DEVELOPMENT OF RISK ASSESSMENT MODEL FOR GAS TURBINE

BY

AMIR HAZWAN BIN ABD GAFAR

DISSERTATION SUBMITTED IN PARTIAL FULLFILMENT OF

THE REQUIREMENT FOR THE

BACHELOR OF ENGINEERING (HONS)

MECHANICAL ENGINEERING

SEPTEMBER 2013

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh, Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Development of Risk Assessment Model for Gas Turbine

by

Amir Hazwan bin Abd Gafar

A Project Dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(MOHD AMIN BIN ABD MAJID)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH PERAK

JANUARY 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project that the original work is my own except as specified in the references and acknowledgement, and that their original work contained herein have not been undertaken or done by unspecified sources or persons.

____

(AMIR HAZWAN BIN ABD GAFAR)

ABSTRACT

Gas turbines are in operation around the world, used by many industries such as petrochemical, power generation, and oil and gas industries. Thus the safety of operating gas turbine is very crucial and is heavily concerned. Failure of gas turbine especially in those industries can result to risk related issues. An effective risk assessment model is required to assess failures associated with gas turbine and to achieve plant availability and efficiency. This study presents the development of a risk assessment model for gas turbine. The project is developed to assist and to help operators of gas turbine in determining the risk level of failures associated with the gas turbine. Several studies related to the project topic are carried out from journals and books available. A comprehensive literature research is conducted which consist of how to develop a risk assessment model, the overview of a gas turbine, getting familiarize with semi-quantitative risk assessment matrix method and Borda method. In this research risk matrix is proposed where it is a method to analyze risk by estimating failure probability and its consequences and categorize their associated failure risks. An input data for FMEA of a gas turbine used to drive electricity system has been adapted to determine each of the risks probability and consequence. For this project, the author has contributed by incorporating Borda method to risk ranking matrix. The Borda method helps to analyze the risk level more accurate than original risk matrix. Borda ranking method is also adapted to minimize the risk ties that exist in risk matrix. The sample of validated historical data of gas turbine system from the input data is used to help and justified the risk level for each failures associated. The results of the failure risks are then analyzed using risk ranking method and Borda method. The study has shown that risks of failure modes of gas turbine system are categorized in high, serious and medium levels based on risk matrix. There are five medium risks which are rotor out of balance, high temperature, high vibration, tip rub and foreign object damage. According to Borda ranking method, rotor out of balance, tip rub and foreign object were found needed more attention than high temperature and high vibration.

ACKNOWLEDGEMENT

This dissertation would not have been possible done without the guidance and helps of several individuals who in directly or indirectly contributed and lend their valuable assistance in the preparation and completion of this final year project.

First, I would like to express my utmost gratitude to Ir. Dr. Mohd Amin Abd Majid, my supervisor for this project. Without his guidance I will never be able to complete the project up to this level. He has been my inspiration as to accept and face all the findings, and new learning also the obstacles in the completion of this research project.

Last but not the least, my family and the one above all of us, God, for answering my prayers for giving me the strength to continue and do not give up in completing this project. Alhamdulillah.

TABLE OF CONTENT

CERTIFICATION OF APPROVAL	ii
CERTIFICATION OF ORIGINALITY	iii
ABSTRACT	1
ACKNOWLEDGEMENT	2
TABLE OF CONTENTS	3
LIST OF FIGURES AND TABLES	4
CHAPTER 1: INTRODUCTION	7
1.1 Background of Study	7
1.2 Problem Statement	7
1.3 Objectives	8
1.4 Scope of Study	8
1.5 Significance of the Project	8
CHAPTER 2: LITERATURE REVIEW	9
2.1 Introduction	9
2.2 Analysis of Risk	9
2.2 Development of a Risk Assessment Model	11
2.3 Risk Matrix Method	12
2.4 Borda Ranking Method	14
2.5 Overview of a Gas Turbine	15
2.6 Common Failures in Gas Turbine System	17
2.5 Conclusion	19

CHAPTER 3: METHODOLOGY 20

3.1 Introduction 20

3.2 Research Methodology 20

3.3 Project Activities 26

3.4 Key Milestone 27

3.5 Tools 28

3.6 Gantt Chart 29

CHAPTER 4: RESULTS AND DISCUSSIONS 31

4.1 Analysis of Failures 31

4.2 Risk Ranking using Risk Matrix 32

4.3 Risk Ranking using Borda Method 39

CHAPTER 5: CONCLUSION AND RECOMMENDATION 43

REFERENCES 44

LIST OF FIGURES AND TABLES

Figure 1: Structure of risk analysis 10

Figure 2: Principle of RAM 11

Figure 3: Original risk matrix 12

Figure 4: Example of a risk matrix 13

Figure 5: Example of a gas turbine 15

Figure 6: Gas turbine system is divided into three sections; compressor, turbine and combustion chamber 15

Figure 7: Functional tree of gas turbine 17

Figure 8: Flowchart of methodology 20

Figure 9: Risk level of overspeed 33

Figure 10: Risk level of rotor out of balance 33

Figure 11: Risk level of rotor bend distortion 34

Figure 12: Risk level of high temperature 34

Figure 13: Risk level of high vibration 35

Figure 14: Risk level of tip rub 35

Figure 15: Risk level of blade failure or inlet guide vane 36

Figure 16: Risk level of thrust bearing failure 36

Figure 17: Risk level of radial bearing failure 37

Figure 18: Risk level of foreign object damage 37

Figure 19: Risk level of explosion in combustion chamber 38

Figure 20: Risk level of failure of refractory lining 38

Table 1: Failure modes of gas turbine system 19

Table 2: Failure modes of a gas turbine system from a case study 21

Table 3: Failure rate range scale 23

Table 4: Failure consequence scale 23

Table 5: Semi-quantitative risk assessment matrix 24

Table 6: Semi-quantitative risk assessment matrix values 24

Table 7: Failure consequence range scale values 25

Table 8: Failure rate range scale values 25

Table 9: Example data to demonstrate Borda method 26

Table 10: Project activities of the project 26

Table 11: Key milestone in FYP1 27

Table 12: Key milestone in FYP2 28

Table 13: Failure modes of gas turbine with assigned probabilities and consequences scale. 32

Table 14: Risk ranking using Risk matrix and Borda method 42

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Risk assessment is the process mechanism to identify hazards, analyze and evaluate the risk associated with that hazard. To determine the appropriate ways to eliminate or control the hazard, there are various ways that we can approach to do the risk assessment. There are lots of risk assessment models are ready made for instances, Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode and Effect Analysis (FMEA), Risk Matrix and etc. Different model has different approach. FMEA for example assumes a failure mode occurs in a system/component through some failure mechanism; the effect of this failure on the other systems is then evaluated [11].

For this project, the approach used to do the risk assessment is risk matrix. A risk matrix approach is a semi-quantitative way of evaluating risk. In order to develop the risk assessment matrix, failure probabilities scale and its consequences scale are developed. After the scales are determined, the semi-quantitative risk assessment matrix 5 by 4 that is taken from Standard Practice for System Safety [17] is applied. The risk level are divided into four categories Low, Medium, Serious and High. However, there are still risk ties existed in the risk matrix. Thus in this research Borda method has been introduced to the model. Borda ranking method helps to minimize risk ties and produces more accurate result of categorizing the risk level [19]. A collection of statistic data of failures in a gas turbine system are then adapted from a case study [18]. The data is the FMEA analysis of gas turbine system that listed every failures probabilities and consequences.

