Failure Mode and Effect Analysis (FMEA) of Gas Turbine Power Plant System (GTPPS)

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ABSTRACT

Failure Mode and Effect Analysis (FMEA) is an approach used for the system reliability analysis. In the present work, FMEA is applied to Gas Turbine Power Plant System (GTPPS). A total of 44 probable failure modes of main subsystems (i.e. compressor, combustion chamber, turbine, and generator) and auxiliary subsystems (i.e. fuel, oil, and electrical subsystems) have been identified and prioritized based on FMEA. The list of failure modes is ranked according to the assigned values in four different FMEA approaches: 1. Risk Priority Number (RPN), 2. Fuzzy RPN based on 10 membership functions, 3. Fuzzy RPN based on 100 membership functions, and 4. Aggregated Fuzzy RPN, where the higher the assigned values indicate the higher rank of criticality for the related failure mode. Furthermore, based on the obtained results, the analysis precision of the utilized approaches is compared and the type of required maintenance activity is proposed for critical failure mode as well.

Keywords: Gas turbine, Failure mode and effect analysis, Power plant, Maintenance policy

ŐZ

Hata ve etki analizi (FMEA) sistem güvenilirlik çözümlemesi için kullanılan bir yaklaşım var. Mevcut çalışma FMEA gaz türbini santral sistemi (GTPPS) uygulanır. Toplam 44 muhtemel başarısızlık modları ana alt sistemler (yani kompresör, yanma odası, türbini ve jeneratör) ve yardımcı alt sistemler (Yani yakıt, yağ ve elektrik alt sistemler) tespit ve öncelik FMEA üzerinde temel. Başarısızlık modları listesi dört farklı FMEA yaklaşımlar atanmış değerlere göre sınıflanır: 1. Risk öncelik sayısı (RPN), 2. Bulanık RPN 10 üyelik fonksiyonları, 3 temel. Bulanık RPN 100 üyelik fonksiyonları ve 4 temel alan. Bulanık RPN toplanan, yüksek yerde kritiklik ilgili başarısızlık modu için daha yüksek değerde atanan değerleri gösterir. Ayrıca, elde edilen sonuçlarına göre çok kullanılan yaklaşımlar analiz duyarlığını karşılaştırılır ve gerekli bakım aktivite türü de kritik hata modu için önerilmiştir.

Anahtar Kelimeler: Gaz türbini, hata türleri ve etkileri analizi, Santral, Bakım politikası

To my family

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

The accelerated evolution of gas turbines from the 1940s was introduction of a substitute for quick replacement with traditional reciprocating engines. Gas turbines are complex systems of energy transformation. Like other internal combustion engines, they are consisted of hundreds of components, which comprise the subsystems and main system is result of the subsystems convening.

First mission of system is carrying out the processes needed for the transformation of fuel chemical energy into mechanical energy. Besides to the aeronautic industry, the gas turbine technology was gaining application in other areas of industry. In 1950, the Westinghouse Company began to produce gas turbines for industrial use. These turbines, despite using the same operating principle of aeronautical gas turbines present some differences to those used in the aviation industry. Main mission of industrial gas turbines is supplying electrical power and the power plants which utilize gas turbine as prime mover are called GTPPS [1]. In GTPPS, natural gas or liquefied natural gas (LNG) are typically used as fuel [2]. Thermal energy and electrical power are two main outputs of the system. Besides supplying electricity, it is possible to utilize the exhaust to obtain useful heat. The cycle can be integrated with a Rankine cycle to increase the efficiency of electricity generated in combined cycle power plants.

The combined cycle power plant which is more common, is designed when network power consumption is at peak demand state and besides steam turbine unit, gas turbine is entered to the system as well. The productivity of GTPPS is optimized by generation and maintenance scheduling, outage planning, and advanced technology up-gradation [3,4]. In the gas turbine system, like other complex systems predictable failure modes can be caused to stop the operation of the system and severe degradation in the gas turbine's performance, significantly reducing the output power. Thus acceptable level of system availability performance is highly demanded and identification of critical parts provides essential information for improving and optimizing the maintenance management and estimating the competence needs for reliable operation. Therefore, for recognition of predictable failure modes and prioritization of failures based on criticality level FMEA method is particularly helpful and scheduling of a maintenance plan according to the taken results in FMEA method will decrease the failure occurrence rate of system in long term operation. Critical components (recognized in FMEA method) are such components that their failure could exact high cost to the system. In new approaches of the maintenance strategies like Reliability Centered Maintenance (RCM), the maintenance activities are planned, prioritized and executed based on equipment criticality with respect to production acceptance criteria. Criticality analysis is a systematic screening process which is performed in various approaches of FMEA and results of each approach have direct effect on the system maintenance plans.

The main objective of this research is application of three unique approaches of FMEA (i.e. traditional Risk Priority Number (RPN), Fuzzy Logic, and Multi-stage Aggregation) to GTPPS. In this manner, the reliability level of GTPPS will be enhanced and the risk level is reduced as well. It is expected that by application of

FMEA approaches, the probability of the system failures occurrence will be diminished and the availability of system operation is going to be improved. Also for the first time, the totally 44 failure modes will be recognized in GTPPS, which it is higher than the previous analyzed failure modes in literatures. Except some limited examples, no previous research is found for application of FMEA to auxiliary subsystems of GTPPS and the gap of failure analysis of all subsystems of GTPPS as an integrated system is the basic idea of the research.

As the final novelty, based on the obtained results a suitable maintenance strategy plan paying attention to the identified critical components of the system is proposed.

Organization of thesis is as follows: In chapter 2, previous researches in the field of applying FMEA method to gas turbine components are surveyed. In chapter 3 (research methodology) the FMEA process and its approaches are introduced and at next chapter, working principles, categories and different configurations of gas turbine incorporated in power plants are described. The possible failure modes found in GTPPSs are explained in chapter 5. In chapter 6, application of four FMEA approaches (RPN, Fuzzy RRN based on 10 and 100 membership functions and Aggregated Fuzzy RPN methods) to GTPPS are compared and according to taken results, the guidelines for scheduling the system maintenance plan are offered.

Chapter 2

LITERATURE REVIEW

Previous researches in analysis of GTPPS failure modes had focused on system blades and vanes, because cyclic loading is the best character representing for loads applied to a gas turbine and as shown in Table 1, fatigue failure is common in all power plants and many modifications have been done on metallurgy of airfoil coating to have a better resistance while operation and offers higher service life.

Table 1: Recent developments in failure analysis of Gas Turbine Subsystems

Subsystem	Component	Literature	Failure type analysis
Turbine section	Rotor blade	Hou et al (2002) [5], Wall et al (1997) [6], Carter (2005) [7], Mazur et al (2005) [8], Vardar et al (2007) [9], Qu et al (2015) [10], Poursaeidi et al (2008) [11], Huda (2009) [12], Kumari et al (2014) [13], Perkins et al (2005) [14]	Cyclic Fatigue
	Stationary nozzle	Mazur et al (2007) [15], Kazempour-Liacy et al (2011) [16]	Stress corrosion cracking

Compressor section	Rotor blade	Kermanpour et al (2008) [17], Witek (2009) [18], Farrahi et al (2011) [19], Witek (2011) [20], Witek (2011) [21], Rama Rao et al (2012) [22], Poursaeidi et al (2013) [23], Biswas et al (2014) [24], Witek et al (2015) [25], Maktouf et al (2015) [26], Cortinovis et al (2016) [27], Troshchenko et al (2000) [28], Ellis (2006) [29].	Cyclic Fatigue
Combustion Chamber	Assembly	Meher & Gabriles (1995) [30]	Thermal Fatigue
Generator	Assembly	NASA CR-159494 (1979) [31]	Mechanical failure of internal components
		Alewine (2011) [32]	
Auxiliary Systems	Oil system components	Gulnar et al (2015) [33]	Mechanical and thermal

Besides blades, other previous researches are focused on turbine nozzle component; because nozzles are located in hot-section of engine and continuously they are in contact with hot gases. So failure modes such as burn of vanes and hot-spots are more recognized while periodic inspection of turbine nozzle.

Results which have been taken at previous researches, have led to introduction of different super alloys for fabrication of nozzles. Super alloys in comparison with other groups of alloys have higher thermal resistance and are less susceptible to burning failures.

In this thesis, the concept of FMEA is applied to all main subsystems (i.e. compressor, combustion chamber, turbine, and generator) and auxiliary subsystems (i.e. fuel, oil, and electrical subsystems) of gas turbine and in the next chapter the process of failure analysis and the various FMEA approaches are presented.

Chapter 3

RESEARCH METHODOLOGY

The emergence of a failure is a phenomenon that can make a disorder in any complex system and result in a delay in production [5]. Therefore, for confronting the different failures which may occur, the experts take the proper measures in different steps like designing, manufacturing, and operation [6]. FMEA is a risk management technique which prevents probable failures in the system and provides the foundation for policies and remedial measures to tackle them.

3.1 Traditional RPN Approach

FMEA was first employed in the 1960s in aerospace industry as a risk management tool during designing phase, and afterwards, this method is being used in other sectors such as automotive industry [7].

Risk management is mandatory based on ISO 31000:2009 which provides generic guidelines and frameworks to risk management processes. Using ISO 31000:3009 is beneficial to effectively achieve organizational objectives and utilize resources for risk treatment by identifying opportunities and threats [8].

In FMEA process, the main objective is to distinguish the critical components of the system, and the output of this technique is scheduled plans for performing preventive or predictive maintenance strategies before any potential failure occurs. In other words, the aim of FMEA is (1) to recognize the failure modes occurring during a definite period of system, (2) to determine the reasons for any failure occurrence, (3) to evaluate the effects of each failure, and (4) to prioritize the failures [9]. The flowchart of FMEA hierarchical process is shown in Figure 1.

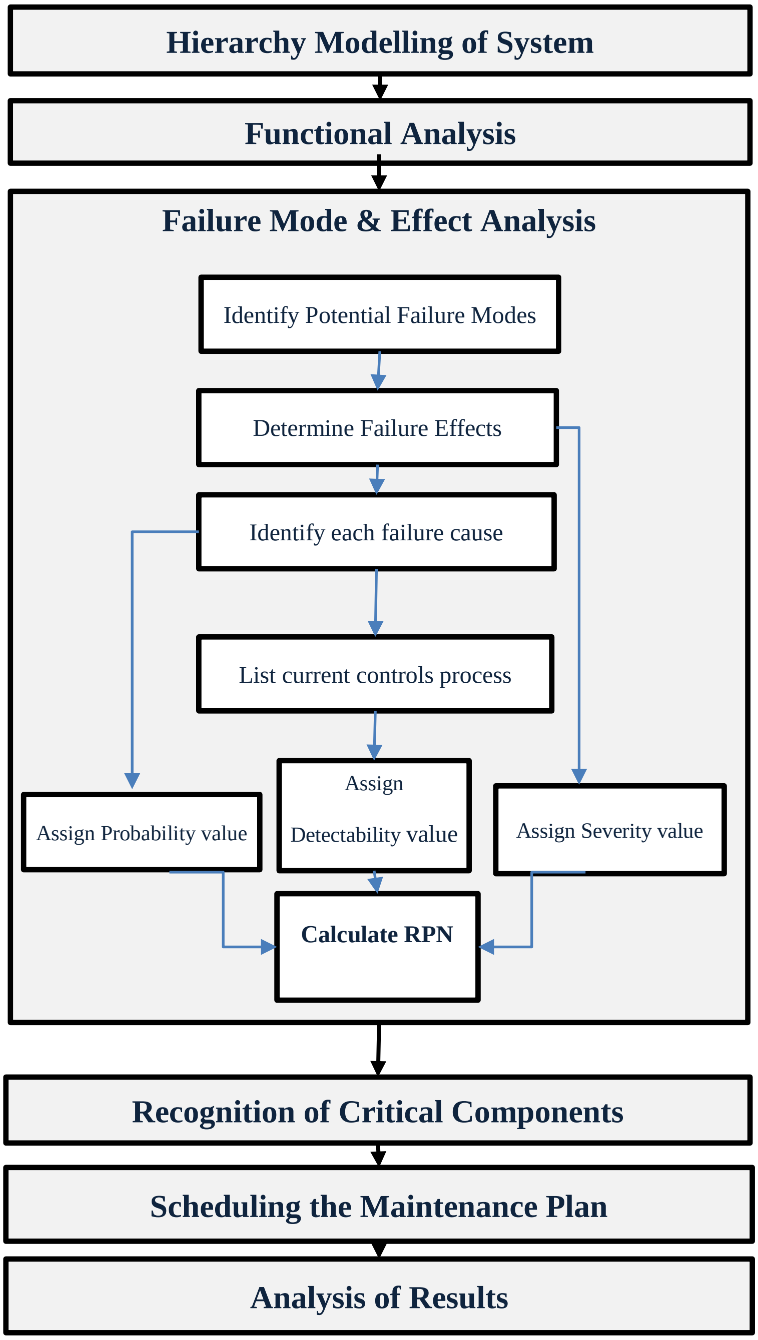

Figure 1: FMEA process flowchart

In general, FMEA method can be categorized in three main types [10]:

System/Concept FMEA "S/CFMEA" (Driven by System functions):

A system is an organized set of subsystems and components to accomplish multi-functions. System FMEAs are typically very early, before determination of specific hardware.

Design FMEA "DFMEA" (Driven by component functions):

A Design / Part is an unit of physical hardware that is imagined as a single replaceable part with respect to repair. Design FMEAs are typically done later in the development process when specific hardware has been specified.

Process FMEA "PFMEA" (Driven by process functions & part characteristics):

A Process is a sequence of duties that is organized to produce a product or provide a service. A Process FMEA can involve manufacturing, assembly, and transactions or services.

An FMEA process is conducted in three basic steps:

Step 1: By dividing the system into subsystems and components, the main modules are categorized in a bottom-up diagram (as shown in Figure 2), and upon the occurrence of any failure in any component, the effect chain is traceable at higher levels [37-39].

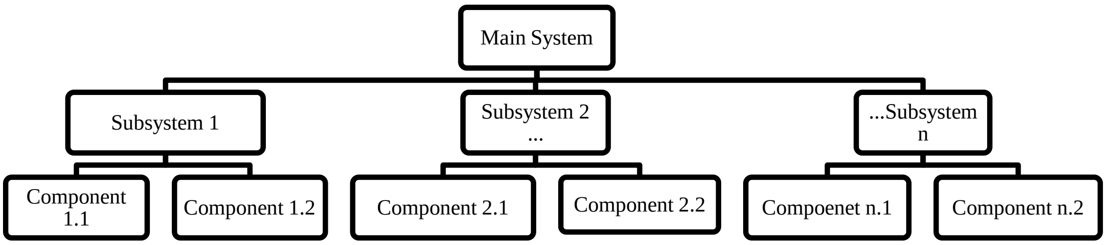

Figure 2: System hierarchical structure

Step 2: FMEA method is evaluable both qualitatively and quantitatively. By considering three parameters, i.e. Severity (S), Occurrence (O), and Detection (D), and allocating a number between1and10, Risk Priority Number (RPN) is calculated according to the following formula [40-42].

$$RPN = S \times O \times D \quad (1)$$

The method of allocating a number to any risk parameter is summarized in Tables 2 to 4. RPN shows the amount of potential risk in the observed failure modes of the system. The key parameter of basic approach of FMEA process in selecting the maintenance policy is allocation of a number between 1 and 10 to every risk factor of failure mode and categorizing them so that the more critical failure is, the allocated number is higher and the more periodic inspection of the related component is required.

