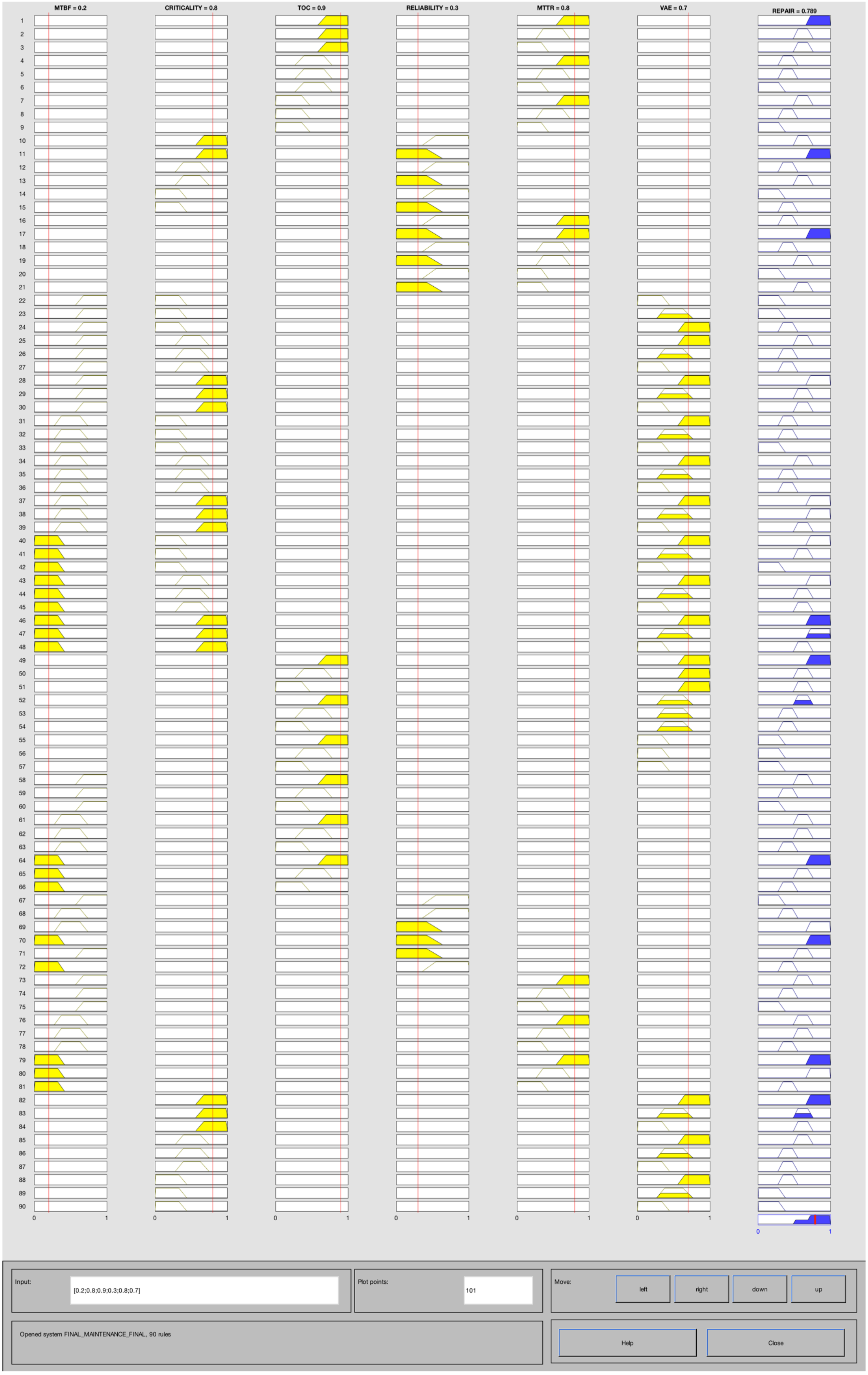
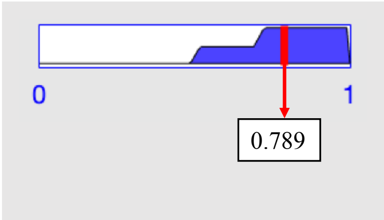


Figure 67 Result of experiment 3

The result of the system is 0.71 and the surface of the output plot is located closer to 1 than 0. Thus, according to our system, maintenance of this device is emergent.

5.3.2 Improved implementation





It is obvious that the results of the initial and the improved system do not differ so much (from 0.71 to 0.789). However, based on the membership functions, the result is moved from “strongly consider” to “do”. That situation provides the state of the system, making it to extract more stable results. This conclusion is strengthened by the fact that if experts take a look at the data, they would consider that this system needs maintenance. Only the result of the improved system corresponds to the statement of experts.

5.4 Experiment 4

5.4.1 Initial implementation

This is the final experiment and for that test the values vary from one rule to another, but also are rendered from 0 to 1. At this time, the values are against the values of the previous experiment. Accordingly, the results which are close to 0 are those that their system does not need maintenance, while the outcome goes from 0 to 1 the system requires maintenance. The values of each input are presented in the table below:

Inputs	
MTBF	0.7
Criticality	0.3
TOC	0.3
Reliability	0.8
MTTR	0.2
VAE	0.3
Output	
Repair	0.378

Figure 68 Input and output values of test 4

The values of the described system seem realistic, as in the previous test. When MTBF is 0.7, means that the system has good MTBF, there is a lot of time from one failure till the next one occurs. The failures of this system are sparse. The criticality is 0.3 and this is a really good factor because it means that once the system fails, it does not affect the whole system in a big percentage. Based on given numbers of TOC and VAE, there are small financial requirements in a case of failure and this is a not a high-valued system. However, this system is kind of reliable and needs a small amount of time to be repaired after a breakdown. The next figure shows all the inference process and the result.