1.2 Problem Statement

Modern gas turbine engines are generally considered to exhibit a high level of hazards and failure rates. Fire and explosion hazards in offshore gas turbines is one of the example of hazards [7]. Failure modes usually happen in the critical component of gas turbine system like blades, nozzle and compressor [14]. Therefore, risk assessment of the failure modes in a gas turbine system is crucial to estimate and categorize the failure risks into certain risk levels. Thus reducing the possibility of failure risks as much as possible. In this project, the author will focus on developing a risk assessment model particularly to determine the risk level of failure modes in a gas turbine system.

1.3 Objectives

The objective of this research is to develop a semi-quantitative risk assessment matrix of a gas turbine used to drive an offshore electricity generating system.

1.4 Scope of Study

The scope of the project covers the following:

i. Main components of gas turbine system, which are compressor, turbine and combustion chamber that are critical and usually exposed to failures.
ii. Input data for the FMECA of a gas turbine system used to drive an offshore electricity generating system is adapted [18].
iii. Semi-quantitative risk analysis that combines both advantages qualitative and quantitative analysis [16].
iv. Borda method that is usually used in voting count is applied to minimize the risk ties exist in risk matrix [21].

1.5 Significance of the Project

The project is significant to assist the small gas turbines operators to evaluate the turbine risks level.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review covers the important elements and foundation of this project research. Few articles and journals that are related to this project are summarized into five reviews which consist of analysis of risk, development of risk assessment model, risk matrix method, Borda method, overview of a gas turbine and common failures in gas turbine system.

2.2 Analysis of Risk

There are many types of explanations about risk in literature. Risk used to mean the danger like being bitten by a beast or infected by a disease in the long past [15]. Then risk was researched and more elaborated descriptions were developed. For example, Rosenbloom [25] defines risk as the uncertainty of loss. Williams and Heins [27] defines risk as the alteration of future results under a given circumstance in a specific period. Wang [26] defines risk as the possibility of unfavourable results and the related loss of a chosen decision plan due to various uncertainties in the decision making process. Furthermore, the standard definition of risk provided by ISO 2002 is the combination of the probability of an event and its consequence. This definition has also been agreed by Dieter [5] where risk is defined as the product of likelihood of occurrence and the impact severity of occurrence of the event. In a simple equation, risk can be concluded as;

$$Risk\ \left(\frac{Consequence}{Time}\right) = Likelihood\left(\frac{Event}{Time}\right) \times Impact\left(\frac{Consequence}{Event}\right)$$

There are three basic components of a risk [15]:

1. Risk factor refers to the conditions leading to the potential loss.

2. Loss means all kinds of unexpected loss, including casualty and financial cost caused by risk.

3. Incident may be the key component as the direct reason which changes potential loss to actual loss.

The author believes that risk is one of the most important criteria that needs to be highlighted at every workplace where most hazards existed. Therefore, risk has to be studied in order to reduce its probability and consequence of each event. Yerevan [13] stated in his journal that the structure of Risk Analysis is categorized into three parts which are Risk Assessment, Risk Management and Risk Communication.

For this development of risk assessment model project, as per title, the author will only focus on Risk Assessment. Figure 1 shows the risk assessment has four components assigned to it which are:

i. Hazard identification
ii. Hazard characterization
iii. Exposure assessment
iv. Risk characterization

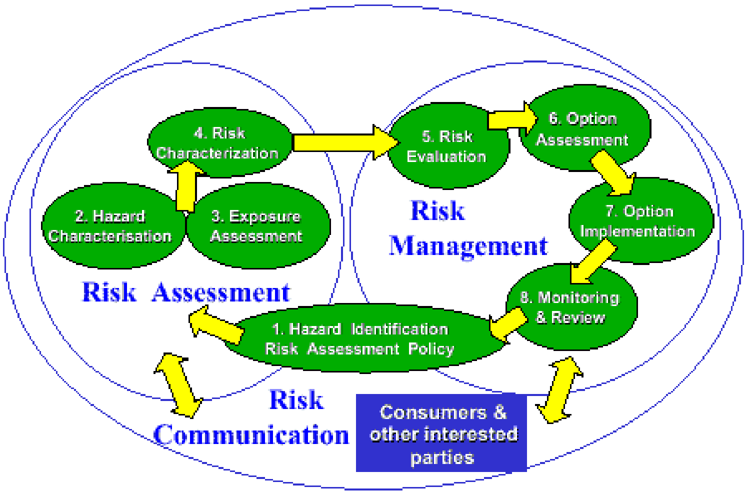


Figure 1. Structure of Risk Analysis. Source: [13]

2.3 Development of Risk Assessment Model

A risk assessment model (RAM) is developed to assist the safety professionals' risk assessment work and to help staffs, specifically the gas turbine operators to understand risks existing in their works. The RAM can provide analysis methods to analyze the historical data and later evaluate and categorize risks based on risk levels [1]. The risk levels of different work trades prioritized by the RAM provide important information for safety professionals for carrying out a reliable risk assessment. The general principle of the RAM can be shown in Figure 2.

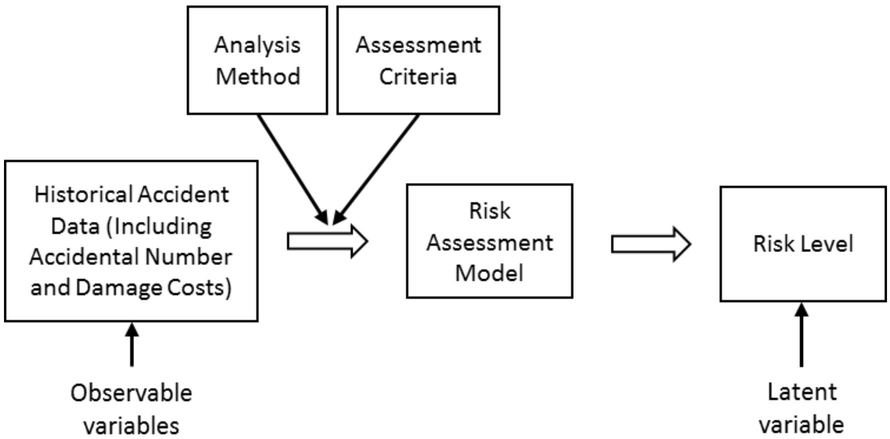


Figure 2. Principle of RAM. Source: [6]

There are lots of approaches to do risk assessment for examples, which are Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode and Effect Analysis (FMEA), and Risk Matrix. Each approach uses different kind of method and thus result in different risk categorization.

Mainly, there are three ways to execute a risk assessment, specifically, qualitative way, semi-quantitative way and quantitative way. Quantitative method depends on probabilistic and statistic and databases. Meanwhile qualitative analysis method uses judgment and sometimes "expert" opinion to evaluate the probability and consequences [10]. Meanwhile the semi-quantitative way combines both advantages of qualitative and quantitative, hence is widely applied in many kinds of assessment problems. In risk management, risk matrix approach (RMA) is a typical semi-quantitative assessment tool to evaluate various kinds of risks based on historically statistic data [15]. Though it is not as accurate as quantitative analysis and lack of meticulous mathematical basis, the criteria of graphical expression, easy to understand and easy to apply still make it well received in manufacture, service and other industries. Moreover, various forms and standards of RMA such as MIL-STD-882D [17] from US Department of Defense are continuously developed.