Table 2: Severity rating criteria of a failure in FMEA [43-48]

Rating	**Effect**	**Severity of effect**
10	Dangerous without warning	Very high severity ranking when a probable failure mode affects system operation without warning
9	Dangerous with warning	Very high severity ranking when a potential failure mode affects system operation with warning
8	Very high	System inoperable with destructive failure without compromising safety
7	High	System inoperable with equipment damage
6	Moderate	System inoperable with minor damage
5	Low	System inoperable without damage
4	Very low	System operable with significant degradation of performance
3	Minor	System operable with some degradation of performance
2	Very minor	System operable with minimal interference
1	None	No effect

Table 3: Occurrence rating criteria of a failure in FMEA [43-48]

Rating	Probability of Occurrence	Failure Probability
10	Almost Certain	>0.5
9	Very High	0.16666666
8	High	0.125
7	Moderately High	0.05
6	Moderate	0.0125
5	Low	0.0025
4	Very Low	0.0005
3	Remote	0.000066
2	Very Remote	0.0000066
1	Nearly impossible	0.00000066

Table 4: Detection rating criteria of a failure in FMEA [43-48]

Rating	Detection	Likelihood of detection by control mechanism
10	Absolute uncertainty	Control mechanism cannot detect potential cause of failure mode
9	Very remote	Very remote chance the control mechanism will detect potential cause of failure mode
8	Remote	Remote chance the control mechanism will detect potential cause of failure mode
7	Very low	Very low chance the control mechanism will detect potential cause of failure mode
6	Low	Low chance the control mechanism will detect potential cause of failure mode
5	Moderate	Moderate chance the control mechanism will detect potential cause of failure mode
4	Moderately high	Moderately high chance the control mechanism will detect potential cause of failure mode
3	High	High chance the control mechanism will detect potential cause of failure mode
2	Very high	Very high chance the control mechanism will detect potential cause of failure mode
1	Almost Certain	Control mechanism will almost certainly detect a potential cause of failure mode

Allocation of numbers in RPN method is accomplished by specialists who are experts in system functions and the amount of the effect of any failure, so two factors, i.e. the experience and knowledge of specialists, are effective on the final results. Therefore, an improved parameter called Weighted RPN is utilized. The weighting is based on the following coefficients given to the obtained RPN: out of question (1), very confident (0.9), confident (0.7), less confident (0.25), and not confident (0.1). By considering experience and knowledge in the final results, the RPN value will be a qualitative evaluation, and the numbers are just comparative in rating the critical parts of the system.

Due to numerous criticisms against RPN method, it has not been considered as an ideal approach and has been replaced by alternative methods in FMEA. The most important criticisms are: ([44], [54], and [55])

- Different combinations of O, S and D ratings may produce the same value of RPN, but their hidden risk concepts may be different totally. For example, two different failure modes with the values of 5, 7, 2 and 10, 1, 7 for O, S, and D, respectively, will have the same RPN value of 70. However, the hidden risk concepts of the two failure modes may be very different because of the different severities of the failure consequence. In some cases, this may cause a high-risk failure mode being unnoticed.

- RPNs are not continuous, and heavily distributed at the scale from 1 to 1000. This causes problems in interpreting the meaning of different RPNs. For example, is the difference between the neighboring RPNs of 1 and 2 the same as or less than the difference between 10 and 20?

3.2 Fuzzy Logic Approach

Because of the mentioned setbacks, many superseded approaches (around 70) are introduced which are generally categorized in 5 main groups (as shown in Figure 3):

1. Multi-criteria decision making (MCDM);

2. Mathematical programming;

3. Artificial Intelligence;

4. Criticality analysis approaches;

5. Hybrid approaches.

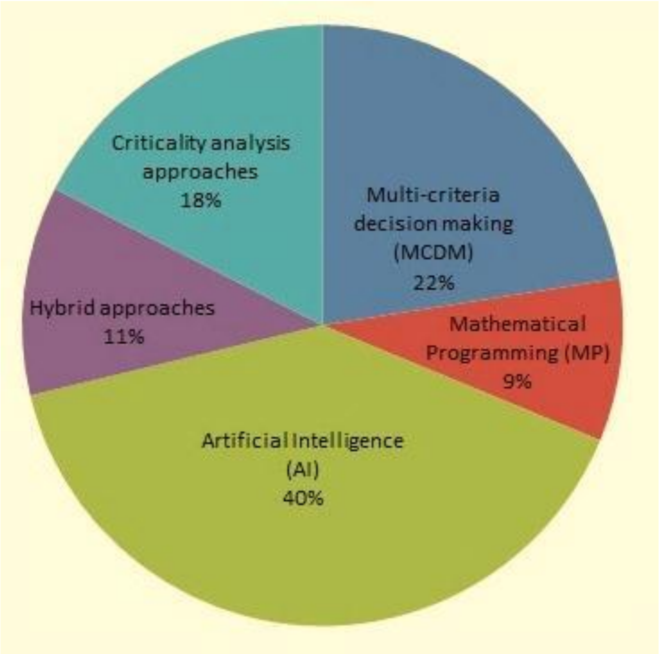

Figure 3: Main groups of FMEA approaches

Among the all of the introduced approaches, 3 methods have been chosen in this research: Fuzzy analysis (based on 10/100 membership functions) and multi-stage aggregation.

The common fuzzy approach can be described as a general method substituting older ones for risk analysis. There are several reasons why this approach is evaluated as better than the previous one [56].

Firstly, it can handle both precise and imprecise information in a consistent manner. Second, it allows combination of probability of failures occurrence, severity and detectability in a more pragmatic manner [35]. Finally, the risk assessment function can be varied according to the specific system under consideration [57]. Basic fuzzy steps at prioritization of failure modes are shown in the following Figure:

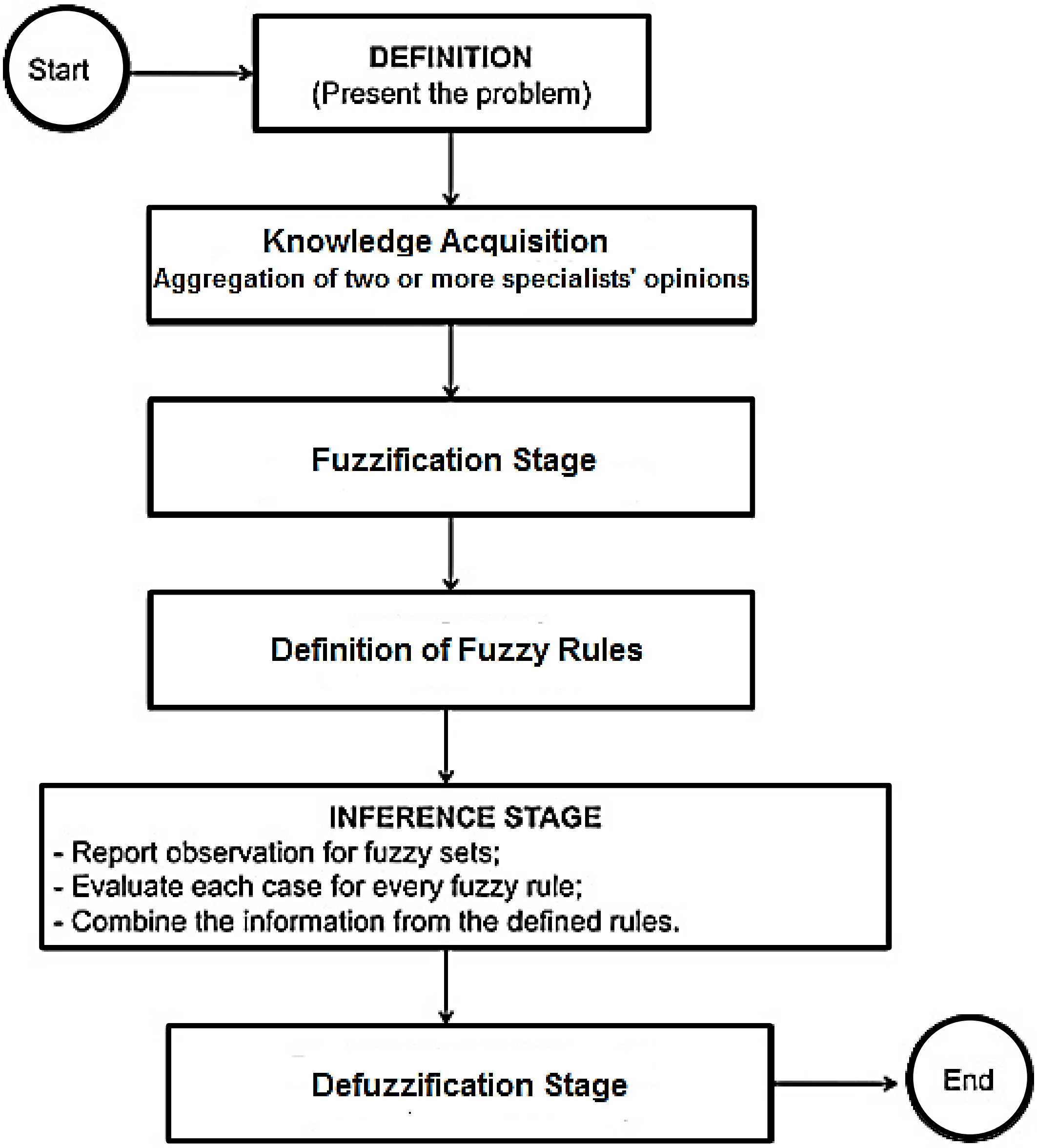

Figure 4: Fuzzy analysis Flowchart (Adapted from Cicília RM Leite et al [62])

Prior to description of Fuzzy RPN approaches (based on 10 or 100 membership functions), it is required to be two concepts of Membership Function and Fuzzy if-then rules introduced.

A membership function (MF) 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 sometimes referred to as the universe of discourse (UOD), a fancy name for a simple concept.

The output-axis is a number known as the membership value between 0 and 1. The curve is known as a membership function and is often given the designation of µ. The only condition a membership function must really satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape we can define as a function that suits us from the point of view of simplicity, convenience, speed, and efficiency. A classical set might be expressed as $A = \{x \mid x > 6\}$.

A fuzzy set is an extension of a classical set. 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. ($A = \{x, \mu A(x) \mid x \in X\}$)

µA(x) is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1.

The simplest membership functions are linear forms using straight lines (Non-linear shapes are introduced in Appendix A). Of these, the simplest is the triangular membership function, and it has the function name trimf. This function is nothing more than a collection of three points forming a triangle. The trapezoidal membership function, trapmf, has a flat top and really is just a truncated triangle curve. These straight line membership functions have the advantage of simplicity (as shown in Figure 5).

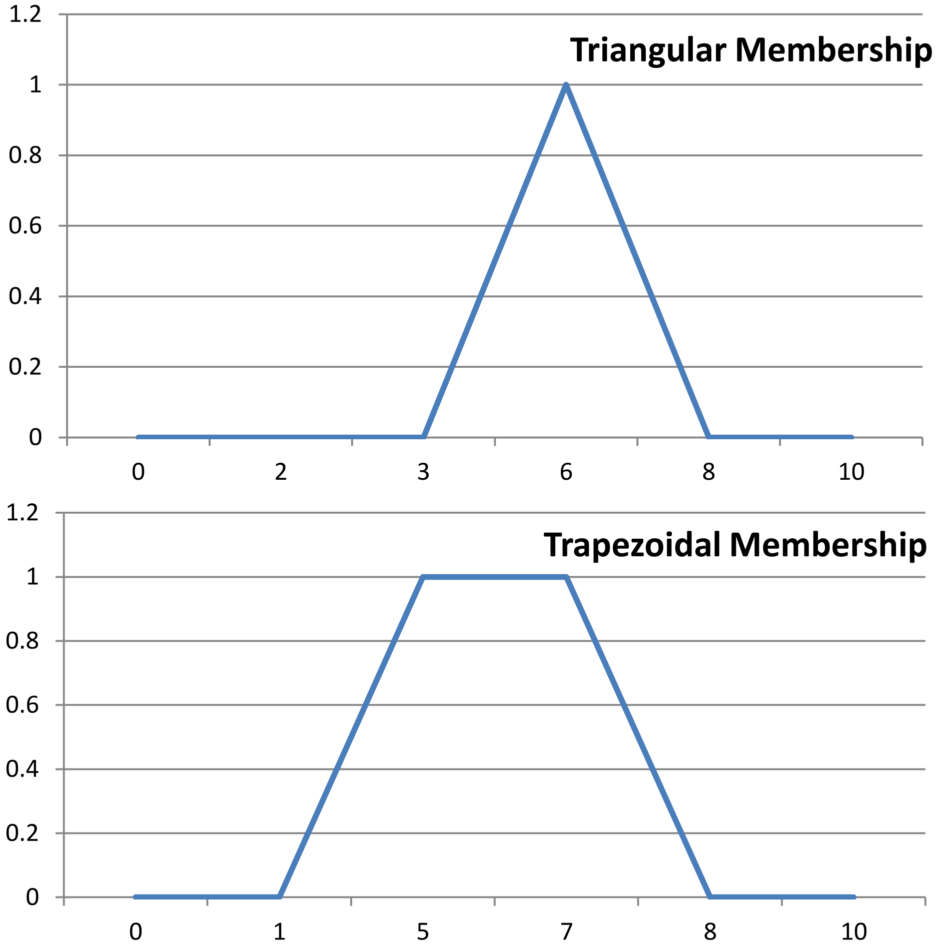

Figure 5: Linear Fuzzy membership functions

Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. 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, respectively. 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. The consequent or conclusion is represented as a number between 0 and 1, and the antecedent is an interpretation that returns a single number between 0 and 1.

In general, the input to an if-then rule is the current value for the input variable and the output is an entire fuzzy set. This set will later be defuzzified, which is assigning one value to the output finally. Interpreting an if-then rule involves distinct parts: first evaluating the antecedent (which involves fuzzifying the input and applying any necessary fuzzy operators) and second applying that result to the consequent (known as implication). The Fuzzy RPN (based on 10 membership functions) is derived from the "if-then" rules and it will be determined based on the integer numbers allocated to S, O, and D (from 1 to 10) and two steps of fuzzy logic control which are mentioned below [58].

Step 1- Based on the combination of S (as input 1 in step 1) and O (as input 2 in step 1) values (each risk factor from 1 to 10), and according to the rules in Table 6 a fuzzy number is exploited [58]. This step is as the first stage of multi-stage fuzzy architecture which the related generated surface of logic controller is shown in Figure 6 [80-89].

Step 2- The rules utilized in this step are same as previous step (Table 5), and just input parameters will be detection value of failure mode (as input 2 in step 2) and the output number of step 1 (as input 1 in step 2) [59-60]. This step is as second stage of multi-stage structure and as far as rules have been kept the same as step 1, so generated surface won't be changed as well.