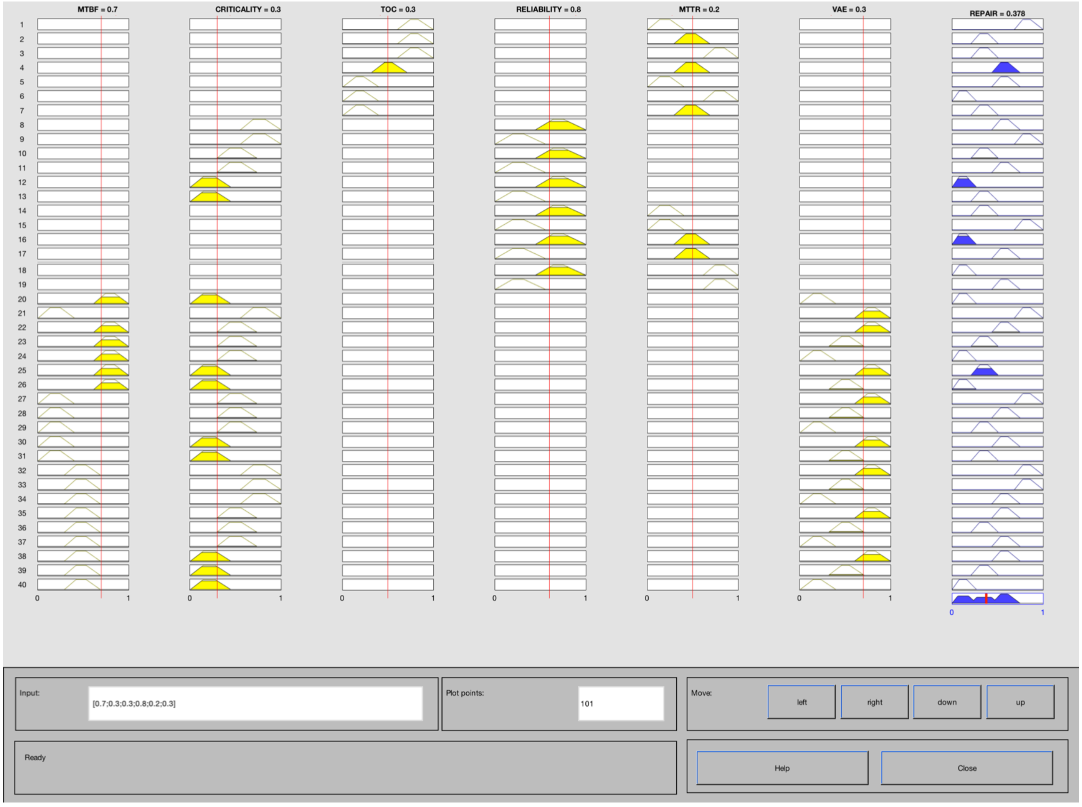


Figure 69 Experiment4-Presentation of inference system

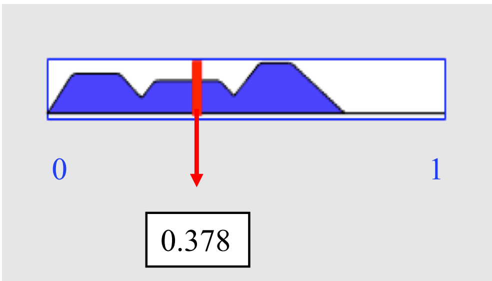
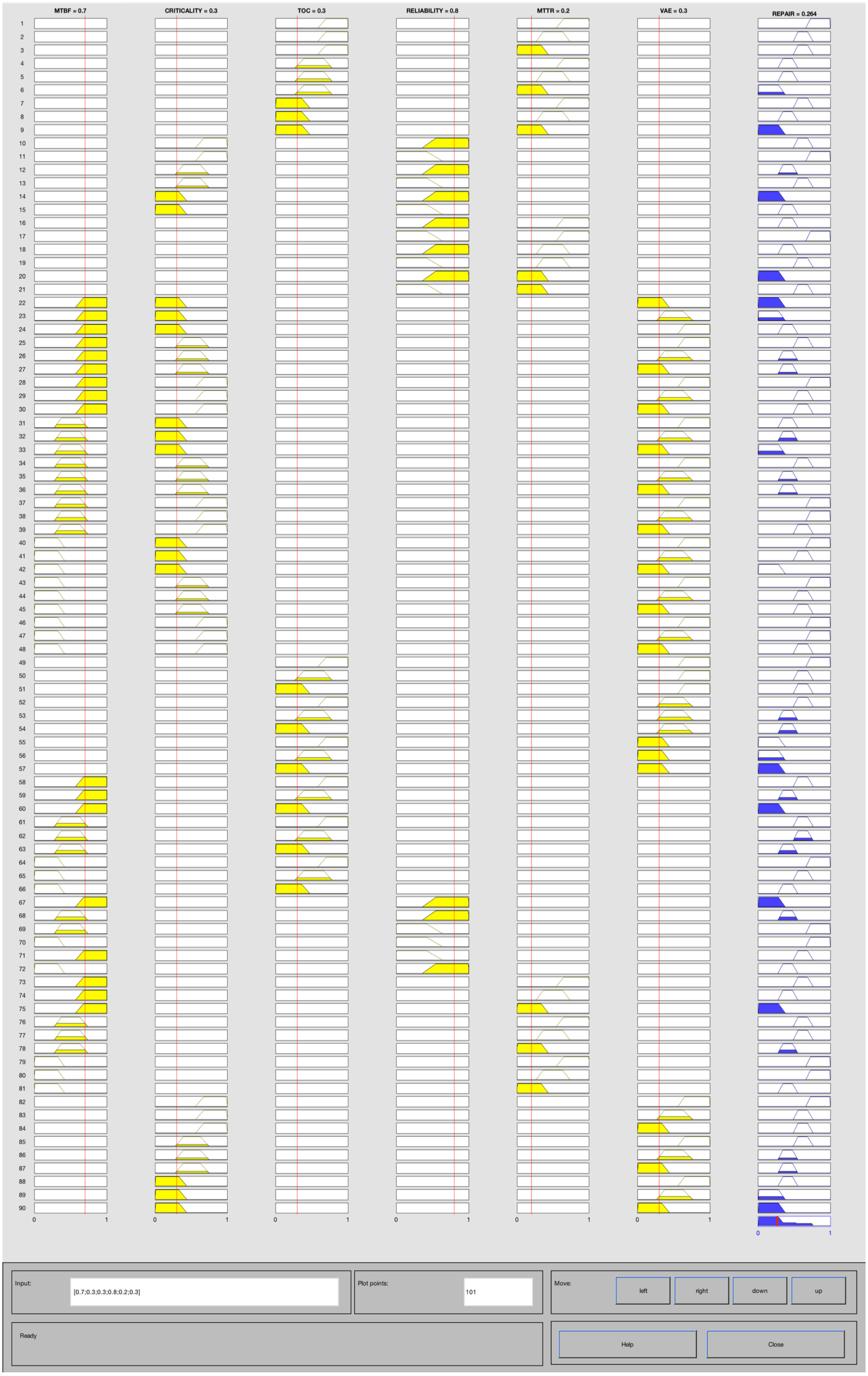
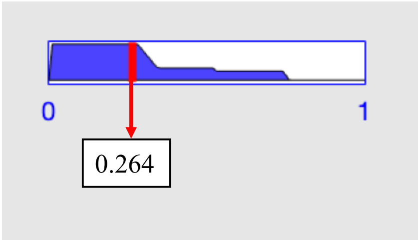


