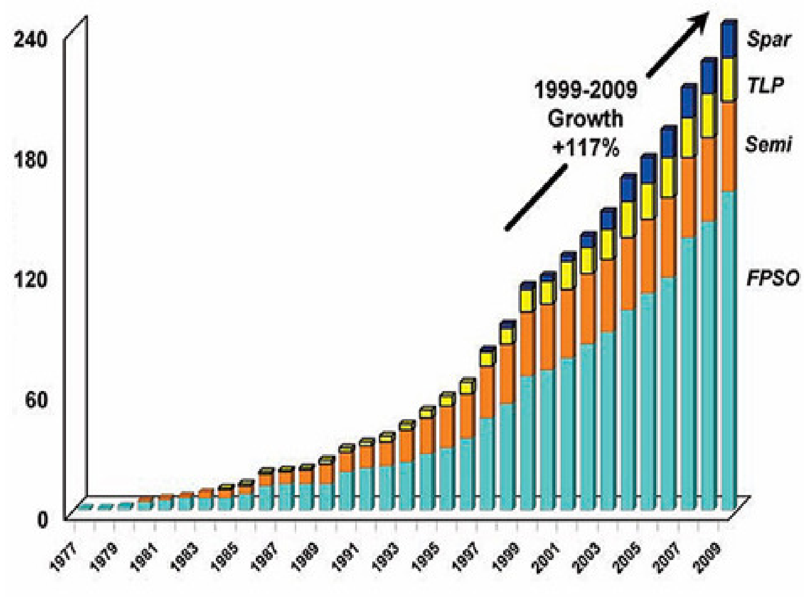
CHAPTER ONE

INTRODUCTION

1.1 Background

Offshore industry needs to develop new technologies in an attempt to conduct offshore operations in various regions, depths and conditions. Offshore operation cost is much higher compared to onshore operation cost because of expensive equipments and technology. Currently the activity of oil and gas industry grows in deeper water, moves from a fixed structure to floating structure requiring safety, efficiency and cost effectiveness. The development of floating production has grown significantly in the past 30 years in response to the need to operate in water depths beyond the reach of fixed platforms as shown in Figure 1.1 (News, 2009).

Units



Years

Figure 1.1. Growth of Production Floaters (News, 2009)

Floating structures need to remain in place throughout their service life, and include floating production, storage and offloading (FPSO), semi submersible, spars, and tension leg platform engaged in drilling, accommodation, production and storage (Gerwick, 2000). Floating structure need to stay floating in whatever weather conditions.

In order to define the related factors that can damage offshore platform, it is needed to do risk based decision making processes. Risk based decision making needs trustworthy input from risk analysis approaches which include identifying, assessing, and reducing the risk and also demonstrating the risk reduction (Salvi, 2006). By doing risk based decision making the possibility of unwanted damage can be prevented and all the risks can be effectively managed. Therefore this study will focus on mooring system failure in order to investigate what are the potential causes, the possible consequences, the risk level classification, the action and safeguard needed to reduce the risk, and also to develop the risk mitigation plan and maintenance strategy for semi submersible. The risk assessment approaches used in this study namely HAZOP, FTA, and ETA are based on the trustworthy standard in the offshore industry.

1.2 Problem Statement

Offshore activities involve many challenges and present various environmental conditions able to cause catastrophic damage and loss of life. Hence lots of works have been done to investigate what thing goes wrong and what cause those failures. There are some issues related to the floating structure e.g. semi submersible for accommodation units as shown in Figure 1.2. Figure 1.2 shows that the second highest number of occurrences of semi submersible for accommodation platform is related to anchor failure. Anchor failure problems are associated with anchor/anchor line, mooring devices, winching equipment or fairleads (e.g. anchor dragging, breaking of mooring lines, loss of anchors and winch failures). Anchor failure is an important issue in mooring the floating units because of its function as the station keeping. The station keeping failure can cause catastrophic damage and loss of life. The platform may loose its position, adrift or even collapse.

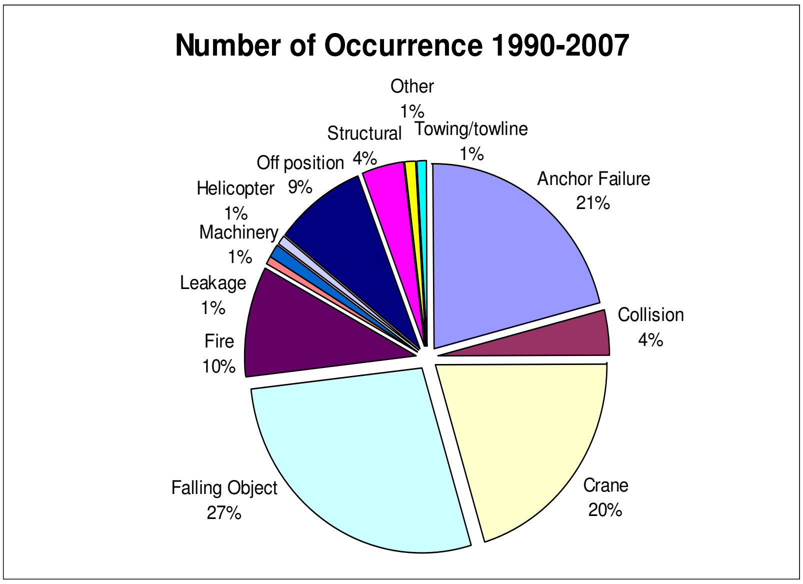


Figure 1.2 Number of Occurrence of Semi submersible (HSE, 2009)

This catastrophic damage has brought new knowledge to analyze what is wrong and how to mitigate the failure in the future. This knowledge has raised the need to perform risk assessment. By doing risk assessment stakeholders in oil and gas industry can examine the worst case scenarios in order to fully understand the risks they are facing. It is also useful to look at various policy alternatives effective in reducing the risks.

The other issues are the rules applied in offshore installation that only covers the measurement on how to protect people against accident. Traditionally, the safety of offshore installations against marine hazards relies on International Maritime Organization (IMO) legislation and classification society rules. Only these rules are rarely based on risk assessment and do not by themselves satisfy the requirement to perform a risk assessment (DNV, 2002). This leads to the importance of developing a methodology with consistent rules to select accident scenarios and determine the approach to mitigate the risk and to handle it on a daily basis.

1.3 Objective of the Study

Offshore activities involve many challenges and present variety environmental conditions that can cause catastrophic damage and loss of life (Kaiser, 2007b). Numerous accidents have happened in all types of installation especially the floating structure with complete mooring system failures found to be adrift (Petruska et al., 2009; HSE, 2006b). There are so many factors involved, such as skill of the employee, weather and environmental conditions, condition of vessel and equipment affect the operability of working configuration. The investigation on the potential hazards that can damage offshore platform is very important in order to minimize the risks of such accidents, therefore it is needed to do a risk assessment (Petruska et al., 2009; DNV, 2002; Deacon et al., 2010).

By doing risk assessment the possibility of unwanted damage can be prevented and all the risk can be effectively managed. The aim of this thesis is to integrate of Risk Based Decision Making (RBDM) for mobile mooring system. In order to achieve the aim of this thesis there are three main objectives need to be investigated, namely as follows:

1. To develop an integrated risk assessment approach consisting of HAZOP, FTA and ETA called MIVTA (Methodology for Investigation of Critical Hazards). Developing MIVTA consist of:
   a. Analyzing the critical hazards that affect safety and operability using HAZOP.
   b. Determining the root causes of an accident hazard and quantifying the frequency index by applying FTA.
   c. Classifying the possible outcomes of an accident hazard and quantifying the severity index using ETA.

2. To develop an integrated risk assessment and risk based maintenance called MIRBA (Methodology for Investigation of Risk Based Maintenance). In order to develop MIRBA, the following Steps need to be taken:
   a. Developing the risk matrix based on frequency and consequence using bow tie analysis.
   b. Determining the mitigation plan to reduce the risk and measuring their mitigation effectiveness.
   c. Generating the best maintenance strategy selection on the basis of likelihood and consequence using AHP.

3. To validate the integrated framework of risk based decision making consisting of MIVTA and MIRBA for mobile mooring system.

The integration of RBDM framework is derived from MIVTA and MIRBA. In order to analyze the risk of the mobile mooring system, four approaches are integrated to be used to determine all the potential hazards that may lead to accident events and to establish proper maintenance to manage the risk daily. These approaches are HAZOP, FTA, ETA and AHP, already been applied successfully in many areas as shown in Table 1.1. The outcome of this research will be useful for stakeholders to assess the safety level in order to mitigate the risk and to handle it on a daily basis. The stakeholders need to be systematically reported on the condition of potential risks in their surroundings.

1.4 Significance of the Research

There is a need from both the industry and the regulatory authorities for methodologies providing consistent rules to determine the accident scenarios and to take into consideration safety management effectiveness for risk control manifestation (Salvi, 2006). The industry has been changing the standards regarding mooring system from a selection of the design return period in developing a proper risk assessment (Petruska et al., 2009). Offshore activities require an expensive cost on the installation, operational and maintenance, it needs efficient and effective methods to make sure the project fit for purpose.

Operations in offshore floating structure involve uncertainty condition that may cause risk people to get injury/death, damage to the structure and finally will affect reputation of the company. Commonly the risk assessment process is conducted individually depending on the objective to be investigated. For instance the hazard identification (HAZID) is used to identify the risk potential failure, HAZID is not suitable to investigate the root causes of risk failure and their consequences. These concerns have led the decision makers to conduct comprehensive risk based decision making. The risk based decision making generally focuses on risk analysis, risk assessment, risk level, risk mitigation and maintenance strategy in order to maintain all those risk in daily activity. Currently the risk assessment approach is done separately because none of the existing methodologies is able to combine all of these concerns in offshore operation. This study develops two methodologies based on the risk assessment approaches and multi criteria decision making technique namely MIVTA and MIRBA. The risk assessment approach is useful to determine the potential causes and the consequences that may cause an accident or disaster. The risk assessments approaches adopted in this study are HAZOP, FTA and ETA. While the multi criteria decision making technique is helpful to establish the best maintenance in order to minimize the risk. The multi criteria decision making techniques implement the AHP approach developed by Saaty (2008).

Table 1.1 show the critical view of MIVTA and MIRBA by integrating four methods namely HAZOP, FTA, ETA and AHP. The critical view focuses on the hazards risk analysis methods which consist of qualitative and quantitative analysis. The chosen methods are based on the recommendations of standards used in oil and gas industry namely DNV, ABS and API. These methods are very useful in order to determine the risk analysis in offshore operation and maintenance (DNV, 2002; ABS, 2001; API, 1993). These methods have been applied in many areas especially in offshore operation, risk assessment and maintenance. Therefore this study will be focus on the integration of HAZOP, FTA, ETA, and AHP through the development of MIVTA and MIRBA.

Table 1.1. Critical View of MIVTA & MIRBA

Critical View	MIVTA			MIRBA	
	Hazard and Operability (HAZOP)	Fault Tree Analysis (FTA)	Event Tree Analysis (ETA)	Bow Tie Analysis	Analytic Hierarchy Process (AHP)
Qualitative	√	√	√	√	√
Quantitative	-	√	√	√	√
DNV (2002)	√	√	√	√	-
ABS (2001)	√	√	√	√	-
API (1993)	√	√	√	-	-
Applications in Offshore	(Raman,1991), (Petruska et al., 2009), (Penny, 2010)	(Niu, 2009), (Cheng, 2009), (Moss & Kurty, 1983), (Mentes, 2011), (Nilsen, 1998)	(Matsuoka, 2004). (Petruska et al., 2009), (Nilsen, 1998)	(Fowler, 2003), (Delvosalle, 2005), (Cockshott, 2005)	(Silvianita, 2009), (Bertolini, 2006), (Dey, 2001), (Bevilavqua, 2000),
Risk Assessment & Reliability	(Dhillon, 2003)	(Geum, 2009), (Souza, 2008), (Dhillon, 2003), (Xie, 2000), (Chelson, 1971)	(Lacasse, 2008), (Ghodrati et al., 2007), (Kozine, 2000)	(Gowland, 2006), (Deacon et al, 2010), (Badreddine, 2010)	(Mentes, 2012), (Dawotola, 2011) (Arunraj, 2010)

The other motivation why this study chooses risk approaches namely HAZOP, FTA, ETA and AHP are because of their comprehensive, systematic and rigorous approach compare to other methods such as Checklist, FMEA and SWIFT. The benefits by using these methods are that methods can be integrated into comprehensive risk based decision making consists of risk identification, risk assessment, risk mitigation and risk based maintenance through the developing of MIVTA and MIRBA. The advantages and disadvantages of risk approaches can be seen in Table 1.2.

Table 1.2. Advantages and Disadvantages of Risk Approaches

Methods	Advantages	Disadvantages	References
HAZOP	➢ Systematic and rigorous ➢ Involves interaction of views from multidisciplinary experts ➢ Can be applied to a wide range of types of system ➢ Creates a detailed and auditable record of the hazards identification process	➢ Requires a considerable amount of preparation ➢ Time consuming	(Maragakis, 2009)
FTA	➢ Identify all the possible causes of a specified undesired event ➢ Improved the understanding of system characteristics ➢ Design flaws and insufficient operational and maintenance procedures may be revealed and corrected during the fault tree construction	➢ It is not fully suitable for modeling dynamic scenarios ➢ It is binary and may therefore fail to address some problems	(Rausand, 2005)
ETA	➢ Visualize event chains following an accidental event ➢ Visualize barriers and sequence of activation ➢ Good basis for evaluating the need for new/improved procedures and safety functions	➢ No standard for the graphical representation of the event tree ➢ Only one initiating event can be studied in each analysis ➢ Easy to overlook subtle system dependencies	(Rausand, 2005)
AHP	It illustrates how possible changes in priority at upper levels have an effect on the priority of criteria at lower levels It provides the buyer with an overview of criteria, their function at the lower levels and goals as at the higher levels Its stability and flexibility regarding changes within and additions to the hierarchy. Able to rank criteria according to the needs of the buyer which also leads to more precise decisions making	The complexity of this method which makes it implementation quite inconvenient If more than one person is working on this method, different opinions about the weight of each criterion can complicate matters It does not consider risks and uncertainties of the performance	(Tahriri, 2008)
Checklist	➢ Can be applied to a wide range of previous knowledge and experience ➢ Can be used by non system experts ➢ Ensure that common and more obvious problems are not overlooked	➢ Limited use when dealing with novel systems ➢ Inhibit imagination in the hazards identification process ➢ Would miss hazards that have not been previously seen	(Maragakis, 2009)
FMEA	➢ Systematic and rigorous ➢ Creates a detailed and auditable record	➢ Time consuming ➢ Only really considers hazards	(Maragakis, 2009)

Methods	Advantages	Disadvantages	References
	of the hazards identification process ➢ Can be applied to a wide range of types of system	arising from single point failure modes rather than combinations of failures ➢ Relies on people with detailed system knowledge	
SWIFT	➢ Creates a detailed and auditable record of the hazards identification process ➢ Time saving	➢ Careful thought is required in preparation for the application of the technique ➢ Relies heavily on the skills of the chairman ➢ Relies heavily on the expertise and experience of the team members	(Maragakis, 2009)

MIVTA and MIRBA are described in more detail through the research mapping as seen in Figure 1.3. MIVTA is developed based on HAZOP, FTA and ETA consists of risk identification using HAZOP, risk analysis using FTA and ETA, and risk assessment by quantifying the FTA and ETA. MIRBA is developed based on bow tie analysis and AHP consists risk management through bow tie analysis, risk mitigation by developing the mitigation plan, and risk based maintenance using AHP. These methods are chosen due to the complexity and systematically in an attempt to develop risk based decision making (RBDM).

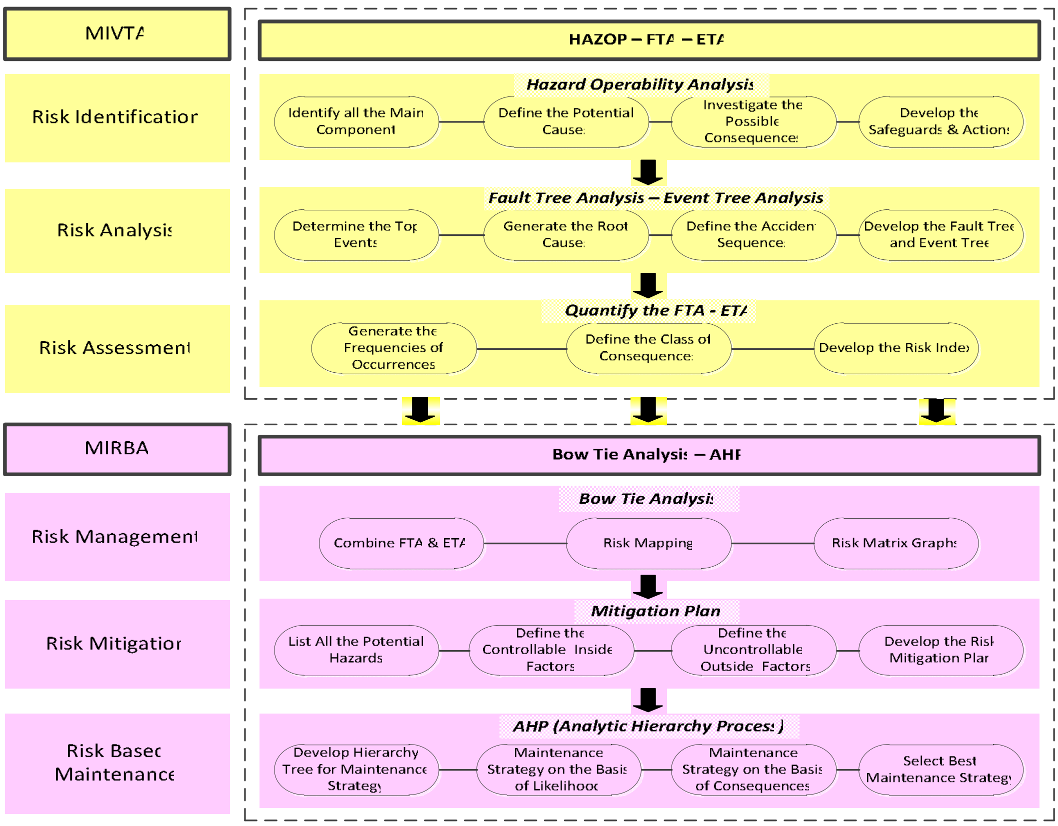


Figure 1.3 Research Mapping

1.5 Scope and Limitation of the Research

The scope and limitation of this study are limited to:

1) Utilize HAZOP as preliminary hazard analysis.
2) Develop the potential causes that may contribute to mooring system failure using FTA.
3) Determine the possible outcome of mooring system failure with ETA and come out with the risk graph. Once the risk graph is achieved the next Step is to determine the mitigation plan in order to minimize the risk.
4) Select the best maintenance strategy using AHP, in an attempt to manage and handle the risk.

This study is investigating the potential causes, the possible outcome of mooring system failure described in the risk matrix and find out the way how to mitigate and maintain the hazards in daily routine. There are four major types of failure in the mooring system namely: mooring line breaks, anchor handling failure, anchor failure and appurtenance connection failure. All of them are contributing to mooring system failure. However, an analysis of the potential causes of mooring system failure of these components must take into account the causes related to the structure adrift or even collapse, such analysis often involves structural analysis on each of the structure support components. These types of analysis are beyond the scope of this study, however in order to portray the analytical process for such component, the frequency of occurrence and the possible outcome of mooring system failure are conducted based on the expert judgment.

As to the type of mooring systems, this study limits its scope to determining the potential causes and the possible outcome in mobile mooring instead of permanent mooring because of the available resources. This study uses semi submersible pipe laying vessel as a case study. In terms of stability there are no differences from those applying for drilling units (HSE, 2006a). The vessels need to be mobile and have to work worldwide, able to operate in rough weather condition and not at any specific site.

The approach to developing comprehensive and systematic methods for risk based decision making used in this study are limited to the following approaches:

- Hazard and Operability (HAZOP) useful to identify hazards as a preliminary risk analysis in a systematic and comprehensive manner.
- Fault Tree Analysis (FTA) a logical combination helpful to determine the potential causes from critical top event until the undesired events are obtained.
- Event Tree Analysis (ETA) useful to define the possible consequence by relating an initiating event to various consequence models.
- Analytic Hierarchy Process (AHP) helpful in multicriteria decision making to evaluate the alternative of several options.

1.6 Structure of the Thesis

This thesis is made up of seven chapters comprising the research topics of this study. The outline of this thesis consists of Chapters 1: Introduction, Chapter 2: Literature Review, Chapter 3: Research Methodology, Chapter 4: Application of MIVTA (Methodology for Investigation of Critical Hazardous), Chapter 5: Application of MIRBA (Methodology for Investigation of Risk Based Maintenance) and Chapter 6: Conclusions and Recommendations. The details of each chapter are described as follows:

(i) Chapter One: Introduction

This chapter consists of general introduction of motivation and background of the study, problem statement related to the object of study, the objective to be accomplished, the significance of the research to be conducted, scope and limitation of the study.

(ii) Chapter Two: Literature Review

This chapter consists of two main parts namely offshore structure and risk based decision making. Offshore structure part provides characteristic of offshore structure mainly in mooring system components, operating condition (mooring motion) and their related problems faced by the oil and gas industry. Risk based decision making part presents definition of risk, risk analysis, risk assessment and risk based decision making. The approaches and the application of risk assessment methods are also discussed in this chapter attached with limitations of each approach. Multi-criteria decision making approach is also discussed in this chapter including the mathematical formulation and its evaluation analysis.

(iii) Chapter Three: Research Methodology

This chapter illustrates research methodology applied for each approach in a systematic method using flowchart system. There are four flowcharts illustrating each Step of analysis of HAZOP, FTA, ETA, and AHP. The last flowchart is combination of all the approaches as an integration of risk assessment.

(iv) Chapter Four: Application of MIVTA (Methodology for Investigation of Critical Hazardous)

This chapter applies three approaches of risk assessment namely HAZOP, FTA and ETA. The development of these approaches requires brainstorming with the experts in mooring system. The brainstorming is useful to determine potential causes, possible consequence and action needed to handle the risk of mooring system failure.

(v) Chapter Five: Application of MIRBA (Methodology for Investigation of Risk Based Maintenance)

This chapter of MIRBA is developed based on the results deriving from the previous chapter of MIVTA. Combination of FTA and ETA is called bow tie analysis whose result will be helpful in the risk matrix mapping of mooring system failure. Based on the risk matrix classification, the mitigation plans can be developed. This chapter will also discuss AHP which is useful to select the best maintenance strategy for mooring system.

(vi) Chapter Six: Conclusions and Recommendations

This chapter explains the conclusions deriving from this study and also gives recommendations to be conducted for further studies.

1.7 Summary of Conclusions

This study investigates the risk based decision making of mooring systems. Mooring systems are the main components in floating platforms which are useful for positioning and station keeping. Mooring system failure can cause disastrous damage to the platform. It can be adrift or even collapse that may lead to the loss of life.

Hence it is important to conduct a comprehensive and systematic risk based decision making in order to achieve maximum safety of the personnel and equipment. The approaches being used in this study are based on the recommendation of proven and trustworthy standard used in offshore industry, such as DNV (Det Norske Veritas), IMO (International Maritime Organizations) and ABS (American Bureau Shipping).

The approaches of risk based decision making consist of four methods namely HAZOP (Hazard Operability), FTA (Fault Tree Analysis), ETA (Event Tree Analysis), AHP (Analytic Hierarchy Process). The objectives of this study are trying to integrate all the four methods into new approaches of risk based decision making. The key objectives of this study are as follows:

a. To develop a methodology for investigation of critical hazard (MIVTA) by using HAZOP, FTA and ETA.
b. To develop a methodology for investigation of risk based maintenance (MIRBA) by Bow Tie Analysis and AHP.

The result of this study will explain the potential causes and the possible consequences of mooring system failures using HAZOP as preliminary analysis. In order to identify in more details about the potential causes of mooring system failure the FTA is used, while ETA is helpful to determine the possible consequences of mooring system failure. Based on the frequency deriving from the potential causes and possible consequence, the risk matrix graphs can be developed. Risk matrix graphs can show the risk level of the mooring systems under study. In regard to risk level classification, the mitigation plans need to be established in an attempt to reduce the risk. The mitigation plans are obtained for each of the undesired events identified in the analysis. The mitigation plans is not the last target in handling the risk, but it is the beginning of a process to evaluate, to monitor and to update condition of the system through maintenance strategy. Maintenance strategies are developed by using AHP which enables to evaluate multi criteria involved in order to select the best maintenance strategy. As a whole, this study is aimed to provide a guidance on systematic methodology of risk based decision making and also to enhance the existing risk assessment approaches which are useful to manage and reduce the risk for offshore platforms.

CHAPTER TWO

LITERATURE REVIEW

As mentioned in the previous chapter, this chapter will discussed in more detail about offshore structure, mooring system and risk based decision making based on the literature review.

2.1. Floating Structure

Chakrabarti (2005) explained that an offshore structure has no fixed access to dry land and may be required to stay in position in all weather conditions. Offshore platform can be fixed structure or floating structures that moored to the seabed or dynamically positioned by the thrusters. Offshore industry start in the late 1800s in California, the techniques and facilities used for production of oil on land were applied to an offshore field thus in 1900s began to conduct in new design concepts for offshore platforms that could be placed and operated economically and reliably in increasingly deeper waters (Paik, 2007). Figure 2.1 shows the development of offshore structure into deeper water and Figure 2.2 shows the floating production and sub sea system.

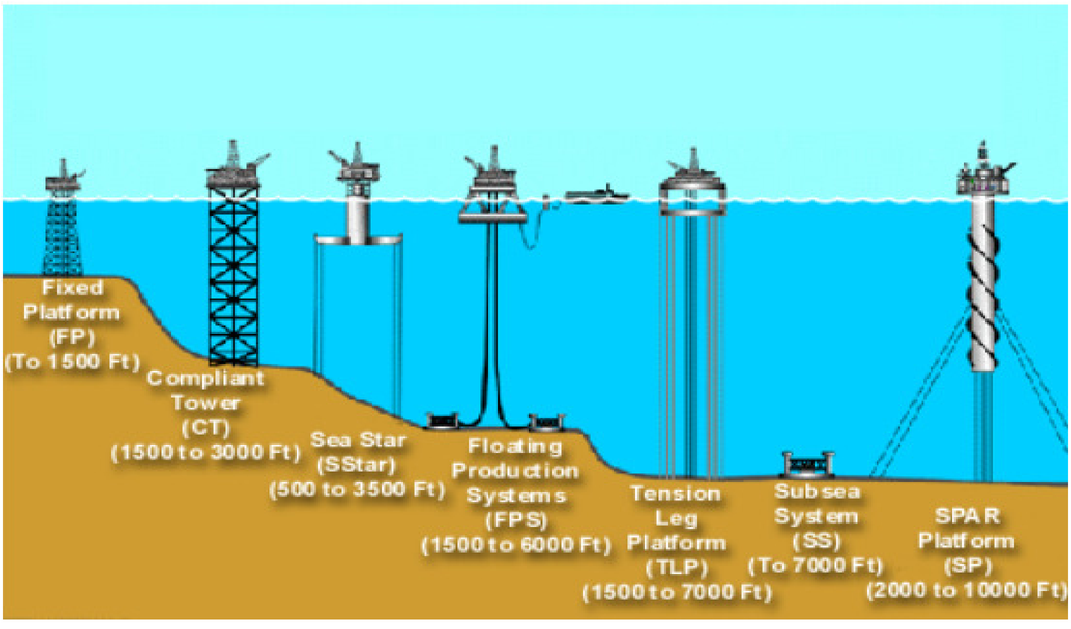


Figure 2.1. Deepwater System Types (Gas, 2011)

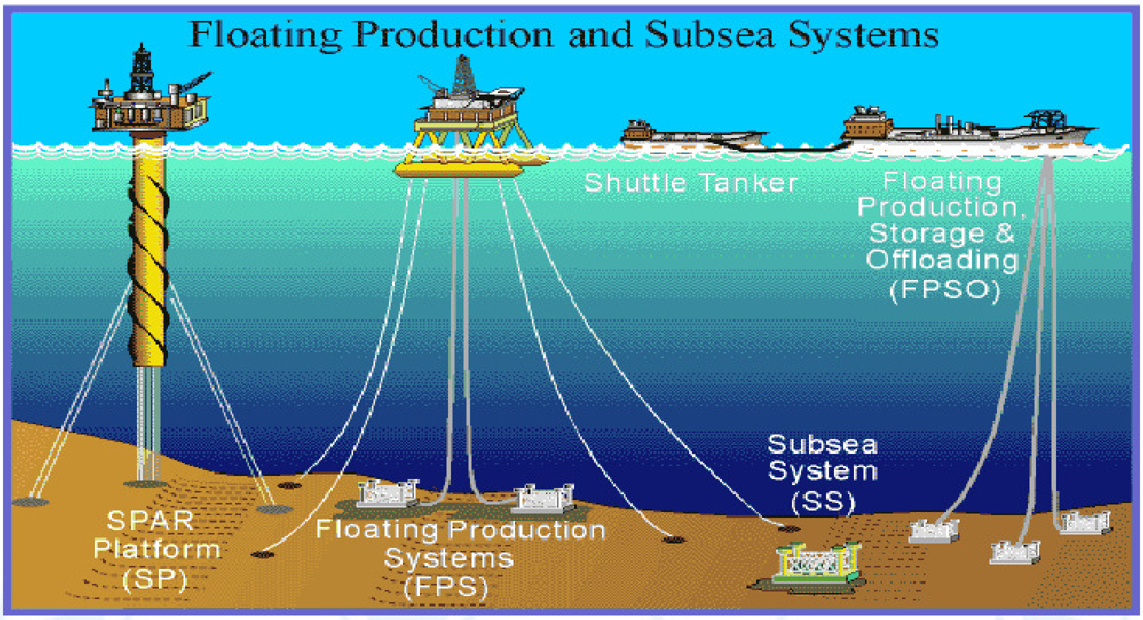


Figure 2.2. Floating Production & Subsea Systems (Topics, 2010)

Offshore structures are used for a broad variety of different operations such as drilling, production, accommodation etc. For instance semi submersible have always been used for various activities for example drilling, diving support, fire fighting, crane operations, pipe laying and accommodation (HSE, 2006a). Generally in terms of stability standards there is no distinction between different operational modes of a semi submersible for instance whether it is used for drilling, production, diving, pipe laying or accommodation (HSE, 2006a). The stability issues with floating platform are related to the mooring system problems. Mooring is the connection to the seabed that keeps the floating systems in place and must withstand whatever weather condition (HSE, 2006b). The mooring systems are freely hanging lines that connect the surface platform to anchors or piles, on the seabed, located at some points from the platform (Chakrabarti, 2005).

It is very important for floating offshore vessels to ensure that the mooring systems are fit for purpose. The design of mooring system is a trade off between constructing the system compliant enough to avoid excessive forces on the platform and constructing it stiff enough to avoid difficulties, such as damage to drilling or production risers, caused by excessive offsets (Chakrabarti, 2005). Mooring line failure is a main issue in the design of floating production and loading systems e.g. chain breakage may happen during a dynamically extreme loading condition or due to fatigue damage (Lassen, 1997). HSE (2006b) reported the failure statistics of probability of line failure per operating year is relatively high for North Sea operations as shown in Table 2.1.

Table 2.1. North Sea Mooring Line Failure Data (HSE, 2006b)

Type of Unit	Number of Operating Years per Failure
Drilling Semi-submersible	4.7
Production Semi-submersible	9.0
FPSO	8.8

Mooring line failure is associated with anchor failure which defined as issues with anchor/anchor lines, mooring devices, winching equipment or fairleads (e.g. anchor dragging, breaking of mooring lines, loss of anchor, and winch failures). Table 2.2 shows the summaries of a number of events (N) and occurrences per year (F) as reported by HSE (2006b).

Table 2.2. Anchor Failure in UK Sector of the North Sea (HSE, 2006b)

Anchor Failure					
Drilling Semis		Production Semis		FPSOs	
N	F	N	F	N	F
170	0.211	8	0.111	8	0.113

The design of mooring systems divided into two types which are permanent mooring systems and mobile mooring systems. Commonly the Floating Production System (FPS) used permanent mooring system because FPS typically has a design life of over 10 years. Mobile drilling units (MODU) most used mobile mooring systems because MODU tend to stay at one location for a much shorter period. A mobile vessel commonly is prepared to spread, turret or dynamic positioning system. Semi submersible platforms are always spread moored with mooring lines deriving from the four corner columns. Unlike the ships semi submersible is possible to use spread mooring because the environmental force on semi submersible is relatively insensitive to direction. The mooring lines are guided through fairleads as shown in Figure 2.3.