2.4 Risk Matrix Method

Risk assessment matrix is a classic tool to perform semi-quantitative risk assessment [12]. There are various type of risk assessment matrix. Some of the risk matrix are 3 by 3, 4 by 4, 5 by 5, and 7 + 7 [23]. Meanwhile Souza showed in his book that he uses 6 by 6 risk matrix as shown in Figure 4 [11]. The risk matrix cells can in form of alphabetical or numerical. For alphabetical ones, commonly Low (L), Medium (M) and High (H) are used. As for the numerical ones, the number range depends on the scaling of the probability and consequence. The original risk matrix (ORM) as in Figure 3 is widely used around the world. Lots of companies realizes the importance for risk assessment, but usually they do not have the tools, experience and resources to assess risk quantitatively [9]. Thus, they use qualitative, quantitative or semi quantitative risk assessment tools, such as risk ranking which is quite easy to develop.

Critical	M	H	H	H	H
Serious	M	M	M	H	H
Moderate	L	M	M	M	H
Minor	L	L	M	M	H
Negligible	L	L	L	M	M
Origin	0.00~0.10	0.10~0.40	0.40~0.60	0.60~0.90	0.90~1.00

Figure 3. Original risk matrix. Source: [15]

Many organizations acknowledge risk matrix is easy to use. However, not many concern that the risk matrix needs to be designed precisely. If not, the risk matrix may produce liability issues and give the wrong sense of security. According to Ozog, an effective risk ranking matrix should have the following attributes [10]:

- Be simple to use and understand
- Not require extensive knowledge of quantitative risk analysis to use
- Have consistent probability ranges that cover the full spectrum of potential scenarios

• Have detailed descriptions of the consequences of concern for each consequence range

• Have clearly defined tolerable and intolerable risk levels

• Show how scenarios that are at an intolerable risk level can be mitigated to a tolerable risk level on the matrix

• Provide clear guidance on what action is necessary to mitigate scenarios with intolerable risk levels

2.4.1 Basic Rules of Risk Matrix

To produce a risk matrix, some basic rules should be followed [14]:

1. The risk matrix is the standard definition of risk as a combination of severity of the consequences and its probability. Meaning that only two input variables are required to construct a risk matrix. The output risk level is determined only by the severity of the consequences and its probability.

2. The severity of consequences, probability and output risk level can be divided into different levels, respectively, with qualitative descriptions and scales.

3. The calculation step of risk matrix is presented by the logic implication as: if probability is P and severity of consequence is C, then risk is R [14].

Probability Category	A	L	M	M	H	H	H
	B	L	L	M	M	H	H
	C	L	L	L	M	M	H
	D	L	L	L	L	M	M
	E	L	L	L	L	L	M
	F	L	L	L	L	L	L
		VI	V	IV	III	II	I
	Consequence Category						

Figure 4. Example of a risk matrix. Source: [11]

2.5 Borda Ranking Method

Once a risk matrix is developed with complete output of risk levels consist of Low, Medium and High, there is a critical argument: Which risk is most critical? [19] As shown in Figure 3 and Figure 4, they only support three distinct ratings (Low, Medium and High). In such risk matrix, there are many risk ties exist. Hence to solve the problem with risk ties, a famous voting theory is incorporated into risk matrix, namely the Borda method.

Borda method is a famous ranking method that assigns scores according to the positions of the item in the ranked lists [21]. Lamboray also explained Borda's well-known rule orders the alternatives according to their sums of ranks they occupy in the profile [20]. Introducing Borda method (BM) [22] to risk matrix has significantly reduced the number of risk ties because of its quantitative calculation. This method helps to rank risks from most critical to least critical on the basis of multiple evaluation criteria [21].

To apply Borda method into the risk matrix approach, the following variables are defined.

N: The number of risk to be evaluated.
k: The evaluation criteria (severity, probability).
r_{ik}: The number of risk with a higher level than risk i under evaluation criterion k.
b_i: The Borda index for risk i.

So the Borda index for each risk can be computed by the following formula.

$$b_i = \sum_k (N - r_{ik}) \qquad \text{(Equation 1)}$$

The risks are then ordered according to the b_i counts. If ties are present in the criteria rankings, the r_{ik} are adjusted by evaluating the rank for a tied alternatives as the arithmetic average of the associated rankings.

2.3 Overview of a Gas Turbine

A gas turbine is a complex system with lots of rotary and stationary parts is used for generating electric power. The gas turbine is quite new in the history of energy conversion. The first practical gas turbine used to generate electricity ran at Neuchafel, Switzerland in 1939 and was developed by the Brown Boveri Company [8].

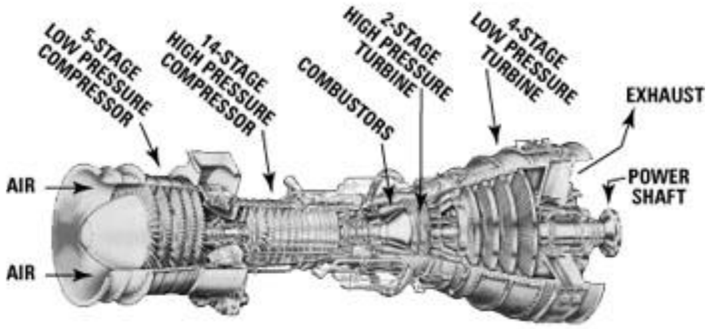


Figure 5. Example of a Gas Turbine. Source: [2]

In a gas turbine unit, the inlet ambient air is compressed by passing through several stages of stationary and rotary blades and can then be used both in the combustion chamber and for cooling purposes. The compressed air that enters the combustion chamber is mixed with fuel and is ignited to provide a high pressure, high velocity, and high temperature gas flow that is able to drive the turbine shaft at high rotary speeds [2]. However, due to the precise design conditions of gas turbine units and the high rotary speeds at which they operate, the malfunction of one component can lead to severe damage to the entire unit. In between, the rotary and stationary parts of the turbine section, such as blades and disks, are more prone to failure because they work in a corrosive environment under a high temperature gas flow with a high pressure gradient [3].

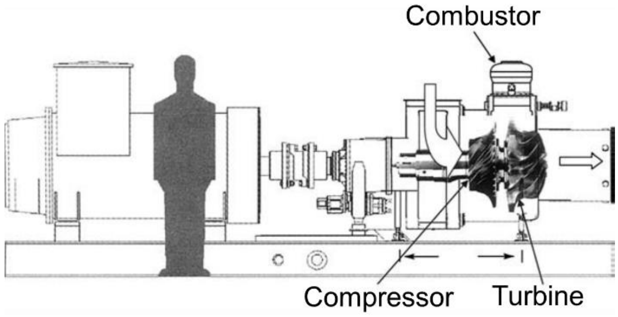


Figure 6. Gas turbine system is divided into three sections; compressor, turbine and combustion chamber. Source: [2]

The reason why gas turbine is very practical and being used by many companies is because it has lots of advantages. Some of the principle advantages of the gas turbine are because it can produce large amounts of useful power for a relatively small size and weight. Since motion of all its major components involve pure rotation (i.e. no reciprocating motion as in a piston engine), its mechanical life is long and the corresponding maintenance cost is relatively low. Even though the gas turbine must be started by some external means (a small external motor or other source, such as another gas turbine), it can be brought up to full-load (peak output) conditions in minutes as contrasted to a steam turbine plant whose start up time is measured in hours. A wide variety of fuels can be utilized. Natural gas is commonly used in land-based gas turbines while light distillate (kerosene-like) oils power aircraft gas turbines. Diesel oil or specially treated residual oils can also be used, as well as combustible gases derived from blast furnaces, refineries and the gasification of solid fuels such as coal, wood chips and bagasse. The usual working fluid is atmospheric air. As a basic power supply, the gas turbine requires no coolant (e.g. water).

Figure 7 shows is the functional tree of a gas turbine where it listed down the main systems and components of a gas turbine system. The equipment is divided into five main subsystems: trunnion support, compressor, combustors, power turbine and start/stop subsystem [11]. Those main subsystems are divided into more detailed components, each one performing a specific function.