Figure 70 Result of experiment 4

The result of the system is 0.378 and that actually means that this is system does not requires maintenance. In addition, if we take a closer look at the plot of the output, it becomes obvious that, except from the "crisp" result, all the surface is located closer to 0 than 1.

5.4.2 Improved implementation





In this case, the difference between the result of initial system and the improved is big, from 0.378 to 0.264. That means that from “weakly consider” result goes to “do not”. Practically this is the same situation as in experiment 3, in a way. Here, if experts take a look to the input data, they would thought that this system does not need maintenance. Again, only the result of the improved system leads to a though closer to the experiments’.

Additionally, if we compare the last two experiments, we conclude that they have a common feature, that those are two extreme cases. Example 3 mimics a very negative case, a system that its maintenance is necessary, while example 4 is the opposite. The system of example 4 is fairly reliable as evidenced by the data and that makes a clear decision. We summarize that the most important common point of the improved implementation of the two experiments, compared to the initial implementation, is that the results of the improved system of the last two experiments give a clear statement of maintenance.

Aggregated Observations

Observing the above examples and their results based on running of the initial system, some general conclusions are drawn for the system created in this research. These observations relate both to the actual operation of the system and to the drawing of conclusions. Different input values can give similar "crisp" results. This happens with cases 1, 4 according to the implementation of initial system. That situation confirms both the utility and the effectiveness of the created system. In addition, "crisp" values of results which close to 0.5 do not solve the problem, so the decision is still difficult. In such cases the output plot, combined with the crisp result, gives the solution. When the output plot covers areas close to 1, then it is likely that we will make the decision to maintain the system. With a small increase of the scope of a maintenance project, from a statistical point of view, it is more likely to avoid future failures. Correspondingly, when the output plot covers areas close to 0, then it is likely that we will make the decision to do not maintain the system because we may spend time and money that is not necessary. In this way and using this system, it is easy to optimize the scope of a maintenance project in an ideal way.

On the other hand, running the improved system we recognize that, thanks to the precision of the results, it became easier to take a decision about the maintenance without necessarily checking plots. It is an effective system, full customizable and really user-friendly. Because of this situation, we decide to use only the improved version of the system in the next chapter. In order to examine how this system corresponds to real-life data, in next chapter we are going to test it. At the same time, a comparative study will be carried out of the system used up to now by industries with the system developed in the framework of this research.

Chapter 6. Comparative study of an established in industrial areas system and the fuzzy logic system.

In this chapter it will be analysed the system that is used nowadays by industries to optimize the scope of large project, such as maintenance projects. Thereafter, there is a testing section with 30 cases analysed firstly with the established system (ES) and secondly with the Fuzzy Logic system (FLS). After all, we contrast an compare the results of each method.

6.1 Description of the established system

The method of the established system solves two basic issues of the maintenance and reliability department of an industry: (a) the workforce which has low availability and ability to analyse the criticality of each equipment or occurred event in detail level (b) once the criticality of each item or event is defined, experts have to decide the best practises of maintenance. That system identifies the really critical events, items that their maintenance is crucial in terms of safety, environment, availability, quality of finished product and maintenance costs, so as to be able to perform a systematic and posterior maintenance plan. This methodology is a Risk-Based Inspection and Maintenance (RBI&M) methodology which leads to a maintenance strategy of minimizing the risky results and failures. The key issue of this system is that identifies the critical equipment based on a level of risk and the acceptable level of risk (which is pre-selected). The prioritisation of the equipment is based on that analysis. The RBI&M methodology is essential in developing cost-effective maintenance policies and reduces the overall risk of a plant. [31] For the majority of industries, that system is widespread and widely used. We can claim that ES reaches the target of this research and leads to scope optimization of large maintenance projects and close on integrates reliability practices. This methodology is implemented in seven steps as it is analysed below and presented in next figure. [31]