Table 5: Fuzzy rules based on 10 membership functions

		The Input 2 value									
The Input 1 value		**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
	10	10	10	9	9	8	8	7	7	6	6
	9	10	9	9	8	8	7	7	6	6	5
	8	9	9	8	8	7	7	6	6	5	5
	7	9	8	8	7	7	6	6	5	5	4
	6	8	8	7	7	6	6	5	5	4	3
	5	8	7	7	6	6	5	5	4	3	3
	4	7	7	6	6	5	5	4	3	3	2
	3	7	6	6	5	5	4	3	3	2	2
	2	6	6	5	5	4	3	3	2	2	1
	1	6	5	5	4	3	3	2	2	1	1

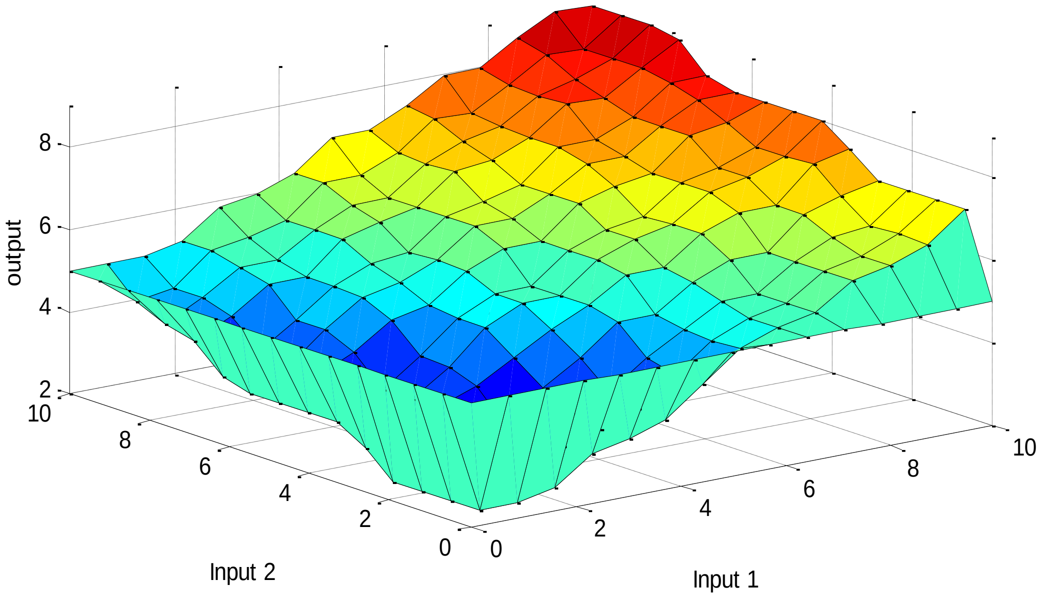

Figure 6: The generated surface of fuzzy controller (based on 10 memberships)

The Fuzzy RPN (based on 100 membership functions) is calculated in the similar manner with two steps of 10 membership functions method and the difference is the number of rules used in the developed approach.

The utilized rules are mentioned in Table 6 and at both of approach steps the same rules are applicable. The related generated surface of this approach is shown in Figure 7.

In appendix B the related program in MATLAB Software and in appendix C, all combination sets of S, O, and D sets (1000 different combination sets) are mentioned.

Table 6: Fuzzy rules based on 100 membership functions

		The Input 2 value									
		10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
The Input 1 value	**10**	10.00	9.569	9.093	8.616	8.140	7.664	7.187	6.711	6.235	5.758
	9	9.440	8.964	8.488	8.011	7.535	7.059	6.582	6.106	5.630	5.153
	8	8.835	8.359	7.883	7.406	6.930	6.454	5.977	5.501	5.025	4.548
	7	8.230	7.754	7.278	6.801	6.325	5.849	5.372	4.896	4.420	3.943
	6	7.625	7.149	6.673	6.196	5.720	5.244	4.767	4.291	3.815	3.338
	5	7.021	6.544	6.068	5.592	5.115	4.639	4.163	3.686	3.210	2.734
	4	6.416	5.939	5.463	4.987	4.510	4.034	3.558	3.081	2.605	2.129
	3	5.811	5.334	4.858	4.382	3.905	3.429	2.953	2.476	2.000	1.524
	2	5.206	4.729	4.253	3.777	3.300	2.824	2.348	1.871	1.395	0.919
	1	4.601	4.124	3.648	3.172	2.695	2.219	1.743	1.266	0.790	0.314

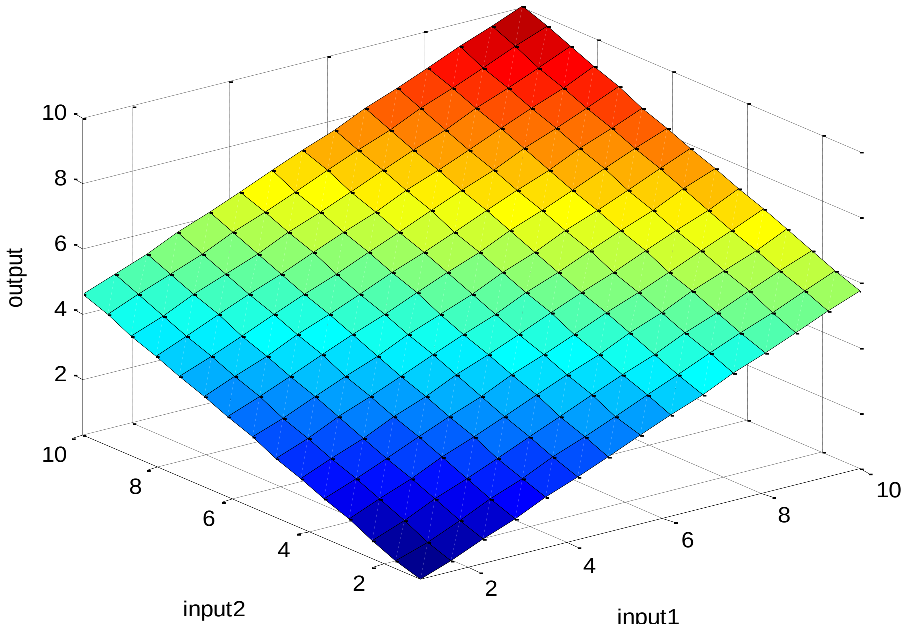

Figure 7: The generated surface of fuzzy controller (based on 100 memberships)

Prioritization of failure modes based on Fuzzy RPN (using 100 membership functions) is more precise than 10-membership function method and for any combination of input values one unique output is assigned accordingly.

3.3 Multi-Stage Aggregation Approach

Aggregated Fuzzy RPN is the name of another approach for prioritization of failures. Because of different opinions of FMEA team members for scoring of failure modes in a specific energy system, it is required to utilize a system for aggregation of members' risk numbers and one of the proposed methods is Aggregated Fuzzy RPN [90-92]. Aggregated Fuzzy approach is an extension of Fuzzy RPN based on 100 membership functions [93-95]; which based on multi-stage structure for determination of final Fuzzy RPN by a FMEA team consisting from 3 members it is required to repeat step 1 of Fuzzy RPN (based on 100 membership functions) for 8 times (as shown in Figure 8). Where red dots represent for times of fuzzy number exploitation out of Table 6 (Fuzzy rules based on 100 membership functions) and S_i (i=1,2,3) represents the severity value of failure mode provided by first, second or third member of team accordingly and there is the same manner for other risk factors (O or D).

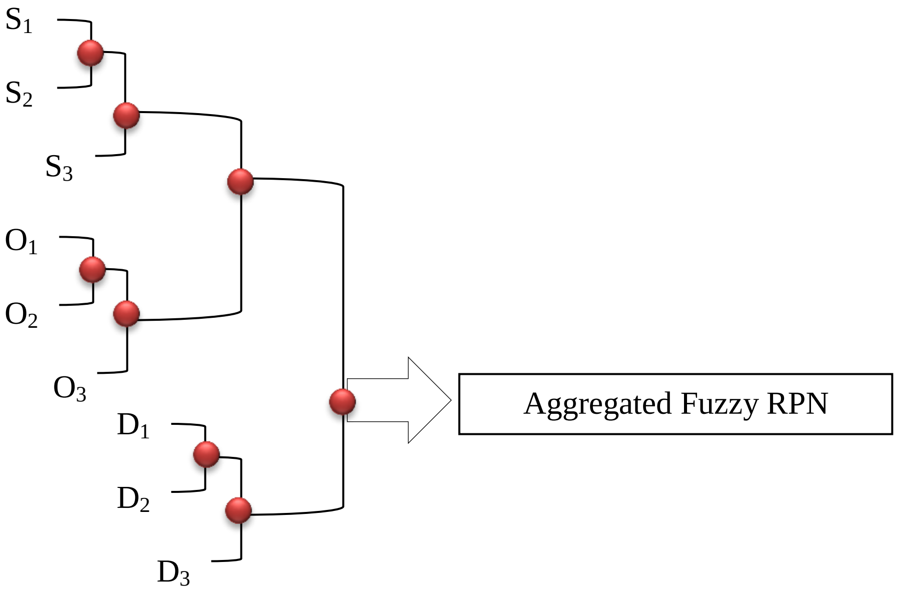

Figure 8: Multi-stage fuzzy structure based on 3-member FMEA team

Quantitative patterns of FMEA are obtained by calculation of Criticality Number and Component Criticality Number (CCN). In this pattern each failure mode has its own criticality number, and when all failure mode criticality numbers of a component are added this will give the component criticality number which is represented as follows [49]:

$$C_r = \Sigma_{i=1}^{N} (C_m)_I \tag{2}$$

where $(C_m)_i$ denotes the failure mode criticality number individually. r – Denotes r^th^ Component, i – Denotes i^th^ failure mode, N – Total number of failure modes of a component and Criticality number of i^th^ Failure mode of a Component is calculated as follows:

$$(Cm)_i = \beta.\ \alpha.\ \lambda.\ T \tag{3}$$

where β be the failure probability, α denotes the failure mode ratio, λ denotes failure rate, T denotes operating hours probability.

The numbers obtained in this method are not just for rating; rather, if the number exceeds a certain level, the related component is recognized as a system critical point, and a predictive maintenance is considered for it. In this kind of maintenance, after a definite lapse of time, failure occurrence is very probable, and the part will be inspected prior to failure. If the total number of criticalities in a subsystem exceeds a definite value, that subsystem needs additional modifications in design.

Step 3- The output of FMEA process can be summarized as in Table 7. In this Table, other than notification of the failure mode, its cause and effect will be evaluated and compared. The RPN obtained before and after holding maintenance policy will determine the quality of confronting the failure. After recognizing and ranking the system critical parts, their availability during the operation is evaluated, and the general system behavior will be analyzed as well [50]. At the end of the mentioned steps, the decision suitable for selection of a maintenance policy will be made.

Table 7: FMEA worksheet

Subsystem	Component	Failure mode analysis			Existing conditions					Feedback results			
		Failure mode	Failure cause	Failure effect	S	O	D	RPN	Failure disposition	S	O	D	RPN

Therefore by selection of RPN method as a basic FMEA approach and different Fuzzy RRN methods as superseded approaches, the possible failure modes of GTPPS introduced at next chapter 4 will be prioritized and compared.

Chapter 4

The SYSTEM MODEL AND ITS COMPONENTS

4.1 Gas Turbine Working Principle

Gas turbine power is derived from burning fuel and air in a combustion chamber and using the fast flowing combustion gases to drive a turbine in much the same way as the high pressure steam drives a steam turbine (as shown in Figure 9).

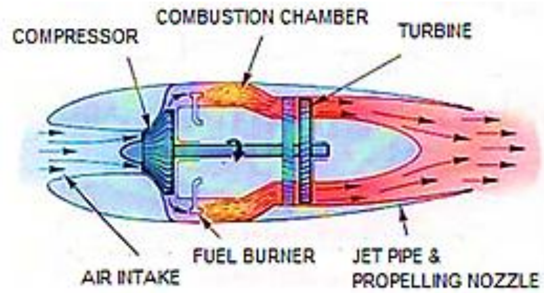

Figure 9: Basic gas turbine sections [61]

The air is drawn to engine through compressor and after compression; at high pressure air is fed to combustion chamber for burning with fuel. As the gas turbine speeds up, compressor speed increases as well and forcing more air through the combustion chamber. Consequently the burn rate of fuel goes up and more high pressure hot gases into the gas turbine cause increment of engine speed even more. Uncontrolled runaway is prevented by controls on the fuel supply line which limit the amount of fuel fed to the turbine thus limiting its speed.

The thermodynamic process used by the gas turbine is known as the Brayton cycle. Much of the power produced in the turbine is used to run the compressor and the rest is available to run auxiliary subsystems (e.g. fuel and oil system components). The system is an open system because the air is not reused so that the fourth step in the cycle, cooling the working fluid, is omitted.

4.2 Gas Turbine Categories:

4.2.1 Aeronautical Gas Turbine

In comparison with internal combustion engines, gas turbines are lighter and smaller and have a very high power to weight ratio. Though they are mechanically simpler than reciprocating engines, and their characteristics of high speed and temperature operation require high precision components and endurable materials making them more expensive to manufacture.

4.2.2 Electrical Power Generation

In electricity generating applications the gas turbine is used to drive a synchronous generator which provides the electrical power output but as far as the turbine normally operates at very high rotational speeds it must be connected to the generator through a high ratio reduction gearbox.

4.3 Gas Turbine Configurations

Gas turbine power generators are used in two basic configurations:

4.3.1 Simple Cycle

This cycle is consisting of the gas turbine driving an electrical power generator (as shown in Figure 10).

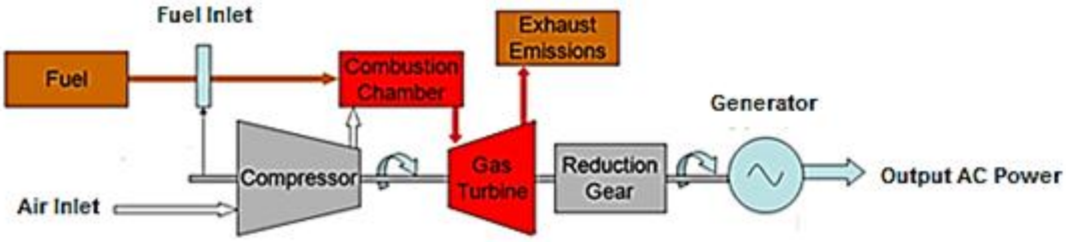

Figure 10: The schematic of simple cycle gas turbine power generator [61]

4.3.2 Combined Cycle

Obtaining the maximum efficiency is the objective of combined cycle designers, also the hot exhaust gases of the gas turbine are used to raise steam to power a steam turbine with both turbines being connected to electricity generators (as shown in Figure 11).

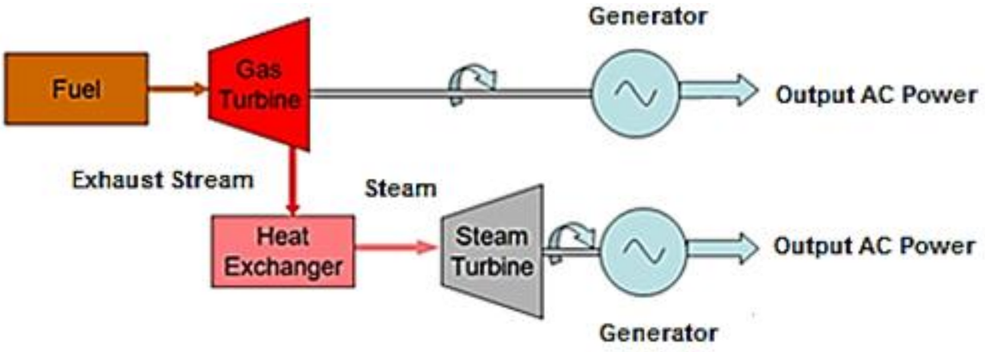

Figure 11: The schematic of combined cycle power generator [61]

4.4 Fuels

One further advantage of gas turbines is their fuel flexibility. They can be adapted to use almost any flammable gas or light distillate petroleum products such as gasoline (petrol), diesel and kerosene (paraffin) which happen to be available locally, though natural gas is the most commonly used fuel.