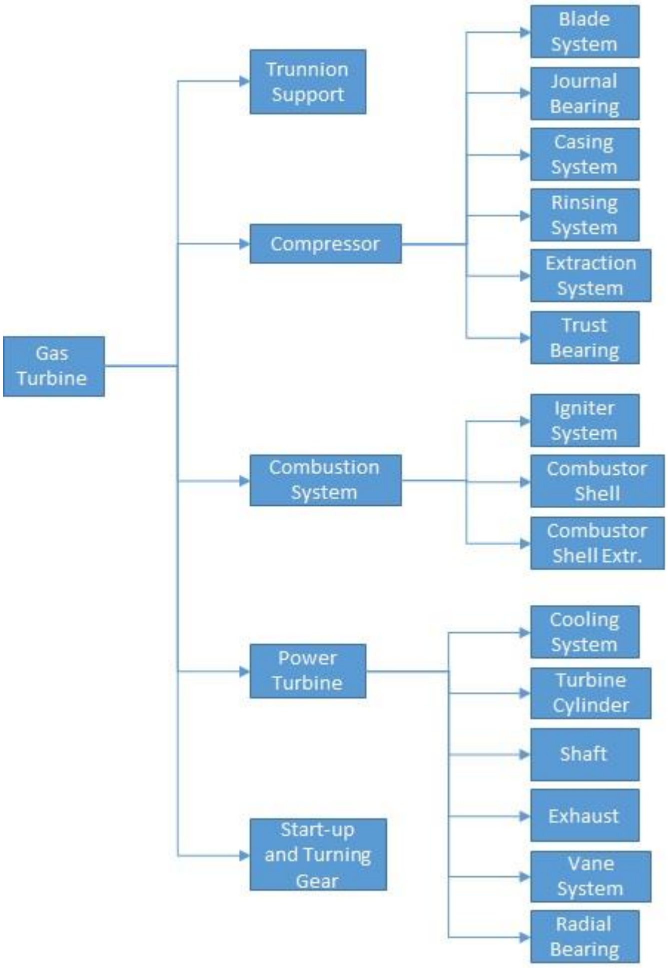


Figure 7. Functional Tree of Gas Turbine. Source: [11]

2.6 Common Failures in Gas Turbine System

Common failures in the gas turbine system were studied by different authors, with the aim of preventing future failures by improving the mechanical design, designing new materials, or proposing guidelines for better maintenance and utilization of gas turbine units. The failure mechanism of the gas turbine due to damage in turbine disks or blades is studied in by using visual inspection, macro and micro fractography, and numerical mechanical analyses. In these studies, the fatigue fracture, existence of region with high stress levels, creep, foreign object damage, and material degradation due to surface erosion were identified as the main failure mechanisms.

The common failure modes of a general gas turbine can be classified as follows, shown in Table 1 [14]:

Table 1. Failure modes of gas turbine system [14]

Component	Element	Failure modes
Compressor	Rotor blades	Fatigue, erosion, foreign object
	Rotor (disk)	Fatigue, creep
Turbine	Rotor blades	Creep, fatigue, corrosion, erosion
	Rotor (disk)	Creep, rupture, fatigue
	Stators	Creep, fatigue, corrosion, erosion, buckling
Combustion chamber	Linear	Fatigue, creep, buckling
	Casing	Fatigue

2.6.1 Foreign object damage (FOD)

Foreign object damage is caused by the intake of huge objects into the flow direction. These happened due to the internal pieces were broken in the components.

2.6.2 Creep

Creep is the tendency of a solid material to slowly move or deform permanently under the influence of stresses. It was the result of long time exposure to high levels of stress that are below the yield strength of the material. Creep is more critical in materials that are exposed to heat for long term, and near melting point. Creep always increases with temperature.

2.6.3 Fouling

Fouling is present in compressor and turbine component. In compressor, fouling is caused by submission of peculiar contaminants to airfoil and annulus surfaces. Meanwhile in turbine, the ash adherence on the turbine blade surfaces has caused the fouling. Fouling altered the shape of blade and elevated surface roughness that decreased mass flow, power output and efficiency. The former investigation showed in which the reduction of 5% mass flow can affect power output to reduce 13%, so it is a severe failure mode in gas turbine.

2.6.4 Hot corrosion

Hot corrosion is an expanded oxidation caused by the existence of deposit. The deposit can contain salt contaminants, such as Na_2SO_4, NaCl, and V_2O_5. These contaminants combine to form molten deposits. But corrosion can also be enhanced by the influence of a solid or a gas. The phenomenon is obviously life limiting for turbine blade structural materials.

2.6.5 Erosion

Gas turbine engines operates in a hostile environment that is polluted with small particles are susceptible to erosion damage. Examination of a number of natural dust samples indicates that quartz is usually the most abundant erosive constituent, rarely falling below 70% by weight. Erosion is caused by the abrasive components that remove component materials from surface. This results in slight changes in shape and an increase in surface roughness, especially on the pressure side.

2.6.6 Fatigue

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material.

2.7 Conclusion of Literature Review

A comprehensive of literature reviews have been conducted after doing few researches from books, journals and websites. The project to develop a risk assessment model can be continued now as the author has grasped the basics understanding of the project.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology explains how the process of developing the risk assessment model. It includes the research methodology of the project and project activities in the given time that consists of phase 1 and phase 2.

3.2 Research Methodology

In order to achieve the objective of the research, a suitable methodology is required. Figure 8 shows the flow chart for the project where steps were defined to develop the semi-quantitative risk assessment matrix for gas turbine.

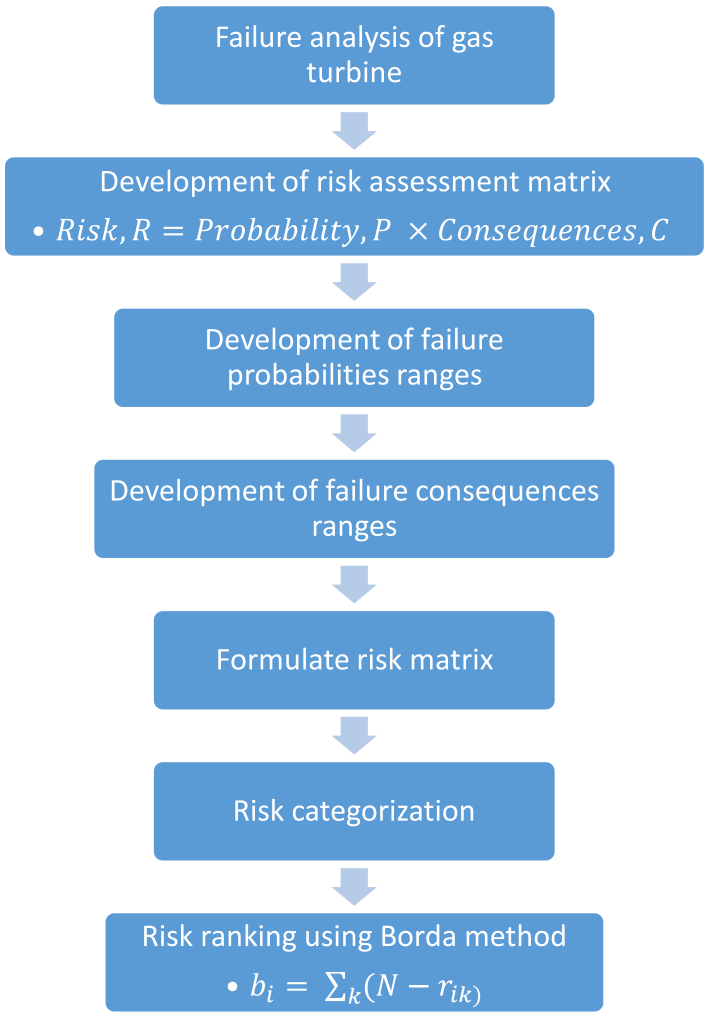


Figure 8. Flowchart of methodology

3.2.1 Failure analysis of gas turbine

First step of the risk assessment model was to analyze the failures associated to gas turbine. Well failure understanding guides to real problem reasons what causes the failure in gas turbine system. In order to analyse the failures of gas turbine system, an input data for the failure mode and effect analysis (FMEA) of a gas turbine used to drive an offshore electricity generating system had been adapted [11]. The input benefited from the combined experience of experts in gas turbine manufacturing and operating companies who were members of the Loughborough University Rotating Machinery Reliability Group. Table 2 shows failure modes of a gas turbine system that had been taken as the case study. There are total of 12 risks from the critical subsystems of the gas turbine which are compressor, turbine and combustion chamber.