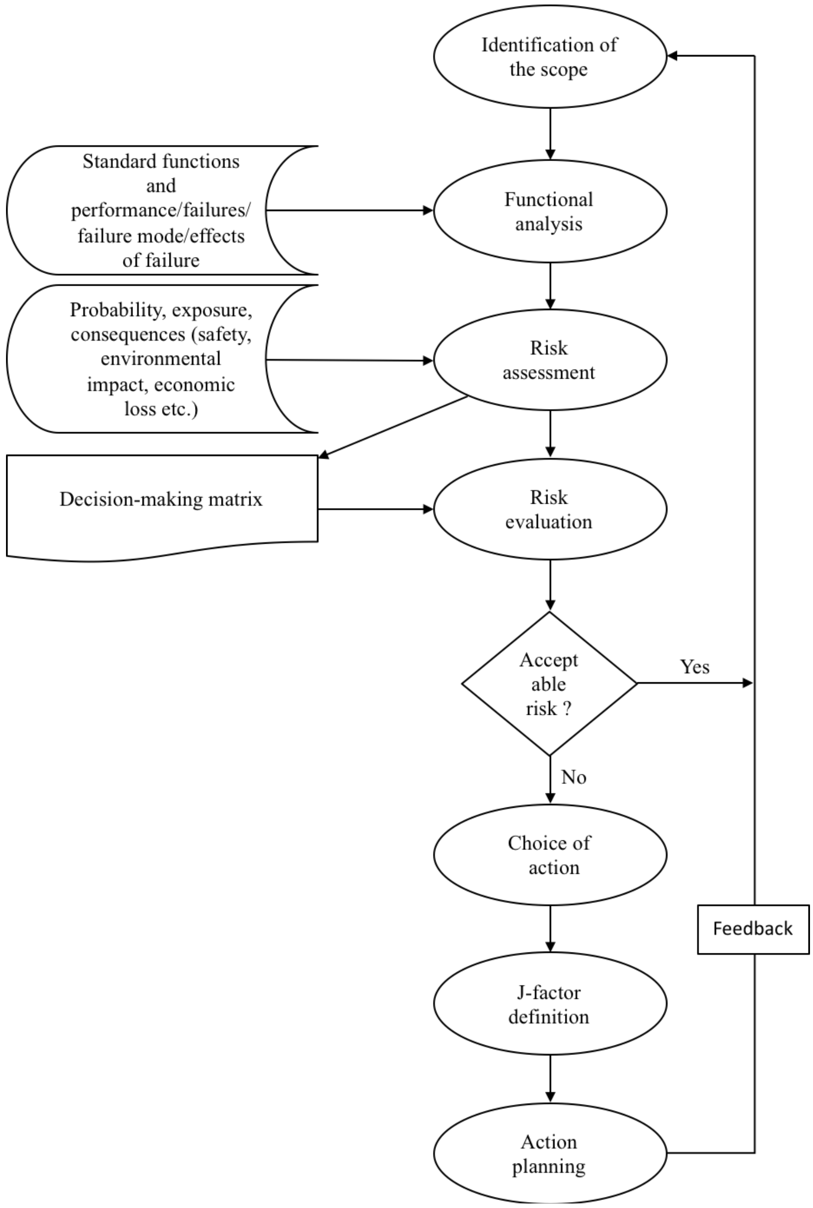


Figure 71 Steps in RBI&M methodology. [31]

Step1 Identification of the scope: the scope of the analysis must be defined and classified, the analysis faces the plant as a whole and identifies the role of each sub-system, item and component. The classification is implemented based on environmental factors, safety, risk criteria and operational activities.

Step2 Functional analysis: the function and the standard performance of each item of the equipment is defined, so as to be able to recognize if there is any deflection. Additionally, in this step there are used three types of data: functional failures, failure mode and effects of failure. For each function it is possible to identify a certain number of functional failures (the system does not perform the standard operations). Each functional failure is occurred by several reasons and by identifying them the failure can be avoided. Each functional failure can occur various effects. Every item of the system is mapped with its failures, failure mode and effects respectively.

Step3 Risk analysis: In order to identify the criticality of a given functional failure, it is crucial to carry out an initial evaluation of probability and an initial evaluation of consequences. A team of experts defines some criteria so to create probability classes, quantifying the probability of an event. Additionally, there four categories of possible consequences: health and safety, environmental impact, loss of reputation and economic loss. Each impact is rated, from 1 to 5 in a level of severity. The output of this step is a decision-making matrix.

Step4 Risk evaluation: This step is based on the output of the previous step. In a case of several competing items, there is a risk score attached by the experts. Finally, the risk is elicited by three factors: probability of an event to be occurred, the possible duration of the event (exposure), the outcome of the event (consequence).

Step5-6 Choice of action and calculation of the J-factor: Before of those steps the team of experts decides if the the level of risk is acceptable or not for each case. If the level of the risk is too high and thus not acceptable, either preventive or mitigating action is necessary. Linking to the previous step (step4), the preventive action reduces the probability of an event to be occurred and the mitigating action reduces the consequences of an event. Based on a decision-making process and on findings, the team identifies the appropriate action. For each improving action, the team calculates the new probability of failure and reconfirms the conditions of consequence and exposure. In some cases the team may suggest more than one alternatives for the same component. So, the complexity of the system is increased especially in a scenario with hundreds of components. Thus, in order to minimize the computational complexity and decrease the time needed for that type of analysis, Bertolini et al. [31] propose an index the J-factor (Justification Factor). J-factor signifies the quantity of risk reduction by euro invested for each case and it is commonly used both to choose between alternatives and decide to maintain or not a component.

This analysis, which uses J-factor as a key-tool, is additionally used for scope optimization of large projects, as the FL system does. A simple form of J-factor is:

$$\mathbf{J-factor} = \frac{\text{Unmitigated Risk Factor} - \text{Mitigated Risk Factor}}{\text{Estimated Maintenance Cost}}$$

In order to calculate the J-factor there is a need about some preliminary information: (i)Unmitigated Risk Factor (ii)Mitigated Risk Factor (iii)Estimated Maintenance Cost. [31]

$$\mathbf{Unmitigated\ Risk\ Factor} = \text{Impact} * \text{Unmitigated Likelihood}$$

$$\mathbf{Mitigated\ Risk\ Factor} = \text{Impact} * \text{Mitigated Likelihood}$$

Impact: that term refers to the impact that will happen if there is no maintenance on the machine. Practically, the selection is easy if we answer to questions such as "what is the risk without fitting maintenance?", "what is the impact if we don't maintain?". Impact is always translated into money so the indicators could be calculated.