4.5 Applications

Gas turbines can be used for large scale power generation. Examples are applications delivering 600 MW or more from a 400 MW gas turbine coupled to a 200 MW steam turbine in a combined cycle system.

Such installations are not normally used for base load electricity generation, but for bringing power to remote sites such as oil and gas fields. Low power gas turbine generating sets with capacities up to 5 MW can be accommodated in transportation containers to provide mobile emergency electricity supplies which can delivered by truck to the point of need.

4.6 System Components

The reliability modeling of the GTPPS is conducted by dividing the whole working process into different functional subsystems and components.

Based on this systematic functional division, the reliability model with one-to-one administrative level is built. The gas turbine is generally consisted from 5 subsystems:

1. Compressor
2. Combustion chamber
3. Turbine
4. Generator
5. Auxiliary subsystems.

Auxiliary subsystems are divided to 3 subdivisions too (fuel, oil, and electrical systems) and control the operation of engine and regulate the amount of fuel and oil consumptions, electrical output, and etc.

Components of auxiliary subsystems are usually located on gearbox. List of components of each subsystem are shown in the following Figure.

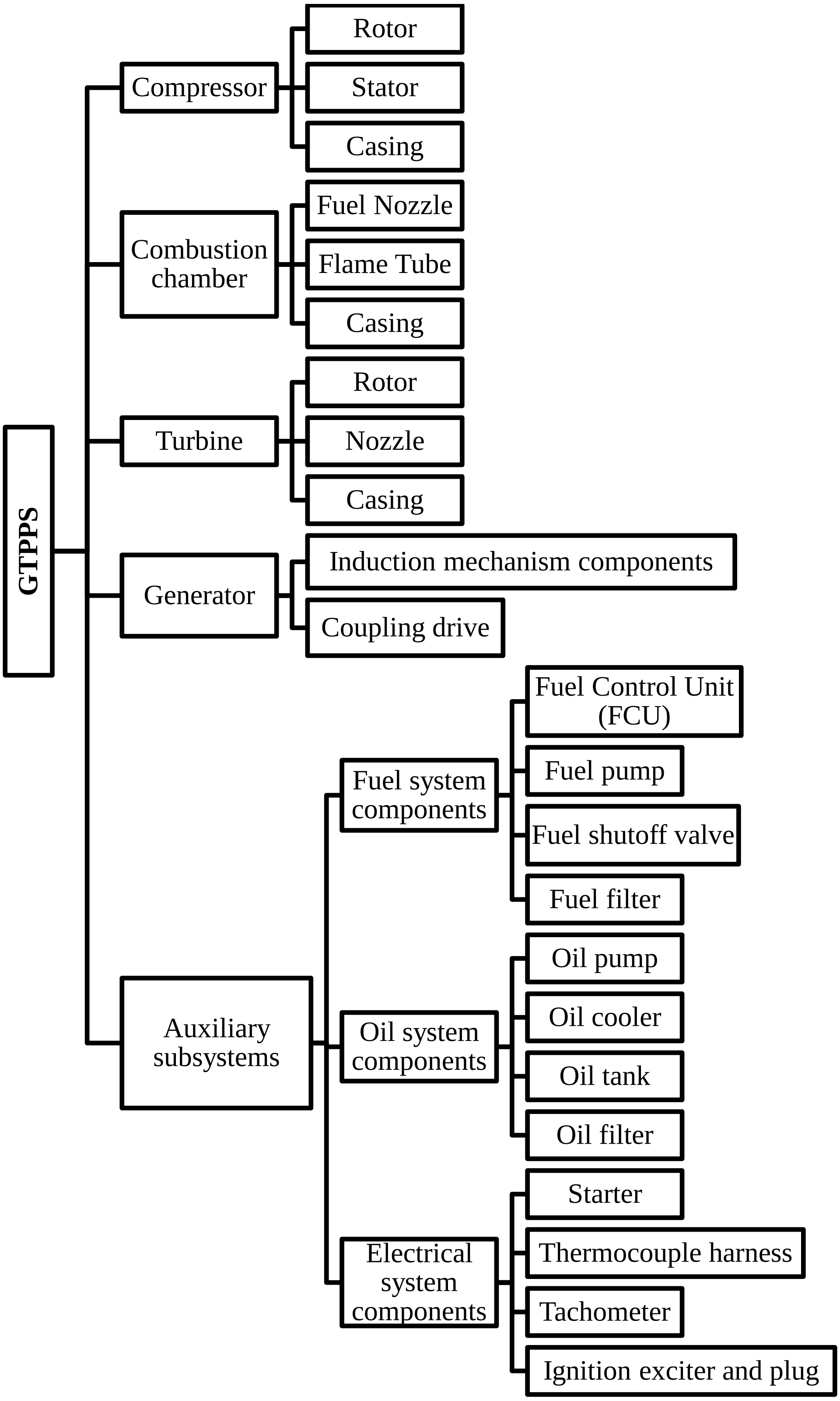

Figure 12: GTPPS subsystems and components

A failure in a component causes a possible degradation in the turbine operation, represented by any reduction in the nominal power output or even environmental degradation [45]. In Figure 13, the station numbering method of subsystems in a gas turbine is shown, where 2 and 3 represent for air characteristics before and after compressor; 3 and 4 represent for combustion chamber inlet and outlet; and finally gas characteristics before and after turbine section are represented by 5 and 6. Also components of each main subsystem (i.e. compressor, combustion chamber, turbine, and gearbox) and auxiliary subsystems (fuel, oil, and electrical subsystems) are listed as well.

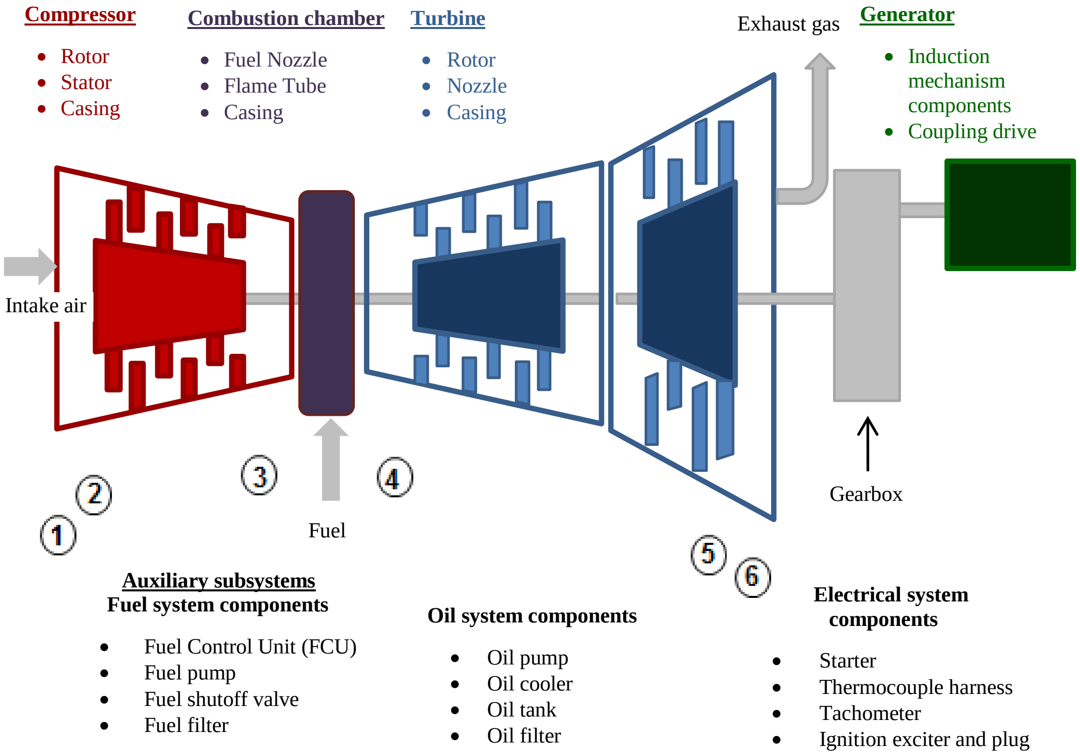

Figure 13: GTPPS main and auxiliary subsystems and detailed components

Chapter 5

THE PROBABLE SYSTEM FAILURE MODES

In this chapter, the possible failures which have been found in GTPPS are introduced individually and for each failure mode, the related failure cause and effect are described as well.

5.1 Failure Mode: No Ignition at Start

5.1.1 Failure Cause

In the engine start process, to start the combustion process there is a need for primary ignition, up with the air-fuel mixture for combustion process at starting, the generated heat is sufficient to continue combustion and ignition ends. One of the failures that may occur in the engine start process is no primary ignition, which the reason lays in the engine's electrical system. One of the main causes of no ignition at start, is erosion on ignition plugs, since electrical energy eventually leads to producing sparks by ignition plug to burn the air-fuel mixture in the combustion chamber and in the event that igniter tip is wore out, no longer has the required efficiency for ignition [65].

5.1.2 Failure Effect

By the initial start of the engine by the electric starter and guiding fuel from the tank to the combustion chamber, everything prepared for ignition and the engine speed reaching the ideal state, which in effect of ignition plugs breakdown, engine speed won’t increase and the engine won’t be sustained.

5.1.3 Failure Disposition

Typically, inspection ports located on combustion chamber have the ignition plugs placed on them and when bore scope inspection is required, igniters will be inspected as well.

5.2 Failure Mode: Low Oil Pressure (and/or High Oil Temperature)

5.2.1 Failure Cause

The importance of oil in the jet engine is compared to blood for human body, such that jet engine without hydraulic fluid circulation stops moving within a short time and undergoes great damages. Oil has 5 main tasks in the engine:

1. Damping vibrations;
2. Cooling;
3. Cleaning;
4. Sealing;
5. Lubrication [66].

In other words, in addition to the primary function of the oil which is to facilitate the movement of moving parts, this fluid helps cooling and absorbing incoming stress of the bearings. Now, if oil pumps pressure to send the fluid to all points of need in jet engine isn’t sufficient or the oil cooler (a component in the engine oil system) doesn’t cool the oil adequately after a circulation in the engine, oil density declines or doesn’t have sufficient pressure for use. In both cases, oil system performance declines and in the first place this is a big threat to engine bearings.

5.2.2 Failure Effect

In the event that for any reason, oil pressure declines or the temperature goes beyond the normal range, the fluid loses its properties in the place of consumption and in the initial and final parts of rotors which bearings are placed, the incoming tension isn’t well disposed by the oil and tension remaining in the bearings damages the engine and when bearing loses its efficiency, the rotary set (compressor or turbine) suffer damages in a short while.

5.2.3 Failure Disposition

To evaluate the engine oil system periodically, we’ll take a sample of the engine oil and assess it in terms of the type and the amount of impurities found and in case we find an undesirable element or more than normal, we’ll search for the origin of wearing that has appeared in the oil. On the hand, to ensure the quality of the used oil, oil is replaced periodically and at regular intervals, oil system components (including the cooler and the filter) are inspected and cleaned.

5.3 Failure Mode: Engine Over-Speed

5.3.1 Failure Cause

Among the indicators that are placed against the user in control panel and are very important in monitoring when the jet engine is operating is speed indicator (RPM indicator) and according to the extent that is defined for these indicators, if engine speed exceeds a certain threshold, safety of the moving parts primarily and also the components that are in their vicinity will be compromised [67]. For the damage caused by over-speed we can mention two main reasons:

1. Excessive fuel consumption in the engine
2. Disconnecting the intermediate shaft between the compressor and the turbine

The type of failures very effective in determining the cause; because when there is a disruption in the fuel system and the engine uses more fuel, engine RPM works permanently in a range higher than normal. But by physically disconnecting the intermediate shaft between the compressor and the turbine, the engine duty cycle suddenly increases and the engine shuts off. Since increase in engine speed will be accompanied by incoming Centrifugal force from the center to the rotor more than normal, therefore fail of the rotor is predictable and rotation will be ceased.

5.3.2 Failure Effect

Over speed failure is usually accompanied with a few symptoms: Apart from engine speed indicator, fuel quantity indicator also declines more quickly than before and if the rate of acceleration gets more than normal, there is the possibility of main caution light turning on. Anyway, all of these signs show a higher speed than normal. This effect isn’t something that ends here and if it continues can cause irreparable damages to the system.

5.3.3 Failure Disposition

In order to prevent this problem, one of the best and most effective actions would be tip clearance periodic inspection, and compressor and turbine blades which typically compressor first row blade from the intake span and the last row of the turbine from the exhaust span are inspected and if the clearance is lower than normal, it indicates over speed in the compressor and over-speed/temperature in the turbine.

5.4 Failure Mode: Misalignment of Generator Coupling Drive

5.4.1 Failure Cause

The result of all the interactions inside the jet engine is the output shaft rotation in the engine which after coupling with the generator and rotating the internal rotor produces electricity. Therefore one of the failures that can disrupt the spinning of the generator is misalignment of the turbine output shaft by the central axis of the generator. In the event of this failure, coupling gears are rapidly worn and the frequency of the electricity produced decreases [68].

Reducing the amount of power available in the first place maybe because of engine low power, but if engine operating parameters are normal, this failure should be sought in lack of proper installation of the engine output shaft or the wearing of generator’s intermediate coupling drive.

5.4.2 Failure Effect

One of the most popular and important flaws of the generator is under-frequency which itself can be the result of other failures including shaft misalignment or engine low power.

Misalignment is usually accompanied with abnormal noise, because gears are bearing a high friction and along with material removal, an unusual noise is also generated. But reduction of the produced frequency without abnormal noise and reduction of the engine duty cycle (usually along with increasing duty temperature) indicates engine low power failure which leads to generator under-frequency.

5.4.3 Failure Disposition

In general, input quill and the gears inside the generator and other fragments which are used for electrical induction mechanism, are corrupted after a period of time and need maintenance. Therefore determining the time for overhaul on the generator component is of great importance and by doing so, before a failure occurs in the inner parts; possible flaws are identified and resolved.

5.5 Failure Mode: Engine Gas Over-Temperature

5.5.1 Failure Cause

With combustion in the engine and gas production in order to rotate the turbine, a large thermal stress is generated in the engine which is transmitted to the turbine along with the flow of gas from the combustion chamber. If the temperature of the gases exceeds a certain limit, a stress higher than the normal stress is to the surface in contact with the gas flow and there is the possibility of burning in those areas [69, 70].

Typically in jet engine the first point that experiences the highest temperature is turbine nuzzle which is considered the most primitive point of the turbine and the possibility of vane burning is the most in this areas.

5.5.2 Failure Effect

Contact of the internal components of the turbine components with the gas flow that is hotter than normal, leads to excessive expansion of turbine nozzle vanes and at first indicates itself as deformation and then as burnt areas. Burnt vanes can no longer properly guide the gas flow towards turbine rotor and disturb the streamline flow of the gases; and this is of great importance in jet engine performance.

5.5.3 Failure Disposition

There are some holes on combustion chamber casings for bore scope inspection through which you can inspect fuel nuzzles and turbine nuzzles. Therefore, since nozzles are very important and there is no indication to this topic, so it is recommended that turbine nozzles be inspected periodically.