Table 2. Failure modes of a gas turbine system used to drive an offshore electricity system [11].

No of risks	System	Subsystems	Failure modes
1	Gas turbine	Compressor/ turbine	Overspeed
2			Rotor out of balance
3			Rotor bend distortion
4			High temperature
5			High vibration
6			Tip rub
7			Blade failure or inlet guide vane failure
8			Thrust bearing failure
9			Radial bearing failure
10			Foreign object damage
11		Combustion chamber	Explosion in combustion chamber
12			Failure of refractory lining

3.2.2 Development of risk assessment matrix

Risk assessment matrix was developed from a quantitative risk analysis and combined with qualitative analysis. To develop semi-quantitative risk assessment matrix, some basic rules are used:

i. The risk matrix is the standard definition of risk as a combination of severity of the consequences and its probability [14]. Meaning that only two input variables are required to construct a risk matrix. The output risk level is determined only by the severity of the consequences and its probability.

ii. The severity of consequences, probability and output risk level can be divided into different levels, respectively, with qualitative descriptions and scales.

iii. The calculation step of risk matrix is presented by the logic implication as: if probability is P and severity of consequence is C, then risk is R [14].

There are various type of risk assessment matrix. Some of the risk matrix are 3 by 3, 4 by 4, 5 by 5 and 7 + 7 [23]. According to MIL-STD-882D, there is also a standard practice of risk matrix for system safety [17] which is 5 by 4 matrix. For this project, the author decided to use the 5 by 4 risk matrix that has been developed by the US military because it is famous and has been widely applied as standard practice for system safety.

3.2.3 Development of failure probability ranges

After the rules of developing risk matrix had been discussed, the failure probability ranges were defined. The failure rate range scale based on the probability of failure shown in Table 3, adapted from MIL-STD-882D [17]. The scales have 5 different attributes which are Frequent, Probable, Occasional, Remote and Improbable. Each attributes have their own descriptions. Frequent was defined as greater than 1 in a year which is the highest range in the probability scales. Meanwhile, Improbable which was defined as less than 0.001 in a year being the lowest range. The scales could be further enhanced since various firms may have their own residual risk criterion.

Table 3. Failure rate range scale

Frequent	Greater than 1 in a year
Probable	Less than 1 but greater than 0.1 in a year
Occasional	Less than 0.1 but greater than 0.01 in a year
Remote	Less than 0.01 but greater than 0.001 in a year
Improbable	Less than 0.001 in a year

3.2.4 Development of failure consequences ranges

The failure consequences are categorized according to their severity of impact. The failure consequences can be based on experiences of personnel and operators of gas turbine and historical statistic data. Qualitative values are used to rank the failure risks of gas turbine. As shown in Table 4, the failure consequences of failure of gas turbine are adapted from MIL-STD-882D [17]. The consequences range scales consist of four attributes which are Catastrophic, Critical, Marginal and Negligible. Catastrophic is the most critical impact which can cause plant shutdown and may affect other system components and environment. The least critical attribute is Negligible where the impact has no effect to the performance of plant.

Table 4. Failure consequence scale

Catastrophic	Plant shutdown, and may affect other system components and environment
Critical	Plant shutdown, no other effect
Marginal	Degraded performance of plant
Negligible	No affect to performance of plant

3.2.5 Formulation of risk matrix

Risk matrix was developed after the risk parameter scales which are failure rate range scale and failure consequence range scale are defined. Table 5 shows the proposed risk assessment matrix that is adapted from MIL-STD-882D [17]. The cell which have number “1” is product of “Catastrophic” failure consequence and “Frequent” failure probability. It is also ranked as the highest risk level. Meanwhile, the cell which have number "20" is product of "Negligible" failure consequence and "Improbable" failure probability. The number "20" ranks as the lowest risk level. The case is uniform for all matrix cells from 1-20, each cell is a product of probability, P and consequence, C.

Table 5. Semi-quantitative risk assessment matrix [13]

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

3.2.6 Risk categorization

For a risk matrix, there are two types. Alphabetical mode, where L (Low), M (Medium), Serious (S) and H (High) are used to define the tolerable level of risk and numerical mode, where value of number 1 until 20 are used instead. The value helps to categorize the failures risk accordingly. Table 6 shows the different ranges of cell values to categorize failures based on combined effect of failure probability and its consequence. In this proposed risk assessment matrix, cell values from 1 to 5 shows High risk and the risk not acceptable. Values 6 to 9 are categorized as Serious where the risk is not desirable. Values 10 to 17 present failures as Medium and the risk is acceptable with review. Lastly, failures in category Low has values from 18 to 20. The Low risk is acceptable without review.

Table 6. Semi-quantitative risk assessment matrix values [13]

Risk assessment value	Failure category	Failure risk acceptance level
1 – 5	High	Not acceptable
6 – 9	Serious	Not desirable
10 – 17	Medium	Acceptable with review
18 – 20	Low	Acceptable without review

3.2.7 Risk ranking using Borda method

To determine which risk is more critical, the risk matrix is still not enough and possible as the risk matrix only separates the failure risks in four categories generally as High, Serious, Medium and Low. These four categories do not represent actual situation whereby there are many risk ties exist. In order to minimize the risk ties, Borda ranking method is employed [19]. Borda ranking method applies Equation 1 to rank failure risks. Borda method needs certain number for each failure consequence and probability category as shown in Table 7 and Table 8.

Table 7. Failure consequence range scale values

Catastrophic	Critical	Marginal	Negligible
4	3	2	1

Table 8. Failure rate range scale values

Frequent	Probable	Occasional	Remote	Improbable
5	4	3	2	1

$$b_i = \sum_k (N - r_{ik}) \qquad \text{(Equation 1)}$$

where, *N* represents the total number of risk to be evaluated, *i* is a particular risk, for criteria *k*. There are two conditions for risk matrix: $k = 1$ is representing failure consequence, C, $k = 2$ refers to failure probability, P. If the risk level is r_{ik} and *i* is within the criteria, then Equation 1 produces Borda count of risk *i*.

After the values of b_i are calculated for each risk, the values can be sorted according to the small to large order. The Borda rank for a given risk is the number of other risks that are more critical.

For example, there is a sample data as in Table 9. Risk 1 has the failure rate range of Remote (2) and failure consequence range of Catastrophic (4). For Risk 2, the failure rate range is Remote (2) and failure consequence range of Critical (3). Risk 3 has the failure rate range of Occasional (3) and failure consequence range of Critical (3). By using the risk matrix in Table 5, Risk 1 and Risk 3 ties to Serious category meanwhile

Risk 2 is categorized as Medium. To categorize the risk ties, the useful Borda method can solve the problem. The calculation should be as follows.