Unmitigated Likelihood: the assessment of the probability of failure in the case of non-maintenance is mainly based on past events and data. Additionally, the space to be followed without maintenance is counted.

Mitigated likelihood: the same procedure as before is followed, but in this case, the identification of the probability of failure is calculated after the implementation of maintenance procedures.

Estimated Maintenance Cost: based on the events and previous maintenance data of each machine, approximately the maintenance cost is estimated.

So, the equation of J-factor transforms into:

$$\mathbf{J-factor} = \frac{(\text{Impact } * \text{Unmitigated Likelihood}) - (\text{Impact } * \text{Mitigated Likelihood})}{\text{Estimated Maintenance Cost}}$$

After the calculation of individual elements the J-factor is calculated. The decision making is based on J-factor and it is formed on the basis of the following rules:

- If $\mathrm{J-factor} > 1.0$ then the decision is DO, because the savings from performing the maintenance are greater than the cost of doing it.
- If $\mathrm{J-factor} < 1.0$ then the decision is DO NOT, because the cost of avoiding failure exceeds the cost or value of the risk.

This set of rules, practically, means that the bigger the J-factor of each item is, the surely this item has to be maintained and the maintenance of items with small J-factor can be avoided. In order to visualize the result, after the calculation of this factor, a matrix is designed which has the next form:

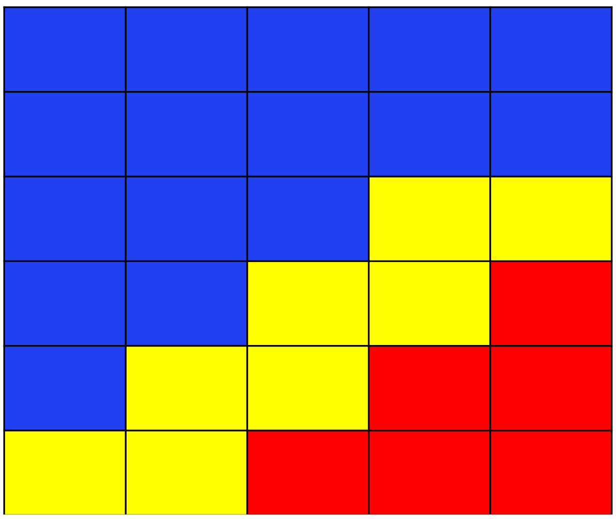


Figure 72 Decision Matrix

Each item, according to its J-factor, is placed to this matrix. Items which are placed in the blue area are the items with the minimum risk and they do not need maintenance. Items which are placed in yellow area are those with medium risk and their maintenance is under discussion. Lastly, items in red area are risky (if we do not maintain them) and their maintenance is compulsory.

Following this chapter, in order to study 30 cases with those two systems (ES, FLS) and compare their results, we have to correspond the criteria of those systems. Thus, we will create a common place-field so we conclude to an efficient comparison.

6.1.1 Correspondence between multicriteria of ES and FL system

The next table shows the criteria of the Established System and the Fuzzy Logic System. This table helps to explain how each criterion of the FLS corresponds to ES criterion in order to extract data and run the 30 examples in the next chapter. This matching is not direct. Based on the data of ES criteria, we rank each FLS criteria, from 0 to 1 as it is referred to chapter 5.

FLS CRITERIA		ES CRITERIA
MTBF	→	Unmitigated likelihood
CRITICALITY	→	Impact of non-included to scope
TOC	→	Unmitigated risk factor
RELIABILITY	→	Unmitigated likelihood
MTTR	→	Impact of non-included to scope
VAE	→	Description and workpiece

Table 6 Correspondence of ES and FLS criteria

As it is referred above, the unmitigated likelihood is the probability of failure in case of non-maintenance and it is based on past events, data and the time until the next maintenance period. We use this probability because it is the only data (in ES) that based on it we can elicit information about MTBF and reliability. We make the assumption that if an item has low probability of failure, its MTBF has low ranking. That kind of matching is not analog. Additionally, if an item has low probability of failure, it has high reliability.

Impact is analysed in previous section of this chapter (6.1) and it refers to an impact that will occur if we will not maintain this item and it is always translated into money. Unmitigated risk factor is the product of the equation [$\text{Impact} * \text{Unmitigated Likelihood}$]. Based on this factor we rank, from 0 to 1, the TOC. Those amounts are proportionate.

The impact of non-included to scope is a criterion of ES and it is a verbal description with two parts. The first part refers to a statement which answers if the maintenance of an item could be in operating time or not and the second part describes how many days does an item requires to be repaired. According to the first part of this criterion, we rank the criticality of the item. If the maintenance of an item could be in operating time, then probably this item has low criticality and vice versa. Additionally, based on the second part we rank the MTTR. The more days an item requires to be repaired, the higher ranking takes its MTTR.

In ES there are some more information-criteria such as the description of each item and the workpiece. The description describes the item and the workpiece describes briefly what kind of maintenance work has to be implemented, so we can assume data about the value of the equipment. Those criteria are a verbal description so there is no numerical data to match with the VAE, so based on them we rank it.

6.2 Experiment: 30 cases examined with ES and FLS

In order to make all the process and the results easy to read and control the entire process, the analysis will be done in 4 step steps. Each step is presented in a table, while the fourth step is the comparison of the results (Table10). The first three tables have a specific form: input-output. Inputs are separated from outputs by a double diving line.

In first stage (Step1), the inputs are: impact, unmitigated likelihood, mitigated Likelihood. Those are real data from a big industry for a scope optimization in a big maintenance project. As output in this step we take the Unmitigated Risk Factor and the Mitigated Risk Factor. The calculation of them is based on the equations of chapter 6.1.