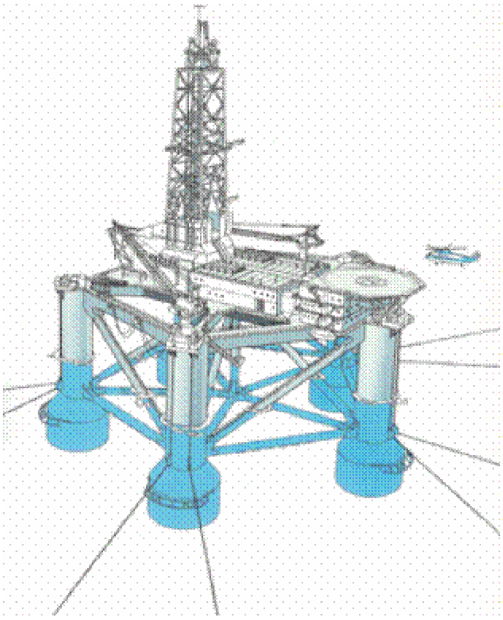


Figure 2.3. Spread Moored Semi Submersible (Moorings, 2007)

The selection of the suitable mooring system may vary from one project to another and be influenced by many factors. In order to design station keeping, there are several factors need to be considered for example off take frequency, environmental conditions, export tanker size, and risk of collision (Paik, 2007). Those factors are important to get the good performance of mooring systems. There are several factors that must be considered in the selection of the mooring systems which are described as the following (d'Hautefeuille, 1991):

- Environmental conditions
- Water depth
- Weather thresholds for disconnection and reconnection
- Installation complexity
- Operation and maintenance
- Safety and reliability from operational and survival points of view
- Design and fabrication schedules
- Capital costs
- Operating costs
- Downtime
- Emergency repairs

There are three types of mooring systems which are tension, taut and catenary as can be seen in Figure 2.4. Tension and taut mooring system have the lines nearly straight among the anchor and the fairleads. The vertical motions are taken up as an anchor and vessel reactions directly. The transverse motion changes in taut/tension mooring systems are not as large as in catenary systems, hence the dynamic effects due to transverse drag loads are moderate. Catenary mooring has few parameters which are submerged weight of the suspended lines, horizontal mooring load, line tension and the line slope at fairleads. The large line geometrical changes make the catenary mooring system has significant dynamic effects caused by the transverse drag load.

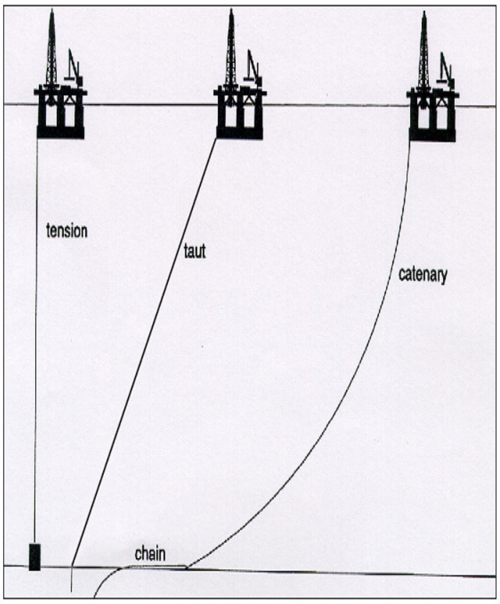


Figure 2.4. Types of Mooring Systems (Moorings, 2009)

2.2. Mooring Systems Components

Mooring system components for moored vessels may be made up to the mooring line, winching equipment, and anchoring system complete with the connecting hardware.

2.2.1. Mooring Line

In order to moor the vessel, offshore industry uses the mooring lines that made up of chain, wire rope, synthetic rope or a combination of them. Table 2.3 shows the advantages and disadvantages of the typical system of mooring lines.

Table 2.3 Classification of Mooring Line (API, 2005)

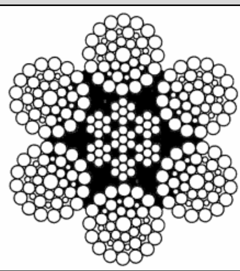
No	Classification	Advantages	Disadvantages
1	All wire rope systems	➢ Wire rope is much lighter than chain ➢ Provides a greater restoring force for a given pretension	➢ Much longer line length is required to prevent anchor uplift ➢ Wear due to long term abrasion where it contact with the seabed ➢ Seldom used for mobile or permanent moorings
2	All chain systems	➢ The chain has good durability ➢ The chain has better resistance to bottom abrasion and contributes significantly to anchor holding capacity.	➢ In deep water imposes an increasing weight penalty on the vessels load carrying capacity by its own self weight ➢ High initial tension requirements
3	Combination system	➢ Combination of chain, wire rope, and fiber rope. ➢ Provides reduced pretension requirements with higher restoring force, improved anchor holding capacity and good resistance to bottom abrasion.	➢ Costly and difficult to deploy at deepwater sites

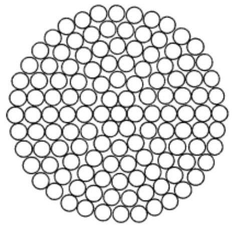
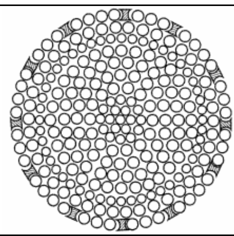
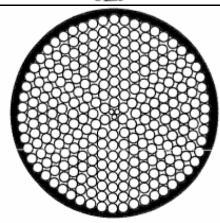
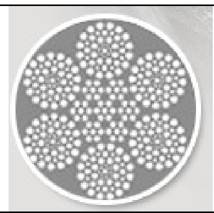
Primary mooring components are the mooring line and anchor, used along with other components such as connecting elements, floats etc. (Harris, 2006). The description of mooring components that generally used by offshore company are the following (API, 2005) :

2.2.1.1. Wire Rope

Wire rope consists of individual wire wound in a helical pattern to form a "strand". The pitch of the helix determines the flexibility and axial stiffness of the strand. Table 2.4 shows the wire rope construction.

Table 2.4. Wire rope construction (API, 2005)

No	Types	Life Expectancy (Years)	Descriptions
1	Galvanized 6 strands	6-8	

No	Types	Life Expectancy (Years)	Descriptions
2	Galvanized unjacketed spiral strand	10-12	
3	Galvanized unjacketed spiral strand with zinc filler wires	15-17	
4	Galvanized jacketed spiral strand	20-25	
5	Galvanized jacketed spiral strand with zinc filler wires	30-35	

2.2.1.2. Chain

Chain and wire make up the strength members of the mooring system. There are two primary chain constructions:

(i) Stud link: has been used for mooring MODUs, FPSOs in relatively shallow water. It has proven strong, reliable and relatively easy to handle.

(ii) Stud less chain: permanent mooring preferred to use open link/studless chain. Removing the stud reduces the weight per unit of strength and increases the chain fatigue life, at the expense of making the chain less convenient to handle.

2.2.1.3. Fiber Ropes

Fiber ropes can be used as segments in steel catenary systems or in taut leg systems. This system has minimum tension requirements, location of fiber rope segment to be away from fairleads and seafloor and also difference handling procedures compare with the wire rope/chain mooring system.

2.2.1.4. Connecting Hardware

Connecting hardware is used to connect together the main mooring line components such as shackles, swivels, fishplates and detachable links. Mobile moorings commonly used to connect links such as Kenter and Baldt link because they can pass through chain fairleads and windlasses and can be periodically inspected and replaced.

2.2.2. Winching Equipment

Winching equipment is used to adjust mooring lien tension, retensioning after anchor drag, and disconnecting individual mooring lines as can be seen in Figure 2.5.

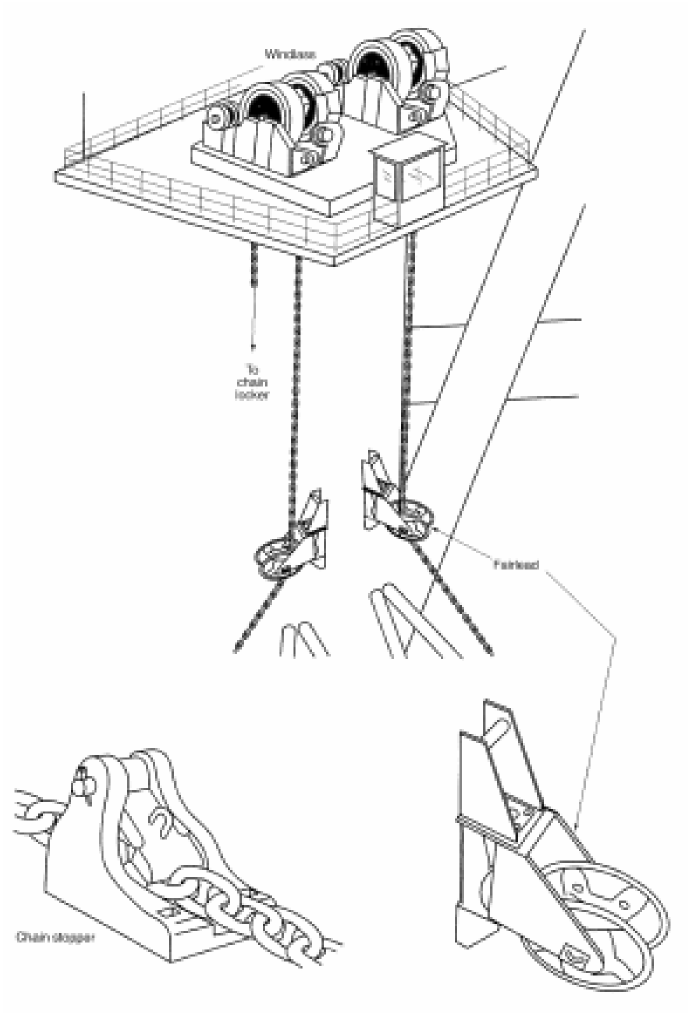


Figure 2.5. Winching Equipment for Chain (API, 2005)

2.2.2.1. Windlass

The windlass is the most common method of handling and tension the chain, it consists of a slotted "wildcat" which is driven by a power source through a gear reduction system (API, 2005).

2.2.2.2. Chain Jack

Chain jack is used to reciprocate linearly to haul in and tension chain, it is a powerful means for tensioning chain but it is very slow and is recommended for applications not requiring frequent line manipulation.

2.2.2.3. Drum Type Winch

Drum type winch is the most common method used for handling wire rope, it is fast and smooth consist of a large drum on which the wire rope is wrapped.

2.2.2.4. Fairlead and Stopper

Fairlead and stopper are the areas of mooring lines that subjected to high wear and stress. Fairleads should give enough sheave to rope diameter ration in order to minimize tension bending fatigue. Sheaves for wire rope have a diameter (D/d) ratios of 16-25 for mobile moorings and 40-60 for permanent mooring (API, 2005).

2.2.3. Anchoring System

There are several types of anchoring floating vessel depend on the required system performance, soil conditions, reliability, installation and proof loading. The types of anchoring system are drag embedment anchors, pile anchors (driven, jetted, drilled and grouted, suction pile and suction caisson, gravity anchor and plate anchor (drag embedded and direct embedded).

2.2.3.1. Drag Embedment Anchors

Traditional drag embedment anchors were initially used for mobile mooring operations, the anchor part can be pre installed and test loaded prior to platform installation as can be seen in Figure 2.6. Recently drag embedment anchor has advanced technology that develops high holding power even in the soft soil conditions. In reality, a lot of existing permanent and mobile moorings use drag embedment anchors because of its proven performance and easy installation (API, 2005).

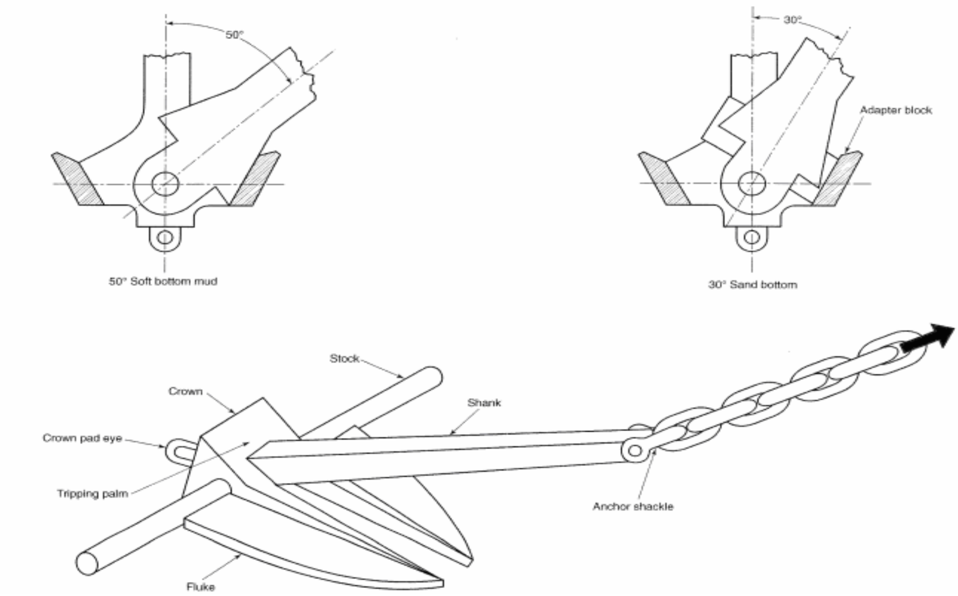


Figure 2.6. Traditional Drag Embedment Anchor (API, 2005)

2.2.3.2. Pile Anchors

Pile anchor has high lateral and vertical resistance and be very stable over time, mostly it is installed using driving hammers although other techniques such as jetting and drilling and grouting techniques have been used.

2.3. Mooring Motions

Mooring system is designed to withstand in any condition of environmental and other loadings to make sure the vessel fit for purpose. In order to appropriately design a mooring system, the mooring motions need to be considered. Mooring motion is the change in the equilibrium position of a moored buoy in response to a change in the direction and speed of the current flowing past the mooring (Fofonoff, 1968). A mooring cable coordinates system is discussed by Fitzgerald (2008) to illustrate the mooring motion as shown in Figure 2.7.

Mooring cable described as the global coordinate system with $\vec{r}$ the position vector of its origin and an orientation angle, α in the horizontal plane. The out of plane axis is defined as the normal to the plane in which the cable rests in its static equilibrium condition. The vertical axis is always parallel to the global heave axis. Make a note of the vertical direction in the cable co-ordinate system is assigned direction 2 while the global vertical heave axis is assigned direction 3 as is conventional.

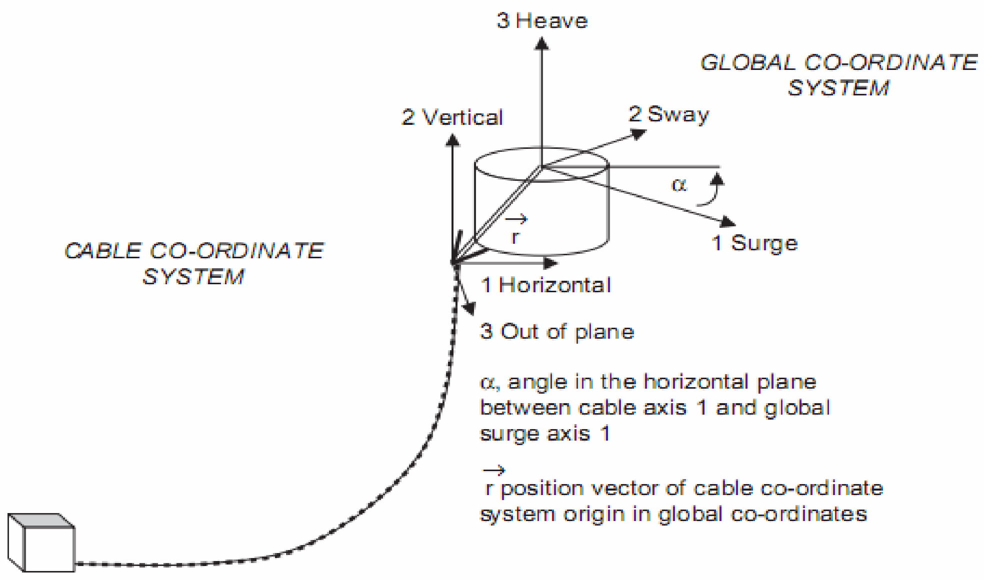


Figure 2.7. Relationship of the cable co-ordinate system to the global motion co-ordinate system (Fitzgerald, 2008)

Dynamic mooring response comprises of two frequency factors namely wave frequency (WF) and low frequency (LF). Wave frequency (WF) factor is induced by the first order wave forces while low frequency (LF) factor is caused by the slowly varying environmental forces (Gao, 2008). Mooring system analysis consists of both the vessel motion analysis and the analysis of mooring line tension. The causes of vessel motion responses are steady wave, wind and current forces, wave frequency (WF) and low frequency (LF), wave loads as well as LF wind forces. While the causes of mooring line tension are mostly because of the motions at the fairlead and the contribution of wave forces directly acting on the lines is relatively small (Gao, 2008).

An offshore platform moored in irregular waves, at the same time experience low frequency horizontal motions as well as wave frequency motions. The mooring system will become stiff under the action of low frequency motions, when superimposed by wave frequency motions the platform will shudder and mooring forces increase rapidly and can be exceed the safety levels. If this condition happens in the long term it will lead to excessive line fatigue (Dongjiao, 1992). An analysis of the potential causes of mooring system failure from the mooring motion analysis must take into account related to the platform collapse. This kind of analysis is beyond of the scope of this study, however on the way to establish the decision making for mooring system failure, the potential causes, the frequency of occurrence and their consequences were conducted based on expert judgments.

2.4. Mooring Failure

The risk analysis methods have been applied in many areas such as manufacturing (Pitt, 1994), mining (Ghodrati et al., 2007), safety (Targoutzidis, 2010), chemical (Cockshott, 2005). Offshore industries have also been conducted risk analysis applied in various types of offshore structure as shown in Table 2.5.

Table 2.5. Risk Assessment of Offshore Industries

Approaches	Authors	Offshore Structure	Topics
FMEA – FTA	(Moss and Kurty, 1983)	Tension Leg Platform (TLP)	Reliability Analysis of TLP
HAZID – Structural Reliability Analysis	(Stiff et al., 2003)	Floating Production Offshore Offloading (FPSO)	Comparative Risk Analysis of Mooring
FTA – ETA	(Jacinto and Silva, 2009)	Shipyard	Ship Building Industry
HAZID - ETA	(Petruska et al., 2009)	Mobile Offshore Drilling Unit (MODU)	Mooring MODU Risk Assessments
Fault Tolerant	(Niu, 2009)	Mobile Mooring System	Fault Tolerant Control of Ship Mobile Mooring System
HAZOP – FTA – ETA	(Deacon et al., 2010)	Semi submersible	Risk Analysis in Offshore Emergencies
Fuzzy FTA	(Mentes, 2011)	Tanker buoy mooring	Safety Assessment for Spread Mooring Systems
Fuzzy Logic	(Chang et al, 2012)	Offshore Power System	Fuzzy Logic for Implementing Maintenance Schedules

The other method of risk assessment is Bayesian network which can provide useful estimation of model parameters for decision makers (Fenton, 2007; Siu, 1998). Bayesian parameter may consist of likelihood functions and prior distribution, some simple but realistic examples and variety of cautions and lessons regarding practical applications (Siu, 1998). However this study is not focus on the Bayesian network because Bayesians promote the idea that a multiplicity of parameters can be handled via hierarchical, typically exchangeable, models, but it seem implausible that this could really work automatically and the other reasons is Bayesian is not clear how to assess subjective knowledge in any case (Gelman, 2008). Bayesian require prior distribution for all unknown parameters, but in many cases, prior knowledge is either vague or non existent, and that makes it very difficult to specify a unique prior distribution. Therefore this study will be focus on the FTA in order to determine the probability of failure.

As an example of FTA application is applied by Mentes (2011) that discussed main sub event failure for spread mooring using fuzzy fault trees analysis. The main sub event failure is classified as tanker anchor failure, buoy anchoring system failure, mooring line failure, buoy quick release hooks failure, human error and loading hose failure. Spread mooring is one of the types of permanent mooring that useful to keep the platform in station in any condition that may come.

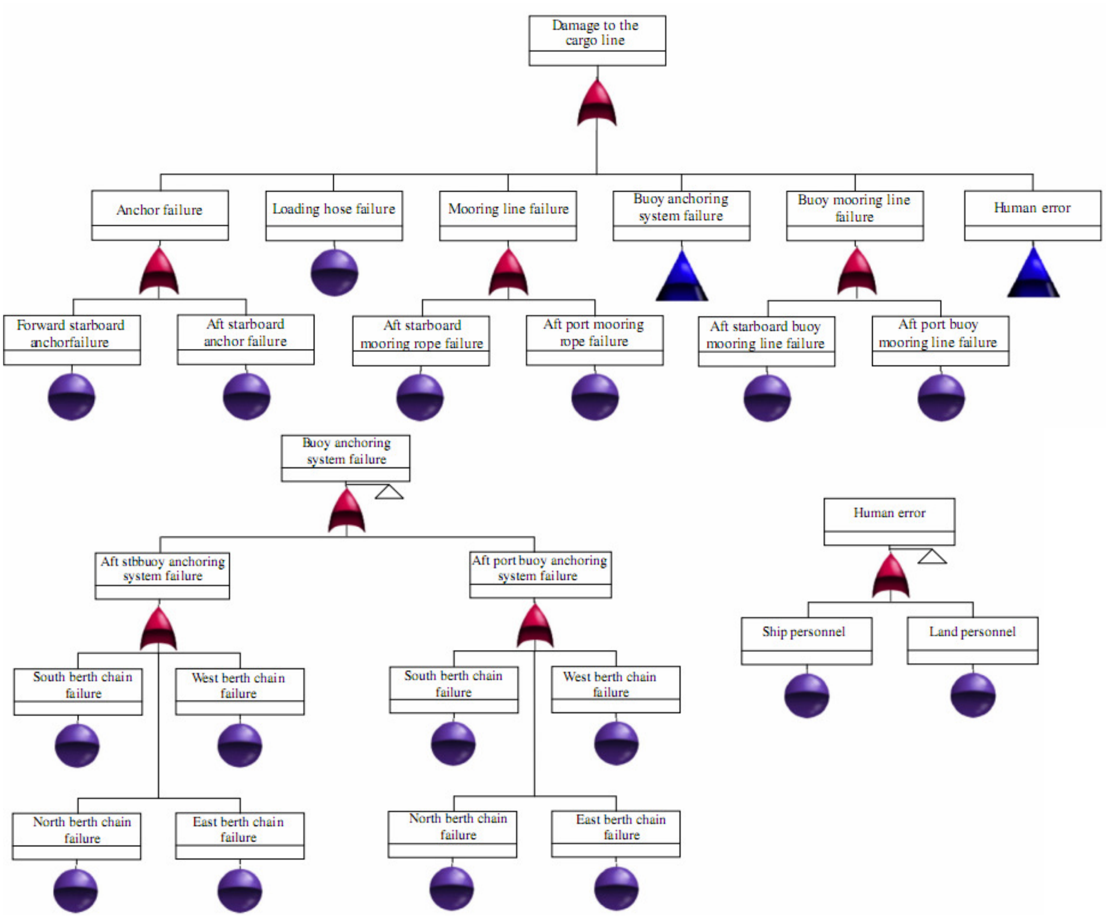


Figure 2.8. Fault Tree Diagram for Spread Mooring (Mentes, 2011)

Figure 2.8 outlines the fault tree diagram that describes the process from the top to bottom events which considered the damage to the cargo line as the top event failure. (Mentes, 2011) develops a model to solve safety assessment problem related to the risk limits of the spread mooring system. The evaluation of the failure frequency of the top event for spread mooring is derived from the frequency of the basic events based on expert knowledge and opinion. The result shows that mooring rope failure is the most critical event in the spread mooring system. Niu (2009) has also developed a fault tolerant control of ship mobile mooring system to explain the performance degradation of the mooring system as shown in Figure 2.9. This paper evaluates the fault tolerant performance under sea wind disturbance. The result indicates that mobile mooring systems have a certain fault tolerant ability in term of when windlasses failed follow by other windlasses failed then the performance of mooring system will be much reduced.

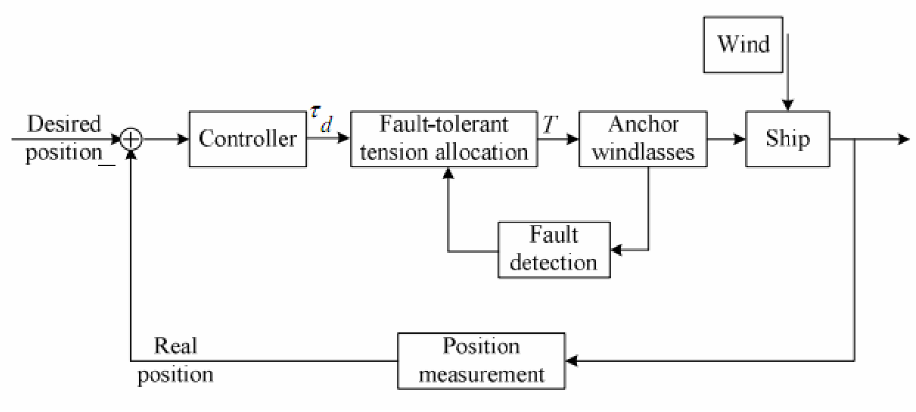


Figure 2.9. Fault Tolerant Control of Ship Mobile Mooring System (Niu, 2009)

Petruska et al. (2009) develop ETA to quantify the likelihood and consequence of each sequence of event of a moored MODU structure as shown in Figure 2.10. In Figure 2.10 the probability of mooring failure during a hurricane namely as initiating event is estimated from the reliability analysis.

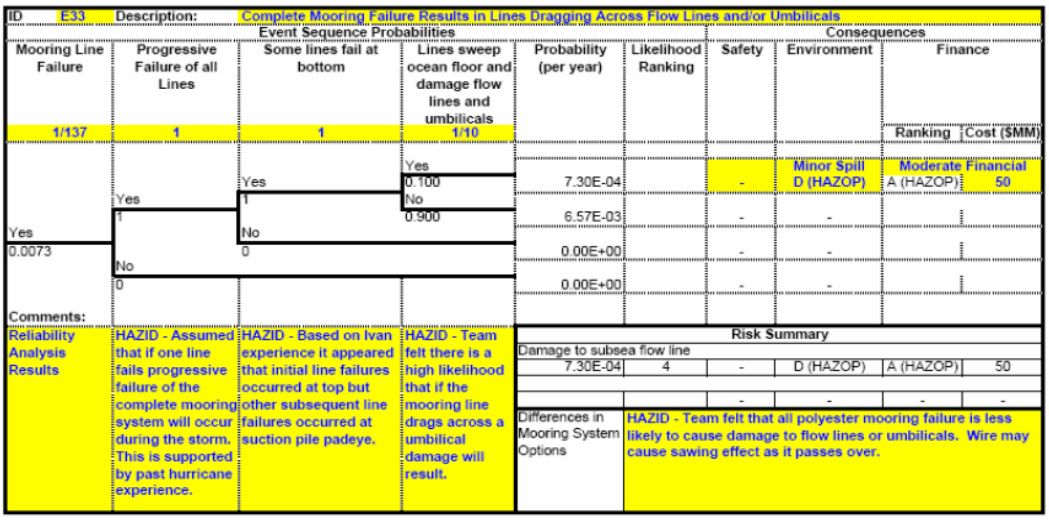


Figure 2.10. ETA Model (Petruska et al., 2009)

The sequence of events is initiated by the failure of one or more mooring lines. The probability of event sequence is gathered from MODU failure data during hurricane seasons. The risk assessment is helpful to determine the risk to nearby deepwater facilities, flow lines and export pipelines. Further analysis is conducted to define the events once a complete mooring system failure occur using HAZID. The HAZID result shows that once a complete mooring system failure occurs it causes:

- Damage to floating production systems (collision or interaction)
- Mooring line/anchor damages to export pipelines
- Mooring line/anchor damages to trees, flow lines or umbilical

Based on the literature review, it is found that mooring system is an essential subsystem of offshore platform whether it is permanent or mobile mooring. The mooring system is used to keep the vessel on station and responsible for the positioning or moving of the vessels. In order to make sure the mooring system fit for purpose, the various potential causes and the possible failure that may result as the consequences need to be investigated. Therefore this study investigates the risk based decision making of the mobile mooring system.

2.5. Risk Based Decision Making (RBDM)

Decision making is a study to identify and choose alternatives based on the values and preferences of the decision maker (Janos, 2006). There are several types of decisions which are deciding whether, decide which, and contingent decisions (Harries, 2009). Decision whether is yes/no decision that must be made before proceed with the selection of an alternative, the decision whether is evaluated by weighing reasons advantages and disadvantages. A decision which involves a choice of one or several alternatives between a list of possibilities, the decision which is evaluated based on how good each alternative measures up to a list of predefined criteria. Contingent decision is a decision that has been made but still on hold until some condition is accomplished for example opportunity, time, price availability are the related criteria that can figure into the necessary conditions that need to be accomplished before the decision maker take the decision (Harries, 2009).

Decision making is a procedure of deciding between alternative courses of action in an attempt to obtain the goals and objectives. Decision making is certainly the most difficult and most important task for manager because they need to make good decisions consistently (Forman, 2002). The formula to develop decision making are describes below (Tools, 2003):

- Prioritizing the decisions by listing all the decisions that need to take and score each item using a scale rating and choose the highest score.
- Evaluating which option is more important by listing all the choices, select a pair of choices and compares the options until left with one option.
- Choosing between options by thinking about possible outcomes by drawing each option of the decision need to take, identify the outcome of each option and review the tree then select the best path.
- Looking at the pros and cons for each possible decision by listing the pros, cons and implications, give scores for each item and finalize the decision by choosing the best score.
- Analyzing the influences for and against making a decision by listing all the influences in decision making, give a score and draw the strengths and weakness of the decision that need to take.
- Assessing the decision from all points of view by looking the decision from all objectives points of view, focus on the data available, focus on the reaction, focus on the bad points of the decision, focus on the benefits of the decisions, focus on creativity and focus on the process control.
- Deciding if a decision is worth making by considering whether the decision is important enough to take, if there is no benefit, the decisions might not be worth taking.

Risk based decision making (RBDM) is a procedure that organizes information about the probability for one or more unwanted consequences to happen in a wide, systematically structure that helps decision makers make more informed management decisions (Macesker, 2009). The flow of RBDM is described in figure 2.11. Risk is determined from the frequency and consequence of a particular scenario, the related frequency data are seldom available and it is recommended that a risk assessment is done by brainstorming with selected expert based on their knowledge and experience operational process (Koivisto, 2009).

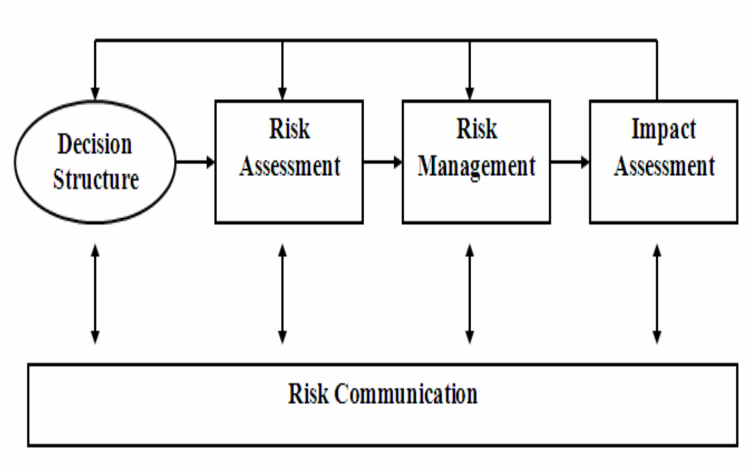


Figure 2.11. Risk Based Decision Making Process (ABS, 2001)

Risk management is a process of selecting appropriate risk mitigation measures and applying them in the ongoing management of the activity, as described in Figure 2.12 (DNV, 2002). There are three types of risk assessment approaches which are qualitative, semi quantitative and quantitative. The intention for conducting risk assessment is to minimize, control and maintain the risk so that any damage or loss can be prevented.