Table 9. Example data to demonstrate Borda method

No of risks	Failure probabilities		Failure consequences	
	Category	Scale	Category	Scale
1	Remote	2	Catastrophic	4
2	Remote	2	Critical	3
3	Occasional	3	Critical	3

Risk 1: $b_i = \sum_k (N - r_{ik)} = (3-1) + (3-0) = 5$

Risk 2: $b_i = \sum_k (N - r_{ik)} = (3-1) = (3-1) = 4$

Risk 3: $b_i = \sum_k (N - r_{ik)} = (3-0) = (3-1) = 5$

Respective to the b_i values, the Borda rank for Risk 1 and Risk 3 are 0, which mean they are most critical and Risk 2 is ranked 2, meaning it is the least critical risk.

3.3 Project Activities

The project activities consists of 8 tasks. There are 2 phases in the execution.

Table 10. Project activities of the project

Task	Activities
Project preparation	• Title Discussion • Title Approval • Preliminary Research Work
Extended Proposal	• Submission of Extended Proposal • Proposal Defense
Project Execution Phase 1	• Literature survey - Overview of a Gas Turbine - Development of Risk Assessment Model (RAM) - Risk Matrix method

	• Familiarization with risk assessment methods - There are many methods of RAM such FMEA, FTA/ETA, HAZOP and etc. - In this project, I will focus on Risk Matrix. • Gathering of parameters and equations for risk assessment - Risk= Probabilty x Consequence • Preliminary work on model development
Project Break	• Submission of Interim Report
Project Execution Phase 2	• Development of risk assessment model
Progress Report	• Submission of Progress Report
Pre - SEDEX	• Poster presentation
Project Closed Out	• Project Documentation – Dissertation (Soft Bound) – Technical Paper – Dissertation (Hard Bound) • Oral Presentation

3.4 Key Milestone

The key milestone of the project is divided into two; Final Year Project 1 and Final Year Project 2.

3.4.1 Final Year Project 1 (FYP1)

Table 11. Key milestone in FYP1

Deliverable	Target Date
Submission of Extended Proposal	Week 6
Proposal Defense	Week 8 – 9
Submission of draft Interim Report	Week 13
Submission of Interim Report	Week 14

3.4.2 Final Year Project 2 (FYP2)

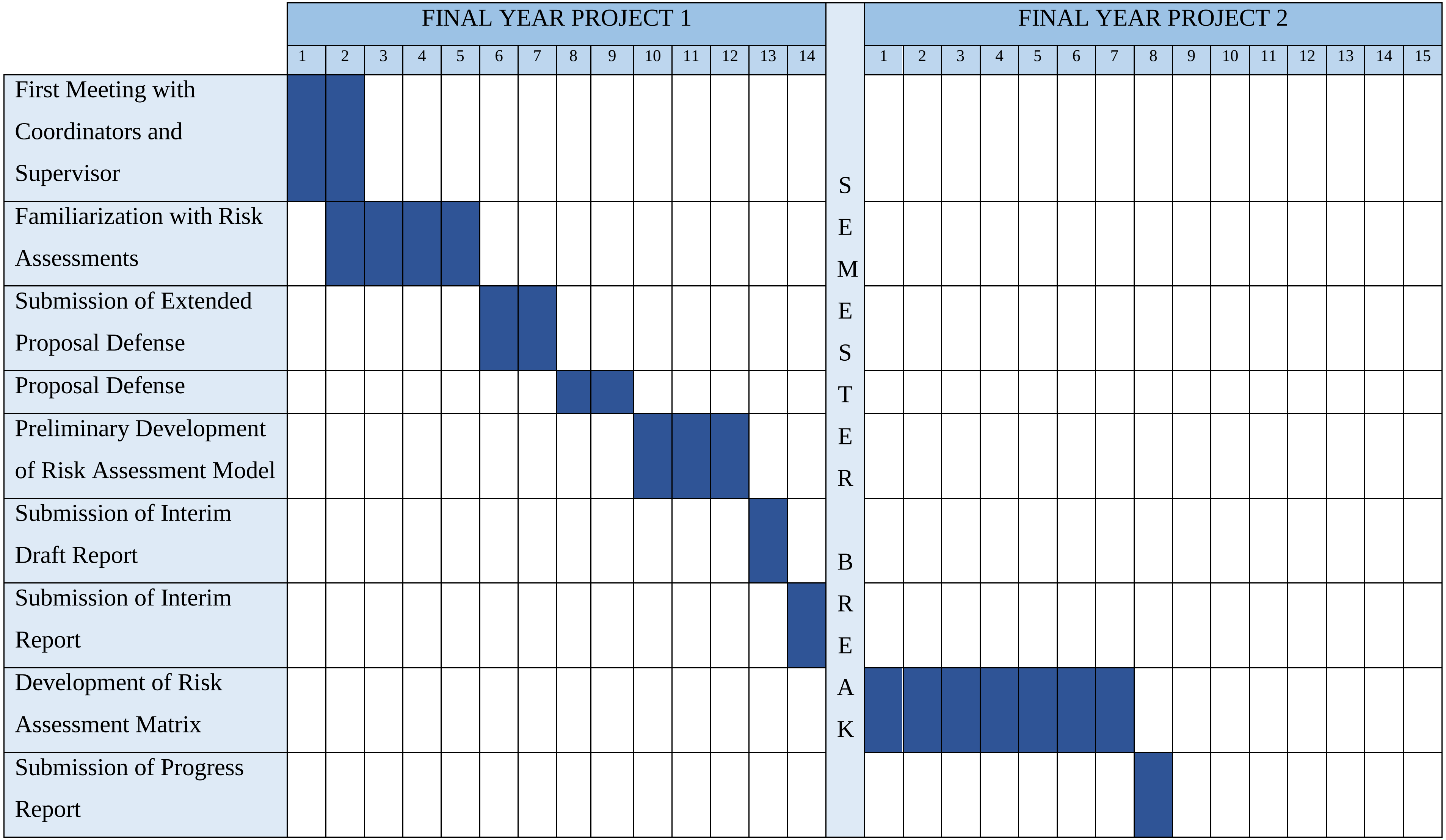
Table 12. Key milestone in FYP2

Event or Deliverable	Target Date
Submission of Progress Report	Week 8
Pre – SEDEX	Week 11
Submission of Draft Report	Week 12
Submission of Dissertation (Soft Bound)	Week 13
Submission of Technical Paper	Week 13
Oral Presentation	Week 14
Submission of Dissertation (Hard Bound)	Week 15

3.5 Tools

The basis of this project is mainly researching and developing theory. In the early part of the research, mostly the author studied and researched technical papers and journal from subscribed online database for research purpose. Microsoft Word and Microsoft Excel are the tools applied in this research.

3.6 Gantt Chart



Development of Risk Assessment Matrix Continues																							■	■	■	■	■			
Pre-SEDEX																										■				
Submission of Draft Report																											■			
Submission of Dissertation (Soft Bound)																												■		
Submission of Technical Paper																												■		
Oral Presentation																													■	
Submission of Dissertation (Hard Bound)																														■

CHAPTER 4

RESULTS AND DISCUSSION

To conduct and demonstrate the use of proposed methods of failure risk assessment model, the case study of FMEA for a gas turbine used to drive an offshore electricity system is applied [18]. There are risk matrix method and Borda method. To carry out the risk assessment, the failure probability and failure consequence for each failure modes of gas turbine system are first determined and discussed. The risk assessment then is executed in the following steps.