STEP 1					
CASES	**Impact (€)**	**Unmitigated Likelihood**	**Mitigated Likelihood**	**Unmitigated Risk Factor (€)**	**Mitigated Risk Factor (€)**
Case 1	1,375,000	0.2	0.01	275,000	13,750
Case 2	100,000	0.75	0.05	75,000	5,000
Case 3	1,375,000	0.5	0.01	687,500	13,750
Case 4	500,000	0.6	0.001	300,000	500
Case 5	103,000	0.8	0.01	82,400	1,030
Case 6	1,200,000	0.3	0.01	360,000	12,000
Case 7	2,400,000	0.3	0.01	720,000	24,000
Case 8	600,000	0.8	0.01	480,000	6,000
Case 9	1,827,000	0.2	0.01	365,400	18,270
Case 10	50,000	0.05	0.01	2,500	500
Case 11	280,000	0.05	0.001	14,000	280
Case 12	1,000,000	0.05	0.01	50,000	10,000
Case 13	880,000	0.05	0.01	44,000	8,800
Case 14	440,000	0.01	0.001	4,400	440
Case 15	55,000	0.9	0.05	49,500	2,750
Case 16	15,000,000	0.1	0.01	1,500,000	150,000
Case 17	5,450,000	0.05	0.01	272,500	53,500
Case 18	59,000	0.1	0.01	5,900	590
Case 19	70,000	0.1	0.01	7,000	700
Case 20	1,250,000	0.01	0.001	12,500	1,250
Case 21	20,000	0.1	0.01	2,000	200
Case 22	10,500	0.3	0.01	3,150	105
Case 23	3,000,000	0.9	0.01	2,700,000	30,000
Case 24	660,000	0.5	0.01	330,000	6,600
Case 25	1,375,000	0.05	0.01	68,750	13,750
Case 26	26,000	0.3	0.01	7,800	260
Case 27	210,000	0.2	0.01	42,000	2,100
Case 28	2,700,000	0.001	0.0001	2,700	270

Case 29	480,000	0.01	0.0001	4,800	48
Case 30	3,500	0.3	0.01	1,050	35

Table 7 Calculation of Unmitigated/Mitigated Risk Factor

The outputs of step1 (Table7) are the inputs of step2 (Table8). Additionally, as input in this step there is one more factor the Estimated Maintenance Cost. Those data are also real data from the same industry. Based on those indicators and the equation of J-factor, which are presented in this chapter above (6.1), the J-factor of each case is calculated and presented in the table below.

STEP 2				
CASES	**Unmitigated Risk Factor (€)**	**Mitigated Risk Factor (€)**	**Estimated Maintenance Cost (€)**	**J-Factor**
Case 1	275,000	13,750	5,000	52.3
Case 2	75,000	5,000	15,000	4.6
Case 3	687,500	13,750	10,000	67.4
Case 4	300,000	500	1,500	199.7
Case 5	82,400	1,030	7,000	11.6
Case 6	360,000	12,000	2,000	174
Case 7	720,000	24,000	50,000	13.9
Case 8	480,000	6,000	12,000	39.5
Case 9	365,400	18,270	70,000	4.9
Case 10	2,500	500	1,000	2
Case 11	14,000	280	500	27.4
Case 12	50,000	10,000	15,000	2.7
Case 13	44,000	8,800	500	70.4
Case 14	4,400	440	500	7.9
Case 15	49,500	2,750	5,500	8.5
Case 16	1,500,000	150,000	600,000	2.3
Case 17	272,500	53,500	55,000	4.0
Case 18	5,900	590	6,000	0.9
Case 19	7,000	700	2,500	2.5
Case 20	12,500	1,250	1,000	11.3

Case 21	2,000	200	500	3.6
Case 22	3,150	105	1,500	2
Case 23	2,700,000	30,000	2,000	1,335.0
Case 24	330,000	6,600	800	404.3
Case 25	68,750	13,750	1,000	55
Case 26	7,800	260	5,000	1.5
Case 27	42,000	2,100	3,000	13.3
Case 28	2,700	270	800	3
Case 29	4,800	48	2,000	2.4
Case 30	1,050	35	500	2

Table 8 J-Factor calculation

J-factor of each case is calculated and confirmed from the file of the data. The colours of column J-factor are mapped depending on the colour each case has on the decision matrix. This matrix is analysed above, in chapter 6.1. An improved display is the following, figure 72. This matrix is made by multi-criteria, data such as J-factor and verbal data such as the description of the item, the workpiece, environmental consequences, risk of work-accident etc. This may be the reason why some cases with similar J-factors are in different coloured areas.

Nevertheless, this matrix helps to take a decision to maintain or not each case. As it is referred above, cases which are placed in blue area are less-risked and the decision about is negative. Cases in yellow area can be characterized as mid-risked and their maintenance is under discussion. Lastly, cases in red area are high-risked and the decision about their maintenance is positive.

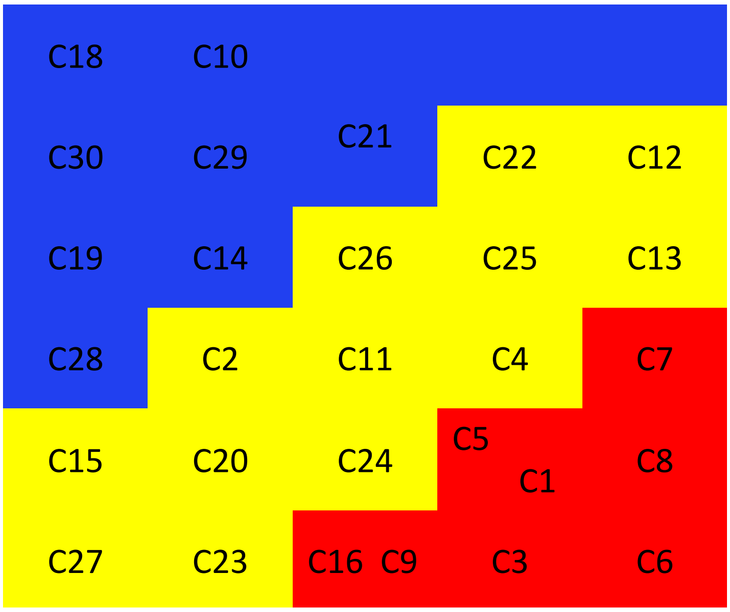


Figure 73 Decision Matrix of 30 cases

The next step refers to FL system and the inputs of this step are the criteria: Mean Time Between Failures (MTBF), Criticality (CRT), Total Operational Cost (TOC), Reliability (REL), Mean Time To Repair (MTTR), Value of Equipment (VAE). The output is the result of FLS which leads to the decision of maintenance. The data of the inputs are extracted from the information given in ES. The correspondence of the criteria between the ES and FLS is analysed above this chapter (6.1.1). We recall that the numbers which are given to those criteria is a result of ranking from 0 to 1. Thus, there are not units attached to them.