5.6 Failure Mode: Compressor Rotor Vibration

5.6.1 Failure Cause

One of the two engine rotors is called compressor rotor which is located at the front of the engine ant its duty is to compress the incoming air. The main reason for the mentioned failure is failing the bearings at the beginning and end of the rotor which damp the incoming vibrations. But among other reasons that are less likely to occur, we can mention loose engine installation mounts that cause the engine to place at an angle to the horizon and despite the low probability of occurrence, severe vibration is entered to the system. Another possibility of this malfunction could also be the electric fault of vibration indicator in which case rotors are serviceable [71].

5.6.2 Failure Effect

Usually around the rotating sections such as compressor section, we’ll have vibration pick-ups which in case frequency exceeds a certain threshold, an illuminator is activated in instrument panel.

5.6.3 Failure Disposition

In case vibration light is activated, the first hypothesis is that compressor rotary section is functioning normally and the fault is in the electrical system. Therefore after investigating this cause and not finding a specific reason for it, we should inspect engine mounts and make sure that they aren’t loose.

Eventually in case we couldn’t determine the cause of the failure, we must take an oil sample from the engine and analyze elements of the impurities in it. Through this we can determine the defective bearing.

5.7 Failure Mode: Compressor Rotor Shaft Locked

5.7.1 Failure Cause

Compressor rotor is very close to the casing around itself which in effect of Centrifugal forces exerted to the compressor rotor and in case theses forces exceed a certain limit, the tip of the blades are gradually taken apart and eventually the blades hit the casing [72].

5.7.2 Failure Effect

In case the blades hit the compressor casing, compressor casing speed reduces and eventually leads to the sudden halt of the engine. This failure causes great damages to the blades and the casing that leaves no other choice except replacement.

5.7.3 Failure Disposition

To prevent the mentioned failure, determining a periodic program in the engine maintenance schedule in order to check clearance of compressor blades’ tip is necessary and since (1) first row blades are longer than other blades and (2) from the engine inlet you can only check first row blades and (3) the thickness of the first row blades is less than other blades. Therefore while inspecting we’ll confine ourselves to the first row and based on the results, we’ll make a decision.

5.8 Failure Mode: Compressor Over Temperature

5.8.1 Failure Cause

Through the section of the intake air, the compressor increases the pressure and the temperature and guides it to the combustion chamber with a minimum speed. In case the intake air has a higher temperature than the limit (the operating environment is hotter than specified) then with the passage of hot air from compressor stages, compressor outlet air isn’t suitable for combustion and compressor over-temperature failure occurs [74].

5.8.2 Failure Effect

When compressor over-temperature failure occurs, inlet air to the combustion chamber will be hotter than normal and in case combustion occurs, intake air to the turbine causes the emergence of hot spot on turbine nozzles and some of nozzle vanes burn and this would reduce turbine serviceability strongly and the continuation of this situation isn’t suitable for the gas turbine.

5.8.3 Failure Disposition

To prevent this failure, functioning conditions of the gas turbine including the temperature should always be monitored before the engine starts and selecting the construction location of the power plant would be of great importance in engine performance.

5.9 Failure Mode: Compressor Stalls

5.9.1 Failure Cause

One of the most important factors that highly affect the performance of the gas turbine is air or gas streamline flow inside the engine, because wherever the flow is distorted from its direct linear form and takes the shape of a vortex, the engine power output is sharply reduced. Stall failure is the result of vortex flows' emergence which that are usually created in effect of ice formation or a barrier in the inlet of the engine or damage to compressor blades in collision with a foreign object which causes disruption of air or gas flow [75].

5.9.2 Failure Effect

The emergence of a vortex can be the main effect of compressor stall failure which is usually accompanied with abnormal sound and RPM fluctuation. If this failure continues, it may reduce engine serviceability dramatically and if operator observes traces of stall failure, he/she should decrease engine duty cycle immediately. In cases when stall occurs with high intensity, the energy of vortexes usually leads to the bending of engine rotary blades.

5.9.3 Failure Disposition

In order to prevent the stall failure, at first and before the jet engine starts, you must make sure there is no foreign object in engine intake part and the engine shouldn't function in conditions where there is the possibility of sand and dust entrance into it.

5.10 Failure Mode: RPM/Temperature Fluctuation

5.10.1 Failure Cause

Combustion requires the combination of the two main elements air and fuel and disruption in the compression ratio of the two elements may show itself in the form of a released energy such as fluctuations. Since at the time of disruption of combustion combination elements, combustion would be left incomplete and the fuel won’t provide the desired energy, therefore factors that cause fluctuation failure are divided into two categories: [76]

1. Disruption of incoming air into the combustion chamber
2. Disruption of fuel delivered to the combustion chamber

So in case compressor casing has air leakage, the intake air into the combustion chamber would be decreased and affects combustion efficiency.

5.10.2 Failure Effect

Incomplete combustion causes the lack of required energy production and rotary sections encounter problems on receiving the required power and besides an increase in combustion by-products (unwanted combustion products which are obtained from incomplete combustion) disrupt the steady rhythm of gas production. These effects demonstrate themselves as fluctuations in RPM and engine duty temperature.

5.10.3 Failure Disposition

In order to prevent fluctuation failure, we must inspect compressor casing first and if we find dent in mating areas or a deep crack on the casing, the casing should be replaced so that besides identifying leakage source, air is prevented from escaping.

5.11 Failure Mode: Flame Out

5.11.1 Failure Cause

The only cause of the rotation of jet engine turbine blades is gas flow which is generated inside the combustion chamber and if any problems arise in this flow, turbine rotor rotation and consequently power generation of generator rotation will be disrupted. Stoppage of the gas flow into the combustion chamber failure is called flame out and one of the main causes of this failure is a component through which fuel is sprayed into the combustion chamber for burning (fuel nozzle). Partial or total cloggage of fuel nozzles is highly effective in produced gas volume and because of nozzle congestion with not burned carbon masses, fuel can't be withdrawn and flame out failure occurs [77].

5.11.2 Failure Effect

By reducing the volume of gas produced in the combustion chamber, the energy of the colliding flow with turbine rotor will be reduced and turbine duty cycle and generator middle shaft speed are reduced. As soon as this failure occurs, another failure called under-frequency failure occurs in the power plant and if it continues eventually the electricity produced in the power plant will become zero.

5.11.3 Failure Disposition

To prevent the mentioned failure through inspection ports we can bore scope check the inner components of combustion chamber and in case nozzles are obdurate, necessary measures to be applied.

5.12 Failure Mode: Hot Spot on Flame Tube

5.12.1 Failure Cause

The contact between combustion chamber inner components and the flame causes burns. If we consider the inner layer of the combustion chamber which is called the flame tube (as the main component of this part), the flame inside the layer causes thermal stress to all of its parts and the engine operation continues by increasing the amount of stress. Therefore finding areas that are discolored and are called "hot spots" is one of the main failures that occur in combustion chamber [78].

5.12.2 Failure Effect

The amount of burnt surfaces in the interior wall of the combustion chamber depends on thermal stresses and proportional to the intensity of the incoming heat, and discolored area (usually purple) is more.

5.12.3 Failure Disposition

Whole of the entered air into the combustion chamber isn’t used for combustion and a portion of it by passing around the wall, is used for cooling flame tube and prevents the generation of hot spots. But misalignment of the flame tube in the right position (because the flame tube is not completely fixed in its place and can expand) or air entering the combustion chamber with a temperature higher than allowed limits can cause the mentioned failure. Therefore careful consideration of ambient air temperature and flame tube placement in the right position after removal, have vital roles in eliminating the risk of downtime.

5.13 Failure Mode: Flame Leakage

5.13.1 Failure Cause

The reason for this failure is as RPM fluctuation, only in this failure we’ll face gas leakage and through combustion chamber casing, gases produced in combustion instead of being sent to the turbine find a way out and the received energy content by the turbine rotor reduces. Finding an escape is done by the gases from the mating line of the chamber or leaves a deep crack on the surface of emission chamber surface [73, 79].

5.13.2 Failure Effect

Air or gas leakage out of the engine and lack of required energy to rotate turbine blades, leaves a similar effect as what was stated in RPM fluctuation section.

5.13.3 Failure Disposition

To prevent this failure, in daily inspections before the engine starts we can determine whether there are any impacts of foreign body collision or physical damage on the engine body or not. And always the plant surrounding environment should be free of sand, soil and gravel. Also in case which there is a need for major repair on the engine and combustion chamber section is disassembled, contact surfaces of upper and lower cases of combustion chamber are inspected in terms of smoothness and lack of dent.

Chapter 6

THE RISK PRIORITY RANKING OF SYSTEM

In this chapter, the typical failure modes of GTPPS are listed based upon [7], [15], [16], [28], [30], and [33] (as shown in Table 8) and for each failure mode, the values of risk factors and the amounts of basic RPN, Aggregated Fuzzy RPN, and Fuzzy RPN (based on 10 and 100 membership functions) are provided. The values are obtained from survey responses from three specialists who are expert in GTPPS (Weight of opinions 1.0). After scoring and determination of failure rankings, critical components are introduced and the related maintenance action for preventing from occurrence should be incorporated prior to other actions.

Generally the whole maintenance actions of GTPPS can be divided to three main categories: Preventive, Predictive, and Corrective actions.

Corrective maintenance is the name of actions which performed at time of component breakdown and before occurrence of failure, this maintenance policy is not scheduled.

Preventive maintenance is basically scheduled for interval inspection of time-independent components (such as casings, stators, and nozzles); because occurrence of failure is not clearly predictable and while engine operation, accomplishment of inspection is necessary.

Predictive maintenance is too similar with preventive maintenance in performing of interval inspections and difference is necessity of inspection of time-dependent components (components which occurrence of failure is predictable at an estimated due) and prior to breakdown of component, by inspection accomplishment serviceability of component is saved. Other than corrective maintenance which is assigned to low cost failures, preventive or predictive maintenance actions are assigned for failures that exact high expense to system.

Periodic inspections are generally classified in Non-Destructive Test (NDT) methods, such as visual inspection (e.g. over compressor inlet blades) and dye-penetration inspection (e.g. for crack tracking on surface of combustion flame tube) and in cases of requirement to special inspections (e.g. over-temperature), turbine blade hardness test is accomplished [51].

Table 8: FMEA Table

Failure mode Sequence No..	Subsystem Component	Failure Mode	Failure Cause	S	O	D	RPN	Aggregated Fuzzy RPN	Fuzzy RPN (10 MFs)	Fuzzy RPN (100 MFs)	Ranking based on (RPN, Aggreg. No., Fuzzy using 10MFs, Fuzzy using 100MFs)
1	Compressor (Rotor)	Vibration	Faulty vibration indication	5	4	1	20	1.81530	3	2.22312	28, 31, 34, 36
2			Loose mounts	6	3	3	54	2.03343	5	3.24728	18, 28, 14, 27
3			Defective bearings	7	2	5	70	3.41144	5	4.27143	16, 13, 14, 12
4		Shaft locked	Deformation of blades and contacting with casing	9	2	3	54	2.85418	6	4.06024	18, 21, 5, 18
5		Over-temperature	Dirty compressor rotor	10	4	5	200	5.42653	8	5.95872	4, 4, 1, 4

6			Foreign object damage	10	3	2	60	2.97322	6	4.24278	17, 20, 5, 15
7	Compressor (Stator)	Stall	Ice formation on engine inlet	6	2	1	12	1.55378	3	2.00865	30, 36, 34, 39
8			Binding of variable stator vanes	7	4	3	84	2.74735	5	3.90456	14, 22, 14, 20
9			Foreign object damage	6	3	2	36	1.80273	4	2.77379	24, 33, 30, 32
10	Compressor (Casing)	RPM or temperature fluctuation	Air leakage	4	2	4	32	1.60965	3	2.68634	25, 34, 34, 33
11	Combustion chamber (Fuel nozzle)	Flame-out	Partial cloggage or blockage of fuel nozzles	8	7	6	336	6.16588	8	6.56358	2, 2, 1, 3
12		Instability of flame pattern	Irregular fuel-to-air ratio	6	4	6	144	4.57655	6	4.96246	7, 8, 5, 7
13	Combustion chamber (Flame tube)	Hot spots on flame tube	Fault in cooling of flame tube and inequality in flame distribution around it	6	2	8	96	4.90718	6	5.34067	12, 6, 5, 5
14	Combustion chamber (Casing)	Flame leakage	Loosing smoothness of mating areas	5	3	3	45	1.41773	4	2.87428	21, 37, 30, 30
15	Turbine (Nozzle)	Over-temperature	Burnt nozzle vanes	10	3	9	270	6.92976	8	7.56969	3, 1, 1, 1
16	Turbine (Rotor)	Shaft seized	Rubbing of rotor blades with turbine casing	9	3	4	108	4.06223	6	4.82959	9, 9, 5, 9
17		Vibration	Faulty vibration indication	5	4	1	20	1.81530	3	2.22312	28, 31, 34, 37
18			Loose mounts	6	3	3	54	2.03343	5	3.24728	18, 28, 14, 27
19			Defective bearings	7	2	5	70	3.41144	5	4.27143	16, 13, 14, 12
20	Turbine (Casing)	Low power	Gas leakage	6	5	6	180	4.94583	6	5.25284	5, 5, 5, 6
21	Generator (Induction mechanism components)	Low electrical output	Low frequency of generator, caused by generator internal failure	7	10	5	350	6.02678	8	6.59043	1, 3, 1, 2
22		No output	Feeder problem	7	3	2	42	1.88342	5	3.14421	22, 30, 14, 29

23	Generator (Coupling drive)	Misalignment of generator with turbine output shaft	Wear in helical teeth of coupling shaft	7	2	5	70	3.41144	5	4.27143	16, 13, 14, 12
24	Auxiliary sys. (Fuel system components)	Post-shutdown fire	Shutoff valve remains open	5	3	3	45	1.41773	4	2.87428	21, 37, 30, 30
25		Over-speed	High fuel flow	10	1	4	40	4.01422	6	4.61403	23, 10, 5, 10
26		Flame-out	Fuel contamination	7	6	1	42	2.99249	5	3.53288	22, 19, 14, 24
27		No start	Fuel shutoff valve not energized	3	1	3	9	0.55148	2	1.54585	32, 43, 41, 42
28			Air, water, or solids in fuel lines	4	2	4	32	1.60965	3	2.68634	25, 34, 34, 33
29		Under-speed	Fuel filter partial cloggage	5	7	3	105	3.12514	5	4.03683	10, 18, 14, 19
30			Low adjustments	5	5	5	125	4.00573	5	4.40487	8, 11, 14, 11
31		Stall	Fuel pressure irregular	6	3	5	90	3.34963	5	4.19622	13, 17, 14, 16
32	Auxiliary sys. (Oil system components)	Oil contamination	Oil tank is contaminated	5	2	1	10	1.23010	3	1.64177	31, 39, 34, 41
33		No oil pressure	Sheared oil pump shaft	8	2	3	48	2.52798	5	3.70115	20, 23, 14, 22
34			Low oil level in tank	8	3	2	48	2.28653	5	3.50798	20, 26, 14, 25
35		High oil temperature	Oil cooler inoperative	7	7	1	49	3.49068	6	3.82191	19, 12, 5, 21
36		Oil pressure fluctuation	Oil leakage and/or low oil level in tank	6	4	3	72	2.43782	5	3.53695	15, 24, 14, 23
37	Auxiliary sys. (Electrical system components)	Faulty temperature indication	Open, short circuit in thermocouple circuit	5	5	1	25	2.19866	4	2.50817	26, 27, 30, 35
38		No RPM indication while starting	Starter inoperative	3	4	1	12	0.59277	2	1.49077	30, 41, 41, 43
39		Starter over-speed	Sheared starter drive shaft	4	3	2	24	0.95394	3	2.04475	27, 40, 34, 38

40		Failure to reach idle speed	Internal failure of starter components	4	6	3	72	2.35178	5	3.37753	15, 25, 14, 26
41			Low electrical power	3	2	1	6	0.33649	2	0.91928	33, 44, 41, 44
42		Faulty speed indication	Internal failure of tachometer	3	2	3	18	0.55492	2	1.87194	29, 42, 41, 40
43		No start	Internal failure of ignition exciter	5	4	5	100	3.40870	5	4.12335	11, 16, 14, 17
44			Erosion on ignition plugs	5	5	6	150	4.58831	6	4.88086	6, 7, 5, 8

After scoring of system failure modes it is possible to prioritize them in descending order. In the resulted ranking, the more critical failures are located at higher ranks and by increment of rates, the criticality decreases.