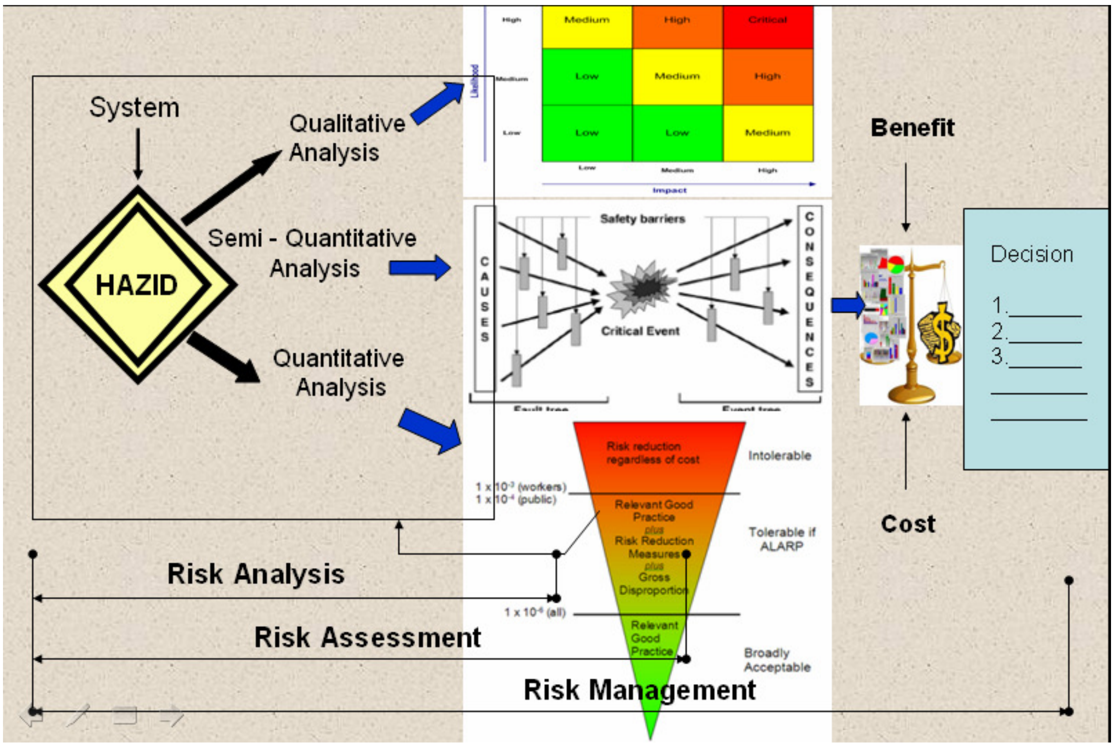


Figure 2.12. Risk Management Approaches (DNV, 2002)

The basic terminology of risk based decision making is based on the term hazard, risk and risk assessment as shown in Table 2.6:

Table 2.6. Basic Terminology of RBDM (Brandsaester, 2002)

Term	Description
Hazards	The assets of a substance or physical condition with a possible to create damage or harm to human health or to the environment.
Risk	The probability of a specific effect initiating from a certain hazard occurring within a specified period or in specified circumstances.
Risk Assessment	This term consists of the following Steps: Step I : Hazard Identification Identification of sources with the possibility to cause undesired outcomes to subjects of concern that is the focus of the estimation of likelihood. Step II : Event Scenario Assessment Identification of the initiators and sequences of events that can lead to the realization of the hazard. Step III : Consequence Assessment Identification and assessment of the consequences of the realized hazard Step IV: Risk Evaluation, this Step consists of two parts: Step IV – A: Risk Assessment: Assessing and evaluating the probability of the consequences and describing the quality of such estimates. Step IV – B: Risk Comparison: Comparing derived risk estimates to specified guidelines / criteria / goals and describing the dependence of these estimates on explicitly specified assumptions. Step V Decision Making Deciding the actions based on the risk evaluation.

As reported by Macekester (2009) the world has increased in demanding more structured and more defensible decisions (especially where risk is involved). At the same time, the systems and operations are becoming more complex, making intuitive risk management decisions more difficult and less reliable. Risk based decision making (RBDM) add the decision making process a systematic consideration of diverse risks that may be important to various stakeholders. Macesker (2009) described a Step by Step of the RBDM process, as the following:

1. Step 1: Establish the Decision Structure

   Step 1a. Define the decision: specifically describe what decision(s) must be made. Major categories of decisions include:

   (i) accepting or rejecting a proposed facility or operation,

   (ii) determining who and what to inpect, and

   (iii) determining how to tbest improve a facility or opreration.

Step 1b. Determine who needs to be involved in the decision: Identify and solicit involvement from key stakeholders who:

(i) should be involved in making the decision or

(ii) will be affected by actions resulting from the decision making process.

Step 1c. Identify the options available on the decision maker: describe the choices available to the decision maker. This will help focus efforts only on issues likely to influence the choice among credible alternatives.

Step 1d: Identify the factors that will influence the decision (including risk factors): few decisions are based on only one factor. Most require consideration of many factors, including costs, schedules, risks, etc., at the same time. The stakeholders must identify the relevant decision factors.

Step 1e. Gather information about the factors that influence stakeholders: Perform specific analysis (e.g., risk assessments and cost studies) to measure against the decision factors.

2. Step 2: Perform the risk assessment

Step 2a: Establish the risk related questions that need answers: Decide what questions. if answered, would provide the risk insights needed by the decision maker.

Step 2b: Determine the risk related information needed to answer the questions: Describe the information necessary to answer each question posed in the previous Step. For each information item, specify the following:

i. information type needed
ii. precision required
iii. certainty required
iv. analysis resources (staff hours, cosrt, etc) available

Step 2c: Select the risk analysis: Select the risk analysis tool(s) that will most efficiently develop the required risk related information.

Step 2d: Establish the scope for the analysis tool(s): Set any appropriate physical or analytical boundaries for the analysis.

Step 2e: Generate the risk based information using the analysis tool(s): Apply the selected risk analysis tool(s). This may require the use of more than one analysis tool and may involve some iterative analysis (i.e., starting with a general, low detail analysis and progressing toward a more specific, high detail analysis).

3. Step 3: Apply the results to Risk management decision making

Step 3a: Assess possible risk management options: determine how the risks can be managed most effectively. This decision can include:

i. accepting/rejecting the risk or

ii. finding specific ways to reduce the risk.

Step 3b: Use risk based information in decision making:

Use the risk related information within the overall decision framework to make an informed, rational decision. This final decision making Step often involves significant communication with a broad set of stakeholders.

4. Step 4: Monitor effectiveness through impact assessment

Track the effectiveness of actions taken to manage risks. The goal is to verify that the organization is getting the expected results from its risk management decisions. If not, a new decision making process must be considered.

5. All Steps: Facilitate Risk Communication:

Encourage two ways, open communication among all stakeholders so that they will:

i. provide guidance on key issues to consider

ii. provide relevant information needed for assessments

iii. provide buy in for the final decisions

2.6. Risk Assessment

Risk assessment is a universal term which includes several analytic techniques that are used in different conditions, depend on the typical of the hazard, the accessibility data, and requirements of decision makers (Haimes, 2001). Risk assessors are tools used for estimating the probability and consequence of risks to human health, safety and the environment and for enlightening decisions about how to deal with those risks. Prioritizing and managing the risk can be obtained with the help of risk assessment by considering the investigation scope of work, the type of data collection, the alternative of analytic methods, and the methods taken on reporting the results.

The most important is the purpose of an assessment should be made obvious before the analytical work starts. Often a risk assessment carries out to help determine whether to decrease risk and if so to create the suitable level of stringency. Risk assessments are used to analyze risk reduction under various policy alternatives to verify if these alternatives are effective in reducing risks. In some organization programs, the results of risk assessments are an important technical input to benefit cost analysis, which are then used to enlighten risk management decisions in rulemakings (Beck, 2006).

Risk assessment can be considered as a structured engineering judgment or a review as to the acceptability of risk based on comparison with risk standards (DNV, 2002). Risk matrix can be used as a framework to describe reflection of the frequency and consequence of hazards. The hazards can be ranked in order of significance or it can be used to evaluate the mitigation of each hazard. DNV (Det Norske Veritas) developed the ISO 17774. It uses a 5 by 6 risk matrix (DNV, 2002) as described in Figure 2.13.

Consequence					Increasing Probability				
Severity Rating	People	Assets	Environment	Reputation	A	B	C	D	E
					Rarely occurred in industry	Happened several times per year in industry	Has occurred in operating company	Happened several times per year in operating company	Happened several times per year in location
0	Zero injury	Zero damage	Zero effect	Zero impact	Manage for continued improvement				
1	Slight injury	Slight damage	Slight effect	Slight impact					
2	Minor injury	Minor damage	Minor effect	Limited impact					
3	Major injury	Local damage	Local effect	Considerable impact					
4	Single fatality	Major damage	Major effect	Major national impact	Incorporate risk reducing measures			Intolerable	
5	Multiple fatalities	Extensive damage	Massive effect	Major international impact					

Figure 2.13. ISO 17776 Risk Ranking

IMO (International Maritime Organization) also developed risk ranking matrix with the frequency index as described in Table 2.7 (IMO, 1997).

Table 2.7. Frequency Index IMO

FI	Frequency	Definition	F (per ship year)
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of ships, i.e. likely to occur several times during a ships life	0.1
3	Remote	Likely to occur once per year in a fleet of 1000 of ships, i.e. 10% chance of occurring in the life of 4 similar ships	10^{-3}
1	Extremely remote	Likely to occur once in 100 years in a fleet of 1000 ships, i.e. 1% chance of occurring in the life of 40 similar ships	10^{-5}

Deacon et al. (2010) explains that the qualitative frequencies of ISO standard 17776 developed by DNV as shown in Figure 2.13 can be compared with the frequency index from IMO as can be seen in Table 2.7. Therefore this study adopts both standards into 7 x 6 risk matrix. The application of 7 x 6 risk matrix, will increase the visibility of risk and assist management decision making. Risk is formulated by the product frequency multiple consequences, then an index of log (risk) can be obtained by adding the frequency and severity indices (DNV, 2002). Risk Index (*RI*) formulated as:

$$RI = FI + SI \quad (2.1)$$

where, FI is Frequency Index and SI is Severity Index.

Based on the frequency and consequence ranges, the risk classes are divided into four as can be seen in Table 2.8. Risk model helps to establish which trades contribute the most to the transition of the portfolio and predict tracking error to a benchmark within acceptable limits (Pearce, 2011).

Table 2.8. Risk Class

Risk Class	Risk Level	Interpretation
A	Very High	Intolerable
B	High	Undesirable and shall only be accepted when risk reduction is impracticable
C	Medium	Tolerable with the endorsement of the Project Safety Review Committee
D	Low	Tolerable with the endorsement of the normal project reviews

Developing an understanding of the risk is called “risk analysis”. It provides an input to decisions on whether risks need to be treated in the most appropriate and cost-effective risk treatment strategies (Lawson, 2005). Risk assessment is an ongoing process and as the facts change, so do the conclusions of the assessment. This has presented a significant challenge for risk assessors who must make judgments even when information is incomplete (Cree, 2003). There are many hazard risk analysis methods that can be used, based on the system that is to be investigated. Offshore environment involves uncertain and unpredictable conditions that can cause accidents. In order to identify and determine the potential failure and the possible consequence it needs to conduct hazard risk analysis. The hazard risk analysis methods used in this study are based on (ABS, 2001) and (API, 1993).

Table 2.9. Characteristic of Hazard Analysis (API, 1993)

API RP 14J	Hazard and Operability (HAZOP)	Fault Tree Analysis (FTA)	Event Tree Analysis (ETA)
Level of Effort / Complexity	Medium to High	High	High
Level of Expertise Required for Analysis Teams	Medium	Medium to High	Medium to High
Qualitative Accident Descriptions	√	√	√
Quantitative Risk Characterizations	-	√	√
Relative Importances of Accident Contributors	-	√	√
Types of Activities or Systems	All types of process/plants/facilities	All, in the design phase, facility modifications and operation	All, in the design phase, facility modifications and operation
Results	A list of problem areas that lead to potential hazards / operability problems, and a list of recommended changes, suggestions or actions to improve safety/operability.	A set of logic diagrams that illustrates how certain combinations of failures and/or errors can result in specific accidents.	A set of logic diagrams that illustrates how certain combinations of failures and/or errors can result in specific accidents.

API (1993) described the characteristics of hazard analysis as shown in Table 2.10. From this table it can be seen that the methods that are going to be used involve the qualitative and quantitative methods and it can be used in all types of facilities. Table 2.10 shows the limitations of the three hazard risk analysis methods. In order to minimize the limitations of each method therefore this study integrated the three methods to formulate the top hazardous accidents events for the mobile mooring system.

Table 2.10. Limitations of Hazard Risk Analysis Methods (ABS, 2001)

No.	Hazard Risk Analysis Methods	Limitations	Tendency to Type of Decision Analysis
1.	Hazard and Operability (HAZOP) Analysis	- Requires a well defined system or activity - Time consuming - Focuses on one event causes of deviations	Used to review procedures and sequential operations
2.	Fault Tree Analysis (FTA)	- Narrow focus - Art as well as science - Quantification requires significant expertise	Assessments generates relative importance of various failure causes and contributing events
3.	Event Tree Analysis (ETA)	- Limited to one initiating event - Can overlook subtle system dependencies	Analysis technique generates relative importance of various failure sequences and contributing events

2.6.1. Hazard and Operability

Hazard and Operability (HAZOP) is a qualitative method with a systematic and structured assessment of a planned or operation in order to define and assess the issues which can cause risks to human resources or equipment (Rausand, 2005a). The objectives of a HAZOP study are as follows (Balchin, 2005):

- To determine and deal with hazards and design insufficiency for the purpose of ensuring safety and health of effective operations.
- To assess the performance that will satisfy SHE (Safety Health and Environment) standards.

In order to implement HAZOP techniques, the brainstorming and discussion with the expert need to be carried out and formulated into systematic records (Dhillon, 2003). The HAZOP records generally consist of guide word, deviation, possible causes, possible consequences, safeguards and action to be taken as shown in Table 2.11.

Table 2.11. HAZOP Worksheet Example

System Identification					
Activity: Description of System Activity					
Guide Word	Deviation	Possible Causes	Possible Consequence	Safeguard	Action

The descriptions for each column of the presented worksheet are:

a. Guide word: A keyword to create the imagination of a deviation of the system.

b. Deviation: Description of a system in which the process condition may depart from their design.

c. Possible Causes: Description of the causes why the deviation could happen that may result in the worst possible consequence.

d. Possible Consequence: Consequence of the occurrence of the failure or the results of the deviation.

e. Safeguards: A facilities that either prevent the cause or safeguard against the consequence such as regular plant inspections.

f. Action: description of the action that should be taken when the consequence occur. It can remove the cause and mitigate or eliminate the consequences.

The importance of performing HAZOP analysis as discussed by Ahmad (2010) are as the following:

- HAZOP defines possible hazards, failure and operational issues.
- HAZOP has been used for over 40 years by professional institutions and legislators.
- HAZOP methods are used by the majority companies handling and processing hazardous material especially oil and gas production, flammable and toxic chemicals and pharmaceuticals etc.
- HAZOP results are integral elements of plant and safety records and also appropriate to plant modifications.

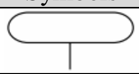
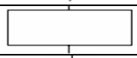
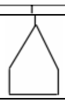
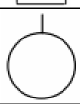
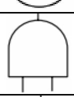
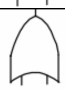
2.6.2. Fault Tree Analysis

The fundamental of FTA and risk assessment processes have been integrated and it was found that both approaches useful to control the uncertainty of significant future and to aid decision making in developing management plans of uncertainty future (Koivisto, 2009).

2.6.2.1. Basic of Fault Tree Construction

FTA is a deductive approach that consists of symbols and gates in order to describe the process of system failure. The symbols and gates which are useful to construct fault tree are illustrated in Table 2.12.

Table 2.12. FTA Symbols (Stamatelatos, 2002)

Fault tree symbols			
Symbols	Code	Name	Descriptions
	Ellipse	Top event	Description of the system level fault or the undesired event.
	Rectangle	Fault event	Description of a lower level fault.
	House	Input event	A normal system operating input which has the capability of causing a fault to occur.
	Circle	Basic event	A failure at the lowest level of examination which has the capability of causing a fault to occur
	And gate		Output occurs only if all inputs exist
	Or gate		Output occurs only if one or more of the input events occur

2.6.2.2. Fault Tree Mathematics

In order to analyze the fault tree, the evaluations uses the rules of Boolean Algebra. A fault tree is translated into an equivalent set of Boolean equations. Figure 2.14 shows the applications of OR gate that described the union of the events attached to the gate. The events above the gate will occur if one or more of the input events occur.

$$P(Q) = P(A) + P(B) = P(A \cap B)$$

Or

$$= P(A) + P(B) - P(A)P(B|A) \qquad (2.2)$$

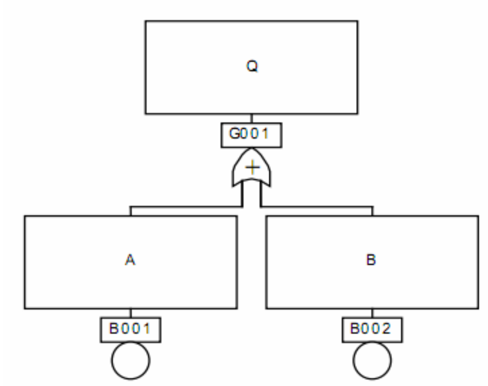


Figure 2.14 Two Input OR Gate (Stamatelatos, 2002)

The formulation of Figure 2.14 can be made as the following:

- If A and B are mutually exclusive events, then $P(A \cap B) = 0$ and $P(Q) = P(A) + P(B)$
- If A and B are independent events, then $P(B|A) = P(B)$ and $P(Q) = P(A) + P(B) - P(A)P(B)$
- If event B is completely dependent on event A, that is whenever A occurs, B also occurs, then $P(B|A) = 1$ and

  $$P(Q) = P(A) + P(B) - P(A)$$
  $$P(Q) = P(B)$$

- The approximation $P(Q) \cong P(A) + P(B)$ for all A, B; $P(A) + P(B) \geq P(A) + P(B) - P(A \cap B)$ for all A, B.

- If A and B are independent, low probability events $P(A), P(B) < 10^{-1}$, then $P(A \cap B)$ is small compared with $P(A) + P(B)$ so that $P(A) + P(B)$ is an accurate approximation of $P(Q)$.

- An Exclusive OR gate with two inputs A and B, the output event Q occurs if event A occurs or event B occurs but not both. The probability expression for the output event Q of an exclusive OR gate is:

$$P(Q)_{ExclusiveOR} = P(A) + P(B) - 2P(A \cap B) \quad (2.3)$$

The comparison between Equations (2.2) and (2.3) mostly not necessary in FTA and the difference in probability between two expressions is negligible. Nevertheless the difference in special cases where exclusive OR gate is required than the intersection term may be long enough to considerably affect the result. The other gate is AND gate that describes the intersection of the events attached to the gate as can be seen in Figure 2.15. The event above the gate will occur if all of the input events attached to the AND gate occurs.

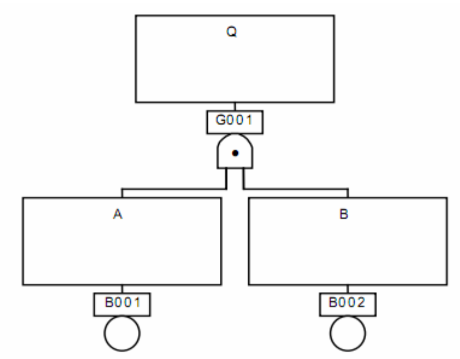


Figure 2.15. Two Input AND Gate (Stamatelatos, 2002)

In this case Q will occur if and only if all the events occur. The probability of two events:

$$P(Q) = P(A)P(B|A) = P(B)P(A|B) \quad (2.4)$$

The formulas based on the Figure 2.15 can be concluded:

- If A and B are independent events, then $P(B|A) = P(B), P(A|B) = P(A)$ and $P(Q) = P(A)P(B)$;

- If A and B are not independent events, then P (Q) may be significantly greater than $P(A)P(B)$.

2.6.2.3. Minimal Cut Set

Cut set (CS) is a group of failure events that if they all occur causing the top event to occur. Minimal cut set (MCS) is a minimal group of failure events that can still cause the top event to occur (Ericson, 2000). The basic mathematical technique involved in the quantitative assessment of fault trees is called probability theory. It defines an analytical treatment of events, and events are the fundamental components of fault tress (Commission, 1981). FTA is useful to describe the root cause of an accident logically. Quantitative analysis of fault trees usually perform two cases (Celik, 2010):

i. Fault Trees without Repeated Events

The fault tree contains independent basic events which appear only once in the structure. The probability of top event can be obtained by calculating the basic event probabilities up through the tree. For an AND Gate, the formulation to obtain the occurrence probability of top events:

$$P = \prod_{i=1}^{n} p_i \qquad (2.5)$$

For an OR Gate, the formulation to determine the occurrence probability of top events:

$$P = 1 - \prod_{i=1}^{n} (1 - p_i) \qquad (2.6)$$

Where P is the occurrence probability of the top events, p_i denotes the failure probabIlity of basic events i, and n is the number of the basic events.

ii. Fault Trees with Repeated Events

In order to obtain the probability of top event when basic events in fault tree appear more than once, then the minimal cut sets (MCS) have to be determined. An MCS is a collection of basic events for example $MCS_i, i = 1,...,n_c$. The formula for top event if basic events appear more than once:

$$Z = MCS_1 + MCS_2 + ... + MCS_{n_c} = \bigcup_{i=1}^{n_c} MCS_i$$

An exact evaluation of the top event occurrence probability is:

$$P(T_Z) = P(MCS_1 \cup MCS_2 \cup ... \cup MCS_N)$$

$$= P(MCS_1) + P(MCS_2) + ...P(MCS_N) - (P(MCS_1 \cap MCS_2)$$

$$+ P(MCS_1 \cap MCS_3) + ...P(MCS_i \cap MCS_j)...)...$$

$$+ (-1)^{N-1} P(MCS_1 \cap MCS_2 \cap ... \cap MCS_N) \quad (2.7)$$

2.6.2.4. DPL Fault Tree Software

The framework of fault tree was developed in the DPL Fault Tree Version 4.03.03, by Syncopation Software (Dalton, 2005). DPL fault tree evaluates a hierarchical model that is used to analyze risk based on the hypothesis that each component of faults or failures has a probability of occurrence. DPL software has been used successfully by Gregory (2009) to develop the decision analysis model. There are few steps to conduct the DPL fault tree software which is consisting of creating a fault tree graphically and analyzing fault tree.

2.5.2.4.1. Creating Fault Trees Graphically

Fault tree has a natural hierarchical structure constructed from top to bottom, the top level or the root is the event that corresponds to the most general statement of the risk. The first level down from the root consists of a list of events that feed into a gate attached to the top events. The hierarchy structure continues down the tree and in the end the events ought to be specific so that it can be evaluated directly. The endpoint events commonly called as basic events or undesired events.

2.5.2.4.2. Analyzing Fault Trees

In order to analyze the fault tree, there are three main analysis need to establish which are fault tree decision analysis, minimal cut sets and partial derivatives (Dalton, 2005).

(i) Fault Tree Decision Analysis

Fault tree decision analysis, reports the probability of an event in the fault tree. In order to run decision analysis the DPL software puts on view the decision analysis option dialog.

(ii) Minimal cut sets

Minimal Cut Sets are a type of sensitivity analysis that is particularly toward fault trees. It is used to determine the most potential ways for the tope event to occur. A list of basic events occur causes the top event will also occur, those lists of basic events are called a cut set. Elements of a cut set may be basic events and a fault tree can have many possible cut sets. A minimal cut set is a cut set such that if any element is detached, the remaining elements are no longer a cut set. The minimal cut sets are helpful to determine the most likely in the top event to occur.

(iii) Partial Derivatives

Partial derivatives present a qualitative method of selecting the events that have a significant impact on the top event. The results are generated for individual events (as opposed to minimal cut sets, whose results are generated for sets), and are quantitative in nature. The partial derivatives chart shows the partial derivatives or the maximum impact. The partial derivatives define how much a change in the probability of each basic event affects the probability of the top event. This value depends on the structure of the model and the probabilities of other events, but not the probability of the event in question. The maximum impact determines how much the probability of the top event can be reduced by setting the probability of each basic event to zero. For example, if a particular basic event is part of every cut set, the maximum impact of that event will be the entire probability of the top event.

2.6.3. Event Tree Analysis

Event tree analysis (ETA) is a useful approach to identify and to assess the sequence of events in a possible accident scenario pursuing the occurrence of an initiating event (Ericson, 2005). ETA is an inductive method that defines all potential consequences resulting from an accidental (initiating) event, those potential consequences is called consequence spectrum (Rausand, 2005b). The concept of ETA is shown in Figure 2.16.

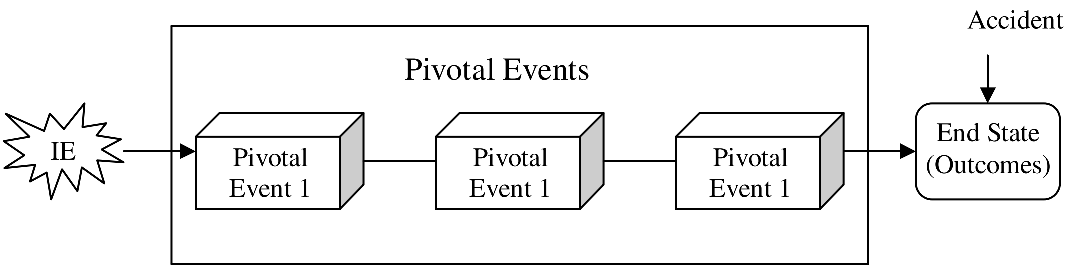


Figure 2.16. Event Tree Concept (Ericson, 2005)

Generally the pivotal event splits in event tree are binary, success or failure, yes or no condition. The failure frequency data can be established through the failure events in the event tree diagram. The frequency of success (P_S) is derived from the frequency of failure (P_F) calculation as formulated below (Ericson, 2005):

$$P_S + P_F = 1 \quad (2.8)$$

A list of the outcomes can be determined and evaluated by multiplying the event frequency in the path events. Figure 2.17 shows the example of the event tree concept into quantitative calculations.

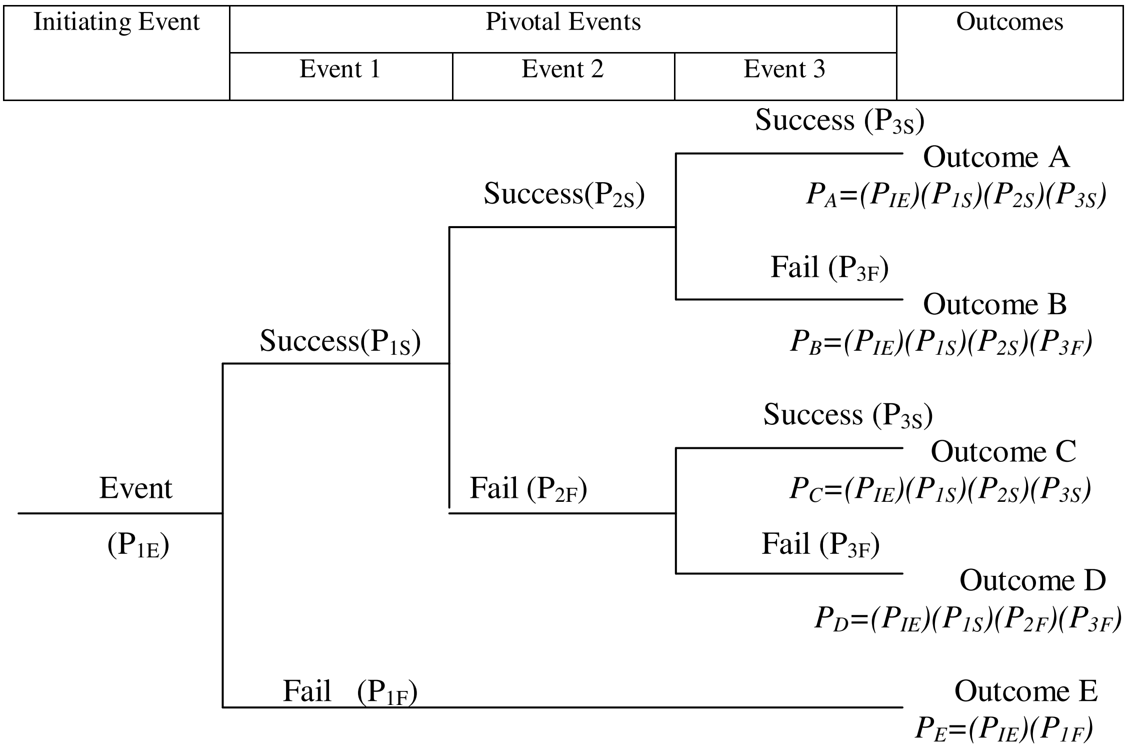


Figure 2.17. ETA Calculations (Ericson, 2005)

Event tree is a graphical model of an accident scenario that illustrates the multiple outcomes and their frequency based on the following definitions (Ericson, 2005):

- IE (Initiating Event) is a failure or undesired event which initiates the beginning of an accident sequence. The IE can result in an accident, depending on successful operation of the hazard corrective techniques of the system.
- PE (Pivotal Event) is mediator event between the IE and the final accident. PE events are the failure/success events of the design safety techniques obtained to avoid the IE coming out from an accident. If pivotal events smoothly succeed, they prevent the accident scenario and are called mitigation events. If a pivotal event fails, then the accident scenario is permitted to continue and it is considered as an aggravation event.
- Accident scenarios are a list of events that eventually come up with an accident. The sequences of events start with an initiating event and are mostly followed by one or more pivotal events which cause the outcome or the consequences.

In order to model the accident scenario of complex system that can have many different outcomes, the ET models handle this complexity very well. ETA is one of the most used methods for risk assessment with the advantage and disadvantages as shown in Table 2.13.

Table 2.13. Advantages and Disadvantages of ETA (Ericson, 2005)

Event Tree Analysis	
Advantages	1. Systematic, clear and methodical approach
	2. A large section of the analysis can be computerized
	3. It can be effectively applied on various levels of design detail
	4. Visually model the cause/effect correlation
	4. Moderately easy to practice, applied and follow
	4. Combines the hardware, software, environment and human interaction
	7. Allow probability assessment
	8. Commercial software is available
Disadvantages	1. ETA can only have one initiating event, therefore it needs multiple ETAs in order to evaluate the outcome of multiple initiating events
	2. ETA can ignore subtle system dependencies when modeling the events. Logical dependencies among accident phenomena very difficult to model properly.
	3. Partial successes/failures are not noticeable
	4. Need an analyst with some training and practical experience

2.7. Maintenance Strategy

Offshore operation needs a maintenance strategy to ensure the safety and efficiency of an installation. Inadequate maintenance has been a major issue in many accidents and incidents therefore it is important to organize the maintenance strategy (HSE, 2004). The maintenance philosophy has been changed into various maintenance types such as corrective maintenance, predetermined maintenance and predictive maintenance. Figure 2.18 illustrates the relationship between failure rate versus change in maintenance philosophy is showing decline trend. This figure also describes the strengths and weaknesses of the different maintenance types.

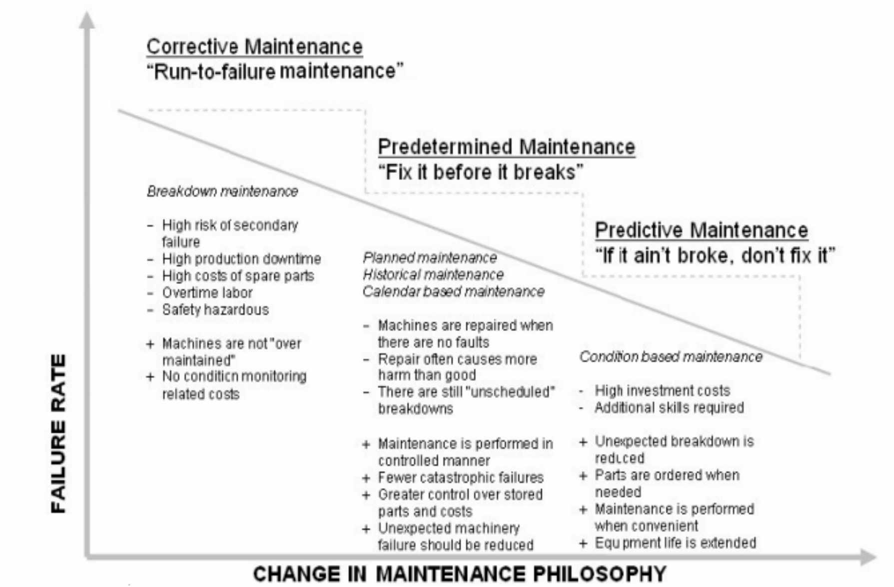


Figure 2.18. Change in Maintenance Philosophy (Sethiya, 2006)

There are many variations among practitioners regarding the terminology used to describe the maintenance strategy, in general the maintenance strategies are briefly the following:

(i) Run to failure maintenance (RFM)

Run to failure maintenance strategy is a reactive management method that does not spend any money on maintenance until the equipment or machine failure. Run to failure maintenance strategy has the disadvantages as the following as reported by KSU (2010):

a. The action of this maintenance strategy are expensive

b. The occurrence of a failure in a component can cause failures in other components in the same equipment, which leads to low production availability

c. The actions of this strategy are very difficult to plan and schedule in advance.

The cost of performing RFM action is lower than performing other action of other types of maintenance because it does not spend any money on maintenance until a equipment or system fails to operate as reported by KSU (2010).