STEP 3							
CASES	**MTBF**	**CRT**	**TOC**	**REL**	**MTTR**	**VAE**	**REPAIR**
Case 1	0.7	0.8	0.65	0.8	0.75	0.8	0.501
Case 2	0.35	0.7	0.56	0.35	0.6	0.7	0.655
Case 3	0.5	0.8	0.8	0.5	0.75	0.85	0.67
Case 4	0.4	0.2	0.65	0.4	0.4	0.3	0.501
Case 5	0.2	0.7	0.7	0.2	0.5	0.7	0.674
Case 6	0.6	0.6	0.7	0.7	0.8	0.3	0.501
Case 7	0.6	0.6	0.82	0.7	0.8	0.4	0.583
Case 8	0.2	0.2	0.7	0.2	0.2	0.4	0.501
Case 9	0.7	0.8	0.7	0.8	0.75	0.4	0.501

Case 10	0.85	0.3	0.12	0.95	0.2	0.4	0.257
Case 11	0.85	0.85	0.4	0.95	0.75	0.4	0.36
Case 12	0.85	0.9	0.55	0.95	0.8	0.9	0.501
Case 13	0.85	0.85	0.55	0.95	0.8	0.5	0.36
Case 14	0.87	0.67	0.18	0.99	0.5	0.2	0.358
Case 15	0.1	0.1	0.4	0.1	0.2	0.5	0.501
Case 16	0.8	0.9	0.9	0.9	0.9	0.99	0.501
Case 17	0.85	0.85	0.65	0.95	0.75	0.5	0.45
Case 18	0.8	0.1	0.18	0.9	0.2	0.6	0.319
Case 19	0.8	0.25	0.18	0.9	0.1	0.3	0.208
Case 20	0.87	0.2	0.3	0.99	0.1	0.2	0.202
Case 21	0.8	0.5	0.11	0.9	0.1	0.7	0.36
Case 22	0.6	0.2	0.12	0.7	0.15	0.1	0.257
Case 23	0.1	0.7	0.99	0.1	0.6	0.85	0.757
Case 24	0.5	0.75	0.68	0.5	0.65	0.6	0.662
Case 25	0.85	0.8	0.56	0.95	0.75	0.9	0.501
Case 26	0.6	0.25	0.18	0.7	0.2	0.7	0.36
Case 27	0.7	0.75	0.56	0.8	0.65	0.7	0.502
Case 28	0.9	0.67	0.12	0.999	0.8	0.2	0.359
Case 29	0.87	0.7	0.18	0.99	0.6	0.3	0.36
Case 30	0.6	0.1	0.1	0.7	0.1	0.2	0.257

Table 9 Repair calculation with FL system

Moving to step 4, it is necessary to mention that the outputs of step 2 and 3 (table 8, 9) are the inputs of this step (table 10). The outputs of this step are the decisions with the ES and FLS. In next chapter there is an analysis of those results in order to contrast and compare the two systems.

6.3 Contrast and compare of conclusions and aggregated observations

In order to make all the process and the results easy to read, we have to mention how this table is built. This table is divided in two parts, the first part is about ES and the second-one to FLS. In first section, the J-factor is a product of step 2 and based on it the column of decision is completed. There are three options about this decision, each of them corresponds to colour (J-factor): DO, U/D, DO NOT. U/D means “under discussion”. In FLS part of this table, there also two columns, column “repair” which is the result of FLS (table 9) and based on it the column of decision is completed. The decision in case has four choices: DO, SC (strongly consider), WC (weakly consider), DO NOT.

STEP 4				
ESTABLISHED SYSTEM			**FUZZY LOGIC SYSTEM**	
CASES	**J-Factor**	**Decision**	**Repair**	**Decision**
Case 1	52.3	DO	0.501	WC
Case 2	4.6	U/D	0.655	SC
Case 3	67.4	DO	0.67	DO
Case 4	199.7	U/D	0.501	WC
Case 5	11.6	DO	0.674	DO
Case 6	174	DO	0.501	WC
Case 7	13.9	DO	0.583	SC
Case 8	39.5	DO	0.501	WC
Case 9	4.9	DO	0.501	WC
Case 10	2	DO NOT	0.257	DO NOT
Case 11	27.4	U/D	0.36	WC
Case 12	2.7	U/D	0.501	WC
Case 13	70.4	U/D	0.36	WC
Case 14	7.9	DO NOT	0.358	WC
Case 15	8.5	U/D	0.501	WC
Case 16	2.3	DO	0.501	WC
Case 17	4.0	U/D	0.45	WC
Case 18	0.9	DO NOT	0.319	DO NOT
Case 19	2.5	DO NOT	0.208	DO NOT
Case 20	11.3	U/D	0.202	DO NOT
Case 21	3.6	DO NOT	0.36	DO NOT
Case 22	2	U/D	0.257	DO NOT
Case 23	1,335.0	U/D	0.757	DO
Case 24	404.3	U/D	0.662	SC

Case 25	55	U/D	0.501	WC
Case 26	1.5	U/D	0.36	DO NOT
Case 27	13.3	U/D	0.502	WC
Case 28	3	DO NOT	0.359	DO NOT
Case 29	2.4	DO NOT	0.36	DO NOT
Case 30	2	DO NOT	0.257	DO NOT