As shown in Table 8 and Figure 14, the most critical failures of system were identified: Under-frequency, Flame-out, and Over-temperature which received the highest ranking numbers (between 1st to 3rd rankings at each approach). Also trend of scored numbers in analysis of each utilized method was very similar and it shows the same risk importance for recognized failure modes of system. Finally it is resulted that by enhancement of Fuzzy rules, precision of results is increased and aggregation of team members' opinions has the same effect at elevation of precision in final findings.

So in FMEA method for increasing the availability of different systems' parts and improving the reliability of system operation, it is necessary to have a special attention to most critical failure modes during scheduling of the maintenance actions.

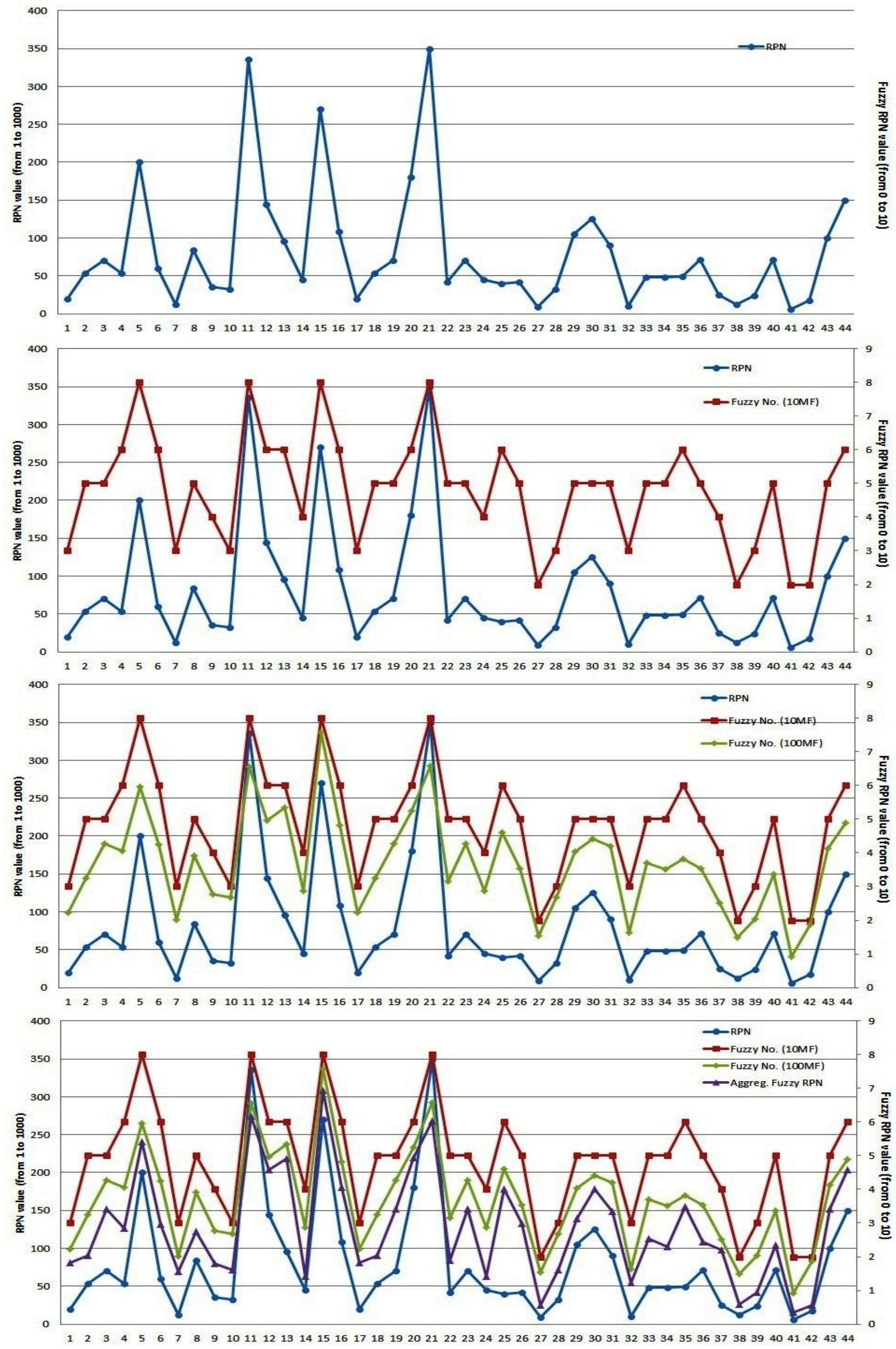

Figure 14: Comparison of values in Basic RPN (blue line) and Aggregated Fuzzy RPN (purple line) and Fuzzy RPN based on 100 membership functions (green line) and Fuzzy RPN based on 10 membership functions approaches (red line). The horizontal axis represents the sequence number of failure mode.

6.1 Designing a Plan for Preventing Generator Failures:

Inside the generator there are many vulnerable parts to failure like bush and windings, which may be damaged after a period of time, so by determining an early safe failure time based on the estimated lifetime and performing a predictive maintenance generator is overhauled (major repair) and afterwards, it is permitted to operate until the next overhaul service. During overhaul process, internal parts are inspected prior to occurrence of failure and necessary measures are taken for maintaining the serviceability of them.

6.2 Designing a Plan for Preventing Flame-Out Failure:

As far as internal components of combustion chamber are in direct contact with flame and there is no possibility of continuous checking of chamber, so performing the preventive maintenance by Bore scope Inspection on time intervals could be a good indicator of the combustion chamber state.

6.3 Designing a Plan for Preventing Turbine Failures:

For getting information about availability of internal components of turbine, it is necessary to perform periodical inspection which is called hot section inspection (HSI) on the hot section components of the engine. This preventive maintenance process is usually accomplished at half of engine time between overhaul (TBO) due.

6.4 Basic Maintenance Guidelines

Determination of a scheduled plan for accomplishment of the required maintenance policy of GTPPS is the output of FMEA method, and the iteration of failure analysis cycle will decrease the obtained RPN at next evaluation. In this manner, the following guidelines are helpful in construction of system maintenance plan [52]:

1. The maintenance policy of a gas turbine is typically based on analysis of gas turbine behavior within one period of engine time between overhaul (T.B.O).

2. Except time based inspections, some annually based basic preventive tasks are performed.

3. As a general division rule, the components of a power plant are classified to time-dependent components (e.g. FCU, starter, and generator) and time–independent components (e.g. combustion chamber, stators, and casings) which the second group is usually known as condition– based components.

4. Dependency of a component on time-based maintenance may be introduced in two ways:
   (1) According to occurrence of failure in some components (e.g. electrical starter and generator) periodically around a certain time, it is necessary to include a major repair (overhaul process) carried out over them, and in this manner they become maintainable again for use in the system.
   (2) Periodic replacement of some components (e.g. compressor and turbine rotor disks) in the system usually because of limited resistance in front of applied stresses, is mandatory in predictive maintenance and no other repair may be taken as substitution over them; therefore, a parameter named Mandatory Replacement Time (MRT) is assigned to them.

Chapter 7

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The aim of this chapter is to present the main conclusions and provide suggestions for further researches.

7.1 Conclusions

In this research, the Failure Mode and Effect Analysis (FMEA) method with approach of failures prioritization based on Risk Priority Number (RPN), Fuzzy RPN (based on 10 or 100 membership functions), and Aggregated Fuzzy RPN values have been applied to GTPPS, where 44 different failure modes are recognized in analysis of main subsystems (i.e. compressor, combustion chamber, turbine, and generator) and auxiliary subsystems (i.e. fuel, oil, and electrical subsystems) components. After scoring of risk factor values by experts of FMEA team members, the obtained results are compared and according to the criticality level, suitable failure dispositions are offered as well.

Among the recognized failure modes, three failures (i.e. over-temperature, flame-out, and low electrical output) are known as the critical system failures and require to be a particular maintenance plan designed for them.

Increasing of Fuzzy rules (from 10 to 100) for the risk analysis is the known factor for enhancement of results precision and the uncertainty level of risk importance factors of failures is diminished.

Because of difficulties in the definition of high number of membership functions, the other way of improvement in the results precession is increment of decision makers in FMEA team; in other words, by aggregating of multi-experts' opinions in assessing of the failure modes, more experience and knowledge are utilized and the final results would be more precise and the related effect is as nearly same as the definition of higher membership functions.

Therefore for overcoming the setbacks of the basic RPN approach, two main ways are usually known as beneficent ways: Risk factors assessment based on 100 membership functions and/or the Aggregation of the multi-experts' opinions.

Accomplishment of maintenance policies such as periodical bore scope inspection on combustion section as preventive maintenance and a comprehensive inspection process of the generator (overhaul) after a predetermined lapse of operation time as predictive maintenance are examples of actions taken for increasing system reliability.

7.2 Suggestions for Further Research

Based on the research presented in this thesis, the following points for future research are suggested:

- Application of Fault Tree Analysis (FTA) in the criticality analysis:

In order to consider the effect of redundancy in more proper and effective way the method of FTA can be used in combination with FMEA. It will also make it easy to study human error in the analysis.

- To develop a framework for data collection in order to be applicable to different situation.

- The four presented methods for risk analysis is aggregated as a model for assessment of failure modes and in future researches will be applied to other energy systems (e.g. wind turbine power plant, steam turbine power plant, photovoltaic system, and etc.).

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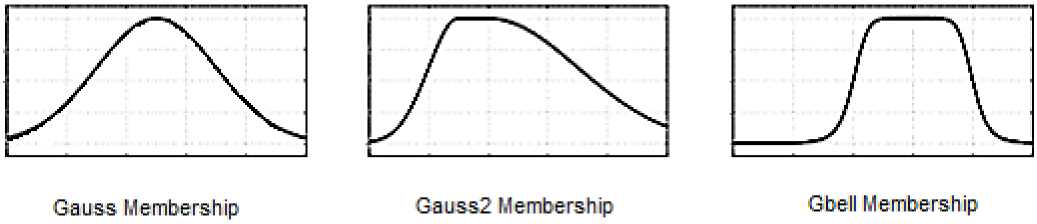
APPENDICES

APPENDIX A: Non-Linear Fuzzy Membership Functions

Two membership functions are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian curves. The two functions are gaussmf and gauss2mf. The generalized bell membership function is specified by three parameters and has the function name gbellmf. The bell membership function has one more parameter than the Gaussian membership function, so it can approach a non-fuzzy set if the free parameter is tuned. Because of their smoothness and concise notation, Gaussian and bell membership functions are popular methods for specifying fuzzy sets. Both of these curves have the advantage of being smooth and nonzero at all points.



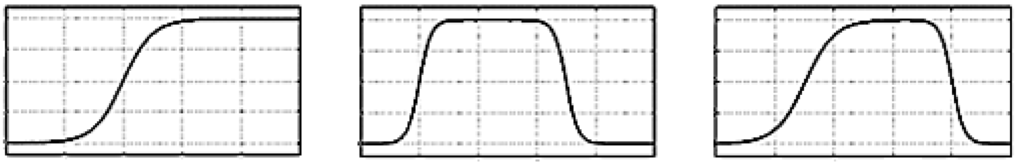
Gauss Membership

Gauss2 Membership

Gbell Membership

Figure A.1: Gaussian Fuzzy membership functions

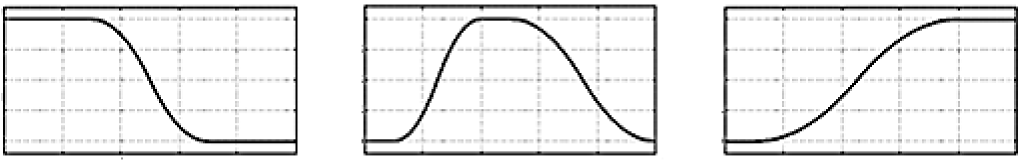
Although the Gaussian membership functions and bell membership functions achieve smoothness, they are unable to specify asymmetric membership functions, which are important in certain applications. Next, you define the sigmoidal membership function, which is either open left or right. Asymmetric and closed (i.e. not open to the left or right) membership functions can be synthesized using two sigmoidal functions, so in addition to the basic sigmf, you also have the difference between two sigmoidal functions, dsigmf, and the product of two sigmoidal functions psigmf.



sigmf dsigmf psigmf

Figure A.2: Sigmoidal Fuzzy membership functions

Polynomial based curves account for several of the membership functions in the toolbox. Three related membership functions are the Z, S, and Pi curves, all named because of their shape. The function zmf is the asymmetrical polynomial curve open to the left, smf is the mirror-image function that opens to the right, and pimf is zero on both extremes with a rise in the middle.



zmf pimf smf

Figure A.3: Polynomial Fuzzy membership functions

APPENDIX B: Fuzzy Risk Number Program in MATLAB Software

As shown in Figure A.4, the fuzzy method is based on two-stage Fuzzy Logic Controller which analysis of each stage is done through the following MATLAB program.