(ii) Preventive maintenance (PM)

Preventive maintenance strategy are time driven that assume the equipment or machined will degrade within a certain time based on their particular specification. Preventive maintenance programs uses bathtub curve to conduct equipment repairs which shown in Figure 2.19. The bathtub curve described new equipment has a high frequency of failure because of installation issues during the early time operation. The next period of time has relatively low frequency of failure for an extended period or called the normal period. The last period shows the increasing frequency of failure of the equipment.

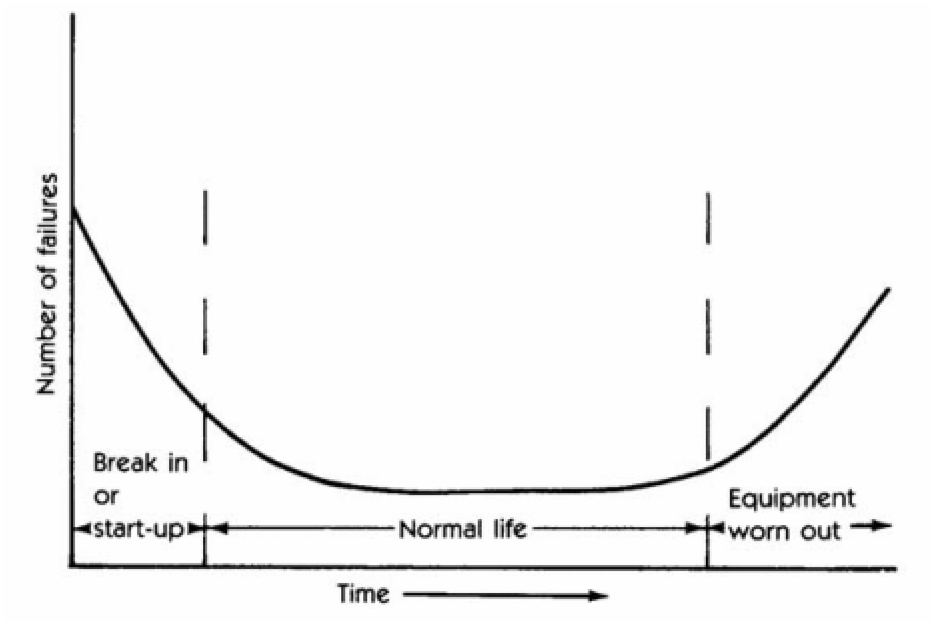


Figure 2.19. Bath up Curve (Mobley, 2002)

(iii) Predictive maintenance (PeM)

Predictive maintenance strategy is a condition driven preventive maintenance that monitored the vibration of rotating machinery in order to identify initial problems and to prevent catastrophic failure. Preventive maintenance performs the repair schedules based on the intuition and the personal experience of the maintenance manager. In order to detect the signs of failure, predictive maintenance divides into two types methods which are condition based predictive maintenance and statistical based predictive maintenance.

Generally there are five nondestructive techniques used for predictive maintenance strategy consist several techniques as the following (Mobley, 2002):

a. Vibration Monitoring

This approach is a computer based system in order to obtain, manage, trend and evaluate the vibration energy created by the electromechanical systems. Vibration monitoring focuses on the critical production systems, this technique evaluates each of the systems as a single machine and not as individual components. Vibration monitoring allows the analyst to detect abnormal operation within a complex system for example tracking, tension and product quality deviations can be identified and repaired using this technique.

b. Thermography

This technique uses instrumentation designed to observe the emission of infrared energy such as surface temperature in order to verify operating condition. Thermography is helpful to observe the condition of plant machinery, structures, systems and electrical equipment. There are three types of thermographic systems which are infrared thermometers, line scanners and infrared imaging systems.

- Infrared thermometers or spot radiometers are useful to monitor the actual surface temperature at a single, relatively small point on a machine or surface.
- Line scanners are a one dimensional scan or line of comparative radiation with a larger field of view.

- Infrared imaging useful to scan the infrared emissions of complete machines, process or equipment through the instrument optics which function more less like a video camera.

c. Tribology

Tribology is useful to design and operating dynamics of the bearing lubrication rotor support structure of machinery. There are two methods of Tribology which are lubricating oil analysis and wear particle analysis.

- Lubricating Oil Analysis

  This technique is useful to identify the condition of lubricating oils used in mechanical and electrical equipment. The major applications for lubricating oil analysis are quality controlled, reduction of lubricating oil inventories and determination of the most cost effective interval for an oil change.

- Wear Particle Analysis

  Wear particle analysis is conducted by drawing a sample of lubricating oil which useful to provide information on the wearing condition of the machines.

d. Visual Inspection

Visual inspection is a daily maintenance of critical production and manufacturing systems in order to determine the potential failure or maintenance related problems which can effect on the reliability, product quality and production costs. This method is a viable predictive maintenance tool and supposed to be conducted in all total plant maintenance management strategies.

e. Ultrasonic

Ultrasound is a noise frequency analysis above 30.000 Hz that helpful to detect leaks that commonly produce high frequency noise. This noise is caused by the expansion or compression of air, gases or liquids as they flow through the orifice or the leak in either pressure or vacuum vessels.

(iv) Condition based maintenance (CBM)

CBM is a maintenance programs that helpful to define incipient faults before they become serious problems which is based on actual condition obtained from in situu, non invasive test, operating and condition measurement (Sethiya, 2006). The advantages of CBM has been reported by Sethiya (2006) are as follows:

- Better product quality.
- Increased component operational life/availability.
- Improved worker and environmental safety.
- Allows for preemptive corrective actions.
- Decrease in costs for parts and labor.

The disadvantages of CBM as discussed by Sethiya (2006) are as follows:

- Diagnostic equipment being costly has increased the investment.
- Staff training increased the investment.
- Management can not see readily potential savings.

(v) Corrective Maintenance (CM)

Corrective maintenance strategy is event driven based on performing repair / maintenance action after the equipment or the system failure has occurred. This maintenance strategy is not concerned with scheduling inspections or service routines on deteriorating on deteriorating components (Kaiser, 2007a). The main goals of corrective maintenance strategy are the maximization of the effectiveness of all critical plant systems, the elimination of unnecessary repair, the elimination of breakdowns and the reduction of the deviations from optimum operating conditions (KSU, 2010). Table 2.14 shows the characteristics of maintenance strategy.

Table 2.14. Characteristics of Maintenance Strategy (KSU, 2010)

The Main Differences of Maintenance Strategy				
CM	PM	RFM	CBM	PeM
Corrective maintenance action is conducted after the failure occurs in order to eliminate the source of this failure or reduce the frequency of its occurrence	Preventive maintenance performs a list of actions before the occurrence of a failure in order to prevent any degradation or to reduce the frequency of failure.	Run to failure maintenance action are unplanned and on schedule, the occurrence of a failure in a component can cause failures in other components in the same equipment	Condition based maintenance uses a list of measurements and data acquisition systems in order to monitor the equipment performance in real time.	Predictive maintenance analyze the acquired controlling parameters in order to find a possible temporal trend, it is useful to predict when the controlled quantity values excess the threshold values

2.8. Analytic Hierarchy Process

An offshore operation is a complex and expensive installation structure, it needs to adopt safety assessments that cover all possible areas. In order to conduct a safety assessment the availability of failure data and uncertainty level of condition should be recognized. But those two factors have been the main issues in safety analysis therefore it is required to develop safety assessment technique using multi criteria decision making techniques. Gathering all the information for the purpose of decision making has developed into a mathematical science now days (Figuera, 2005).

AHP is a commonly used mathematical approach particularly if the subjectivity may affect on the overall result of the decision making process (Tuzmen, 2011). AHP has been applied around the world in a wide variety of decision making in order to define a ranking level from pairwise comparison (Zhai, 2010; Salem, 2010; Koul, 2010). AHP is one of the most appropriate multi criteria approaches that used in decision making by combining various different types of criteria (Yurdakul, 2004). Analytic Hierarchy Process (AHP) is an approach of measurement throughout the matrix pairwise comparisons and relies on the experts' judgments in order to define the priority scales (Saaty, 2008). Compare with other decision theories, AHP is better in representing the way experts make decisions (Demko, 2005). AHP also allows to evaluate both tangible and intangible factors, the other merit of this method are described below (Dipak, 2008) :

- The numerous subjective factor can be quantified in order to construct decision making.
- Qualitative judgment and quantitative data can be incorporated in the priority setting process.
- The sensitivity analysis of AHP offer the decision makers a sense of the effects of their decisions.
- AHP is an effective method in order to carry out group discussion in an analytical and systematic manner.
- It requires collection of information which is ultimately of use during the detailed engineering stage.

In order to obtain the priorities in decision making, there are several Steps to do as developed by Saaty (2008):

2. Determine the issue or related matters and establish the correlated knowledge.
3. Develop the decision hierarchy start with the top level which is the goal of the decision, continue to second level which is the objective from a wide perspective, through the intermediate levels which is the criteria of subsequent elements depend) until the lowest which is usually a list of the alternatives.
4. Perform a set of pairwise comparison matrices. Every aspect in an upper level is utilized to compare the aspects in the level directly below with respect to it.
5. Get the priorities established from the comparisons to weigh the priorities in the level directly below. Conduct this Step for every aspect and continue for every aspect in the level below to add its weighing values and establish its overall or global priority. This procedure of weighing and adding are carried on until the final priorities of the alternatives in the bottom most level are established.

In order to make the judgment between two factors, AHP uses the fundamental scale to make the comparison easier. Table 2.15 shows the fundamental scale of absolute number developed by Saaty (1988).

Table 2.15. The Fundamental Scale of Absolute Numbers (Saaty, 1988)

Intensity of Importance	Definition	Description
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favor very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	A reasonable assumption
1.1 – 1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

To select the best alternatives in decision making, the evaluation of hierarchical structure should follow the seven pillars of AHP. The seven pillars of AHP are highlighted below (Saaty, 2001):

a. Ratio scales derived from reciprocal paired comparisons. Ratio scales are the merely option to specify a decision making in general structure consisting some of hierarchies.

b. Paired comparisons and the psychophysical origin of the fundamental scale used to make the comparison. The fundamental 1-9 scales derive the eigenvector based on the reciprocal paired comparison. The inconsistency in judgment is tolerated by performing sensitivity analysis, the judgment of alternatives is considered as random variables with probability distributions. Three types to rank the alternative are the following:

   (i) Relative that ranks at a small number of alternatives by evaluating them in pairs. It is very helpful in new and tentative decisions.

   (ii) Absolute that rates an infinite number of alternatives at one time. It is helpful if there is knowledge to judge and to prioritize the relative importance of the occurrence.

   (iii) Benchmarking that ranks the alternatives by containing a recognized alternative in the team and start evaluating them to find the priorities.

c. Conditions for sensitivity of the eigenvector to changes in judgments. The eigenvector as reciprocal to establish the relative dominance of the other element by evaluating how much better the elements are.

d. Homogeneity and clustering to extend the scale from 1-9 to 1 - ∞. Clustering is important and need to be done independently for each criterion and feasibly it can go up to several adjacent ranges of homogeneous elements.

e. Additive synthesis of priorities, leading to a vector of multi linear forms as applied within the decision structure of a hierarchy or the more general feedback network to reduce multi dimensional measurements to a uni-dimensional ratio scale.

f. Rank preservation and reversal, allowing rank preservation (ideal mode) or allowing rank reversal (distributive mode). Those modes of synthesis are used in AHP and rank can be used in the ideal mode in both absolute measurement and relative measurement.

g. Group judgments, group decision making using a mathematical justifiable way of synthesizing individual judgments which allow the construction of a cardinal group decision compatible with the individual preferences.

2.8.1. AHP Application for Maintenance Purpose

AHP is a structured approach that deals with multi criteria decision making. The AHP helps the decision makers determine the best alternative based on their needs and requirements. Maintenance strategies involve many choices, hence the AHP will help to choose the best maintenance policy to be selected. AHP approach has proved to be a valid support for selecting maintenance strategy (Zhaoyang, 2011). Maintenance strategy usually developed based on centralized or decentralized organization systems.

Centralized system of maintenance represents that all maintenance functions and services are supplied to the organization from a centrally administered location while the decentralized system means each production area managers its own maintenance functions generally under the supervision of the area production manager. (Ali, 2004) was compare the centralized and decentralized system using AHP, the results shows that the centralized system is more productive compare to decentralized system. However in actual condition the maintenance plan consists a mixture of these two systems even though the organization / company has different operational areas it is generally established to be centrally managed to the maintenance service of the whole plant. AHP has been applied for maintenance purpose in many areas such as in the chemical industry, electrical industry, onshore and offshore pipeline, etc as can be seen in Table 2.16.

Table 2.16. AHP Applied for Maintenance Strategy

No	Research Area	References
1	Pipeline Maintenance	(Nataraj, 2005; Dawotola, 2011; Dey, 2001; Dey, 2003;Dey, 2004a; Dey, 2004b;Khalil, 2005; Silvianita, 2009)
2	Maintenance of Chemical Industry	(Arunraj, 2010; Young, 2006)
3	Maintenance of Electrical Industry	(Lin, 2006)
4	Maintenance & Repair Industry	(Burhanuddin, 2010;Wang, 2009)
5	Pavement Maintenance	(Birre, 2010;Danial, 2011; Javed , 2009; Ramadhan, 1999;Dong, 2008)
6	Maintenance Organizational Structure	(Ali, 2004, Mishra, 2007)
7	Maintenance of Oil Refinery	(Liu, 2008; Bevilacqua, 2000; Bertolini, 2006; Zhaoyang, 2011)
8	Forest Road Maintenance	(Cavalli, 2011; Fennica, 2006; Coulter, 2005)

For an example Figure 2.20 is an AHP model developed by Zhaoyang (2011) to determine maintenance plan based on risk matrix output that used for oil refinery plant. The most common maintenance policies in oil refineries are:

- Preventive Maintenance (PM)
- Condition Based Maintenance (CBM)
- Corrective Maintenance (CM)
- Reliable Centered Maintenance (RCM)

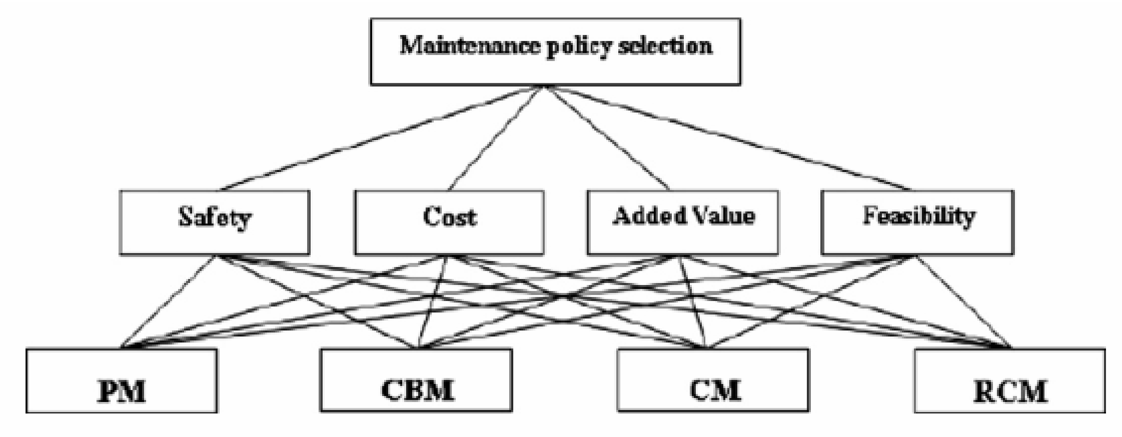


Figure 2.20. AHP Model (Zhaoyang, 2011)

The hierarchy is developed based on risk matrix output that have four conditions which are unsatisfactory, critical, tolerable and acceptable/favorable. The result shows that best maintenance strategy for unsatisfactory conditions is RCM, critical is PM, tolerable and acceptable/favorable is CM.

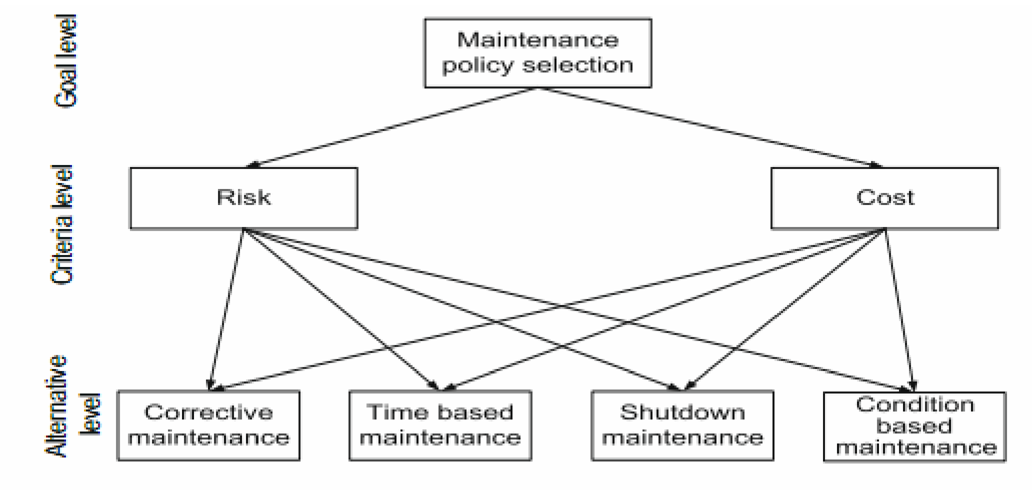


Figure 2.21. Hierarchy Scheme for Maintenance Policy Selection (Arunraj, 2010)

Maintenance policy selection using AHP also developed by Arunraj (2010) for benzene extraction unit of a chemical plant as described in Figure 2.21. The AHP results define that from risk as a criterion point of view, condition based maintenance (CBM) is preferred policy over time based maintenance (TBM). The other criterion which is cost, corrective maintenance (CM) is preferred. Based on above review of maintenance strategy using AHP, and the significance of mooring system to make sure the positioning of the vessel it is need to select the maintenance strategy so that the mooring system can fit for purpose. Therefore this study is trying to develop the maintenance strategy for mooring system using AHP. A framework or hierarchy is built based on AHP method. AHP is used to select the most practicable maintenance strategy which was located in each risk ranking level. The AHP start with the hierarchy level commonly consists of four levels. These four levels are the goal or the objective as the highest level, criteria in second level, sub criteria in third level and finally the lowest level is the alternative strategies.

2.8.1.1. Mathematical Model in Analytic Hierarchy Process

The basic tool in Analytic Hierarchy Process is a matrix number, representing the judgments of pair wise comparisons. Consider the elements C1, C2, ...,Cn of some level in a hierarchy. Weights of influence w_1, w_2, ...w_n on some element in the next level. Denote aij as the number indicating the strength of C_i, when compared to Cj. The matrix of these number aij is denoted A, or A = (a_{ij}). $a_{ji} = 1/a_{ij}$, that is the matrix A is reciprocal. If judgments is perfect in all comparison, then $a_{ik} = a_{ij}.\ a_{jk}$ for all i, j, k and the matrix A is called consistent (Saaty, 2003).

Then the mathematic formulation is : $a_{ij} = w_i/w_j$; i,j = 1,2,…n (2.9)

And thus $a_{ij}.a_{jk} = {w_i}/{w_j} . {w_j}/{w_k} = {w_i}/{w_k} = a_{ik}$

The matrix equation A . x = y , where $x = (x_1,...,x_n)$ and $y = (y_1,...,y_n)$ is a shorthand notation for the set of equations.

$\sum_{j=1}^{n} a_{ij} x_i$, where i = 1,… n

From equation (2.9) $a_{ij} . {w_j}/{w_i} = 1$ i, j = 1, …, n

And consequently $\sum_{j=1}^{n} a_{ij}.w_j.\frac{1}{w_i} = n$, i = 1, … n

Or $\sum_{j=1}^{n} a_{ij}.w_j = nw_i$, i = 1, …, n

Which is equivalent to Aw = n w (2.10)

$$\begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \cdots & \cdots & \cdots & \cdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \\ w_n \end{bmatrix}$$

In matrix theory, the above formula expresses the fact that w is an eigenvector of A with eigenvalue n. The aij are not based on exact measurements, but on subjective judgments. Thus, the aij will deviate from the "ideal" ratio wi/wj, and therefore Eq. 2.10 will no longer hold. But, there are two matrix theory, the first of is, if $\lambda_1,...,\lambda_n$ are the numbers satisfying the equation $Ax = \lambda x$, i.e., are the eigenvalues of A, and if a_{ii} = 1 for all I, then $\sum_{i=1}^{n} \lambda_i = n$

Therefore, if Eq.2.10 holds, then all eigenvalues are zero, except one, which is n. Clearly then in the consistent case, n is the largest eigenvalue of A. Second is if one changes the entries aij of a positive reciprocal matrix A by small amounts, then the eigenvalues change by small amounts. It will result the diagonal of a matrix A consisting of ones (a_{ii} = 1), and if A is consistent, then small variations of the aij keep the largest eigenvalue, $\lambda_{\max}$ close to n, and the remaining eigenvalues get close to zero.

Then, if A is the matrix of pairwie comparison values, in order to find the priority vector, so the vector w is: $Aw = \lambda_{\max} w$. Since it is desirable to have a normalized solution, alter w slightly by setting and replacing w by $\left(\frac{1}{\alpha}\right)w$. This ensures uniqueness, and also that $\sum_{i=1}^{n} w_i = 1$. Since small changes in aij imply a small change in λ_{max}, the deviation of the latter from n is a measure of consistency. Then, the consistency index, as indicator of "closeness to consistency less then 0.1 (Saaty, 2003) is given by:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (2.11)$$

(Saaty, 2003) suggests that a consistency index less or equal to 0.10 indicates that the decision maker has adequately structured the problem in question, but according to Apostolou (1993) if the consistency index is greater than 0.10 then the response by subject can be considered as random. (Saaty, 2003) proposes the following index for measuring consistency ratio:

$$CR = \frac{CI}{RI} \qquad (2.12)$$

where '*RI'* is the average value of '*CI*' for a random matrices using the Saaty's scale. CR is a normalized value, because it is divided by an arithmetic means of a random index (*RI*) consistency indexes as shown in Table 2.17.

Table 2.17. Random Index for A Several Matrix Dimensions (Saaty, 1988).

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.45	1.49

Table 2.17 shows the random index (RI) for each eigen value with value n. For instance the random index for eigen value 4 is 0.89 and eigen value 8 the random index is 1.45 and so on.

2.8.1.2. Expert Choice Professional Software

Expert choice helps a decision maker to solve complex problems that involve many criteria and numerous actions (Professional, 2000). EC is based on AHP a methodology for decision making that provide the users with the tools to develop decision frameworks from both routine and non routine problems and ways to calculate the judgments in the decision frameworks. There are two Steps conducting Expert Choice software which is structuring, evaluation and choice. The following section will describe the Steps using the Expert Choice software.

2.8.1.2.1. Structuring

Decision makers can identify the alternative and their probability and consequence, determine the goal, criteria and develop an evaluation and choice hierarchical decision model visually. The decision maker organizes the fundamental factors of the decision using either bottom approach or top down approach as shown in Table 2.18.

Table 2.18. Methods of Structuring (Professional, 2000)

Methods of Structuring	
Bottom Up Structuring	Top Down Structuring
The decision maker lists the alternatives, their probability and consequences, converts the pros and cons into objective and subjective	The decision maker first lists the objectives and subjective groups them then lists the alternatives.
It is helpful when the alternatives are better understood than the objectives. The pros and cons of the alternatives are used to help identify the objectives. The objectives can be clustered into groups, and subsequently groups of groups, etc.	It is better suited to more strategic decisions where the objectives are better understood than the alternatives. Major objectives are identified, followed by the identification of sub objectives, sub-sub objectives, etc.

2.8.1.2.2. Evaluation and Choice

Decision makers can directly build their models in the evaluation and choice component or use structuring to visually organize the decision elements and build the hierarchy. There are two Steps of evaluation and choice which consist of synthesizing the results and sensitivity analysis.

(i) Synthesizing the result

Synthesis is the process of weighting and combining priorities throughout the model that leads to the overall results. Synthesis from the goal node multiplies the weight of each parent node times the local priorities of its child nodes and of those children times the local priorities of their children. This process continues down to and including the alternatives. Synthesis converts all the local priorities into global priorities throughout the model, the object being to obtain global weights for the alternatives. The global weights for each alternative are summed to get its final synthesized weight, or overall priority.

(ii) Sensitivity analysis

Sensitivity analysis is used to investigate the sensitivity of the alternatives to changes in the priorities of the criteria. There are five graphical sensitivity analysis modes: Performance, Dynamic, Gradient, 2D Plot (Two-Dimensional), Differences which described in Table 2.19. The five graphical sensitivity modes all provide views of priorities and alternatives in the model and how they relate. The views available in the different modes provide emphasize different aspects of the model's priorities. Though all include views of the model's criteria and alternatives, what is emphasized in the graphical visualization for the sensitivity modes varies.

Table 2.19. Sensitivity Analysis Modes (Professional, 2000)

Sensitivity analysis				
Performance	Dynamic	Gradient	2D Plot (Two-Dimensional)	Differences
The performance provides a composite sensitivity presentation showing how well each alternative performs on each criterion and overall, when all the criteria are taken into account.	The dynamic sensitivity analysis emphasizes the priorities of the criteria in the model and how changing the priority of one criterion affects the priorities of the others.	The linear presentation of the alternatives against a single criterion in gradient sensitivity emphasizes how the alternatives relate to any priority assigned to the criterion shown on the x-axis.	The two dimensional plots show how well the alternatives perform with respect to any two criteria. One criterion is represented on the Y-axis and one on the X-axis. The alternatives are represented by the circles.	In the Differences graph one of the alternatives is selected to be compared against each of the other alternatives, in turn, as to how they differ on the criteria below the current node.

2.9. Expert Opinion Survey (EOS)

The experts are people who have a good knowledge of the field under study and who are able to express their opinion in a simple probabilistic fashion. The experts can be engineers, physicists, lawyers, actuaries etc (Goulet, 2009). Expert opinion can often provide a valued resource to aid in decision making especially when there is conflicting or incomplete knowledge (Sharon, 1998). The objective of the expert opinion survey is to collect expert opinion on different knowledge and experience. Table 2.20 describes the type of expertise.

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Table 2.20. Type of Expertise (Collins, 2007)

No	Type	Characteristics
1	Contributory Expertise	Fully developed and internalized skills and knowledge, including an ability to contribute new knowledge or to teach
2	Interactional Expertise	Knowledge gained from learning the language of specialist groups, without necessarily obtaining practical competence
3	Primary Source Knowledge	Knowledge gained from the primary literature, including basic technical competence
4	Popular Understanding	Knowledge from the media, with little detail and less complexity
5	Specific Instruction	Formulaic, rule based knowledge, typically simple, context specific and local

Encoding is a stage when the expert is asked to state their beliefs for each variable, for example as probabilities or relative weights. Different encoding approaches can be chosen, depending on the type of information being elicited as shown in Table 2.21.

Table 2.21. Encoding Approaches (Marissa, 2012)

Criteria/Methods	Quantitative Measures					
	Probability	Frequency	Quantity	Weighting	Quantitative Interval	Probability Distribution
Type of elicitation	Direct	Indirect	Direct	Indirect	Direct/ Indirect	Direct
Benefits from multiple experts	√	√	√	√	-	-
Language easily interpreted	-	√	√	√	-	-
High level of expertise required	√	√	√	-	√	√
Fast and easy	√	√	√	√	-	-
Uncertainty explicitly specified	-	-	-	-	√	√

Identification and selection of the experts are based on the several criteria as discussed by NRC (1997):

1. Strong relevant expertise through academic training, professional accomplishment and experiences, and peer reviewed publications.
2. Familiarity and knowledge of various aspects related to the issues of interest.
3. Willingness to act as proponents or impartial evaluators.
4. Availability and willingness to commit needed time and effort.
5. Specific related knowledge and expertise of the issues of interest.
6. Willingness to effectively participate in needed debates, to prepate for discussions, and provide needed evaluations and interpretations.
7. Strong communication skills, interpersonal skills, flexibility, impartiality, and ability to generalize and simplify.

The diversity and completeness of the panel of experts is essential for the success of the elicitation process. For example, it can include the following:

a. Proponents who advocate a particular hypothesis or technical position.
b. Evaluators who consider available data, become familiar with the views of proponents and other evaluators, quation the technical bases of data, and challenge the views of proponents.

c. Resource experts who are technical experts with detailed and deep knowledge of particular data, issue aspects, particular methodologies, or use of evaluators.

2.10. Research Validation

In order to conduct the research validation, the conceptual frameworks of this research are validated using the expert's validation method. Expert validation methods are derived from the triangulation method using both qualitative interview (Jabareen, 2009; Jean, 2005) and quantitative analysis (Ligaarden, 2011; University, 2002).

The respondents were asked to validate the framework procedure using Likert Scale as shown in Table 2.22. Likert Scale uses five points ranged from 1 to 5 in order to transform to relative importance indices (RII). The larger the index value is the better the evaluation of alternative will be (Zavadskas, 2010; Sambasivan, 2007). A relative importance index with the value 0.80 is considered highly important (Sambasivan, 2007; Enshassi, 2011).

Table 2.22. Likert Scale Response Categories

	1	2	3	4	5
Scale	Always	Often	Sometimes	Seldom	Never
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
	Not important at all	Unimportant	Neutral	Important	Most Important

Relative importance is the proportionate contribution each predictor makes to R^2, considering both the unique contribution of each predictor by itself and its incremental contribution when combined with the other predictors (Johnson and Lebreton, 2004). RII is one of the most widely used measures to determine the relative critical attributes and assessing the overall ranking of the attributes (Johnson, 1966; Healy, 1990; Hemanta, 2009). The RII is evaluated using the following formula:

Relative Importance Index $RII = \frac{\sum w}{AxN}$ (2.13)

where:

w is the weight given to each attribute by the responded with ranges from 1 to 5.

A is the highest weight (i.e. 5 in this study).

N is the total number of the respondents in the sample.

2.11. MIVTA and MIRBA Application

MIVTA and MIRBA as discussed in the previous section are an integrated of four methods namely HAZOP, FTA, ETA, and AHP. These methods are integrated in an attempt to develop risk based decision making for mobile mooring system. There are tenth expert opinion survey will be distributing to the respondents to achieve research objectives. There are seven phase need to be conducted in MIVTA and MIRBA application which will be discussed further in the next chapter.

2.12. Summary of Literature Review

Offshore structure mainly consists of fixed platform and floating platform with various different purposes for example drilling, production, accommodation etc. Currently the development of floating structure increase significantly especially for FPSO, Semi submersible, TLP (Tension Leg Platform), and Spar platform. The offshore structure needs to conduct offshore operations in rough weather condition with maximum safety applied to personnel and equipment.

Floating structure uses mooring system to keep the station in place. Basically there are two types of mooring systems namely permanent and mobile mooring systems. Permanent mooring system is commonly used by FPS (Floating Production Storage) for positioning. While the mobile mooring system is generally used by MODU (Mobile Offshore Drilling Units) because MODU tends to stay at one location for a much shorter period.

Mooring line failure is mainly caused by anchor failure defined as issues with anchor/anchor lines, mooring devices, winching equipment or fairleads (e.g. anchor dragging, breaking of mooring lines, loss of anchor, and winch failures). Therefore it is very important to investigate the potential causes that may lead to an accident. This study will focus on the semi submersible as a case study which used mooring system for positioning. The goal of this study is to investigate all related problems and their consequences in mooring system. The other objectives of this study are to determine the mitigation plan and the maintenance strategy for mooring system failure.

Risk communication is the basis of risk based decision making by considering decision on structure, risk assessment, risk management and the impact of assessment. This study will elaborate qualitative and quantitative analysis by using HAZOP (Hazard Operability), FTA (Fault Tree Analysis) and ETA (Event Tree Analysis).

Risk assessment starts with hazard identification using preliminary risk analysis HAZOP, determine the potential causes using FTA, and identify the possible consequence using ETA. FTA is a deductive approach that consists of symbols and gates in order to describe the process of system failure. Commonly the gate used in FTA are AND gate and an OR gate. The evaluations of FTA use the rules of Boolean algebra into an equivalent set of Boolean equations. The AND gate between two events is evaluated by multiplying the frequency of occurrence while OR gate between two events is evaluated by summing the frequency of occurrence. This study uses the DPL Syncopation software in order to evaluate the fault tree diagram of the mooring system.

The decisions of ETA are binary which can be a success or failure, yes or no condition. Event tree is a graphical model to describe the accident scenario which consists of initiating event, pivotal event and the outcomes of the failure system. Multi criteria decision making is developed in this study in order to select the best maintenance strategy using AHP (Analytic Hierarchy Process). AHP is a useful method because it can incorporate the qualitative and quantitative data. It is also an effective method to select the best alternative using scale system. In order to evaluate the AHP, this study uses Expert Choice software to analyze the maintenance strategy for the mobile mooring system. There are five maintenance strategies investigated namely CM (Corrective Maintenance), PM (Preventive Maintenance), RTF (Run to Failure Maintenance), CBM (Condition Based Maintenance) and PeM (Predictive Maintenance). The next Step in this study is to validate the research work. The research validation of the framework procedure is conducted by distributing the questionnaires to the experts using Likert Scale. Based on the Likert Scale judgements then the relative importance index (RII) can be determined. In the next chapter will be discussed in more detail about the research methodology used in this study.