Table 10 Comparison of results

In general, the two systems agree on the results without significant variations. However, there are cases with a deviation, such as case 9. This case, based on ES, has a J-factor equal to 4.9, red color and the decision is DO. On the other hand, based on FLS, the decision is “Strongly Consider”. Those decision do not differ that much, especially if we compare the J-factor with the decision of the FLS. Based in theory, each item which its J-factor is over 1, we maintain it, the bigger is this number the surely its maintenance should be. According to this statement case 9 is not an obvious DO but catches up the “Strongly consider”. That divergence maybe comes from that the decision in ES are based, except the j-factor, on the decision matrix, which is based on expert’s opinion. Respectively, case 22 has J-factor equal to 2, the decision of ES is “Under Discussion” and the FLS decision is “DO NOT”. In this case J-factor, Repair and FLS Decision advocate in the same direction (negative decision). An important observation is that case 21 with J-factor 3.6 is “blue” and ES decision is DO NOT at the same time that has higher J-factor from case 22 which is “yellow” and with “DO NOT” ES decision. We assume that this difference is due to reasons which are presented in the first example (case9). One more case with the same “problem” is case 26.

In first glimpse, ES is a system which needs “help” from experts in order to export results. Basically, because it is really complicated in its form. On the other hand FLS is a system which can be used not only from experts, it’s a user-friendly system which does not requires huge specialization. ES and FLS require computational load as basis, such as the calculation of unmitigated likelihood. However, FLS is full adaptive and customizable, as far as that the weighting of each rule can vary, we can add or exclude or change criteria, based on the needs of the “customer” of this system. Even after these changes, the system becomes more complex, but the user environment does not change. User continues to add inputs and take the output. All computational complexity “weighs” only the system and not the user. On the other hand, any change on ES weighs the user and not the system. In this case, all the work which has to be made in order to export results, has to be done by experts-managers, contrariwise in FLS this work can be done from employees without a specific specialization. ES is cumbersome, rough and not easily adaptable. As we used the ES and FLS we made some more observations about their time-need. The calculation time that is needed to export an output by ES is bigger than the time which is needed by FLS. Based on our experience we can doubtless say that FLS need only the 1/3 of time than ES.

Finally, one major difference between those systems is that FLS offers visualization in both the results and the entire process, with plots. So that the control of the process is easy. Additionally, offers comparative visualization between Repair (result) and 2 criteria (the user chooses which criteria). The export of the result and the plots are done at the same time. These are products that ES could not provide and any diagram has to be done in extra work. Those systems are efficient, based on results, but they differ in time and effort.

Chapter 7. Conclusions and future work

In the scheme of this research, the basic notions of reliability, availability and maintenance were analysed. The decision-making system, that we built in this research, has as its main pillars the theory of fuzzy logic. Fuzzy logic theory was widely presented above. Afterwards, for better understanding of the system, a simple example was presented, the "basic tipping problem".

Primarily, the system was analysed and the decision criteria were presented. Those criteria have emerged from actual maintenance needs. Subsequently, we created the rules, which are considered as the heart of system. Then, a verbal explanation and description of each set of rules had followed, in order to be understandable the usage of each rule. Thereafter, using the Matlab tools, our system was created and graphical representations were provided for the intermediate stages so for the outputs. Then, after observing the system and its products we decided to improve it. Eventually, tests were performed on the system in order to observe its operation. In conclusion, the outputs were analysed, as what is happening about maintenance when we change the numbers given on inputs. These inputs took values simplified for computational ease and values that correspond to reality. Additionally, we presented an established system which is used by industries nowadays for scope optimization. After this, we tested 30 real cases with the 2 systems, ES and FLS, and we made an comparative analysis in order to extract observations about our system.

We conclude that the results meet the original research goal, and the way they were presented through the system we have created, gives a more accurate solution than the "crisp" results. Thus, it is considered that a system contributes to the scope optimization of industrial maintenance projects. Finally, this is a system full adaptive and customizable, because each user can adapt criteria, categories, rules and weights, depending on its system requirements. Complementary, this system has "intelligence" and this is the reason that makes it really user-friendly and easy-used, even if the user is not an expert. Additionally, it meets the basic maintenance requirements of technological systems, and alongside, the requirements of reality. Finally, The main features of the system, that was analyzed in this paper in relation to the established system, are the adaptability, usability and the minimization of failures caused by human error.

Further research could be carried out by incorporating the following ideas. Firstly, in this research all inputs were random values. It would be of great interest a research with input values that could have been drawn from real systems. Taking real data about the time of failures and repairs, cost and criticality, we could derive values for MTBF, MTTR, TOC, Reliability, Criticality. This differentiation of our research can be accomplished by modifying real systems as Markov or semi-Markov models.

Mathematical modeling is the method of simulating real-life situations with mathematical equations to predict their future behavior. Mathematical models offer convenience and considerably low cost compared to common laboratory methods. Mathematical modeling uses tools such as decision theory, queue theory, mathematical programming, and requires a large amount of compressed numeric data. Markov processes can be used in modeling systems whose behavior changes either discretely or continuously in relation to time and space. This random change is called stochastic progression. However, Markov's theory cannot be applied to all stochastic processes, but to those in which the behavior of systems is characterized by a lack of memory. In particular, the future states of the system are independent of all the past situations except the previous one. Therefore, the future behavior of the system depends only on the present position and not on the positions of the past or the way it has reached the present position. In Semi-Markov processes (SMP) the transition from the state i to another condition j, depends on the residence time in state I and the residence time in a state can follow any distribution. The Semi-Markovian process is a generalized form of the Markov processes. A Semi-Markov Process (SMP) is a stochastic process in which situations change according to a Markov chain, but mediates a random interval between transitions. Another idea is to study contribution of the inputs and adapt the membership function respectively.

In addition, in this research, the weights of rules were the same (weight=1). If we want the system to fit to reality, we could change the weights of each rule based on the experience of specialists and analyze the new outputs. The numbering of weights and its' justification could be a whole new research that would complement this research. Finally, we could add more reliability-driven or no-reliability-driven criteria, such as environmental impacts, and transform that system into a general quality tool.

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