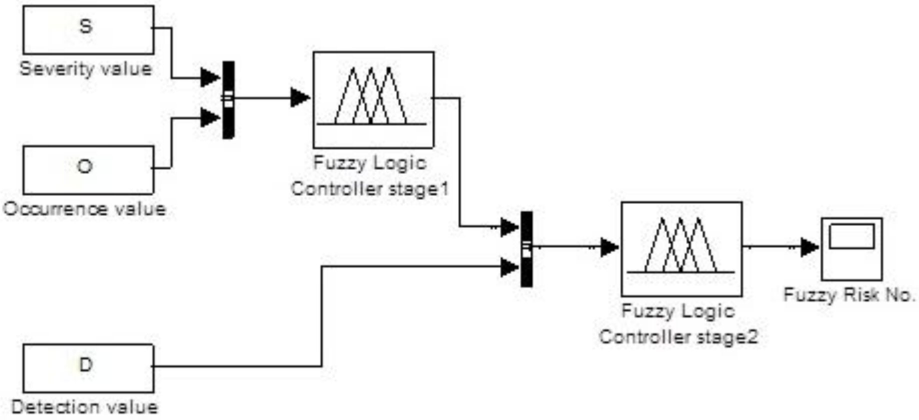


Figure A.4: Fuzzy RPN model in Simulink

Fuzzy Program in controller stage1: (It is mentionable that Fuzzy Controller stage 2 rules are same as stage 1 and the only difference is name of inputs, i.e. stage 1 inputs are Severity and Detection and stage 2 inputs are output of stage 1 and Detection)

1. [System]; Name='RPN1'; Type='mamdani'; Version=2.0; NumInputs=2; NumOutputs=1; NumRules=100; AndMethod='min'; OrMethod='max'; ImpMethod='min'; AggMethod='max'; DefuzzMethod='centroid'

2. [Input1]; Name='Severity'; Range=[0 10]; NumMFs=10
3. MF1='1':'trimf',[0 1 2]; MF2='2':'trimf',[1 2 3]; MF3='3':'trimf',[2 3 4]; MF4='4':'trimf',[3 4 5]; MF5='5':'trimf',[4 5 6]; MF6='6':'trimf',[5 6 7]; MF7='7':'trimf',[6 7 8]; MF8='8':'trimf',[7 8 9]; MF9='9':'trimf',[8 9 10]; MF10='10':'trimf',[9 10 11]

4. [Input2]; Name='Occurrence'; Range=[0 10]; NumMFs=10
5. MF1='1':'trimf',[0 1 2]; MF2='2':'trimf',[1 2 3]; MF3='3':'trimf',[2 3 4]; MF4='4':'trimf',[3 4 5]; MF5='5':'trimf',[4 5 6]; MF6='6':'trimf',[5 6 7]; MF7='7':'trimf',[6 7 8]; MF8='8':'trimf',[7 8 9]; MF9='9':'trimf',[8 9 10]; MF10='10':'trimf',[9 10 11]

6. [Output1]; Name='Failure_effect'; Range=[0 10]; NumMFs=100
7. MF1='10.000':'trimf',[9.667 10 10.333];
8. MF2='9.667':'trimf',[9.333 9.667 10]
9. MF3='9.333':'trimf',[9 9.333 9.667];
10. MF4='9.000':'trimf',[8.857 9 9.333]
11. MF5='8.857':'trimf',[8.714 8.857 9];
12. MF6='8.714':'trimf',[8.571 8.714 8.857]
13. MF7='8.571':'trimf',[8.429 8.571 8.714];
14. MF8='8.429':'trimf',[8.286 8.429 8.571]
15. MF9='8.286':'trimf',[8.143 8.286 8.429];
16. MF10='8.143':'trimf',[8 8.143 8.286]
17. MF11='8.000':'trimf',[7.909 8 8.143];
18. MF12='7.909':'trimf',[7.818 7.909 8]
19. MF13='7.818':'trimf',[7.727 7.818 7.909];
20. MF14='7.727':'trimf',[7.636 7.727 7.818]
21. MF15='7.636':'trimf',[7.545 7.636 7.727];
22. MF16='7.545':'trimf',[7.455 7.545 7.636]
23. MF17='7.455':'trimf',[7.364 7.455 7.545];
24. MF18='7.364':'trimf',[7.273 7.364 7.455]

25. MF19='7.273':'trimf',[7.182 7.273 7.364];
26. MF20='7.182':'trimf',[7.091 7.182 7.273]
27. MF21='7.091':'trimf',[7 7.091 7.182];
28. MF22='7.000':'trimf',[6.933 7 7.091]
29. MF23='6.933':'trimf',[6.867 6.933 7];
30. MF24='6.867':'trimf',[6.8 6.867 6.933]
31. MF25='6.800':'trimf',[6.733 6.8 6.867];
32. MF26='6.733':'trimf',[6.667 6.733 6.8]
33. MF27='6.667':'trimf',[6.6 6.667 6.733];
34. MF28='6.600':'trimf',[6.533 6.6 6.667]
35. MF29='6.533':'trimf',[6.467 6.533 6.6];
36. MF30='6.467':'trimf',[6.4 6.467 6.533]
37. MF31='6.400':'trimf',[6.333 6.4 6.467];
38. MF32='6.333':'trimf',[6.267 6.333 6.4]
39. MF33='6.267':'trimf',[6.2 6.267 6.333];
40. MF34='6.200':'trimf',[6.133 6.2 6.267]
41. MF35='6.133':'trimf',[6.067 6.133 6.2];
42. MF36='6.067':'trimf',[6 6.067 6.133]
43. MF37='6.000':'trimf',[5.947 6 6.067];
44. MF38='5.947':'trimf',[5.895 5.947 6]
45. MF39='5.895':'trimf',[5.842 5.895 5.947];
46. MF40='5.842':'trimf',[5.789 5.842 5.895]
47. MF41='5.789':'trimf',[5.737 5.789 5.842];
48. MF42='5.737':'trimf',[5.684 5.737 5.789]
49. MF43='5.684':'trimf',[5.632 5.684 5.737];

50. MF44='5.632':'trimf',[5.579 5.632 5.684]
51. MF45='5.579':'trimf',[5.526 5.579 5.632];
52. MF46='5.526':'trimf',[5.474 5.526 5.579]
53. MF47='5.474':'trimf',[5.421 5.474 5.526];
54. MF48='5.421':'trimf',[5.368 5.421 5.474]
55. MF49='5.368':'trimf',[5.316 5.368 5.421];
56. MF50='5.316':'trimf',[5.263 5.316 5.368]
57. MF51='5.263':'trimf',[5.211 5.263 5.316];
58. MF52='5.211':'trimf',[5.158 5.211 5.263]
59. MF53='5.158':'trimf',[5.105 5.158 5.211];
60. MF54='5.105':'trimf',[5.053 5.105 5.158]
61. MF55='5.053':'trimf',[5 5.053 5.105];
62. MF56='5.000':'trimf',[4.941 5 5.053]
63. MF57='4.941':'trimf',[4.882 4.941 5];
64. MF58='4.882':'trimf',[4.824 4.882 4.941]
65. MF59='4.824':'trimf',[4.765 4.824 4.882];
66. MF60='4.765':'trimf',[4.706 4.765 4.824]
67. MF61='4.706':'trimf',[4.647 4.706 4.765];
68. MF62='4.647':'trimf',[4.588 4.647 4.706]
69. MF63='4.588':'trimf',[4.529 4.588 4.647];
70. MF64='4.529':'trimf',[4.471 4.529 4.588]
71. MF65='4.471':'trimf',[4.412 4.471 4.529];
72. MF66='4.412':'trimf',[4.353 4.412 4.471]
73. MF67='4.353':'trimf',[4.294 4.353 4.412];
74. MF68='4.294':'trimf',[4.235 4.294 4.353]