CHAPTER THREE
RESEARCH METHODOLOGY

As discussed in the previous chapter, chapter three will be focused on the research methodology. Research methodology will described each Step in conduction risk based decision making (RBDM).

3.1 Introduction

This chapter begins with a brief background about the research method for data collection. There are two types of data collection which are primary data and secondary data. Primary data derived from expert opinion survey which distributed to the experts in order to achieve the objectives. The secondary data consist of operation manual, general arrangements etc, which useful to understand the system under study. This study uses methods triangulation for data collection in order to seek reliable and valid results. Triangulation is an integrated method of qualitative and quantitative, it minimized the inadequacies of individual methods and it captures a more complete and holistic to portray and reveal the varied dimensions of a given phenomena (Jennifer, 2003). The same opinion by Olsen (2004) explained that methodological triangulation consists of a discourse analysis (a qualitative methodology) and survey data (a quantitative methodology) to get two or three viewpoints upon the things being studied.

The aim of the study is supported by two main objectives which are MIVTA and MIRBA. MIVTA is derived from integration of HAZOP, FTA and ETA continues with MIRBA by integrating the result from MIVTA using bow tie analysis and AHP. The expert opinions are derived in order to obtain the probability of occurrence of an events due to the difficulties to gather the past record data, therefore expert opinion are obtained in order to determine the probability of occurrence (Deacon et al., 2010 ; Mentes, 2011).

Nine experts were obtained in an attempts to the maximize the quality and the effectiveness of the survey (Vargas, 1998; Wang, 2004). The experts list is shown in Appendix D1. The questionnaires were developed with the objective of getting each expert gave their knowledge and experience for mobile mooring system failure. This study establishes tenth expert opinion surveys (EOS) in an attempt to achieve the aim of this study which is to integrate risk based decision making (RBDM) for mobile mooring system. First EOS is HAZOP preliminary risk analysis, second EOS is FI for basic events of FTA, third EOS is FI for pivotal events, fourth EOS is consequences classification using ETA, fifth EOS is mitigation plan, sixth EOS is risk criticality, seventh EOS is mitigation measure effectiveness, the eighth EOS is maintenance strategy on the basis of likelihood, the ninth EOS is maintenance strategy on the basis of consequence and the tenth EOS is validation framework of integration MIVTA and MIRBA for mobile mooring system.

The knowledge acquisition process is generally divided into seventh phase. MIVTA consists of three phases namely the first phase is useful to determine the HAZOP preliminary analysis, second phase is quantifying the frequency index for basic event of FTA and pivotal events, third phase is classifying the consequence class of ETA. Continuing from the MIVTA is the fourth phase in MIRBA by developing risk mapping using bow tie analysis. The fifth phase is determining the mitigation plan, investigating risk criticality and mitigation measure effectiveness. The sixth phase is selecting the best maintenance strategy on the basis of likelihood and consequence. The seventh phase is the last phase which is useful to determine the framework validation of MIVTA and MIRBA for mobile mooring system. Table 3.1 discusses all the process of risk based decision making for mobile mooring system.

Table 3.1. Research Methodology

Aim	Developing an integration of Risk Based Decision Making (RBDM) for mobile mooring system						
Objectives	1. To develop an integration of risk assessment approaches consist of HAZOP, FTA and ETA called MIVTA			2. To develop an integration of risk assessment and risk based maintenance called MIRBA			3. To validate the integration framework of MIVTA and MIRBA for mobile mooring system.
Phases	Phase I	Phase II	Phase III	Phase IV	Phase V	Phase VI	Phase VII
	Analyze the critical hazards that affect safety and operability	-Determine the root causes of an accident hazard - Quantify the frequency index	- Classify the possible consequence of an accident hazard - Quantify the severity index	Developing the risk matrix based on frequency and consequence using bow tie analysis	- Determining the mitigation plan to reduce the risk - Measure the risk criticality and mitigation measure effectiveness	Generating the best maintenance strategy selection on the basis of likelihood and consequence using AHP	Validating the integration framework of MIVTA and MIRBA using Likert Scale
Research Tools & Processes	Expert Opinion Survey 1 HAZOP Preliminary Risk Analysis	Expert Opinion Survey 2 FI for basic events of FTA Expert Opinion Survey 3 FI for Pivotal Events	Expert Opinion Survey 4 Consequences Classification using ETA	Risk Mapping using Bow Tie Analysis	Expert Opinion Survey 5 Mitigation Plan Expert Opinion Survey 6 Risk Criticality Expert Opinion Survey 7 Mitigation Measure Effectiveness	Expert Opinion Survey 8 Maintenance Strategy on the Basis of Likelihood Expert Opinion Survey 9 Maintenance Strategy on the Basis of Consequence	Expert Opinion Survey 10 Validation Framework of MIVTA and MIRBA for mobile mooring system
Achievement	To achieve Objective (1a)	To achieve Objective (1b)	To achieve Objective (1c)	To achieve Objective (2a)	To achieve Objective (2b)	To achieve Objective (2c)	To achieve Objective 3
Instrument	Interview	Questionnaire	Questionnaire	Questionnaire	Questionnaire	Questionnaire	Questionnaire

Semi quantitative analysis is useful to investigate the risk level. The risk levels are classified into categories like low, medium, high and very high. The reason why this study chooses semi quantitative analysis rather than quantitative analysis is because most operational risk assessment in oil and gas industry are using semi quantitative analysis in order to identify the most critical activities (DNV, 2003; Marine, 2011; UK, 2012). The other reason why semi quantitative has been chosen is based on suggestions from UKOOA (1999) that quantitative analysis is most appropriate for decisions involving risk trade offs, deviation from standard practice or significant economic implications. Since this study is focus on the risk based decision making for mobile mooring system, therefore semi quantitative analysis has been chosen.

3.2 HAZOP Procedure

HAZOP as preliminary hazard approach is used to identify and define the potential hazards or problems of a system that may lead to an accident. The HAZOP result can be implemented as suggestion action to reduce the risk and operational matters. The summary of HAZOP Step is described in Figure 3.1:

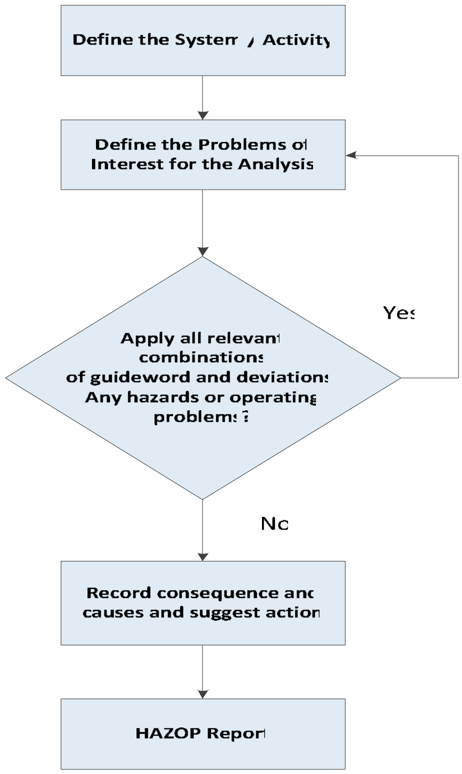

Figure 3.1. HAZOP Procedure

The few Steps in order to carry out HAZOP are as follows:

1. Step 1: Define the system/activity
   Identify and examine the system/activity that is going to be analyzed.
2. Step 2: Define the problems of interest for the analysis
   Define the potential hazards and significant impact on the system by using guideword and deviation parameters.
3. Step 3: Record outcome and causes and suggest action
   Analyze the findings that focus on the critical hazards as well as critical operational problems.

4. Step 4: HAZOP record

   The results of HAZOP are recorded using HAZOP spreadsheets which generally include the guideword, deviation, possible causes, outcome, safeguards and suggestion action, etc.

3.3. FTA Procedure

The FTA is carried out to find the root cause of potential failure until the controllable cause is reachable. FTA is a useful approach using logical symbols to understand the failure system and how to fix or prevent the failure. Figure 3.2 shows the outline how to develop fault tree.

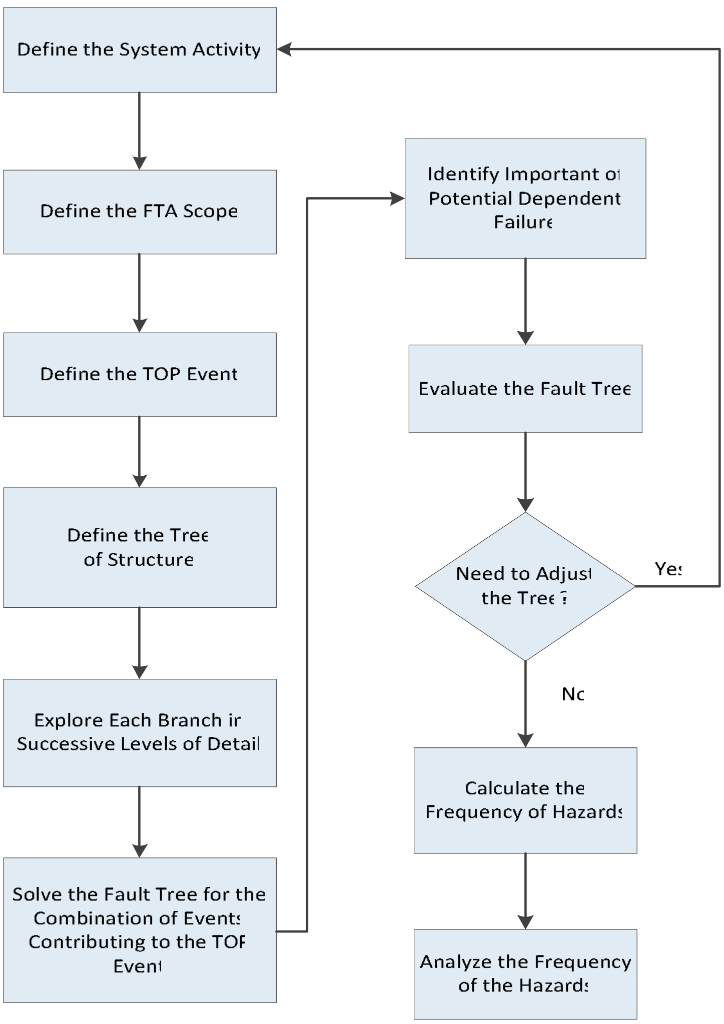

Figure 3.2. FTA Procedure

Here are the following Steps that help to construct the FTA:

1. Step 1: Define system activity

   Define the system activity and identify the potential causes that may lead to an accident.

2. Step 2: Define the FTA scope

   Define and identify the FTA scope which is the physical boundary conditions of the system.

3. Step 3: Define the Top event

   Define and select a top event for the analysis. The top event needs to be specific based on the preliminary hazard analysis that discusses the potential failure of the system that may lead to the accident.

4. Step 4: Define the tree of the structure

   Define and develop the tree of structure by identifying the faults that could lead to the accident or top event.

5. Step 5: Explore each branch in successive levels of detail

   For each branch of fault tree, search and explore as many causes as possible that related to the fault. Connect each event with the gate symbol, which usually consist of AND gate and OR gate.

6. Step 6: Solve the fault tree for the combination of events contributing to the top event. The combination events connect with the gate symbols that represent the sequencing of the faults and causes.

7. Step 7: Identify important of potential dependent failure

   Keep on identifying the causes of each fault until the basic event or undesired event are reached. Basic event or dependent failures are the undesired event that we can do preventing on it.

8. Step 8: Evaluate the fault tree

   Once the fault tree diagram is complete, the next thing to do is to evaluate. In order to quantify the fault trees the frequency for each of the basic event need to be established.

9. Step 9: Calculate the frequency of hazards

   FTA utilizes Boolean algebra to calculate the frequency of the hazards. The gate symbol or logical input is the expression of Boolean algebra. The rules of combination of the probabilities with OR gate is representing add frequency.

The other rule of combination of the probabilities is AND gate which is representing multiply probabilities.

10. Step 10: Analyze the frequency of the hazards

    Analyzing the frequency of the hazards begins with the basic events frequency and proceeds toward the top event. The basic event frequency or probabilities is gathered from the experts judgments based on EOS 2. By computing all the bottom gates and proceed to the higher level finally the frequency of the top event can be determined.

3.3.1. DPL Software Procedure

In order to analyze the FTA, this study used DPL software to develop the fault tree and analyze the minimal cut set. The Step of developing model tree in DPL software is shown in Figure 3.3.

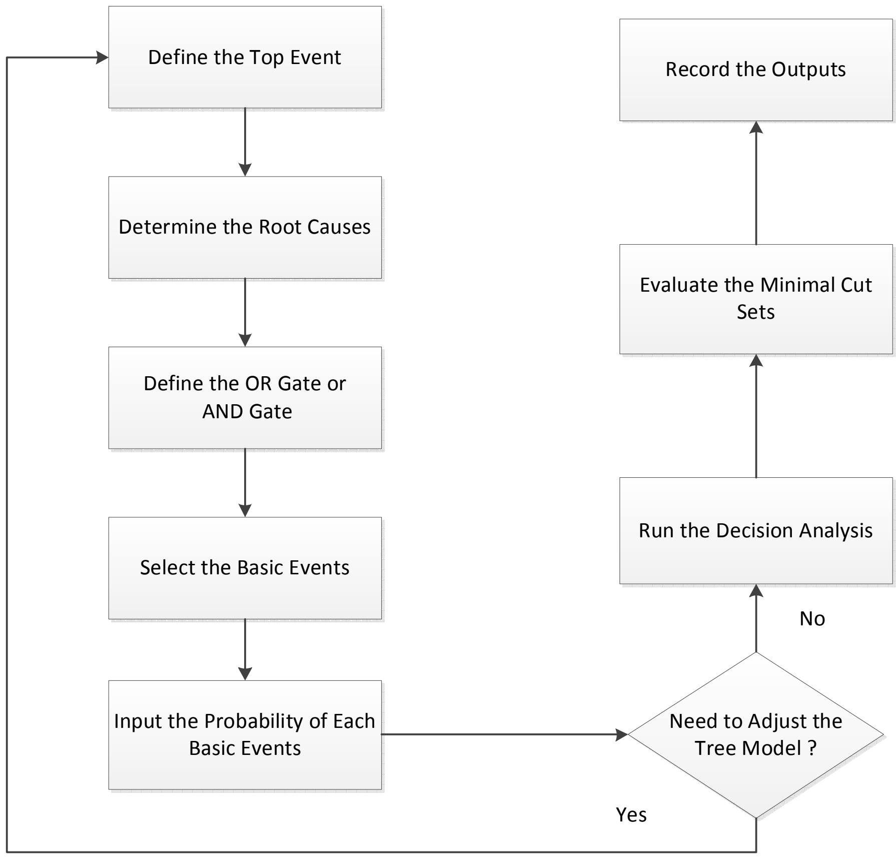

Figure 3.3 DPL Software Procedure

The overview of DPL software procedure:

1. Step 1: Define the top event

   Define the top event in model tree in DPL software

2. Step 2: Determine the root causes

   Determine the root causes for each of the top events until the basic events or undesired events are identified.

3. Step 3: Define the OR gate or AND gate

   Define the OR gate or AND gate for each events.

4. Step 4: Select the basic events

   Select the basic events in model tree to be inserted the probability of failure.

5. Step 5: Input the probability of each basic events

   Input the probability of each basic events based on the data gathering.

6. Step 6: Run the decision analysis

   Once all the probability of each event has been inserted the next Step is run the decision analysis.

7. Step 7: Evaluate the minimal cut sets

   Evaluate the minimal cut sets derived from the software and record systematically in order to determine the total probability of failure for the top events. The probability of failure for the cut set is derived from the frequency of basic events, if it is second order then multiply both frequencies, and if it is third order then multiply the three frequencies of basic events.

8. Step 8: Record the outputs

   Record the outputs from DPL software and define the probability of failure of top events.

3.4. ETA Procedure

ETA approach is conducted to evaluate the entire possible outcome that can result from an accidental event and it is used to define the logical connection between top events and sub event. The general overview of ETA is shown in Figure 3.4.

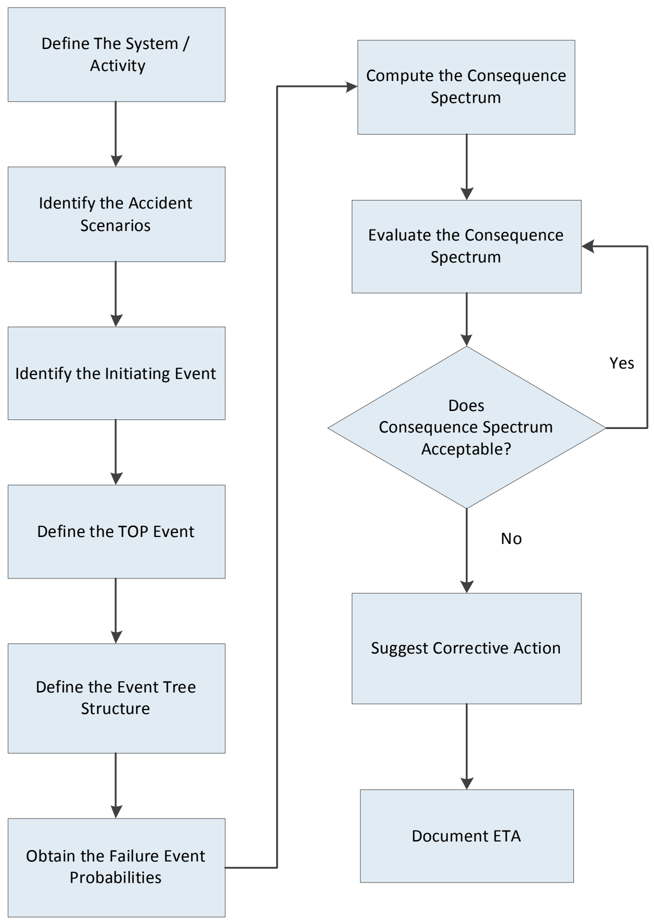

Figure 3.4. ETA Procedure

The overviews of ETA procedure are as follows:

1. Step 1: Define the system/activity

   Define the system and examine the system boundaries, subsystems and interfaces.

2. Step 2: Identify the accident scenarios

   Accomplish the system assessment or hazard analysis in order to identify the system hazards and accident scenarios occur in the system under study.

3. Step 3: Identify the top event

   Develop the hazard analysis in order to identify the significant initiating events (top event) in the accident scenarios.

4. Step 4: Define the pivotal events

   Define the sequence of all the potential outcome resulting from an initiating event involved with the accident scenario that may lead to a disaster.

5. Step 5: Define the event tree structure

   Develop the logical event tree diagram, beginning with the top event, pivotal events and completing with the frequency of occurrence of each path.

6. Step 6: Obtain the failure event probabilities

   Obtain the failure probabilities of the top events on the event tree diagram by using the rules of Boolean algebra logic gates.

7. Step 7: Compute the outcome spectrum

   Identify and compute the outcome frequency for each path in the event tree diagram using the Boolean algebra. The computation starts from the left of top event and continue to the right of branching.

8. Step 8: Evaluate the outcome spectrum

   Evaluate the outcome spectrum of each path and determine whether the frequency of the outcome spectrum is acceptable or not.

9. Step 9: Suggest Corrective Action

   If the outcome spectrum in the event tree diagram is not acceptable, then develop a corrective plan/strategy to minimize the outcome.

10. Step 10: Document ETA

    Record the entire ETA process on the event tree diagrams. Revise the ETA documents for new information or new data finding.

3.5. AHP Procedure

AHP is developed in order to prioritize the best maintenance plan. The overall procedures of AHP are described in Figure 3.5.

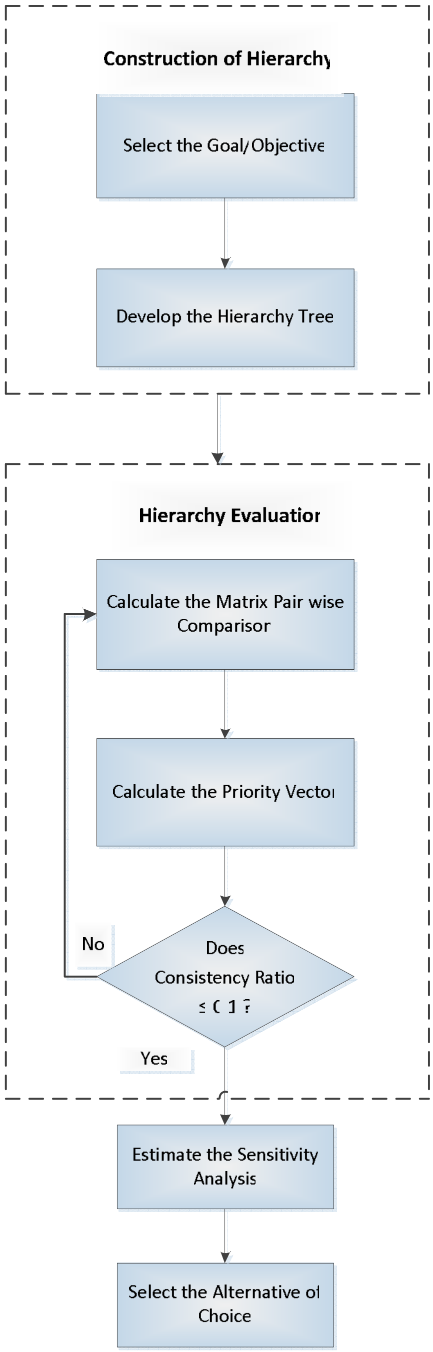

Figure 3.5. AHP Procedure

Here are the descriptions of AHP procedure:

1. Step 1: Construction of Hierarchy

Construction of hierarchy in AHP is starting with system identification and hierarchical structure. Here are the definitions of each Step;

1.1 System Identification

The first Step to applying AHP is by identifying the system. In this framework the information is gathered to develop the hierarchy.

1.2 Hierarchical Structure

Based on the system identification, the information can be constructed to a hierarchy. The hierarchy of AHP usually involved four levels;

i. First level is the goal that needs to be achieved.

ii. Second level is the criteria of the factor to enable the goal to be achieved.

iii. The third level is the sub factor of the factor in the previous level.

iv. The fourth level is the alternatives of the pipeline under study.

2. Step 2: Hierarchy Evaluation

Hierarchy evaluations consist of the matrix pair wise comparison, priority vector completed with the consistency ratio then investigate the result with the sensitivity analysis. Here are the definitions for each Step;

2.1 Matrix Pair Wise Comparison

The judgments of the relative importance of the elements with respect to the overall goal of prioritizing the pipeline maintenance are made. The judgment is made on a numerical scale ranging from 1 to 9 (Table 2.14.). Elements at each level of the hierarchy are compared with each other in pairs with their respective parents in the next higher level.

2.2 Priority Vector

Next Step is to calculate the synthesis by multiplying the vectors of priority by the weight of the criteria, and taking the sum over all weighted priority entries corresponding to those in the next lower level, and so on.

2.3 Check Consistency Ratio

The AHP provides a theory for checking the inconsistency throughout the matrix. The consistency ratio must be less or equal to 0.10 in an attempt to insure the consistency of experts judgments. The detail calculation to determine the consistency ratio can be seen in formula 2-12.

3. Step 3: Sensitivity Analysis

Establish the sensitivity analysis with five graphs, it is useful to investigate the sensitivity of the rank of alternative.

4. Step 4: Summarize the result

Summarize all the result from the structuring model and evaluation analysis and tabulated in systematic table.

3.6. Integrating Approach Framework

The idea of this study is to integrate four methods of risk assessments which are HAZOP, FTA, ETA and AHP into comprehensive risk based decision making (RBDM). Integrating approach framework as shown in Figure 3.6 are consist of MIVTA means Methodology for Investigation of Critical Hazardous and MIRBA means Methodology for Investigation of Risk Based Maintenance (MIRBA). The Steps to be followed in MIVTA are:

1. MIVTA Step 1 : Literature review

   The research starts with the literature review by analyzing and reviewing the existing risk assessment approach applied in oil and gas industry. This Step comes up with the theoretical mapping for the particular topic as the basis to achieve the goal.

2. MIVTA Step 2: Defining the objective

   Define the objective of the research, and helps to maintain the focus of the research. Most importantly it will affect the problems that are going to be analyzed.

3. MIVTA Step 3: Determining the scope

   Determine the scope in order to list the works. It is very important to highlight the sections that are addressed and the sections that are not.

4. MIVTA Step 4: Data compilation

   Data compilation investigates the top hazardous scenarios. There are two kinds of data that need to be gathered are as follows:

   (i) Primary data: brainstorming session, interview and EOS are conducted to address the problems.

   (ii) Secondary data: general data about the system such as general arrangement, operation manual, description of equipment etc.

5. MIVTA Step 5: Starting HAZOP by defining the system/activity
   Define the system/activity that going to be analyzed so that can be focused on the system. HAZOP is derived as preliminary analysis to determine the possible causes and potential consequence and to determine the safeguards of handling the risk. The HAZOP procedures continue until Step 5.1 and Step 5.2.
6. MIVTA Step 5.1: Defining problems of interest
   Define and identify the potential failure of the system that may lead to an accident.
7. MIVTA Step 5.2: Recording HAZOP results
   The results of HAZOP are recorded on the worksheet and contain the outcomes and the potential causes of the failure system, attached with the guideword, deviation, safeguard and suggestion action to mitigate the failure.
8. MIVTA Step 6: Determining the Top Event
   Once the preliminary hazard analysis (HAZOP) has been completed, the next Step is to determine the top event. This Step parallels between FTA and ETA methods, the FTA focusing on the prevention strategy and ETA focusing on the mitigation strategy.
9. MIVTA Step 6.1.a: Starting FTA for each top event, built fault tree
   Steps from 6.1.a to 6.1.d are for developing the FTA. FTA begins with the top event to find the root cause or undesired event that may lead to an accident.
10. MIVTA Step 6.1.b: Developing the fault tree
    Develop and construct the fault tree complete with the gate symbols and combine each event contributing to the major failure.
11. MIVTA Step 6.1.c: Calculating the frequency of hazards
    Calculate the frequency of hazards by identifying the frequency of basic event or the undesired event.
12. MIVTA Step 6.1.d: Analyzing the fault tree contributing to the top event
    When the frequencies of basic events are gathered, the next Step is to evaluate the fault tree by using the rules of Boolean algebra. By calculating all the basic events and the logical gates and proceed to the higher level, in the end the frequency of the top event can be reached.
13. MIVTA Step 6.2.a: Starting ETA for each top event, built event tree

ETA begins with the top event to observe the chronological level of subsequent events. This method concentrates on the mitigation strategy of the system.

14. MIVTA Step 6.2.b: Determining the Pivotal Events

    Determine the pivotal events or the subsequent response events so that the frequency of occurrence for each sequence can be computed.

15. MIVTA Step 6.2.c: Defining accident sequences

    Develop the event tree that shows the accident sequences among the top event and the subsequent or pivotal event. Once it is completed, the variety of accident sequence can be clarified and the frequency of occurrence for each path can be quantified.

16. MIVTA Step 6.2.d: Obtaining outcome spectrum

    Obtain the failure event probabilities of the top events using the Boolean algebra logic gates and continue to the right of the branching nodes.

17. MIVTA Step 6.2.e: Analyzing the frequency of the outcomes

    Analyze the frequency of each outcome and check whether it is acceptable or not based on the standard level of safety. Finally based on the ETA result the mitigation strategy can be constructed.

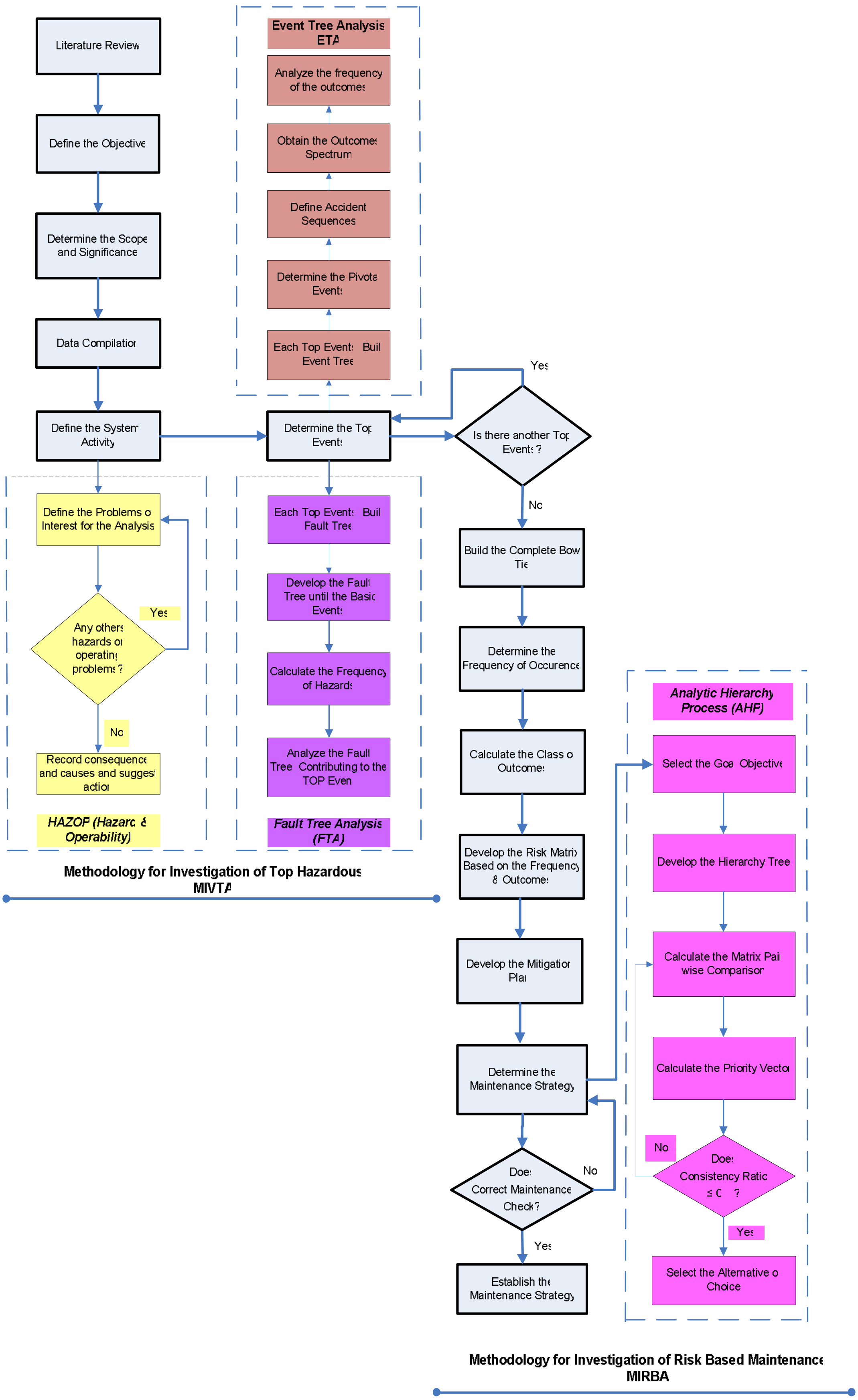

Figure 3.6. Integrating Approach Framework

After all the Steps in MIVTA are reached, the next Step is continuing with MIRBA. MIVTA is the basis for the application of the MIRBA in order to determine the correct maintenance strategy for the system. The overviews of the Steps in MIRBA are as follows:

1. MIRBA Step 1: Building the complete bow tie

   A bow tie is the combination method of fault tree analysis on the left and event tree analysis on the right. These bow ties are the basis for the application of the MIRBA methodology.
2. MIRBA Step 2: Determining frequency of occurrence. The frequency of occurrence is considered for bow ties by means the same frequency for the critical event in FTA and ETA. Firstly is to make an estimation of the frequency of occurrence in FTA on the basic event or undesired event based on the expert judgment. Then solve and explore each branch and gate combination events using Boolean algebra. Finally all the parameters proceed to the higher level to calculate the frequency of the top event. Once finished with the FTA then put the frequency of top event in ETA to calculate the possible outcome. Calculate the outcome frequency based on expert judgments for each path progress to the right branching continually using the rules of Boolean algebra.
3. MIRBA Step 3: Calculating the class of outcomes

   Once the outcome frequency has been identified, it is carrying on the class of outcome of hazardous phenomena. There are four points of view to determine the class of outcome that involves aspects of people, assets, environment and reputation. Each aspect has six levels to choose by the expert judgment in order to identify the outcome class.
4. MIRBA Step 4: Developing the risk matrix

   The risk matrix graph is constructed based on the frequency as x axis and outcome as the y axis. Four zones of risk level are classified in the risk matrix.