4.0 Analysis of Failures

The failure modes of gas turbine used to drive an offshore electricity system has been adapted [15] as in Table 13 and failure ranges were assumed. The input benefited from the combined experience of experts in gas turbine manufacturing and operating companies who were members of the Loughborough University Rotating Machinery Reliability Group. Gas turbine system has 12 failure modes where each failure mode contributed to the failure of gas turbine system. The failure modes are from the critical parts of the gas turbine system which are compressor, turbine and combustion chamber. As stated in MIL-STD-882D standard, scales for failure probability are adjustable depending on the suitable situation. For each failure mode, the failure ranges were assigned and categorized based on their rate of occurrence. There are remote, probable and occasional ranges having the value of 2, 3 and 4 as shown in Table 13. Every category of failure probabilities has four risks assigned to them which means there are 4 remote, 4 occasional and 4 probable occurrence rate.

Consequences of failure categories are defined for each failure modes of the gas turbine system as shown in Table 13. There is only one failure mode which is Risk no. 1 (Overspeed) has catastrophic impact. Mostly, the risks have critical impact to the gas turbine system. There are 8 out of 12 risks having critical consequence that is third-quarter of the total risks. There is also a single failure mode that has marginal impact which is Risk 9 (Radial bearing failure). The remaining two failures found having negligible impact when they occur.

Table 13. Failure modes of gas turbine with assigned probabilities and consequences scale.

No of risks	Failure modes	Failure probabilities		Failure consequences	
		Category	Scale	Category	Scale
1	Overspeed	Remote	2	Catastrophic	4
2	Rotor out of balance	Remote	2	Critical	3
3	Rotor bend distortion	Occasional	3	Critical	3
4	High temperature	Probable	4	Negligible	1
5	High vibration	Probable	4	Negligible	1
6	Tip rub	Remote	2	Critical	3
7	Blade failure or inlet guide vane failure	Occasional	3	Critical	3
8	Thrust bearing failure	Occasional	3	Critical	3
9	Radial bearing failure	Probable	4	Marginal	2
10	Foreign object damage	Remote	2	Critical	3
11	Explosion in combustion chamber	Occasional	3	Critical	3
12	Failure of refractory lining	Probable	4	Critical	3

4.1 Risk ranking using Risk Matrix

All of the failure modes are first determined using risk matrix. Based on the assumed failure probability and impact scales for each failure mode, a figure of risk level for every failure mode is shown for better understanding. There are 12 figures showing the products of probability, P and consequence, C. The results are risk rating, their category level and the risk acceptance level for Risk 1 until Risk 12. Later the results of risk ranking for each failure mode are tabulated in Table 14.

Risk no. 1: Overspeed

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 9. Risk level of overspeed

Risk rating = 8

Serious risk – Not desirable

Risk no. 2: Rotor out of balance

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 10. Risk level of rotor out of balance

Risk rating = 10

Medium risk – Acceptable with review

Risk no. 3: Rotor bend distortion

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 11. Risk level of rotor bend distortion

Risk rating = 6

Serious risk – Not desirable

Risk no. 4: High temperature

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 12. Risk level of high temperature

Risk rating = 16

Medium risk – Acceptable with review

Risk no. 5: High vibration

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 13. Risk level of high vibration

Risk rating = 16

Medium risk – Acceptable with review

Risk no. 6: Tip rub

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 14. Risk level of tip rub

Risk rating = 14

Medium risk – Acceptable with review

Risk no. 7: Blade failure or inlet guide vane

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 15. Risk level of blade failure or inlet guide vane

Risk rating = 6

Serious risk – Not desirable

Risk no. 8: Thrust bearing failure

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 16. Risk level of thrust bearing failure

Risk rating = 6

Serious risk – Not desirable

Risk no. 9: Radial bearing failure

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 17. Risk level of radial bearing failure

Risk rating = 9

Serious risk – Not desirable

Risk no. 10: Foreign object damage

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 18. Risk level of foreign object damage

Risk rating = 10

Medium risk – Acceptable with review

Risk no. 11: Explosion in combustion chamber

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 19. Risk level of explosion in combustion chamber

Risk rating = 6

Serious risk – Not desirable

Risk no. 12: Failure of refractory lining

	Consequence				
Probability		Catastrophic	Critical	Marginal	Negligible
	Frequent	1	3	7	13
	Probable	2	5	9	16
	Occasional	4	6	11	18
	Remote	8	10	14	19
	Improbable	12	15	17	20

Figure 20. Risk level of failure of refractory lining

Risk rating = 5

High risk – Not acceptable

As shown in these figures above, the failure risks are distributed in three risk categories which are high, serious and medium. None is assigned as low. Most of the failure modes of gas turbine system which are six in total have serious risk level. Five failure modes have medium risk and only single has high risk that is Risk 12 (Failure of refractory lining). Based on risk categorization acceptance shown in Table 6, the failure has high risk require immediate action and detailed research to reduce the level of risk because such failure is not acceptable. The failure modes have serious risk level need as soon as practicable action to minimize the risk level because they are not desirable. As for medium risk level, preventive plans are needed to avoid the risk of the failure modes but they are acceptable with review.

4.2 Risk ranking using Borda Method

Results of failure risks assessed are shown in Table 14. The results are obtained from the estimated probability and consequences scale of risk assessment matrix for gas turbine system. Even though the failure are categorized into 4 different risk levels: low, medium, serious and high, there are still risk ties happened. The results show that there are five failure modes of gas turbine system have medium risk and six failure modes have serious risk. Nevertheless, there is one failure mode has high risk. Unfortunately, it is impossible to determine which risk from medium, serious and high categories is more critical. Hence the use of Borda ranking method is most useful to improve associated risk levels of the gas turbine system failure modes.

After defining the number of scale for failure probability and consequence of each failure modes, the number assigned are used and the b_i values were calculated using Equation 1. For every failure mode, the calculation process is shown as follows for better understanding.

Risk no. 1: Overspeed

$$b_1 = \sum_k (N - r_{1k)} = (12 - 8) + (12 - 0) = 16$$

Risk no. 2: Rotor out of balance

$$b_2 = \sum_k (N - r_{2k)} = (12 - 8) + (12 - 1) = 15$$

Risk no. 3: Rotor bend distortion

$$b_3 = \sum_k (N - r_{3k)} = (12 - 4) + (12 - 1) = 19$$

Risk no. 4: High temperature

$$b_4 = \sum_k (N - r_{4k)} = (12 - 0) + (12 - 10) = 14$$

Risk no. 5: High vibration

$$b_5 = \sum_k (N - r_{5k)} = (12 - 0) + (12 - 10) = 14$$

Risk no. 6: Tip rub

$$b_6 = \sum_k (N - r_{6k)} = (12 - 8) + (12 - 1) = 15$$

Risk no. 7: Blade failure or inlet guide vane

$$b_7 = \sum_k (N - r_{7k)} = (12 - 4) + (12 - 1) = 19$$

Risk no. 8: Thrust bearing failure

$$b_8 = \sum_k (N - r_{8k)} = (12 - 4) + (12 - 1) = 19$$

Risk no. 9: Radial bearing failure

$$b_9 = \sum_k (N - r_{9k)} = (12 - 0) + (12 - 9) = 15$$

Risk no. 10: Foreign object damage

$$b_{10} = \sum_k (N - r_{10k)} = (12 - 8) + (12 - 1) = 15$$

Risk no. 11: Explosion in combustion chamber

$$b_{11} = \sum_k (N - r_{11k)} = (12 - 4) + (12 - 1) = 19$$

Risk no. 12: Failure of refractory lining

$$b_{12} = \sum_k (N - r_{12k)} = (12 - 0) + (12 - 1) = 23$$

The calculated b_i values are 16, 15, 19, 14, 14, 15, 19, 19, 15, 15, 19, and 23. Based on these values, the Borda ranking for each failure modes executed is as shown in Table 14. The most critical failure mode is clearly Risk 12 because it has Borda rank of 0. The number zero means that no failure mode is more critical than Risk 12 and this failure mode needs immediate action plan. Four risks have Borda ranking 1 are the second most critical which are Risk 2, Risk 7, Risk 8 and Risk 11. Risk 1 has Borda ranking 5 which means there are 5 more critical failure modes than failure mode overspeed. Four failure modes have Borda ranking 6 and they should be given fair attention. The last two failure modes which are Risk 4 and Risk 5 have Borda ranking 10 and they should be treated only after 10 more vital failure modes are given attention.