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MF69='4.235':'trimf',[4.176 4.235 4.294];
MF70='4.176':'trimf',[4.118 4.176 4.235]
MF71='4.118':'trimf',[4.059 4.118 4.176];
MF72='4.059':'trimf',[4 4.059 4.118]
MF73='4.000':'trimf',[3.857 4 4.059];
MF74='3.857':'trimf',[3.714 3.857 4]
MF75='3.714':'trimf',[3.571 3.714 3.857];
MF76='3.571':'trimf',[3.429 3.571 3.714]
MF77='3.429':'trimf',[3.286 3.429 3.571];
MF78='3.286':'trimf',[3.143 3.286 3.429]
MF79='3.143':'trimf',[3 3.143 3.286];
MF80='3.000':'trimf',[2.909 3 3.143]
MF81='2.909':'trimf',[2.818 2.909 3];
MF82='2.818':'trimf',[2.727 2.818 2.909]
MF83='2.727':'trimf',[2.636 2.727 2.818];
MF84='2.636':'trimf',[2.545 2.636 2.727]
MF85='2.545':'trimf',[2.455 2.545 2.636];
MF86='2.455':'trimf',[2.364 2.455 2.545]
MF87='2.364':'trimf',[2.273 2.364 2.455];
MF88='2.273':'trimf',[2.182 2.273 2.364]
MF89='2.182':'trimf',[2.091 2.182 2.273];
MF90='2.091':'trimf',[2 2.091 2.182]
MF91='2.000':'trimf',[1.857 2 2.091];
MF92='1.857':'trimf',[1.714 1.857 2]
MF93='1.714':'trimf',[1.571 1.714 1.857];
```

100. MF94='1.571':'trimf',[1.429 1.571 1.714]

101. MF95='1.429':'trimf',[1.286 1.429 1.571];

102. MF96='1.286':'trimf',[1.143 1.286 1.429]

103. MF97='1.143':'trimf',[1 1.143 1.286];

104. MF98='1.000':'trimf',[0.667 1 1.143]

105. MF99='0.667':'trimf',[0.333 0.667 1];

106. MF100='0.333':'trimf',[0 0.333 0.667]

107. [Rules]

108. 10 10, 1 (1) : 1; 10 9, 2 (1) : 1; 9 10, 3 (1) : 1; 10 8, 4 (1) : 1; 10 7, 5 (1) : 1; 9 9, 6 (1) : 1; 9 8, 7 (1) : 1, 8 10, 8 (1) : 1; 8 9, 9 (1) : 1; 7 10, 10 (1) : 1; 10 6, 11 (1) : 1; 10 5, 12 (1) : 1; 9 7, 13 (1) : 1, 9 6, 14 (1) : 1; 8 8, 15 (1) : 1; 8 7, 16 (1) : 1; 7 9, 17 (1) : 1; 7 8, 18 (1) : 1; 6 10, 19 (1) : 1, 6 9, 20 (1) : 1; 5 10, 21 (1) : 1; 10 4, 22 (1) : 1; 10 3, 23 (1) : 1; 9 5, 24 (1) : 1; 9 4, 25 (1) : 1 , 8 6, 26 (1) : 1; 8 5, 27 (1) : 1; 7 7, 28 (1) : 1; 7 6, 29 (1) : 1; 6 8, 30 (1) : 1; 6 7, 31 (1) : 1, 5 9, 32 (1) : 1; 5 8, 33 (1) : 1; 4 10, 34 (1) : 1; 4 9, 35 (1) : 1; 3 10, 36 (1) : 1; 10 2, 37 (1) : 1, 10 1, 38 (1) : 1; 9 3, 39 (1) : 1; 9 2, 40 (1) : 1; 8 4, 41 (1) : 1; 8 3, 42 (1) : 1; 7 5, 43 (1) : 1, 7 4, 44 (1) : 1; 6 6, 45 (1) : 1; 6 5, 46 (1) : 1; 5 7, 47 (1) : 1; 5 6, 48 (1) : 1; 4 8, 49 (1) : 1, 4 7, 50 (1) : 1; 3 9, 51 (1) : 1; 3 8, 52 (1) : 1; 2 10, 53 (1) : 1; 2 9, 54 (1) : 1; 1 10, 55 (1) : 1, 9 1, 56 (1) : 1; 8 2, 57 (1) : 1; 8 1, 58 (1) : 1; 7 3, 59 (1) : 1; 7 2, 60 (1) : 1; 6 4, 61 (1) : 1, 6 3, 62 (1) : 1; 5 5, 63 (1) : 1; 5 4, 64 (1) : 1; 4 6, 65 (1) : 1; 4 5, 66 (1) : 1; 3 7, 67 (1) : 1, 3 6, 68 (1) : 1; 2 8, 69 (1) : 1; 2 7, 70 (1) : 1; 1 9, 71 (1) : 1; 1 8, 72 (1) : 1; 7 1, 73 (1) : 1, 6 2, 74 (1) : 1; 5 3, 75 (1) : 1; 4 4, 76 (1) : 1; 3 5, 77 (1) : 1; 2 6, 78 (1) : 1; 1 7, 79 (1) : 1, 6 1, 80 (1) : 1; 5 2, 81 (1) : 1; 5 1, 82 (1) : 1; 4 3, 83 (1) : 1; 4 2, 84 (1) : 1; 3 4, 85 (1) : 1, 3 3, 86

(1) : 1; 2 5, 87 (1) : 1; 2 4, 88 (1) : 1; 1 6, 89 (1) : 1; 1 5, 90 (1) : 1; 4 1, 91 (1) : 1, 3 2, 92 (1) : 1; 3 1, 93 (1) : 1; 2 3, 94 (1) : 1; 2 2, 95 (1) : 1; 1 4, 96 (1) : 1; 1 3, 97 (1) : 1, 2 1, 98 (1) : 1; 1 2, 99 (1) : 1; 1 1, 100 (1) : 1.

APPENDIX C: Fuzzy Rule-Based Risk Number Based on Integer Risk Factors

Table A.1: Combination modes of risk factors

Severity	Occurrence	Detection	Fuzzy Rule-based RPN
10	10	10	10.00000000000
10	9	10	9.75182598539
10	10	9	9.56955204735
9	10	10	9.67986285310
10	9	9	9.30158532168
10	8	10	9.49043730670
9	10	9	9.22371921861
10	7	10	9.20004921765
9	9	10	9.41816741363
9	8	10	9.12170460573
8	10	10	9.33638327030
10	10	8	9.09321880487
10	9	8	8.82597937914
8	9	10	9.04463249995
10	8	9	9.01836702247
9	10	8	8.74811726587
7	10	10	8.96883294180
10	10	7	8.61688537659
10	8	8	8.54228452421
10	7	9	8.72407816802
10	9	7	8.35058595483
9	9	9	8.94188639559
9	8	9	8.64575430553
10	6	10	8.91632212713
8	10	9	8.86026013382
8	9	9	8.56865221223
10	7	8	8.24834825869
10	5	10	8.62291734166
7	10	9	8.49277192957
9	7	10	8.84268956971
9	6	10	8.54395419479
8	8	10	8.76075001755
8	7	10	8.46645706240
10	6	9	8.44017402190
9	10	7	8.27272902902
9	9	8	8.46564035888
7	9	10	8.67929048345
7	8	10	8.39042610759
6	10	10	8.59929682428

6	9	10	8.31586136454
9	8	8	8.17005890390
5	10	10	8.24276259666
10	5	9	8.14671938924
10	4	10	8.33786847872
8	10	8	8.38427700454
9	7	9	8.36637434502
9	6	9	8.06777184665
8	9	8	8.09290681365
9	5	10	8.26433405182
10	3	10	8.04616979764
10	10	6	8.14055211991
8	8	9	8.28447930094
9	4	10	7.96644637256
10	8	7	8.06627535755
8	7	9	7.99027024481
10	9	6	7.87537275498
7	10	8	8.01689202932
7	9	9	8.20306955268
8	5	10	7.88838191029
8	6	10	8.18574104582
7	8	9	7.91421474681
9	10	6	7.79752195535
7	7	10	8.10319257118
6	10	9	8.12310560576
10	10	5	7.66421872548
6	8	10	8.02230309397
7	6	10	7.81197658724
6	9	9	7.83960538691
10	8	6	7.59032814371
10	7	7	7.77289214481
6	7	10	7.73723027275
9	9	7	7.98943394733
10	6	8	7.96414902821
5	10	9	7.76644192835
9	8	7	7.69465297098
8	10	7	7.90845277544
8	9	7	7.61742822585
5	8	10	7.66414301718
5	9	10	7.94307273183
7	10	7	7.54121795069
10	5	8	7.67076926531
10	7	6	7.29770803686
10	9	5	7.40025299719
10	6	7	7.48826405647

9	7	8	7.89007095498
4	10	10	7.86550139158
9	6	8	7.59186588300
8	8	8	7.80832306699
8	7	8	7.51435155148
7	9	8	7.72705435126
7	8	8	7.43822643381
9	9	6	7.51326666505
6	10	8	7.64717454731
10	4	9	7.86162785736
6	9	8	7.36349056449
10	5	7	7.19513493008
3	10	10	7.50320015836
4	9	10	7.58637278080
5	10	8	7.29014370627
9	5	9	7.78803470565
10	3	9	7.56969272169
9	4	9	7.48994271943
9	7	7	7.41378132733
8	5	9	7.41187488222
8	6	9	7.70936261805
10	4	8	7.38555657413
9	8	6	7.21953464800
7	7	9	7.62674805734
6	8	9	7.54581569628
7	6	9	7.33548938647
6	7	9	7.26078610153
9	6	7	7.11631210184
9	10	5	7.32240886228
5	8	9	7.18776507776
5	9	9	7.46656565256
9	5	8	7.31179693029
10	3	8	7.09343096164
10	2	10	7.75927122389
8	10	6	7.43278628372
8	8	7	7.33231288129
4	10	9	7.38899783295
9	3	10	7.68569094600
10	1	10	7.46998692196
8	4	10	7.61144449274
9	2	10	7.38939040450
3	10	9	7.02650790318
4	9	9	7.10990675059
7	5	10	7.52772723076
8	3	10	7.31062654566

8	7	7	7.03877460233
6	6	10	7.44584264387
7	4	10	7.23369536638
8	9	6	7.14221474196
9	4	8	7.01369422436
5	7	10	7.36579077345
6	5	10	7.15859690371
10	2	9	7.28281184138
4	8	10	7.28757159937
5	6	10	7.08533113254
7	9	7	7.25130133767
3	9	10	7.21118511645
4	7	10	7.01241285943
8	5	8	6.93562807566
8	6	8	7.23305163082
2	10	10	7.13663129651
3	8	10	6.92814325005
1	10	10	6.76548796540
2	9	10	6.84583496043
7	8	7	6.96252259457
9	3	9	7.20929089967
10	1	9	6.99322500732
9	1	10	7.10691395785
7	7	8	7.15047004757
7	10	6	7.06574835986
6	8	8	7.06955908751
7	6	8	6.85923269195
8	4	9	7.13506063903
9	2	9	6.91251123510
6	10	7	7.17157498449
8	1	10	6.73345752630
8	2	10	7.03493622750
10	8	5	7.11441320636
6	7	8	6.78450794256
10	10	4	7.18788539677
5	8	8	6.71145387787
5	9	8	6.99031886829
7	5	9	7.05109411213
8	3	9	6.83370764656
10	9	4	6.92507367033
7	2	10	6.65586743313
7	3	10	6.95298291475
6	9	7	6.88755611339
4	10	8	6.91274929673
9	10	4	6.84723587821

6	6	9	6.96903778537
7	4	9	6.75681426273
10	7	5	6.82272969127
6	4	10	6.87009170709
9	9	5	7.03712918327
10	8	4	6.63847780664
9	8	5	6.74463384370
8	10	5	6.95723922861
10	6	6	7.01251816733
5	7	9	6.88889170024
6	5	9	6.68183112061
8	9	5	6.66720171864
5	10	7	6.81387492074
6	3	10	6.58023865611
10	10	3	6.71155209649
7	10	5	6.59043335706
3	10	8	6.54993096930
4	9	8	6.63348326396
5	5	10	6.78916182213
4	8	9	6.81065583654
5	6	9	6.60875819512
10	6	5	6.53687738512
3	9	9	6.73433018910
4	7	9	6.53602670831
10	5	6	6.71986243387
10	7	4	6.34779453226
4	6	10	6.71019330510
5	4	10	6.50657120325
9	7	6	6.93750527230
9	6	6	6.64116184491
2	10	9	6.65991472981
3	8	9	6.45130800705
8	8	6	6.85646998550
8	7	6	6.56358916507
10	4	7	6.90970149178
7	9	6	6.77584873538
7	8	6	6.48714455730
9	5	7	6.83563833943
10	3	7	6.61748337705
6	10	6	6.69635525720
4	5	10	6.43486510272
9	4	7	6.53781781450
6	9	6	6.41182805702
1	10	9	6.28816454519
2	9	9	6.36868729439

8	5	7	6.45976064705
8	6	7	6.75683973149
5	10	6	6.33763942489
10	5	5	6.24493491669
3	7	10	6.63318612334
7	7	7	6.67443522631
9	9	4	6.56099803959
6	8	7	6.59363915091
7	6	7	6.38331205112
10	2	8	6.80654127052
10	4	6	6.43409389922
10	9	3	6.44962348821
6	7	7	6.30847189601
3	6	10	6.35381019347
9	3	8	6.73299072838
10	1	8	6.51660082523
5	8	7	6.23524023211
5	9	7	6.51445162281
8	4	8	6.65869289330
9	2	8	6.43580752685
4	10	7	6.43687254891
9	7	5	6.46123938642
7	5	8	6.57455728973
8	3	8	6.35697700210
3	10	7	6.07356049800
4	9	7	6.15713621892
6	6	8	6.49238447627
7	4	8	6.28010927205
5	7	8	6.41217449443
6	5	8	6.20520437371
10	2	7	6.33054601713
4	8	8	6.33392732401
5	6	8	6.13226228198
2	7	10	6.27063896309
2	8	10	6.55814025021
3	9	8	6.25764295981
4	7	8	6.05964288265
9	8	4	6.26977868714
2	10	8	6.18332137380
3	8	8	5.97449513143
9	5	6	6.35957009207
10	3	6	6.14195313691
9	6	5	6.16639633925
1	10	8	5.81088527367
2	9	8	5.89157593681

9	3	7	6.25683635946
10	1	7	6.04022314042
9	1	8	6.15373532280
9	1	9	6.63027561131
1	8	10	6.18948228523
1	9	10	6.48505570764
8	8	5	6.38078652256
8	1	9	6.25610177795
8	2	9	6.55854521162
7	2	9	6.17852803393
7	3	9	6.47626686655
9	4	6	6.06243579490
9	10	3	6.37179053776
8	10	4	6.48171728281
6	4	9	6.39302261847
8	7	5	6.08877705059
8	4	7	6.18235435786
9	2	7	5.95941769973
6	3	9	6.10305227501
5	5	9	6.31187636207
4	6	9	6.23282814261
5	4	9	6.02967450928
7	1	10	6.37891657582
4	5	9	5.95839476472
6	2	10	6.29514661377
3	7	9	6.15587792729
3	6	9	5.87699034962
5	3	10	6.21339122101
8	5	6	5.98439734400
8	6	6	6.28075908923
2	7	9	5.79331856458
2	8	9	6.08102568955
4	4	10	6.13365038084
7	9	5	6.30068252283
8	1	8	5.77879161926
8	2	8	6.08217271733
3	5	10	6.05592411892
2	6	10	5.98021241951
1	8	9	5.71184993667
1	9	9	6.00827145133
7	5	7	6.09819294221
8	3	7	5.88058306043
1	7	10	5.90651527820
6	1	10	6.00250316139
7	7	6	6.19872332466

8	9	4	6.19223076974
7	8	5	6.01207721357
7	1	9	5.90228184960
6	8	6	6.11816648601
7	6	6	5.90783796058
7	2	8	5.70123348922
7	3	8	5.99956786650
6	6	7	6.01600234445
7	4	7	5.80371924363
6	10	5	6.22149767617
10	10	2	6.23521872378
6	4	8	5.91598633224
10	8	3	6.16244895456
6	7	6	5.83275751388
7	10	4	6.11515082085
10	9	2	5.97367629213
5	2	10	5.92820728185
5	7	7	5.93578260610
6	5	7	5.72882628633
9	10	2	5.89584546635
6	3	8	5.62590391242
6	2	9	5.81795528048
6	9	5	5.93629686438
4	6	8	5.75550898842
5	4	8	5.55280289697
5	5	8	5.83463335778
4	8	7	5.85753370696
5	6	7	5.65590416342
5	8	6	5.75915605437
5	9	6	6.03908869046
10	7	3	5.87263348845
5	1	10	5.63856646487
4	5	8	5.48193047073
10	8	2	5.68624875881
9	9	3	6.08483416842
3	9	7	5.78125564182
4	7	7	5.58326835476
3	4	10	5.78001462268
4	2	10	5.55815195394
4	3	10	5.85592598035
3	7	8	5.67861319126
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3	6	1	2.06710064236
1	4	5	2.64876043298
4	1	4	2.41299198358
2	1	6	2.69004117760
1	2	6	2.68091516451
1	1	6	2.64712331310
1	3	5	2.36009080942
3	5	2	2.24360681775
2	7	1	1.98422825987
2	8	1	2.27607468737
5	1	3	2.29166967546
1	1	5	2.16306678349
1	2	5	2.20222222444
2	1	5	2.21279675800
1	8	1	1.90325782386
1	9	1	2.20090397242
2	6	2	2.16812896489
4	3	3	2.51992860923
4	2	3	2.20844576707
1	7	2	2.09488863124
3	4	3	2.44280265891
7	1	1	2.09209650276
3	2	4	2.34828259135
3	3	3	2.12931495859
6	2	1	2.00865885457
2	5	3	2.35260903680
6	1	2	2.19032692380
5	3	1	1.92712316958
4	4	1	1.84748943112
2	4	3	2.05427724905
3	1	4	2.02853597246
3	5	1	1.76975766483
2	6	1	1.69392785500

5	2	2	2.11642158917
1	6	3	2.26650851771
1	7	1	1.61999999722
5	1	2	1.81633328981
6	1	1	1.71626545871
4	3	2	2.04475379367
2	3	4	2.25632979938
4	2	2	1.73333231720
1	5	3	1.98333263365
3	4	2	1.96669774423
2	2	4	1.95202450562
3	3	2	1.65425543826
2	5	2	1.87701484249
4	1	3	1.93592155178
2	4	2	1.57910265206
1	4	4	2.16847654932
1	6	2	1.79125603754
5	2	1	1.64177232858
3	2	3	1.87194664195
1	5	2	1.50787395388
1	3	4	1.87970938154
3	1	3	1.54585637791
5	1	1	1.34181018928
2	3	3	1.77715187870
4	1	2	1.46016208878
4	3	1	1.56918117045
2	2	3	1.46960844465
1	4	3	1.68728607544
2	1	4	1.73527904543
1	1	4	1.67669350170
1	2	4	1.72282147222
4	2	1	1.25921401772
1	3	3	1.39839897402
3	4	1	1.49077917566
3	3	1	1.18023506571
2	5	1	1.40202362151
1	1	3	1.18779319981
1	2	3	1.24264865688
2	1	3	1.25746322307
2	4	1	1.10487333250
3	2	2	1.39561531135
1	6	1	1.31688529008
1	5	1	1.03312881342
3	1	2	1.06300794946
2	3	2	1.29789827624

4	1	1	0.98487080231
2	2	2	0.98703056198
1	4	2	1.20596638073
3	2	1	0.91928565702
1	3	2	0.91695616013
3	1	1	0.58086171979
1	2	2	0.76284106248
2	1	2	0.77978841901
1	1	2	0.70008829765
2	3	1	0.81895943139
2	2	1	0.50512572239
1	4	1	0.72518412038
1	3	1	0.43606405915
2	1	1	0.30564266254
1	2	1	0.29217331070
1	1	1	0.24229892070

APPENDIX D: List of FMEA Team Opinions at Scoring

Table A.2: FMEA team scores

Failure Sequence No.	S1	S2	S3	Aggreg. Fuzzy S	O1	O2	O3	Aggreg. Fuzzy O	D1	D2	D3	Aggreg. Fuzzy D	Aggreg. Fuzzy RPN
1	6	5	4	4.6	5	4	3	3.3340	2	1	1	0.336343	1.815302
2	7	6	5	5.6	4	3	2	1.7111	4	3	2	1.711160	2.033439
3	8	7	6	6.60475646	3	2	1	0.77714726	6	5	4	4.6	3.411443
4	10	9	8	8.93573758	3	2	1	0.77714726	4	3	2	1.711160	2.854185
5	10	10	9	9.59706975	5	4	3	3.33403664	6	5	4	4.6	5.426537
6	10	10	9	9.59706975	4	3	2	1.71116016	3	2	1	0.777147	2.973222
7	7	6	5	5.6	3	2	1	0.77714726	2	1	1	0.336343	1.553784
8	8	7	6	6.60475646	5	4	3	3.33403664	4	3	2	1.711160	2.747357
9	7	6	5	5.6	4	3	2	1.71116016	3	2	1	0.777147	1.802730
10	5	4	3	3.33403664	3	2	1	0.77714726	5	4	3	3.334036	1.609658
11	9	8	7	7.66759674	8	7	6	6.60475646	7	6	5	5.6	6.165889
12	7	6	5	5.6	5	4	3	3.33403664	7	6	5	5.6	4.576554
13	7	6	5	5.6	3	2	1	0.77714726	9	8	7	7.667596	4.907181
14	6	5	4	4.6	4	3	2	1.71116016	4	3	2	1.711160	1.417736
15	10	10	9	9.59706975	4	3	2	1.71116016	10	9	8	8.935737	6.929761
16	10	9	8	8.93573758	4	3	2	1.71116016	5	4	3	3.334036	4.062231
17	6	5	4	4.6	5	4	3	3.33403664	2	1	1	0.336343	1.815302
18	7	6	5	5.6	4	3	2	1.71116016	4	3	2	1.711160	2.033439
19	8	7	6	6.60475646	3	2	1	0.77714726	6	5	4	4.6	3.41144373
20	7	6	5	5.6	6	5	4	4.6	7	6	5	5.6	4.94583333
21	8	7	6	6.60475646	10	10	9	9.59706975	6	5	4	4.6	6.02678913
22	8	7	6	6.60475646	4	3	2	1.71116016	3	2	1	0.777147	1.88342854
23	8	7	6	6.60475646	3	2	1	0.77714726	6	5	4	4.6	3.41144373
24	6	5	4	4.6	4	3	2	1.71116016	4	3	2	1.711160	1.41773672
25	10	10	9	9.59706975	2	1	1	0.33634368	5	4	3	3.334036	4.01422922
26	8	7	6	6.60475646	7	6	5	5.6	2	1	1	0.336343	2.99249562
27	4	3	2	1.71116016	2	1	1	0.33634368	4	3	2	1.711160	0.55148272
28	5	4	3	3.33403664	3	2	1	0.77714726	5	4	3	3.334036	1.60965811
29	6	5	4	4.6	8	7	6	6.60475646	4	3	2	1.711160	3.12514299

30	6	5	4	4.6	6	5	4	4.6	6	5	4	4.6	4.00573473
31	7	6	5	5.6	4	3	2	1.71116016	6	5	4	4.6	3.34963707
32	6	5	4	4.6	3	2	1	0.77714726	2	1	1	0.336343	1.23010450
33	9	8	7	7.66759674	3	2	1	0.77714726	4	3	2	1.711160	2.52798038
34	9	8	7	7.66759674	4	3	2	1.71116016	3	2	1	0.777147	2.28653280
35	8	7	6	6.60475646	8	7	6	6.60475646	2	1	1	0.336343	3.49068016
36	7	6	5	5.6	5	4	3	3.33403664	4	3	2	1.711160	2.43782473
37	6	5	4	4.6	6	5	4	4.6	2	1	1	0.336343	2.19866123
38	4	3	2	1.71116016	5	4	3	3.33403664	2	1	1	0.336343	0.5927729
39	5	4	3	3.33403664	4	3	2	1.71116016	3	2	1	0.777147	0.95394065
40	5	4	3	3.33403664	7	6	5	5.6	4	3	2	1.711160	2.35178513
41	4	3	2	1.71116016	3	2	1	0.77714726	2	1	1	0.336343	0.33649963
42	4	3	2	1.71116016	3	2	1	0.77714726	4	3	2	1.71116016	0.55492936
43	6	5	4	4.6	5	4	3	3.33403664	6	5	4	4.6	3.40870405
44	6	5	4	4.6	6	5	4	4.6	7	6	5	5.6	4.58831396