   Through the risk graph it can be seen the risk level and it will be easier to control and manage the risks.
5. MIRBA Step 5: Determining the mitigation plan

   Developing the mitigation plan is based on the highest risk level, by doing so the cost will be more efficient and effective. Mitigation plan is established for each of the undesired events on how to handle and manage the risk on daily basis. In order to make sure the effectiveness of mitigation plan therefore it is need to conduct EOS for evaluating the risk criticality and mitigation measure effectiveness using seven degree rating systems. Risk criticality is obtained for each of the basic events to determine the most critical basic events. Mitigation measure effectiveness is established in order to investigate the effectiveness of the mitigation plan for each of basic events.

6. MIRBA Step 6: Determining the Maintenance Strategy

   Maintenance strategy is developed in order to manage the risk failure. The method that is used to select the best maintenance is AHP, it is one of the most widely used of multi criteria decision making methods (Xu, 2001).

7. MIRBA Step 6.1: Starting AHP by selecting the goal/objective

   This Step is the starting point of AHP procedure in order to prioritize the best maintenance plan for the mooring system. Construction of hierarchy in AHP is beginning with system identification by selecting the goal/objective.

8. MIRBA Step 6.2: Developing the hierarchy tree

   The hierarchical structure is developed based on the system identification that divided into several levels. Generally AHP involved three levels:

   (i) First level: Description of the goal that need to be achieved

   (ii) Second level: The criteria of the factory to enable the goal to be achieved

   (iii) Third level: The alternative or the choices of the system in order to achieve the goal.

9. MIRBA Step 6.3: Calculating the matrix pair wise comparison

   The hierarchy evaluation starts with the calculation of the matrix pair wise comparison. The judgment is made on a numerical scale ranging from 1 to 9. The judgments of the relative importance of the elements with respect to the overall goal of the hierarchy tree are made. Elements at each level of the hierarchy are compared with each other in pairs with their respective parents in the next higher level.

10. MIRBA Step 6.4: Calculating the priority vector

    The priority vector described the preference, importance or the likelihood of its elements with respect to a certain criteria. The priority vector is obtained from normalized eigenvector of the matrix.

11. MIRBA Step 6.5: Selecting the alternative of choice

    Once the calculation process through pair wise comparison of each element relative to the overall goal produce a goal priority vector, then check the consistency ratio throughout the matrix. The consistency ratio must be less than 0.1. Continuing the selection of the best choice the next thing to do is to conduct sensitivity analysis. When there are no significant changes in the sensitivity analysis then select the best alternative of the choice.

12. MIRBA Step 7: Establish the maintenance strategy

    The last Step in MIRBA is to establish the maintenance strategy and action. This is important to control and manage the risk by understanding their individual risks and knowing the alternatives.

3.7. Validation Framework

The methodology to carry out the validation process is described in Figure 3.7.

Steps of conducting the validation framework are discussed below:

1. Identification of Validation Criteria

   The identification of validation criteria starts by questioning whether the proposed framework and its procedures make sense not only to the researcher but also to other practitioners. The questions need to be validated by the experts for example does the framework systematic, is it easy to understand etc.

2. Assess the framework by the experts

   The experts need to assess and validate the framework on the EOSs using Likert Scale. Likert scales have five points to derive the expert judgments which strongly agree, agree, neither agree nor disagree, disagree, and strongly disagree.

3. Validate the framework

   The experts are asked to validate the framework through the questions or statements using the Scale Likert and give their reasons on their judgments.

4. The framework validation for mobile mooring system consists of HAZOP, FTA, ETA and AHP. The framework validations are divided into four frameworks which are HAZOP, FTA, ETA and AHP. The experts need to

validate each of the methods whether the process/procedures are acceptable or not.

5. The framework validation of MIVTA and MIRBA

   After each of the four methods is validated, the next level is to validate the interrelated of each method. The experts need to validate whether the MIVTA and MIRBA can be combine as an integrated method of risk based decision making. The experts will validate the integration method of MIVTA and MIRBA framework as seen in Figure 3.6. The experts also give their judgments for the innovation of the proposed methodology.

6. Evaluate the Indicator Values

   Evaluate the indicator values by transforming the Likert scale to relative importance indices (RII). RII is one of the most widely used measures to determine the relative critical attributes and assessing the overall ranking of the attributes (Hemanta, 2009).

7. Checked the Relative Important Index (RII)

   Checked the relative important index for all the questions/statements that have been validated and rank their RII. The larger the index value is the better the evaluation of alternative will be (Zavadskas, 2010, Sambasivan, 2007).

8. Framework Implementation

   Once the frameworks have been validated and receive all the feedback then the last Step is to implement the framework. This framework implementation is the result of new knowledge of integrating the risk based decision making.

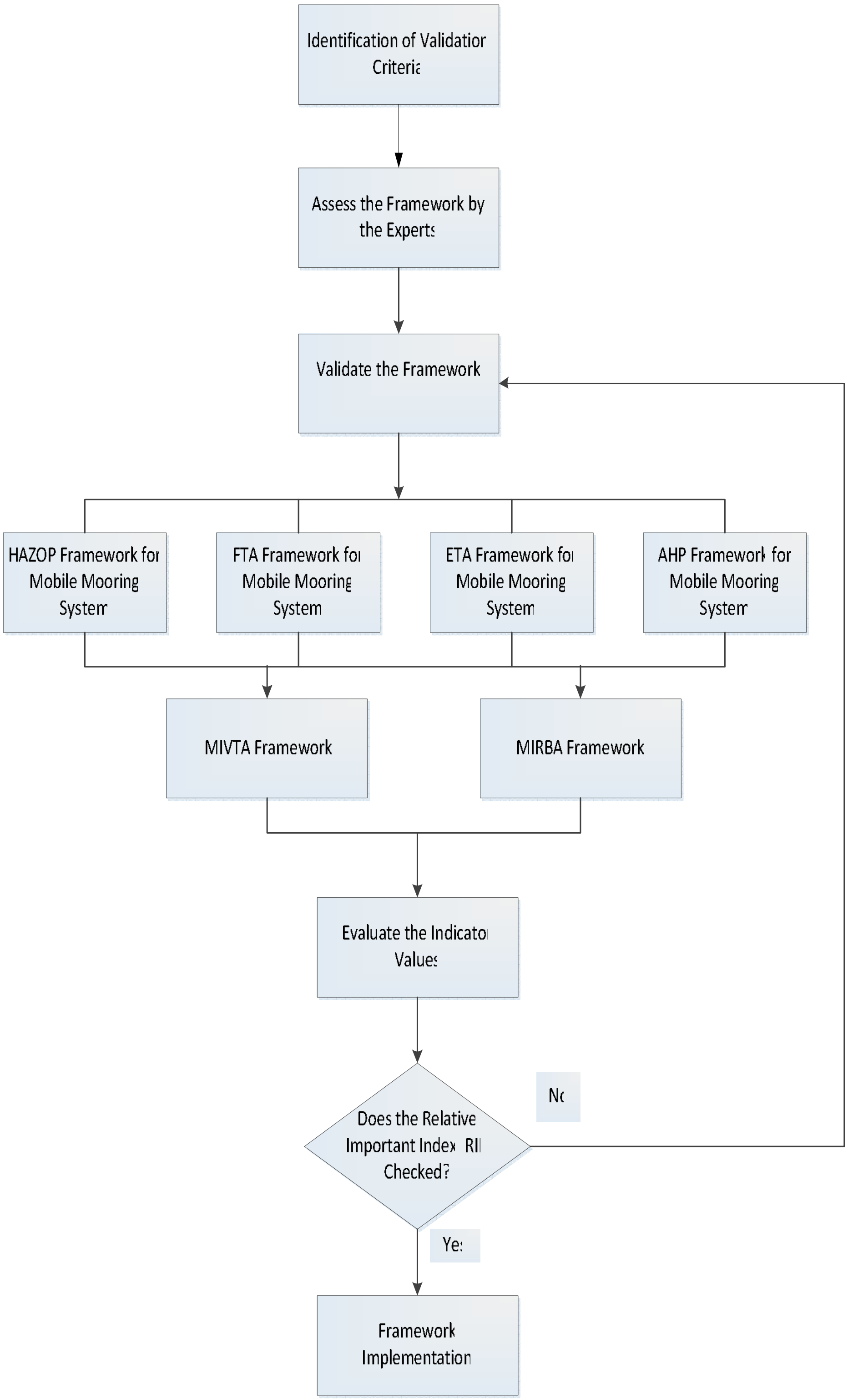

Figure 3.7. Validation Framework

3.8. Expert Opinion Elicitation

The risk assessment in offshore structure involves uncertainty and imprecision in parameters of the systems. It is crucial to represent the uncertainty and imprecision appropriately according to the information which is available. In engineering practice, the available data are frequently quite limited and of poor quality (Beer, 2013). Information is often not available in the form of precise models and parameter values. Moreover information may variously be objective or subjective, possibly including random sample data, expert opinion or team consensus. Uncertainty based on knowledge is called epistemic which described uncertainty in the model itself and in its descriptive parameters (Ellingwood, 2009; Kiureghian, 2009). Epistemic uncertainty is a collection of all problematic cases and does not imply a specific mathematical model due to its subjectivity.

In this case a suitable framework for modeling may be provided by subjective probababilities which are consistent with the axioms of probability (Kolmogorov, 1950; Savage, 1954). The subjective probabilities used in this study is based on the IMO (1997) to determine the frequency index and based on DNV (2002). In order to determine the probability of failure in basic events of FTA, this study uses expert judgments due to the unavailability of historical data. The probability of failure using expert judgments have used because of the difficulty to determine an exact estimation of the failure rates. By using expert judgment the estimation of the failure rates of an event can be determined (Mentes, 2011; Cheng, 2009). The result of expert opinion of this problem can be determined through expert opinion aggregation (Ayyub, 2006).

Dealing with the uncertainty and system complexity requires relying on the experts to address the issues. The primary reason for using expert opinions is because dealing with the uncertainty in selected technical issues related to a system of the interest. Issues with limited objective information or issues that can have a significant effect on risk are most suited for expert opinion elicitation. Expert opinion elicitation can be defined as a heuristic process of gathering information and data or answering questions on issues or problems of concern. The measures of dissonance and confusion which are constructed in the framework of the theory of evidence are applied herein for aggregating the expert opinions. The aggregation of the opinions should be performed and handled carefully by recognizing uncertainties associated with the opinions.

3.9. Summary of Research Methodology

This study develops methodology of risk based decision making for mobile mooring systems consisting of HAZOP, FTA, ETA and AHP. The HAZOP procedure can be seen in Figure 3.1, FTA procedure is shown in Figure 3.2, ETA procedure is as seen in Figure 3.4 and AHP procedure is shown in Figure 3.5. The goal of this study is to integrate the four risks based decision makings into a new approach as shown in Figure 3.6. The validation framework of proposed methods is described in the Figure 3.7. The new approach consists of two methodologies namely Methodology for Investigation of Critical Hazardous (MIVTA) and Methodology for Investigation of Risk Based Maintenance (MIRBA).

Integrating approach framework derived from four methods can be seen in Figure 3.6. Since it is difficult to collect the historical data of the failure system the engineering judgment is established in order to evaluate the frequency of occurrence and the class of consequences of the mooring system. The expert judgments are obtained using the frequency index developed by IMO (International Maritime Organizations) and the class of consequence developed by DNV (Det Norske Veritas). There are nine experts involved sharing their knowledge and experience on the maintenance strategy. The experts filled up tenth expert opinion survey (EOS) according to the phases of this study as seen in Table 3.1.

MIVTA is developed based on the three approaches namely HAZOP as preliminary risk analysis, FTA to identify the root causes and ETA to determine the possible consequences. Each Step in conducting MIVTA is described in a systematic method to model the potential causes and their consequences. In order to develop the fault tree diagram this study uses DPL Syncopation software to evaluate the frequency of occurrence.

MIRBA is developed based on the result of MIVTA by constructing the complete bow tie analysis, and then continued by the selection of maintenance strategy using AHP. Bow tie analysis derives from fault tree analysis on the left part and event tree analysis on the right part. The result of bow tie described in the risk matrix so that the risk level of the system can be classified. The risk level is useful to determine the mitigation plan in an attempt to minimize the risk. The next goal of this study is to select the best maintenance strategy using AHP.

Structural hierarchy is developed to select the best maintenance strategy on the basis of likelihood and that of consequences. In order to evaluate the AHP this study uses the Expert Choice software to calculate the matrix pair wise comparison for each level in the hierarchical structure. This approach is expected to enhance the existing risk assessment method that is useful to identify the potential critical hazards, the possible consequences, to evaluate the risk level, mitigation measure effectiveness and also to select the best maintenance strategy. The weightage on expert opinion is described in the Appendix E. The next chapter will be discussing in more detail about MIVTA application for mobile mooring system.

CHAPTER FOUR
APPLICATION OF METHODOLOGY FOR INVESTIGATION OF CRITICAL HAZARDS (MIVTA)

Chapter four as described in the previous chapter will be more discussing the MIVTA application for mobile mooring system.

4.1 Application of MIVTA

As discussed in the previous chapter MIVTA consists of three approaches namely HAZOP, FTA and ETA. There are few steps that have to be followed in MIVTA, namely:

4.1.1 MIVTA Step 1 : Literature Review

This study begins with literature review on the risk assessment methods that have been applied in oil and gas industry. Generally the risk assessment used in oil and gas industry is either qualitative or quantitative analysis. Few researches conduct both qualitative and quantitative analysis especially for mobile mooring system. Therefore this study is trying to develop methodology of risk based decision making for mobile mooring system.

4.1.2 MIVTA Step 2: Defining the objective

The aim of this study is to establish risk based decision making (RBDM) for mobile mooring system. In an attempt to achieve the aim, there are two main objectives need to be developed. The first main objective is to conduct Methodology for Investigation of Critical Hazard (MIVTA) which is useful to determine the potential causes of mooring system failure and to develop the possible consequence of an accident. The second main objective is to create Methodology for Investigation of Risk Based Maintenance (MIRBA) which is helpful to define the mitigation plan and maintenance strategy.

4.1.3 MIVTA Step 3: Determining the scope

The scope of this study is limited to the mobile mooring system of semi submersible pipe laying barge and determining the possible accident scenario on their main components of the mooring system. The significance of the study covers risk assessment, risk management, risk mitigation and risk based maintenance which will come out through the combination or integration of RBDM using four approaches HAZOP, FTA, ETA and AHP. The outcome of this study will be useful for oil and gas industry to manage and handle their assets in daily routine.

4.1.4 MIVTA Step 4: Data Compilation

Data compilation consists of primary data and secondary data which are useful to develop the risk based decision making (RBDM) of mobile mooring system. RBDM consists of two parts, namely MIVTA and MIRBA which need both primary and secondary data to establish a comprehensive RBDM.

4.1.4.1 **Primary data:** is developed through expert opinion survey (EOS), interview and brainstorming with the engineers, the consultant and the supplier. There are tenth EOS distributed to the experts in order to achieve the objectives of this study.

4.1.4.2 **Secondary data:** are collected from oil and gas industry which has been chosen as the case study. The list of secondary data needs to be collected are as follows:

(i) Plant layout of the system.
(ii) General descriptions of processes.
(iii) Operation manual/procedures.
(iv) Marine operations.
(v) Equipment descriptions.
(vi) System descriptions.

Both primary data and secondary data are recorded in a systematical method to be used in the risk assessment approach. As previously discussed, there are many risk assessment approach able to be to identify the system failure. Since this study is to investigate the risk assessment of offshore platform therefore as recommended by

(API, 1993; DNV, 2002), three approaches are going to be used to develop MIVTA, namely HAZOP, FTA, and ETA. The HAZOP is used as the preliminary method to identify the possible hazards and potential causes of system failure. FTA is used to break down the potential causes into possible faults until the undesired events are found. ETA is helpful to describe the sequence of outcomes and to determine the possible consequence of accidents. Each of this method will be discussed in more detail in the next section.

4.1.5 MIVTA Step 5: Starting HAZOP by Defining the System/Activity

Starting HAZOP analysis by defining the system / activity and continue to step 5.1 and step 5.2 in MIVTA. Defining the system/activity is helpful to insure the scope of study. The platform used for the case study is owned by one of the oil and gas industries operating around the world. All the figures and information taken in this section belong to the company.

Due to particular circumstances, profile of the company under this study will remain confidential. The platform under this study is a semi submersible column stabilized pipe lay barge fitted with twelve point mooring system to aid controlled movement during pipe lay operations. The main particulars of the vessel are described in Table 4.1.

Table 4.1. Main Particular of Vessel

No.	Parameters	Units (m)
1.	Length Overall LOA	188.06
2.	Breadth Overall	54.86
3.	Depth Overall	27.7
4.	Lightship Draught (mean)	4.56
4.	Operating Draught (normal)	13.72
4.	Operating Draught (maximum)	14.76

The twelve mooring winches are mounted near each of the four corners of the barge. At each corner there are three winches, two in the pontoon and one in the column. The vessel has a hull with four columns and two pontoons as illustrated in Figure 4.1. The vessel utilizes the semi submersible concept, providing a motion reduced mobile platform from which a number of offshore operations, principally pipe laying, may be carried out in sea states of 15ft (4.57m) significant wave height. The twin pontoon, variable draft feature, permits the operator a degree of flexibility when deploying in various sea states in order to obtain maximum efficiency from the vessel.

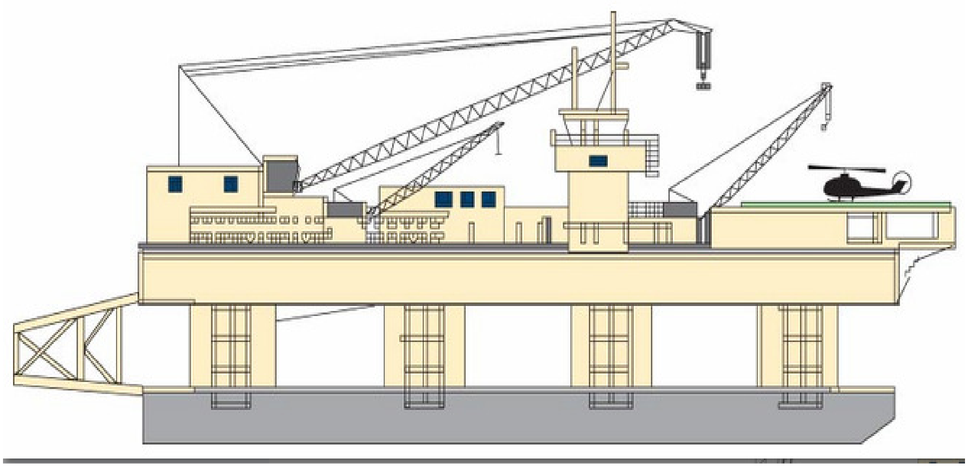

Figure 4.1. A semi submersible column stabilized pipe lay barge (Eni, 2010)

The type of mooring system for sea line laying for vessel is shown in Figure 4.2. The vessel has been adapted, and customized into units which optimize pipe lay production levels with pipe of varying diameters in deep water locations throughout the world. Commonly the 12 mooring lines used in this operation are 6 ones fore and 6 ones aft.

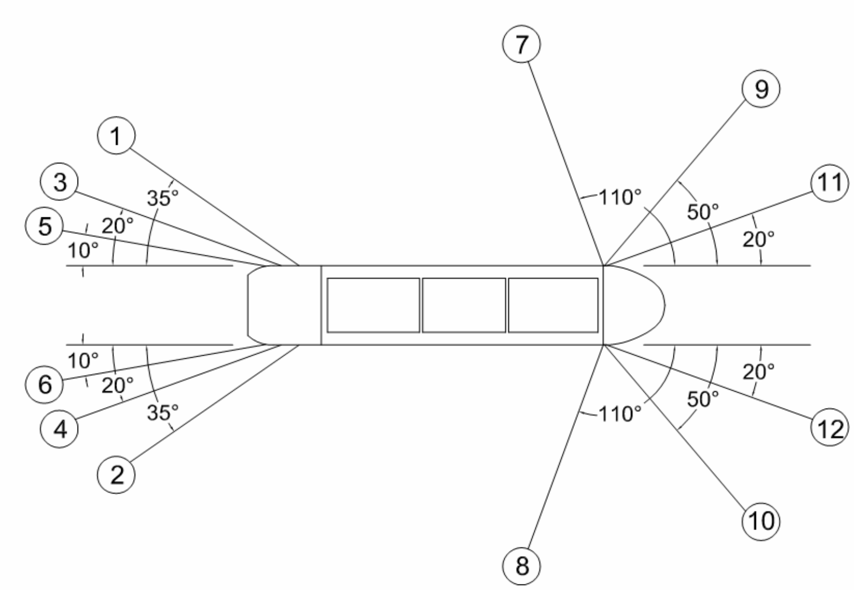

Figure 4.2. Mooring Configuration

The vessels need assistance from an anchor handling tug (AHT) in order to moor the vessel in a working pipe lay configuration. The vessel has no dynamic positioning capability and is not able to run its own anchors. As the vessel is reliant on the AHT performance, it is essential that anchor running does not commence before preparations have been completed and that environmental conditions are favorable. The mooring forces to be applied will be determined in order to keep the vessel within the specified limits at the water depth for the project in question. While laying pipe, the winch tensions are controlled by the winch operators taking the force exerted by the pipeline on the vessel into account and also the holding capacity of the seabed.

The overview of principal production line running down through the barge center is commonly referred to as the ‘firing line’ as shown in the Figure 4.3. The principal of firing line are as the following:

(i) Double jointed pipes are loaded onto the line up system at the head of the firing line by the transverse conveyors.

(ii) The new pipe is then lined up with the main pipe string and welding commences at the first station or ‘bead stall’.

(iii) The main pipe string passes over rollers.

(iv) Through the tensioners.

(v) And the X Ray Station.

(vi) It then passes through the field jointing system.

(vii) Over the fixed truss.

(viii) The Stinger through the sea and onto the seabed.

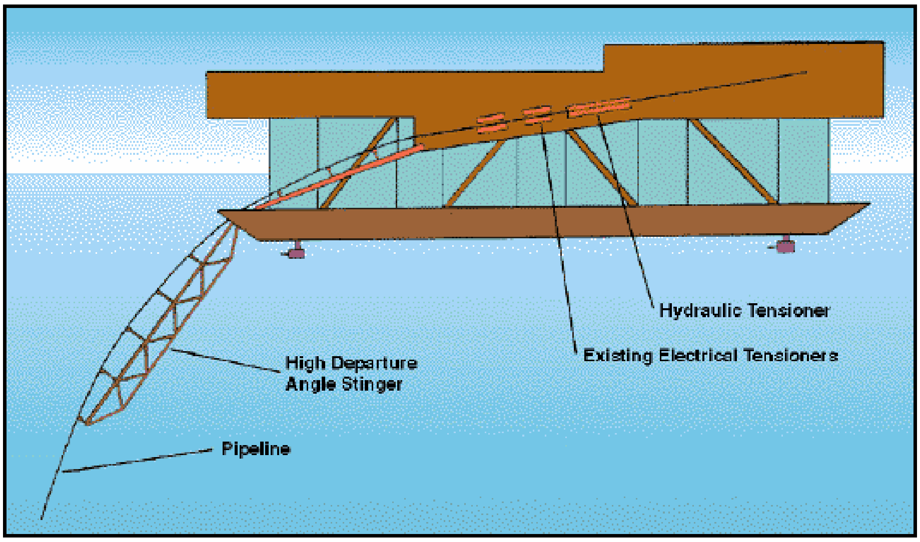

Figure 4.3. The Principal of Firing Line (Gifford, 1995)

As discussed previously the vessel needs to operate in rough weather conditions in order to conduct offshore construction operations. There are several problems related to mooring system that may cause damage to the platform, injury and even death to the people, loss of the assets and in the end will effect the reputation of the company. Therefore it is necessary to conduct risk based decision making to investigate all potential causes that may lead to an accident, their consequences and to develop the mitigation strategy to reduce the risk and to control it daily. The risk based decision making approach used in this study consists of qualitative and quantitative analysis. The approaches derive from HAZOP as preliminary risk analysis, FTA to define the potential causes, ETA to determine the possible consequences and AHP to select the best maintenance strategy. The following section will discuss each approach further and how to apply it in mobile mooring system.

4.1.6 MIVTA Step 5.1: Defining Problems of Interest

The problems of interest are analyzed in an attempt to determine the potential causes and their consequence able to bring serious damage. The problem is investigated based on the main component of the system. The purpose of the HAZOP is to investigate the hazard of mooring system which focuses on how the system will deal with rough weather conditions rather than on how it will carry out under severe weather conditions. The investigation contains a review of each system operation, determining each of the potential causes of system failure, their consequences and how to handle it daily. Figure 3.6 shows the HAZOP Steps as a part of MIVTA framework that will be discussed in details and also the result that has been accomplished.

The first site visit is important in order to enlighten the method to identify and discuss which hazards or operational issues in the mooring system might occur. The first EOS is developed as a preliminary risk analysis study to investigate the problems related to mooring system. Expert opinion survey and direct interview with many people during offshore seminars, offshore exhibition and workshops that include consultant, supplier, engineers, managers involved in mooring system are conducted in order to get an idea and shaping the idea of the common issues and problems related to mooring system failure. The question structure to help shaping idea is in first EOS can be seen in Appendix A and the result of the interview with the people in seminars and offshore exhibitions are combined with the feedback from nine experts are summarized in HAZOP record tabulated in Table 4.2. Once the general problems of mooring system are formulated the next Step is to choose the mooring system as a case study. As discussed in previous sections the mobile mooring system of semi submersible pipe laying barge is under study.

The first task to develop HAZOP analysis is through brainstorming session with the people involved in the system. The brainstorming session is involving nine experts that balance in terms of experience, knowledge and disciplines. The HAZOP teams generally consist of four to eight people to achieve comprehensive results (Shewring, 2010). For this study, those nine experts remain to be the main respondents. All of the experts are recognized professionals in the mooring system with experience more than 10 years, therefore their combined knowledge and experience are sufficient to develop the framework of risk assessment of the mooring system. These numbers are kept to ensure the maximum quality and effectiveness during the brainstorming session (Vargas, 1998; Wang, 2004). The HAZOP study is developed through the following procedure:

(i) The experts outline the specific objective of the vessel under study and describe the general arrangements of the mooring systems. This procedure contains the design arrangement, operational procedure, weather condition specification, description of equipment and system descriptions.

(ii) Any related questions to the scope and concept of the system are discussed.

(iii) The main components of mooring system consisting of mooring line, anchor failure, anchor handling failure and appurtenances connection failure are highlighted due to their main contribution in mooring system.

(iv) Any related issues about these components are then discussed and answered by the experts.

(v) The specific components are studied from this point using the HAZOP guide words. Every guide word is a systematic list of deviation perspectives to describe certain conditions that may lead to operational problems and even causes an accident. Then continued to investigate the potential causes and the consequence of an undesired event. When the safeguards are considered inadequate by the experts because of high contribution of likelihood and consequences then an action should be taken.

The HAZOP is developed in a systematic method using the guidewords and deviation to consider each component of mooring systems, their potential causes of failure, the consequences and the safeguard action. The HAZOP results are tabulated in Table 4.2. The HAZOP result recorded in this study are generally in the operational and maintainable categories. Formerly there are no significant records of potential causes that may lead to an accident. Detailed HAZOP actions must be reviewed and recorded by the project manager to ensure that all system are fit for purpose. The HAZOP results are qualitative risk assessment based on the experience and knowledge of the experts involved in the mooring system. It is as a preliminary study to identify the potential causes of mooring system and their consequence. Therefore it needs to conduct a risk assessment in more detail using FTA and ETA as a quantitative study. FTA and ETA will be discussed in more detail in the following section.

4.1.7 MIVTA Step 5.2: Recording HAZOP Results

Once the HAZOP analysis has been done, the next Step is to tabulate the results into systematic worksheets. The HAZOP worksheet consists of the components under study, guideword, deviation, potential causes, possible consequence, safeguard and suggested actions in order to minimize the failure. The table 4.2 shows the HAZOP result of a mobile mooring system.

Table 4.2. HAZOP Result

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
Mooring Line	Unable to control the movement	Mooring Line Breakage	Corrosion	➢ Reduced the mooring capacities for example the moorings no longer meet their allowable loads ➢ Decrease the mooring line service life ➢ Broken wires ropes	➢ Uses heavier zinc coating to enhance corrosion protection properties ➢ The larger diameters of wires may use heavier zinc coatings to enhance the attainable design life ➢ An anti corrosion blocking compound should be applied during manufacture to increase corrosion prevention measure. ➢ Regular maintenance and inspection in order to avoid huge damage.	➢ Conduct visual inspection for example pitting inspection in order to determine the remaining life of the chain. ➢ Perform corrosion measurement using ROV to measure corrosion potential
			Abrasion	Decrease the service life of mooring lines	Uses braided jacket or sheathed spiral strand wire to minimize particle ingression that cause harmful abrasion of the ropes.	➢ In situ water inspection is needed to inspect the touchdown zone where rocks or debris on the sea bed can cause mooring line abrasion ➢ In situ water inspection of wire rope using ROV
			Mooring line clashed	➢ Operation activities delayed ➢ Vessel damage	Uses a mooring failure detector that can be attach with mooring chain or wire rope inculdes a power source which supply power to a transmitter to signal the failure by acoustic or radio frequency means.	ROV inspection in order to identify if the lines are intact and or suffer of breakage using inclinometers
			Collision	➢ Operation shutdown ➢ Vessel damage	➢ Checking the ARPA radar	➢ Monitored the radar plant as a navigational aid and for

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
					➢ Checking the day vision radar	weather surveillance in order to detect and to track weather fronts, storm clouds ➢ Observe the radar with antenna arrays to define the anchor location match with target acquisition
Anchor	Loss of position	Anchor Failure	Insufficient holding	➢ Unable to penetrate at certain depth ➢ Incapable to provide sufficient resistance of applied load	Check as well all monitoring equipment before start the activities & make good coordination with project people	Checking and monitoring the equipment with Remotely Operated Vehicle (ROV)
			Part of anchor breaks	➢ Unable to hold the vessel on location ➢ The vessel moves or even breakaway	➢ Conduct NDT test on anchor in order to define flaws ➢ Awareness of extreme environmental condition especially in deep anchorages when to consider anchor and evacuate the anchorage	Monitoring of current weather conditions in order to maintain the safety of anchored vessels
			Mooring line clashed	➢ Operation activities delayed ➢ Vessel damage	Uses a mooring failure detector that can be attach with mooring chain or wire rope inculdes a power source which supply power to a transmitter to signal the failure by acoustic or radio frequency means.	ROV inspection in order to identify if the lines are intact and or suffer of breakage using inclinometers
						➢ Monitored the radar plant as a navigational aid and for weather surveillance in order

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
			Collision	➢ Operation shutdown ➢ Vessel damage	➢ Checking the ARPA radar ➢ Checking the day vision radar	to detect and to track weather fronts, storm clouds ➢ Observe the radar with antenna arrays to define the anchor location match with target acquisition
Mooring winches	Uable to shifting, holding & positioning	Winch handling failure	Barge Winch Failure	➢ Disruption of operations ➢ Damage or harm to life ➢ Damage nearby installations	Record and monitor the stability of vessel	Checking various parameters that effect the stability of the vessel through stability control console such as pipe tension, anchor winch tension etc.
Anchor Handling Tugs (AHT)	Misconfiguration work	Anchor handling failure	Anchor Handling Tugs Failure	Unable to configure the working pipe lay	Radio and navigational warnings should be given to other traffic to keep safely away from the construction activities.	The positions of the AHT should be monitored when handling anchors, in order to ensure that they fulfill with the anchoring requirements in general and that lowering of an anchor does not start until the AHT is at the approved location.
Appurtenances Connection	Unable to connect together the main mooring line components	Appurtenances connection failure	Corrosion	➢ Reduced the connection equipment capacities for example the connecting no longer meet their allowable loads ➢ Decrease the connecting equipment service life ➢ Connecting equipment broken	➢ Uses heavier zinc coating to enhance corrosion protection properties ➢ The larger diameters of wires may use heavier zinc coatings to enhance the attainable design life ➢ An anti corrosion blocking compound should be applied during manufacture to increase corrosion prevention measure. ➢ Regular maintenance and inspection in order to avoid	➢ Conduct visual inspection for example pitting inspection in order to determine the remaining life of the chain. ➢ Perform corrosion measurement using ROV to measure corrosion potential.

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
					huge damage.	
			Fatigue Cracking	➢ Crack of connecting equipment such as shackles, swivels. ➢ Decrease the serviceability of the appurtenance connection such as shackle, ➢ The vessel breakaway	➢ All the arrangements for appurtenance connections should be strong enough and capable to endure fatigue loading over the life design and beyond ➢ Regular maintenance and inspection in order to avoid huge damage	➢ Conduct break testing to detect the presence of any fatigue cracks by doing magnetic particle inspection (MPI) ➢ Checking & monitoring the equipment with Remotely Operated Vehicle (ROV)

4.1.8 MIVTA Step 6: Determining the Top Event

Determining the top event derives from the HAZOP results already been identified. Top event is generated into two parts which are useful to determine the root causes using FTA and the other part to define the consequence classification using ETA. The next approach to be discussed is FTA with regards to MIVTA framework as seen in Figure 3.6. These Steps are parallels with FTA and ETA methods, in which FTA focuses on the prevention strategy while ETA focuses on the mitigation strategy.