Table 14. Risk ranking using Risk matrix and Borda method

No of risks	Failure modes	Failure probabilities		Failure consequences		Risk matrix ranking	Category	b_i values	Borda ranking
		Category	Scale	Category	Scale				
1	Overspeed	Remote	2	Catastrophic	4	8	Serious	16	5
2	Rotor out of balance	Remote	2	Critical	3	10	Medium	15	6
3	Rotor bend distortion	Occasional	3	Critical	3	6	Serious	19	1
4	High temperature	Probable	4	Negligible	1	16	Medium	14	10
5	High vibration	Probable	4	Negligible	1	16	Medium	14	10
6	Tip rub	Remote	2	Critical	3	14	Medium	15	6
7	Blade failure or inlet guide vane failure	Occasional	3	Critical	3	6	Serious	19	1
8	Thrust bearing failure	Occasional	3	Critical	3	6	Serious	19	1
9	Radial bearing failure	Probable	4	Marginal	2	9	Serious	15	6
10	Foreign object damage	Remote	2	Critical	3	10	Medium	15	6
11	Explosion in combustion chamber	Occasional	3	Critical	3	6	Serious	19	1
12	Failure of refractory lining	Probable	4	Critical	3	5	High	23	0

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Failure modes of gas turbine system, their failure range rate, failure consequence and associated risks were assumed and classified using semi-quantitative risk matrix. The Borda ranking method was used to minimize the risk ties exist in risk matrix ranking. Failure of refractory lining in combustion chamber was found having high risk. It needed most attention compared to other failure modes. Overspeed, rotor bend distortion, blade failure or inlet guide vane failure, thrust bearing failure, radial bearing failure and explosion in combustion chamber were categorized as serious risk. Out of these six, rotor bend distortion, blade failure or inlet guide vane failure, thrust bearing failure and explosion in combustion chamber required more attention for treatment based on Borda ranking method. Then only overspeed and radial bearing failure should be treated, respectively. Lastly, there are five medium risks which are rotor out of balance, high temperature, high vibration, tip rub and foreign object damage. According to Borda evaluation, rotor out of balance, tip rub and foreign object were found demanding more urgent action than high temperature and high vibration. The last two should be treated last because they are the least critical. Risk matrix is an approved tool of semi-quantitative risk assessment to evaluate failure risk because the feasible way to risk and easy-to-use feature. Although risk ties exist in risk matrix but with the introduction of Borda method, the risk assessment matrix developed becomes more efficient to analyze the failure risks as it managed to reduce the risk ties exist in the risk matrix method. The objective of this project is achieved where a risk assessment model for gas turbine is successfully developed. Every failure risks associated with gas turbine system are well assessed and discussed. This study can be further extended to determine maintenance action plan to mitigate risk of gas turbine system.

REFERENCES

[1] Aref Majdara, M. R. (2007). Development and application of a Risk Assessment Tool. *Elsevier*.

[2] Boyce, M. P. (2011). *Gas Turbine Engineering Handbook.* Butterworth Heinemann.

[3] Carter, T. J. (2004). Common failures in gas turbine blades. *Elsevier*.

[4] *CGE Risk Management Solutions*. (2013). Retrieved from http://www.cgerisk.com/

[5] G. E. Dieter, L. C. (2013). *Engineering Design (5th Edition).* Americas: McGraw-Hill.

[6] Ivan W. H. Fung, V. W. (2009). Developing a Risk Assessment Model for construction safety. *Elsevier*.

[7] Kiho Moon, S.-R. S. (2009). Fire risk assessment of gas turbine propulsion system for LNG carriers. *Elsevier*.

[8] Langston, L. S., & Opdyke, G. (1997). Intorduction to Gas Turbines for Non-Engineers. *Global Gas Turbine News*.

[9] Lozier, T. (2011, March 4). *Risk Assessment: Creating a Risk Matrix*. Retrieved from EtQ Blog: http://blog.etq.com/blog/bid/57768/Risk-Assessment-Creating-a-Risk-Matrix

[10] Ozog. (2009). *Designing an effective risk matrix.* Retrieved from ioMosaic: www.iomosaic.com

[11] Souza, G. F. (2012). *Thermal Power Plant Performance Analysis.* London: Springer.

[12] Talbot, J. (2013). *What's right with risk matrices?* Retrieved from JBS: http://jakeman.com.au/media/whats-right-with-risk-matrices/

[13] Yerevan, A. (2010). Introduction to Risk Analysis. *Fiat Panis*.

[14] Yang, H., & Hong, X. (2011). Reliability Analysis of Gas Turbine Based on The Failure Mode and Effect Analysis. *IEEE*. Retrieved from http://www.sciencedirect.com

[15] Huihui, N., An , C., & Ning, C. (2010). Some extensions on risk matrix approach. *Elsevier*. Retrieved from http://www.elsevier.com/locate/ssci

[16] Aven, T. (2007). A semi-quantitative approach to risk analysis, as an alternative to QRAs. *Elsevier*. Retrieved from http://www.sciencedirect.com

[17] DoD, M. US Department of Defense, (2000). *882D Standard Practice for System Safety*

[18] Andrews, J. D., & Moss, T. R. (1993). *Reliability and risk assessment.* Longman Scientific & Technical.

[19] Garvey, P. R., & Lansdowne, Z. F. (1998). Risk matrix: An approach for identifying, assessing, and ranking program risks. *Air Force Journal of Logistics, XX11*(1), 18. Retrieved from http://www.dtic.mil/dtic

[20] Lamboray, C. (2007). A comparison between the prudent order and the ranking obtained with Borda's, Copeland's, Slater's and Kemeny's rules. *Elsevier*. Retrieved from http://www.sciencedirect.com

[21] Akritidis, L., Katsaros, D., & Bozanis, P. (2011). Effective rank aggregation for metasearching. *Elsevier*. Retrieved from http://www.sciencedirect.com

[22] Zhu, Qichao, Kuang, Xinghua, Shen, & Yongping. (2003). Risk Matrix Method and its Application in the Field of Technical Project Risk Management. *Engineering Science, 5(1)*, 89-94 (in Chinese).

[23] Welch, B. (2003). *Comparison of various risk rating matrices*. Retrieved from http://www.onsafelines.com/risk-assessment-matrix-comparisons.html

[24] Markowski, A. S., & Mannan, M. S. (2008). Fuzzy risk matrix. *Journal of Hazardous Materials*, *159*, 152-157. Retrieved from http://www.sciencedirect.com

[25] Rosenbloom, J.S. (1972). *Case Study in Risk Management*. Prentice Hall.

[26] Wang, M. (2003). *Security Investment Risk: Evaluation, Prediction and Control*. Press of University of Shanghai Finance and Economics (in Chinese).

[27] Willams, C. A., Heins, R. M. (1985). *Risk Management abd Insurance.* New York: McGraw Hill.