4.1.9 MIVTA Step 6.1. a: Starting FTA for Each Top Event, Built Fault Tree

Each top event is generated through FTA in order to determine the root causes of mobile mooring system failure. The fault tree of each top event is developed until the basic events or the undesired events have been identified. Fault tree is a systematic approach, therefore in order to construct the fault tree, the potential causes of the accidents are classified, following the approach developed by Labor (1990), Program (2002); Taylor (2006) namely direct causes, indirect causes and basic causes. Furthermore the direct causes and indirect causes are broken down into detailed direct causes and detailed indirect causes until the basic causes or undesired events are found.

The lowest level is the direct cause, an accident happens once an object or people obtain an amount of energy sources or hazardous material. The direct cause mostly happens because indirect causes related to inadequate training, unsafe acts and conditions. Consecutively indirect causes take place when management policies, personal or environmental factor are poor, this condition is called basic causes. Basic causes are related to poor management policies, personal or environmental factor e.g. incompetence crew, uncertified crew, etc. Human error problems are systematically considered in the safety assessment framework, since they will result in human injuries/illnesses/deaths. The problems related to human error are commonly caused by language, education and training (Wang, 2002).

4.1.10 MIVTA Step 6.1.b: Develop the Fault Tree

Developing the fault tree until the undesired/basic events occur is important in order to determine the root causes of mobile mooring system failure. The fault tree construction uses gate symbol to describe the relation between each events. The gate symbol consists of OR gate and AND gate. OR gate means that the events will happen if one or more of the input events arise. While the meaning of AND gate is that the events will arise if all the input happen.

The fault tree structure of the models is based on a previous structure developed by Niu (2009) and Mentes (2011) and it has been applied based on literature and experts knowledge. The investigation is started from the checklist of mooring system, the information is gathered together with the expert through brainstorming and discussion to map the mooring system failure. The main components of mooring system are the mooring line and anchor, used along with the other components such as connecting elements, floats etc as discussed by Harris (2006) and API (2005).

The semi submersible under study requires assistance from an anchor handling tug (AHT) in order to moor the vessel in a working pipe lay configuration. The vessel has no dynamic positioning capability. It is not able to run its own anchors, therefore the vessel is reliant on the AHT performance. Based on those main components of mooring system and brainstorming with the experts, this study formulates the four direct causes of mooring system failure as follows:

(i) Mooring line breakage (MLB)
(ii) Anchor failure (AF)
(iii) Anchor handling failure (AHF)
(iv) Appurtenances connection failure (ACF)

These four direct causes later on are called top events in order to construct the fault tree. Direct causes are breakdown into detailed direct causes such as corrosion, abrasion, collision, fatigue cracking etc. Furthermore the detailed direct causes also broken down until the undesired events are identified. The following sections will discuss in more detail the critical events of mooring system failure, namely MLB, AF, AHF and ACF.

4.1.10.1 Fault Tree Model for Mooring Line Breakage (MLB)

The following fault tree model determines the potential causes of mooring line breakage as seen in Figure 4.4a. In order to develop a fault tree for the mooring line breakage, there are four events to be considered which include corrosion, abrasion, mooring line clashed with another mooring line and collision. These events are related by using an OR gate because any one of them may cause the structure adrift. Furthermore these events are developed in more detailed causes until the undesired events are identified.

Corrosion is the degradation of material by chemical reaction with its environment or sea water that can accelerate the beginning and growing of fatigue cracks. Corrosion events include adverse environmental condition and material damage as seen in Figure 4.4b. These events are related by using OR gate because any one of them may cause corrosion of mooring line. The material damage event is developed further using AND gate into the following problems related to the inadequate coating protection and inadequate maintenance. These events are related by using AND gate because both events need to occur to cause the material damage. Inadequate maintenance event is developed further using OR gate into inadequate maintenance schedule and human error.

Human error in this thesis indicates the physical fatigue or lack of the awareness of the worker. Tiredness, sleepiness and illness can be caused danger, wrong procedures, and fatality due to human error. The probability of human error is derived from the expert opinion survey. This thesis assumes the probabilities of human error are the same since it is placed in the basic events. Even though the probabilities of human error are the same, in different conditions it will trigger different events, which may cause the failure of mooring system. In fault tree model, the probability of higher level will be different although the probabilities of human error are the same as basic events (Silvianita, 2013).

Abrasion happens when the ropes are exposed to abrasive surfaces or by the ingress of particles into the rope that can reduce the strength of the rope. Abrasion events include an abrasive particle which is broken down using AND gate into rocky seabed and debris in the seabed as seen in Figure 4.4c.

Mooring line clashed with other mooring line events includes wrong operational procedure and excessive environmental loads, they are related by an OR gate as seen in Figure 4.4d. Wrong operational procedure due to uncertified and incompetence crews, both events are related by an OR gate. Furthermore excessive environmental loads are associated with waves, winds and currents. These three events are connected by AND gate. Collision event incorporates problems between collision with supply vessel and collision with another vessel (AHT) connected by OR gate. Collision with supply vessel is divided into natural hazard and maneuvering gear error by connecting OR gate.

Furthermore maneuvering gear error includes problems related to electrical failure, mechanical failure and human error in OR gate connection. Collision with another vessel (AHT) is caused by natural hazard and maneuvering gear error connected OR gate. The symbol * shows the same events in one top event so that there will not be any duplicate events in the analysis.

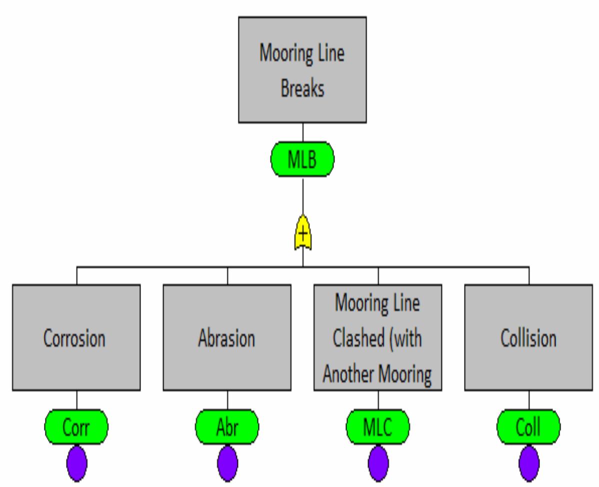

Figure 4.4a. FT Model Mooring Line Breakage (MLB)

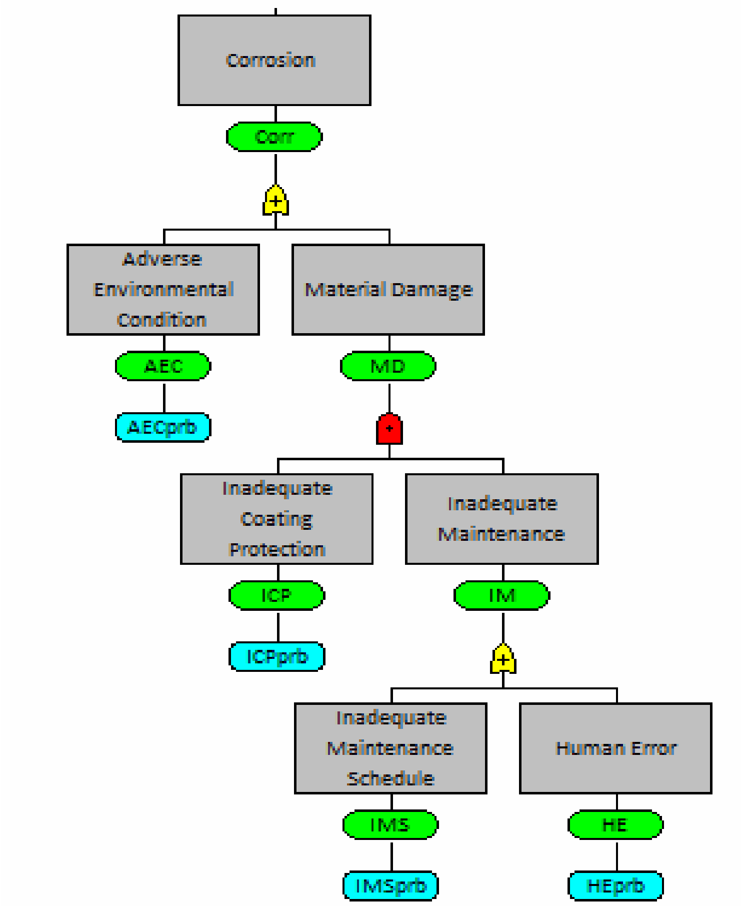

Figure 4.4b. FT Model Corrosion with regards of Mooring Line Breakage (MLB)

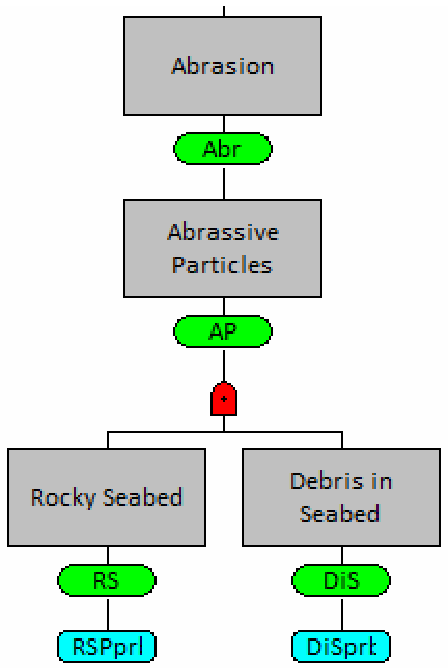

Figure 4.4c. FT Model Abrasion with regards of Mooring Line Breakage (MLB)

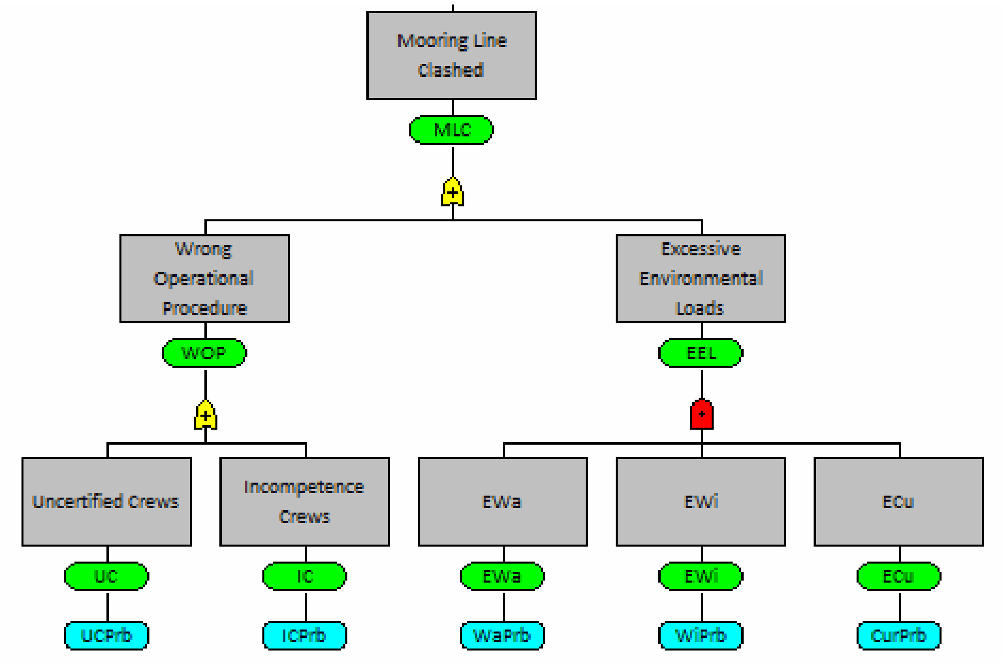

Figure 4.4d. FT Model Mooring Line Clashed with regards of MLB

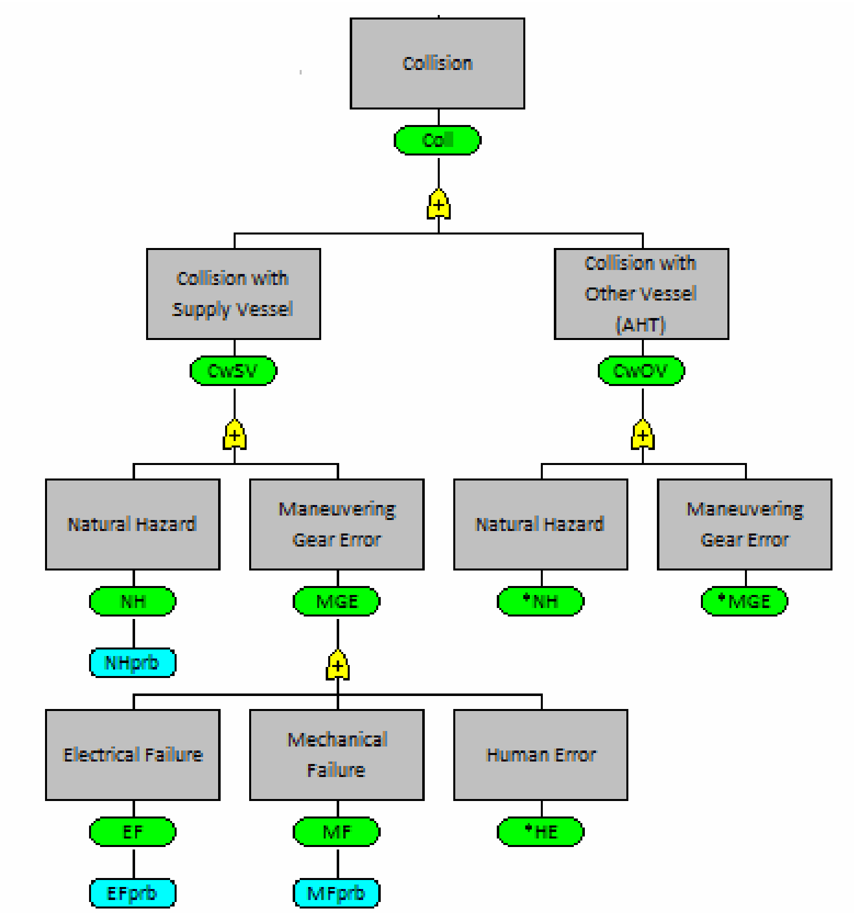

Figure 4.4e. FT Model Collision with regards of MLB

4.1.10.2 Fault Tree Model for Anchor Failure (AF)

Anchor failure event is the case where the mooring systems fail due to insufficient holding, part of anchor breaks, mooring line clashed and collision as seen in Figure 4.5a. These events are connected with OR gate. Insufficient holding problems include poor holding ground, high tension on mooring line and natural hazard. These problems are related by OR gate as seen in Figure 4.5b. Moreover poor holding ground events are related to problems of improper anchoring and improper soil data sampling connected by AND gate. A good holding ground will provide a strong connection to the anchor flukes. Improper anchoring events are due to human error, rocky seabed and soft clay, these three events are related to AND gate.

High tension on the mooring line (over the anchor holding capacity) events include problems with design error and adverse environmental condition. Both events are related by an OR. Part of anchor breaks (fluke or shank) is due to problems caused by improper design, natural hazard, and corrosion. These problems are related to OR gate as seen in Figure 4.5c. Improper design events consist of material defect and human error with problems connected to an OR gate. Material defect events are caused by improper quality control and poor raw material, and these events are connected to AND gate. Corrosion problem is an event that includes material damage and adverse environmental condition related to OR gate. Material damage consists of problems related to the inadequate coating protection and inadequate maintenance, and these events are developed using AND gate. Inadequate maintenance is broken down further with OR gate into inadequate maintenance schedule and human error.

There are two causes of mooring line clashed events constituting wrong operational procedure and excessive environmental loads that are related by an OR gate as seen in Figure 4.5d. Wrong procedure events are divided into incompetent and uncertified crews associated with an OR gate. Excessive environmental load events consist of waves, winds and currents that are related by an AND gate. Collision events involve collision with supply vessel and collision with another vessel. These two events are related by an OR gate. Collision with supply vessel is caused by maneuvering gear error and natural hazards related by an OR gate as seen in Figure 4.5e. Maneuvering gear error consists of electrical failure, mechanical failure and human error. Collision with another vessel has the same root causes of failure with supply vessel consisting of maneuvering gear error and natural hazards associated with an OR gate.

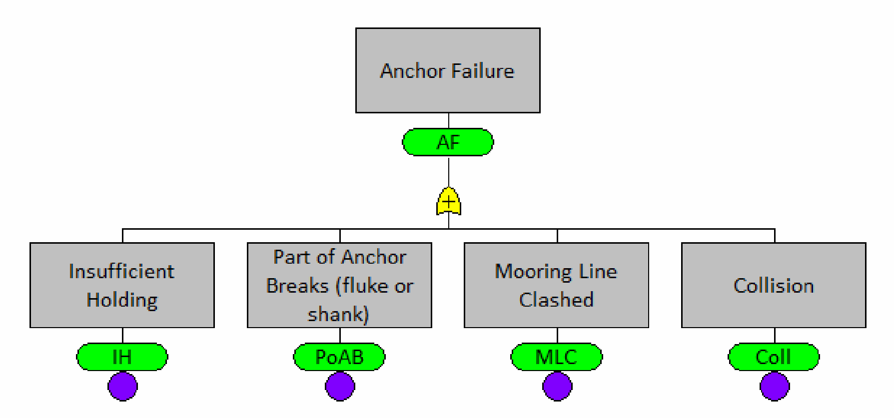

Figure 4.5a. FT Model Anchor Failure (AF)

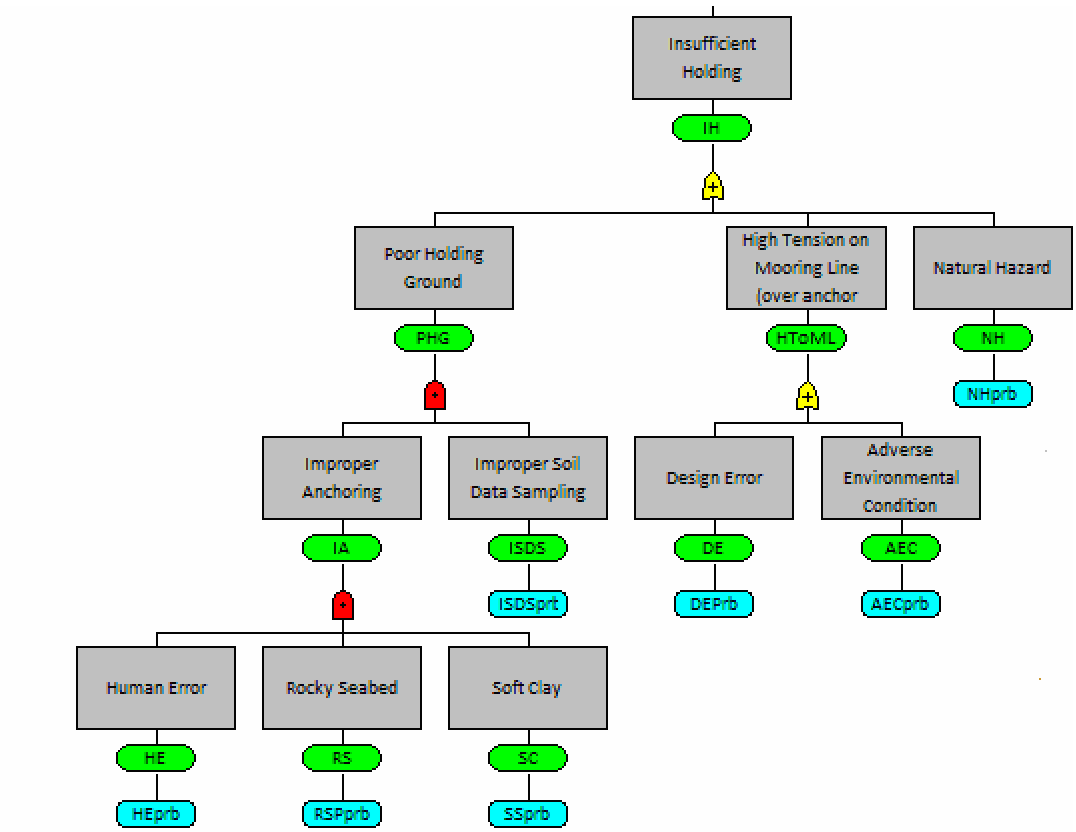

Figure 4.5b. FT Model Insufficient Holding with regards of AF

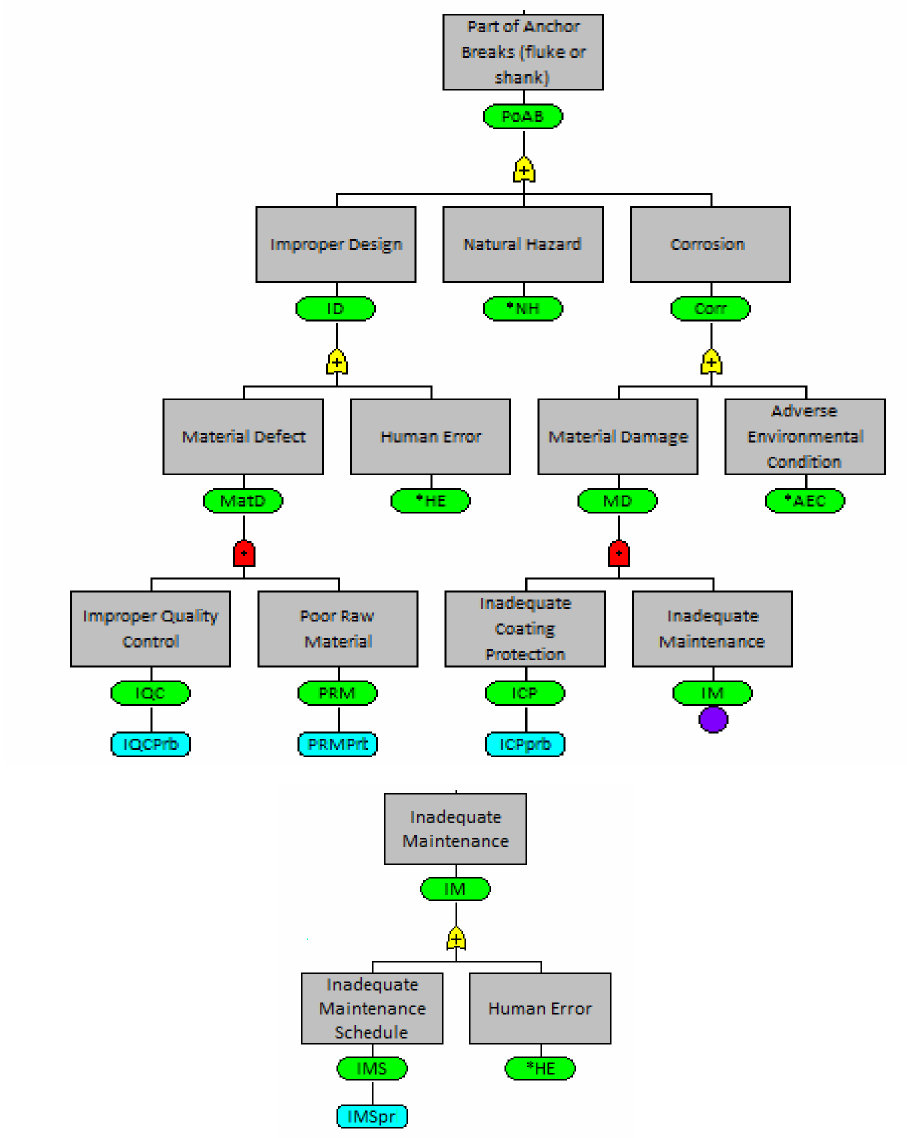

Figure 4.5c. FT Model Part of Anchor Breaks with regards of AF

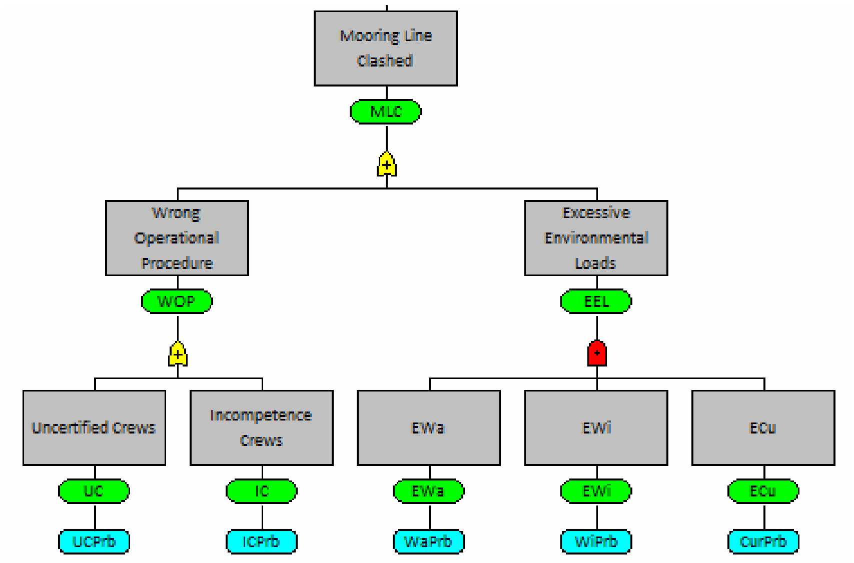

Figure 4.5d. FT Model Mooring Line Clashed with regards of AF

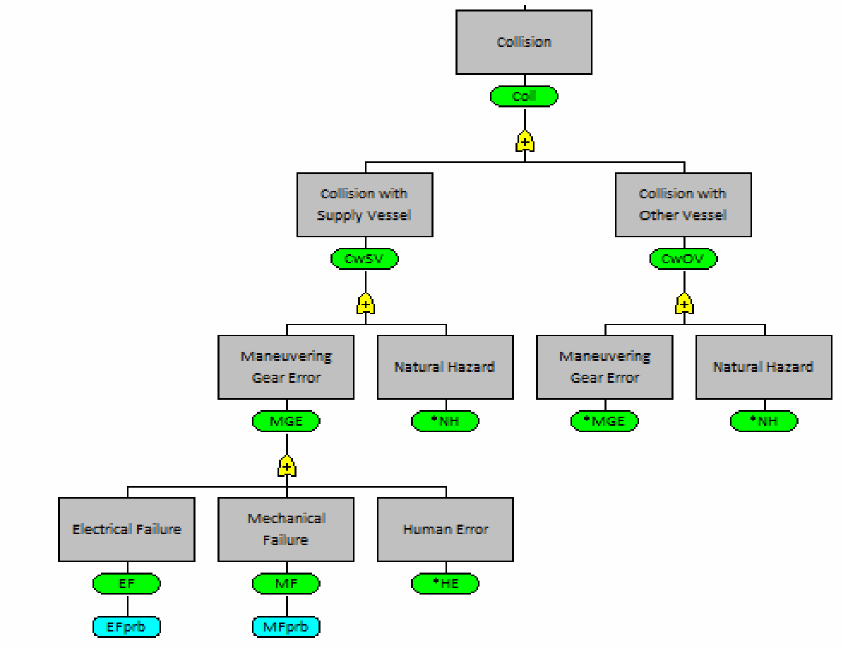

Figure 4.5e. FT Model Collision with regards of AF

4.1.10.3 Fault Tree Model for Appurtenances Connection Failure (ACF)

Appurtenances connection failure is divided into corrosion and fatigue cracking. These events are connected by OR gate as seen in Figure 4.6a. The corrosion problem as discussed previously, consists of material damage and adverse environmental condition associated with OR gate as seen in Figure 4.6b. Material damage involves the inadequate coating protection and inadequate maintenance. These events are developed using AND gate.

Inadequate maintenance is divided by OR gate into inadequate maintenance schedule and human error. Fatigue cracking involves four events namely improper material, inadequate maintenance, design failure and high tension as seen in Figure 4.6c. These events are connected by OR gate. Improper material includes wrong material, uncertified equipment and manufacturing error are connected by an OR gate. Inadequate maintenance is divided into human error and inadequate maintenance schedule associated with an OR gate. Design failure consists of incomprehensive data collection and human error that are related to OR gate.

High tension on the mooring line (over the anchor holding capacity) events include problems with mooring line clashes and adverse environmental condition.

Both events are related by an OR gate. Mooring line clashed with other mooring line events includes wrong operational procedure and excessive environmental loads, they are related by an OR gate. Wrong operational procedure due to uncertified and incompetent crews. These two events are related by an OR gate. Furthermore, excessive environmental loads are associated with waves, winds and currents, these three events are connected by AND gate.

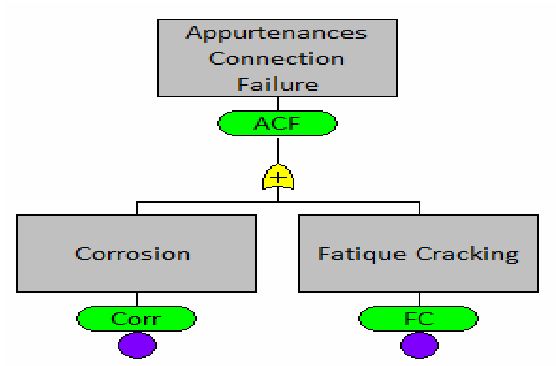

Figure 4.6a. FT Model Appurtenances Connection Failure (ACF)

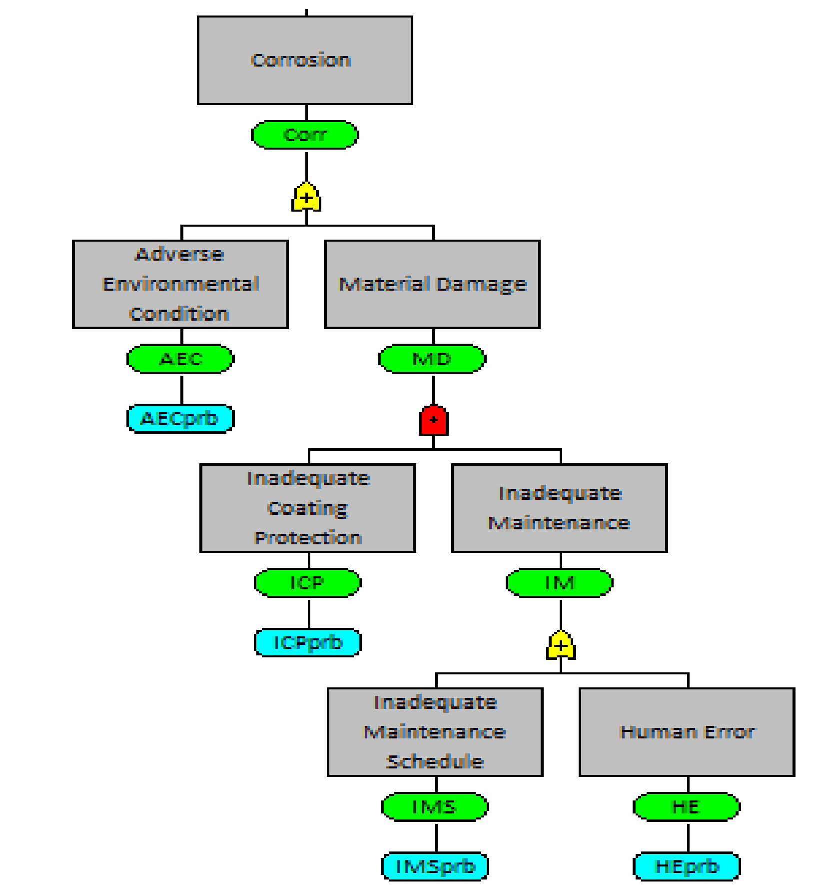

Figure 4.6b. FT Model Corrosion with regards of ACF

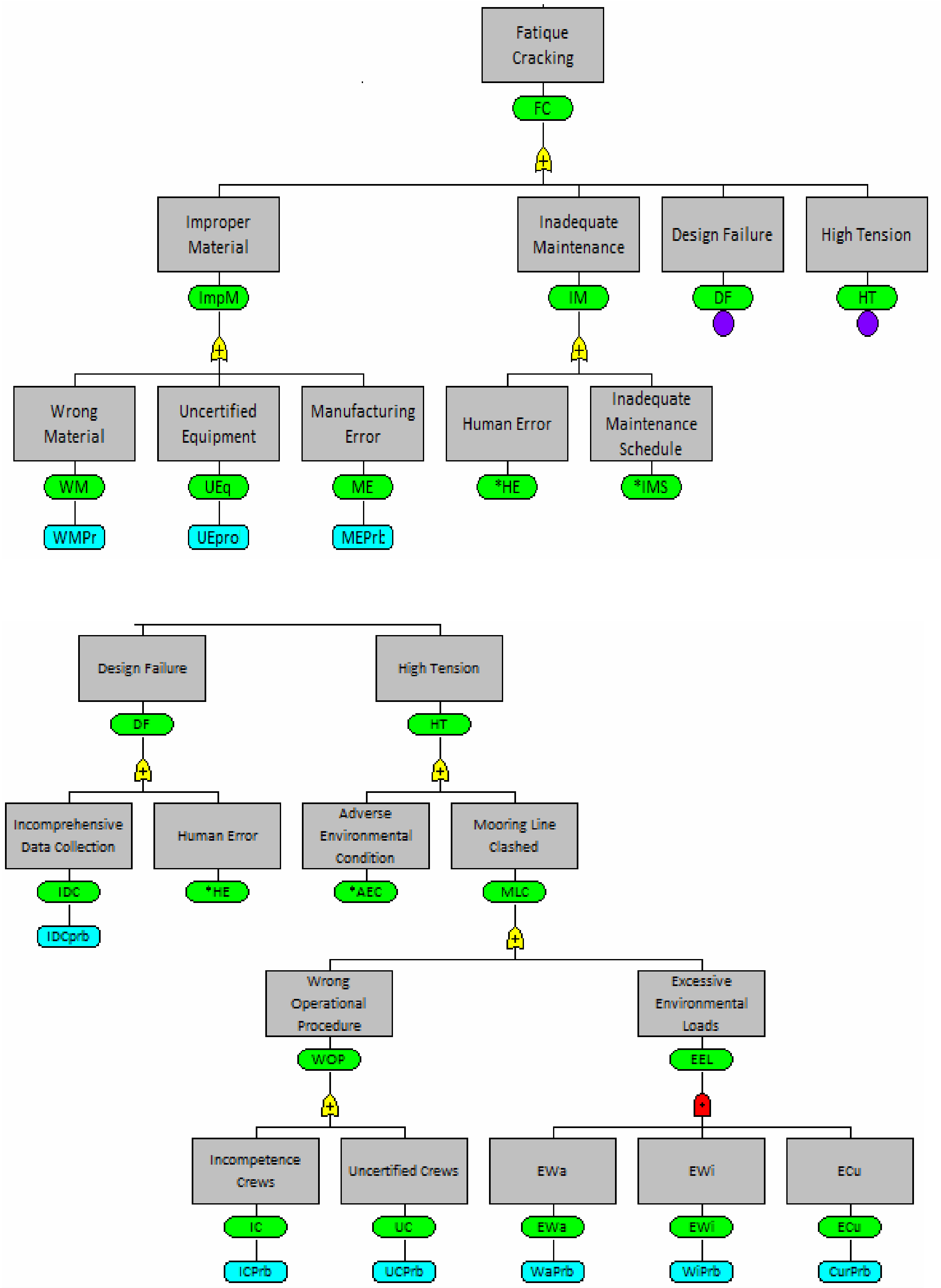

Figure 4.6c. FT Model Fatigue Cracking with regards of ACF

4.1.10.4 Fault Tree Model for Anchor Handling Failure (AHF)

There are two causes of anchor handling failure, namely barge winch failure and anchor handling tugs failure. These events are related by an OR gate as seen in Figure 4.7a. Barge winch failure is related to winch power error and breaking system error that are connected by an OR gate as seen in Figure 4.7b. Winch power error consists of inadequate winch maintenance and inappropriate electrical supply of winch, these two events are connected by an OR gate.

Furthermore inadequate winch maintenance is divided into inadequate winch maintenance and human error connected by an OR gate. Inappropriate electrical supply of winch includes electrical failure of winch and human error in OR gate connection. A breaking system error is caused by inadequate winch maintenance and insufficient brake holding power related to an OR gate. Insufficient brake holding power includes incorrect specification of the mooring and incorrect reeling of mooring lines associated with an OR gate as seen in Figure 4.7c. Incorrect specification of mooring consists of design error and human error, these events are connected by an OR gate. Incorrect reeling of mooring lines incorporates with design error and human error associated with an OR gate.

Anchor handling tugs failure is caused by two events, namely winch failure and tugs breakdown as seen in Figure 4.7d. These two events are related by an OR gate. Furthermore winch failure is broken down into improper winch maintenance and winch operating procedure failure associated with an OR gate. Occurrence of unsuitability of AHT survey is caused by incompetent and uncertified crews that are related to OR gate. While winch operating procedure failure includes incompetent crews and human error associated with AND gate. Tugs breakdown consists of irregular AHT maintenance and improper winch maintenance related to OR gate. The basic events of improper winch maintenance concerning with tugs breakdown events is not broken down further because it has the same root cause as that in winch failure events. As discussed previously, the symbols of * has the meaning that the events have the same root cause in one top events. This symbol is used to avoid duplicate analysis through the software.

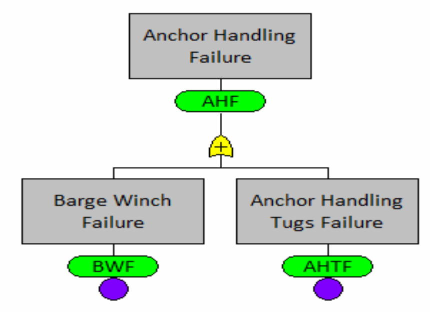

Figure 4.7a. FT Model Anchor Handling Failure (AHF)

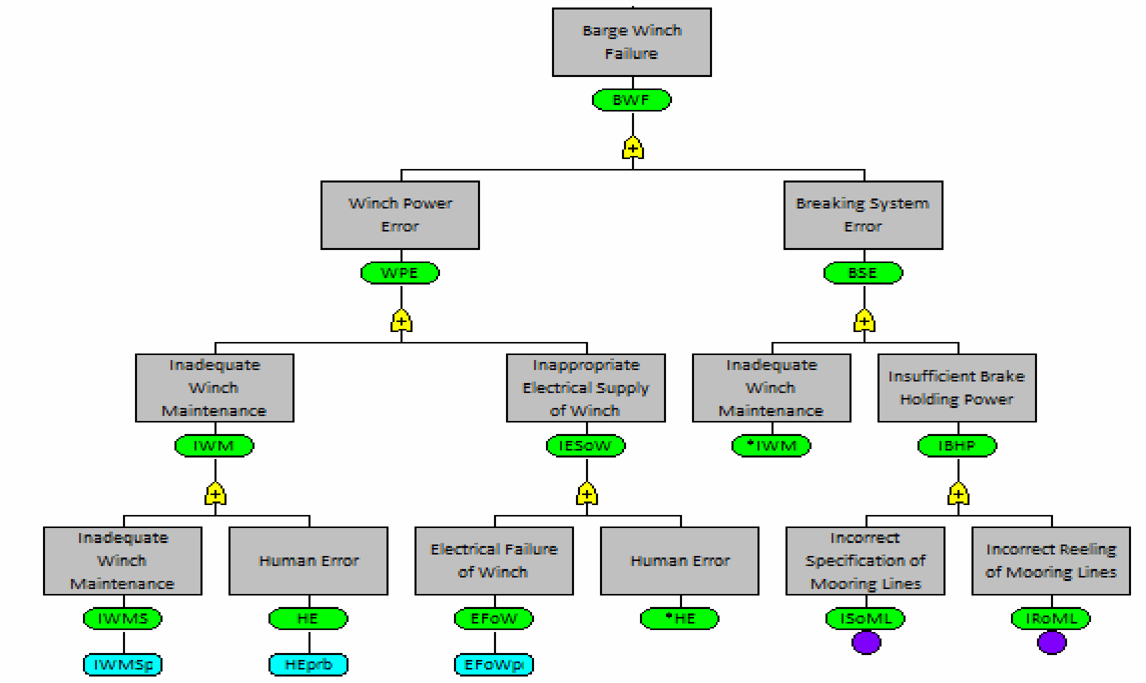

Figure 4.7b. FT Model Barge Winch Failure with regards of AHF

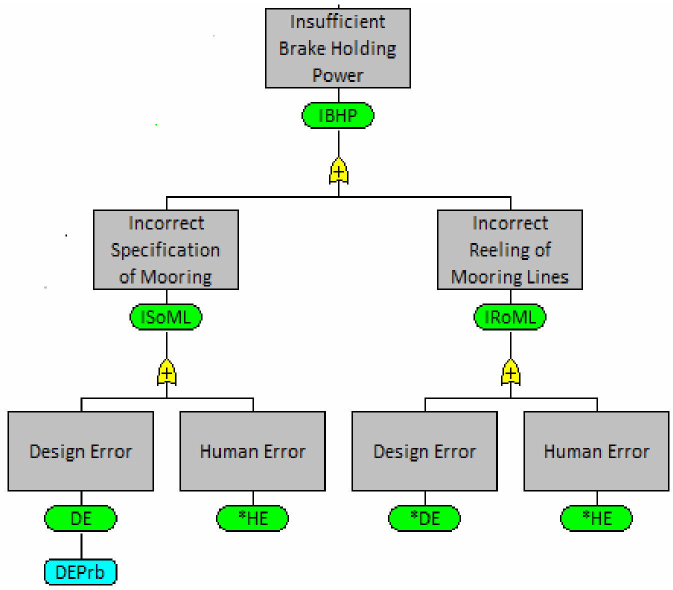

Figure 4.7c. FT Model Insufficient Brake Holding Power with regards of AHF

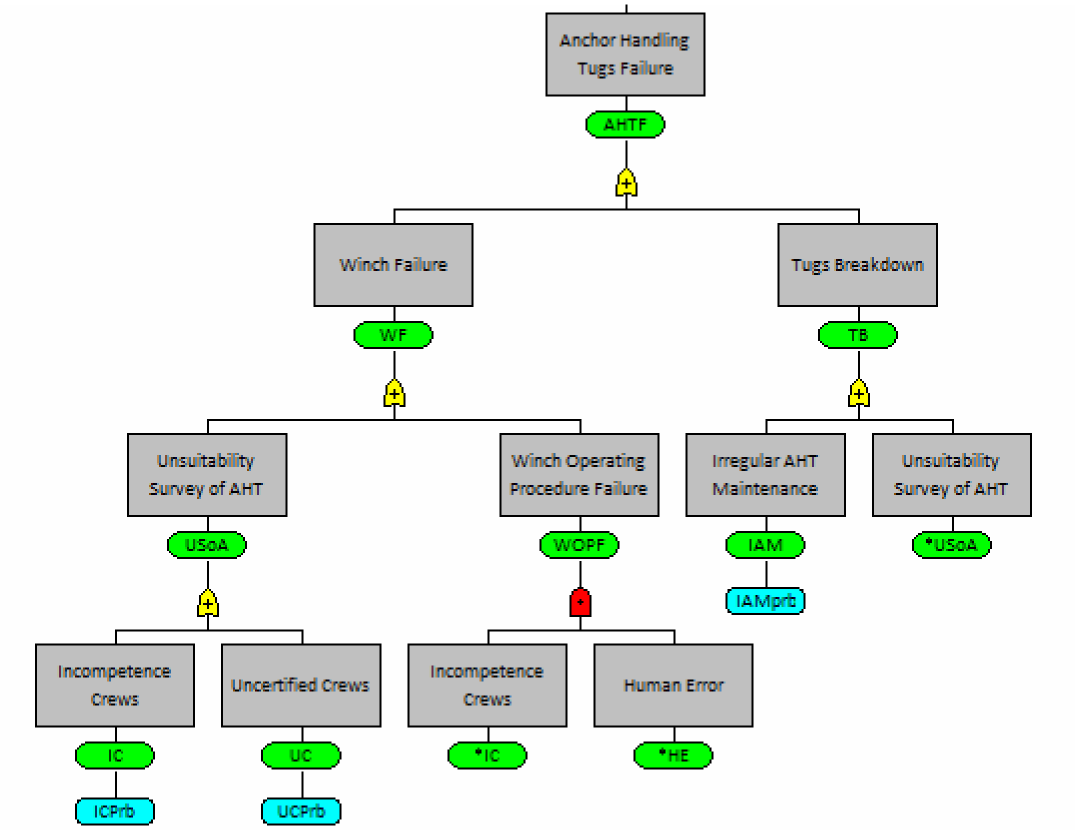

Figure 4.7d. FT Model Anchor Handling Tugs Failure with regards of AHF

4.1.11 MIVTA Step 6.1.c: Calculating the Frequency of Hazards

In order to calculate the frequency of hazards, the frequency of basic event or undesired event needs to be determined. The first thing to do to quantify the frequency of fault tree is to summarize all the basic events and define their frequency. But sometimes it is very difficult to gather the past record data, therefore we need the expert opinion and experience to determine the frequency of the basic events (Deacon et al., 2010; Mentes, 2011). In this study the experts gave their judgment for frequency of occurrence of mobile mooring system failure based on the IMO (International Maritime Organization) standard as shown in Table 2.7. The expert opinions are measured with 95th percentile of the aggregate series in order to measure precise value of the judgments.

This IMO standard illustrates the frequency of event in linguistic expressions such as extremely remote, remote, reasonably probable and frequent so that the experts can estimate the frequency of an event based on their experience and knowledge. Table 4.3 shows the list of all the basic events.

Table 4.3. List of Basic Events

No	Basic Events	Code
1	Adverse Environmental Condition	AEC
2	Debris in Seabed	DiS
3	Design Error	DE
4	Electrical Failure of Winch	EFoW
5	Electrical Failure	EF
6	Excessive Waves	EWa
7	Excessive Winds	EWi
8	Excessive Currents	ECu
9	Human Error	HE
10	Incomprehensive Data Collection	IDC
11	Improper Quality Control	IQC
12	Inadequate Winch Maintenance Schedule	IWMS
13	Inadequate Coating Protection	ICP
14	Inadequate Maintenance Schedule	IMS
15	Improper Soil Data Sampling	ISDS
16	Incompetence Crews	IC
17	Manufacturing Error	ME
18	Mechanical Failure	MF
19	Natural Hazard	NH
20	Poor Raw Material	PRM
21	Rocky Seabed	RS
22	Soft Clay	SC
23	Uncertified Crews	UC
24	Irregular AHT Maintenance	IAM
25	Uncertified Equipment	UE
26	Wrong Material	WM

The second EOS derives from identifying the frequency index of basic events as shown in Table 4.4. This table shows the second EOS distributed to the experts in order to determine the frequency of occurrence for each basic events/undesired event.

Table 4.4. Second EOS for Frequency Index

No.	Undesired Events	Code	Frequency			
			1	3	5	7
1	Adverse Environmental Condition	AEC	1	3	5	7
2	Debris in Seabed	DiS	1	3	5	7
3	Design Error	DE	1	3	5	7
4	Electrical Failure of Winch	EFoW	1	3	5	7
5	Electrical Failure	EF	1	3	5	7
6	Excessive Waves	EWa	1	3	5	7
7	Excessive Winds	EWi	1	3	5	7
8	Excessive Currents	ECu	1	3	5	7
9	Human Error	HE	1	3	5	7
10	Incomprehensive Data Collection	IDC	1	3	5	7
11	Improper Quality Control	IQC	1	3	5	7
12	Inadequate Winch Maintenance Schedule	IWMS	1	3	5	7
13	Inadequate Coating Protection	ICP	1	3	5	7
14	Inadequate Maintenance Schedule	IMS	1	3	5	7
15	Improper Soil Data Sampling	ISDS	1	3	5	7
16	Incompetence Crews	IC	1	3	5	7
17	Manufacturing Error	ME	1	3	5	7
18	Mechanical Failure	MF	1	3	5	7
19	Natural Hazard	NH	1	3	5	7
20	Poor Raw Material	PRM	1	3	5	7
21	Rocky Seabed	RS	1	3	5	7
22	Soft Clay	SC	1	3	5	7
23	Uncertified Crews	UC	1	3	5	7
24	Irregular AHT Maintenance	IAM	1	3	5	7
25	Uncertified Equipment	UE	1	3	5	7
26	Wrong Material	WM	1	3	5	7

4.1.12 MIVTA Step 6.1.d: Analyzing the Fault Tree Contributing To the Top Event

When all the frequencies of basic event have already been gathered, the next Step is to evaluate the fault tree by using the rules of Boolean algebra. By calculating the entire basic events and the logical gates and proceeding to the higher level, in the end the frequency of the top event can be reached.

This study applies DPL Syncopation software to construct the fault tree structure and to evaluate the frequency of events. The evaluation of FTA begins with the calculation of the cut set. The cut sets of MLB, AF, AHF, ACF need to be analyzed so that the frequency of top event can be found. The smallest combinations of basic events that leads to the occurrence of top event are called minimal cut set. The results of the minimal cut set derive from the DPL Syncopation software. The output from DPL Syncopation software for FTA can be seen in Appendix F.

The minimal cut set of the mooring line breakage is shown in Table 4.5. The highest cut set is the highest contribution of basic events to cause the system failure. The highest cut set derives from three basic events (third order) consisting of EWa, EWi, ECu. These events are related to AND gate indicating that all the three events need to occur to cause the system failure with frequency 1. The lowest cut set is obtained from two basic events (second order) containing ICP and IMS. These events are also related to AND gate with the frequency of 0.000001. Furthermore the basic events in first order are related to OR gate indicating that any one of the events may cause the system failure. The minimal cut set of MLB derives from all the cut set frequencies, the result shows the frequency of MLB is 1.025011 that is classified as probable frequency.

Table 4.5. Cut Set of MLB

Rank	Cut Set	Order	Importance Level
1	EWa, EWi, ECu	3^{rd}	1
2	AEC	1^{st}	0.01
3	NH	1^{st}	0.01
4	IC	1^{st}	0.001
5	UC	1^{st}	0.001
6	HE	1^{st}	0.001
7	EF	1^{st}	0.001
8	MF	1^{st}	0.001
9	RS, DiS	2^{nd}	0.00001
10	ICP, IMS	2^{nd}	0.000001
Frequency of MLB			1.025011

The minimal cut set for anchor failure is shown in Table 4.6. The highest cut set is obtained from three basic events (third order) which consist of EWa, EWi, ECu. As discussed before, these events are related to AND gate with frequency of 1. The lowest cut set is obtained from two basic events (second order) containing ICP and IMS. These events are also related to AND gate with the frequency of 0.000001. The other basic events related to OR gate indicates that they are considered as the first order. The minimal cut set of AF is 1.026011 classified as probable frequency.

Table 4.6. Cut Set of AF

Rank	Cut Set	Order	Importance Level
1	EWa, EWi, ECu	3rd	1
2	NH	1st	0.01
3	AEC	1st	0.01
4	EF	1st	0.001
5	DE	1st	0.001
6	UC	1st	0.001
7	IC	1st	0.001
8	MF	1st	0.001
9	HE	1st	0.001
10	IQC, PRM	2nd	0.00001
11	ICP, IMS	2nd	0.000001
Frequency of AF			1.026011

The minimal cut set for appurtenances connection failure is shown in Table 4.7. The highest cut set is obtained from three basic events (third order) consisting of EWa, EWi, ECu related to AND gate with frequency of 0.001. The lowest cut set is ME with the frequency of 0.00064. The other basic events related to OR gate indicates that they are considered as the first order. The minimal cut set of ACF is 1.01764 classified as probable frequency.

Table 4.7. Cut Set of ACF

Rank	Cut Set	Order	Importance Level
1	EWa, EWi, ECu	3rd	1
2	AEC	1st	0.01
3	IDC	1st	0.001
4	WM	1st	0.001
5	IMS	1st	0.001
6	HE	1st	0.001
7	IC	1st	0.001
8	UC	1st	0.001
9	UE	1st	0.001
10	ME	1st	0.00064
Frequency of ACF			1.01764

The minimal cut set for anchor handling failure is shown in Table 4.8. The highest cut set derives from the first order events, namely IAM, EFoW and IWMS with frequency of 0.001 respectively. The lowest cut set is achieved from UC, IC, DE, HE events with frequency of 0.001 respectively using OR gate. The minimal cut set of AHF is 0.0034 classified as occasional frequency.

Table 4.8. Cut Set of AHF

Rank	Cut Set	Order	Importance Level
1	IAM	1st	0.01
2	EFoW	1st	0.01
3	IWMS	1st	0.01
4	IC	1st	0.001
5	UC	1st	0.001
6	DE	1st	0.001
7	HE	1st	0.001
Frequency of AHF			0.034

Figure 4.8 shows the frequency of occurrence for each of the top event, namely MLB, AF, ACF and AHF. Minimal cut set expression for the top event is expressed (Andrews, 1998) : $T = C_1 + C_2 + C_3 + ... + C_N$ (4.1)

$T = C_{MLB} + C_{AF} + C_{AHF} + C_{ACF}$ = 1.025011 + 1.026011 + 0.034 + 1.01764 = 3.102662 per year, and based on Table 2.7 it is classified as probable events. This result is based on the expert opinion using 95th percentile and it is relatively close to the mooring line failure data reported by HSE (2006) which is 4.7 per year failure. Therefore the result of expert opinion can be considered valid and represent probability of failure in the uncertainty condition. The result of frequency of occurrence will be used in the bow tie analysis in order to find the consequence of failure. Through the result of bow tie analysis the risk matrix graphs can be determined and the mitigation plan can be established based on the risk level.

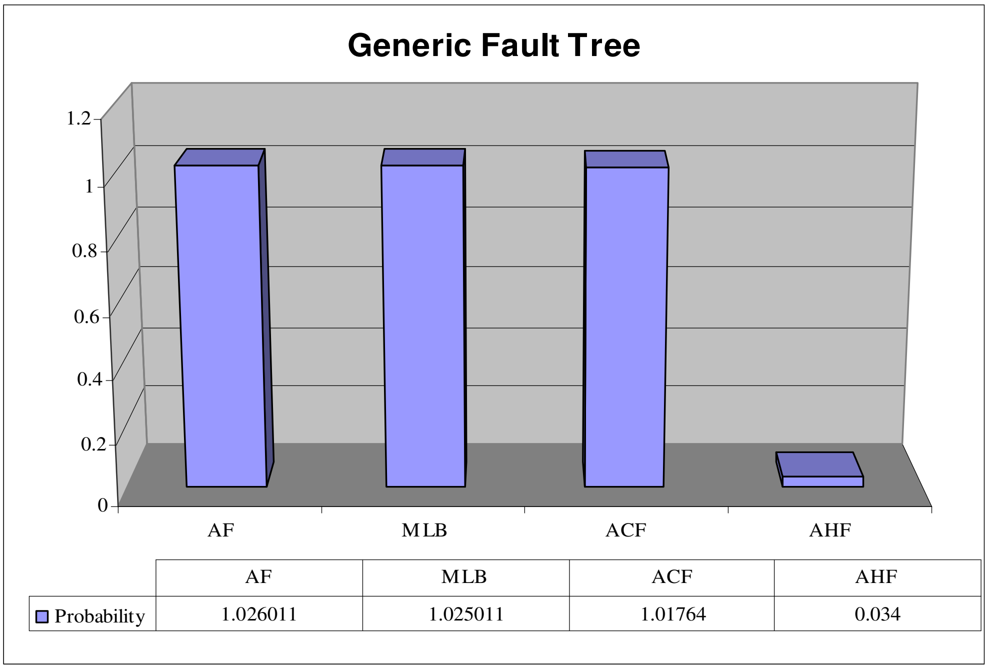

Figure 4.8. Frequency of Generic Fault Tree

4.1.13 MIVTA Step 6.2.a: Starting ETA for Each Top Event, Built Event Tree

ETA framework starts by developing the event tree for each top event in order to determine the sequence of the consequence of failure. The ETA Steps can be seen in Figure 3.6 as a part of MIVTA framework and the result of ETA already been accomplished will be discussed in details.

Event tree analysis (ETA) is helpful to model the sequence of all possible outcomes resulting from an accidental event in a systematic method. There are several possible outcomes resulting from a single initiating event and using ETA the frequency for each outcome can be determined. ETA starts from the left to the right part of a critical event. The sequence of split events is a binary which shows whether the occurring or non occurring phenomenon uses the following terms, namely yes or no, success or failure. The purpose of ETA is to determine whether the initiating event will cause a serious accident or the event is adequately controlled by the safety systems (Ericson, 2005). The development of event tree involves the utilization of a detailed operation manual procedure in order to establish ETA for each of the critical events.

4.1.14 MIVTA Step 6.2.b: Determining the Pivotal Events

Determining the pivotal events is useful to model the accident scenario between the initiating event and the resulting damage. There are two paths that divide each event with success and failure. Pivotal events start by identifying an initiating event at the left of the diagram.

The pivotal events contributing to the hazardous outcome are described in the system at the top column of the diagram that can be characterized as having outcomes of either success or failure of the systems. The sequences of pivotal events and their frequencies derive from expert judgments based on their experiences and knowledge in the mooring system. The frequency of occurrence for the pivotal events are derived from the fourth EOS as seen in Table 4.9

4.1.14.1 Pivotal Events for MLB

The pivotal events in MLB consist of:

a. Single line mooring breakage due to the adverse environments or other events. The frequency of occurrence is 1.10^{-4} per year.
b. Multiple line mooring breakage due to adverse environment or other events. The frequency of occurrence is 1.10^{-4} per year.
c. Pipe lay vessel lost its position & AHTS assist pipe lay vessel in its position. The frequency of occurrence is 1.10^{-5} per year.
d. AHTS fail to assist pipe lay vessel to maintain its position. The frequency of occurrence is 1.10^{-5} per year.

4.1.14.2 Pivotal Events for AF

The pivotal events and their frequencies in AF are as follows:

a. Mooring Line Tension Reduce due to Anchor Failure (Anchor/Part of Anchor Breaks). The frequency of occurrence is 1.10^{-4} per year.
b. Winch/Operators Fail to Preserve Tension of the Mooring Line as Operation Procedure. The frequency of occurrence is 1.10^{-4} per year.
c. AHTS Fails to Take Safety Action (As Mooring Line Breakage). The frequency of occurrence is 1.10^{-4} per year.
d. Mooring Line Clashed to Other Line / Pipe Lay Vessel Drift From Its Position. The frequency of occurrence is 1.10^{-5} per year.

4.1.14.3 Pivotal Events for ACF

The pivotal events and their frequencies of ACF are described below:

a. Mooring Line Lost Its Connection From Anchor. The frequency of occurrence is 1.10^{-4} per year.
b. Mooring Line Breaks Free / Clashed with Other Line. The frequency of occurrence is 1.10^{-4} per year.
c. Pipe Lay Vessel Lost Its Position & Other Mooring Line Fails to Keep Pipe Lay Vessel to Its Position. The frequency of occurrence is 1.10^{-5} per year.
d. AHTS Fails to Take Immediate Safety Action of The Mooring Line. The frequency of occurrence is 1.10^{-5} per year.

4.1.14.4 Pivotal Events for AHF

The pivotal events and their frequencies of AHF are described below:

a. Pipe Lay Vessel Winch Failure / Anchor Handling Tugs Services Failure. The frequency of occurrence is 1.10^{-4} per year.
b. Multiple Pipe Lay Vessel Winch Failure / Anchor Handling Tugs Services Failure. The frequency of occurrence is 1.10^{-4} per year.
c. Pipe Lay Vessel Unable to Maintain Its Position to Pipe Lay Configuration. The frequency of occurrence is 1.10^{-5} per year.
d. Pipe Lay Vessel Suspend Its Operation. The frequency of occurrence is 1.10^{-4} per year.

4.1.15 MIVTA Step 6.2.c: Defining Accident Sequences

Defining the accident sequences consist of initiating event and mostly followed by one or more pivotal events that may result in an accident. The accident sequences are derived from the investigation of what can go wrong in the system. The ETA worksheet consists of the following information:

(i) Initiating events
(ii) The sequence path/system pivotal events
(iii) The outcome events
(iv) The frequency of outcomes

For each critical event investigated in the FTA, an event tree is built to identify the consequences. The following section will discuss the ETA with the same critical event built in FTA consisting of MLB, AF, ACF and AHF that will focus on the possible consequences.

4.1.16 MIVTA Step 6.2.d: Obtaining Outcome Spectrum

The outcome spectrum derives from several outcomes or the consequence of an accident. The accident sequences are defined by determining the initiating event and the pivotal events along each path leading to the outcomes.

4.1.17 MIVTA Step 6.2.e: Analyzing the Frequency of the Outcomes

Analyzing the frequency of each outcome by multiplying the initiating event frequency and the pivotal frequency along each path leading to the outcomes. Table 4.9 shows the third EOS in order to determine the frequency index of outcomes sequence.

Table 4.9. Third EOS of Frequency Index for Outcomes Sequence

No.	Undesired Events	Code	Frequency			
			1	3	5	7
1	Mooring Line Breakage (MLB)	Single Line Mooring Breakage due to Adverse Environment or Other Events	1	3	5	7
		Multiple Line Mooring Breakage Occurs due to Adverse Environment or Other Events	1	3	5	7
		Pipe Lay Vessel Lost Its Position & AHTS Assist Pipe Lay Vessel to Its Position	1	3	5	7
		AHTS Fail to Assist Pipe Lay Vessel to Maintain Its Position	1	3	5	7
2	Anchor Failure (AF)	Mooring Line Tension Reduce due to Anchor Failure (Anchor/Part of Anchor Breaks)	1	3	5	7
		Winch/Operators Fails to Preserve Tension of the Mooring Line as Operation Procedure	1	3	5	7
		AHTS Fails to Take Safety Action (As Mooring Line Breakage)	1	3	5	7
		Mooring Line Clashed to Other Line / Pipe Lay Vessel Drift From Its Position	1	3	5	7
3	Appurtenances Connection Failure (ACF)	Mooring Line Lost Its Connection From Anchor	1	3	5	7
		Mooring Line Breaks Free / Clashed with Other Line	1	3	5	7
		Pipe Lay Vessel Lost Its Position & Other Mooring Line Fails to Keep Pipe Lay Vessel to Its Position	1	3	5	7
		AHTS Fail to Take Immediate Safety Action of The Mooring Line	1	3	5	7
4	Anchor Handling Failure (AHF)	Pipe Lay Vessel Winch Failure / Anchor Handling Tugs Services Failure	1	3	5	7
		Multiple Pipe Lay Vessel Winch Failure / Anchor Handling Tugs Services Failure	1	3	5	7
		Pipe Lay Vessel Unable to Maintain Its Position to Pipe Lay Configuration	1	3	5	7
		Pipe Lay Vessel Suspend Its Operation	1	3	5	7

4.1.17.1 Event Tree Diagram for Mooring Line Breakage (MLB)

The event tree shows the chronological progression of an accident graphically. Figure 4.9 shows the event tree diagram of mooring line breakage (MLB). Each path in the event tree corresponds to a condition of several outcomes taking place if the pivotal event has occurred. The frequency of every outcome is defined by multiplying the initiating event frequency and the pivotal frequency along each path leading to the outcomes. The frequency of initiating event derives from the result of the FTA, as seen in Table 4.5 the frequency of MLB is 1.025011 per year. This frequency is then used as the frequency of initiating event in the ETA as shown in Figure 4.9.

The pivotal events start from an initiating event to a failure having hazard outcomes of either success or failure path. There are five outcome paths that cover the most possible combinations of MLB. The upper paths represent the yes path of every sequence associated with hazardous events resulting the pipe lay vessel lost its position with damage to pipeline objects, project delay, and partial construction damage on pipe lay vessel. The frequency of this outcome is $1.02501.10^{-18}$ per year obtained by multiplying the frequency of MLB with all the frequency of yes paths.

The lower paths represent the no path resulting the outcomes, namely the safe mooring line with frequency of 1.02491 per year. This frequency obtained by multiplying the initiating events MLB with the frequency of first sequence of no path. The same procedures are repeated to the second, third and the fourth paths of MLB event tree diagram associated with all their frequencies of pivotal event paths. Each path will result the outcome events with the frequency based on their frequency of success and failure path.

The other three paths of MLB outcomes consist of mixed yes and no paths of pivotal events. As shown in Figure 4.9 the frequency of five MLB paths derives from the following calculation:

(i) The frequency of the first outcomes of MLB is as follows:

$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(Y)} =$

$1.025011 \times 0.0001 \times 0.0001 \times 0.00001 \times 0.00001 = 1.02501.10^{-18}$ per year.

(ii) The frequency of the second outcomes of MLB is as follows:

$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(N)} =$

$1.025011 \times 0.0001 \times 0.0001 \times 0.00001 \times 0.99999 = 1.025.10^{-13}$ per year.

(iii) The frequency of the third outcomes of MLB is as follows:

$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(N)} =$

$1.025011 \times 0.0001 \times 0.0001 \times 0.9999 = 1.026.10^{-8}$ per year.

(iv) The frequency of the fourth outcomes of MLB is as follows:

$IE \times PE_{1(Y)} \times PE_{2(N)} =$

$1.025011 \times 0.0001 \times 0.9999 = 1.02491.10^{-4}$ per year.

(v) The frequency of the fifth outcomes of MLB is as follows:

$IE \times PE_{1(N)} =$

$1.025011 \times 0.9999 = 1.02491$ per year.

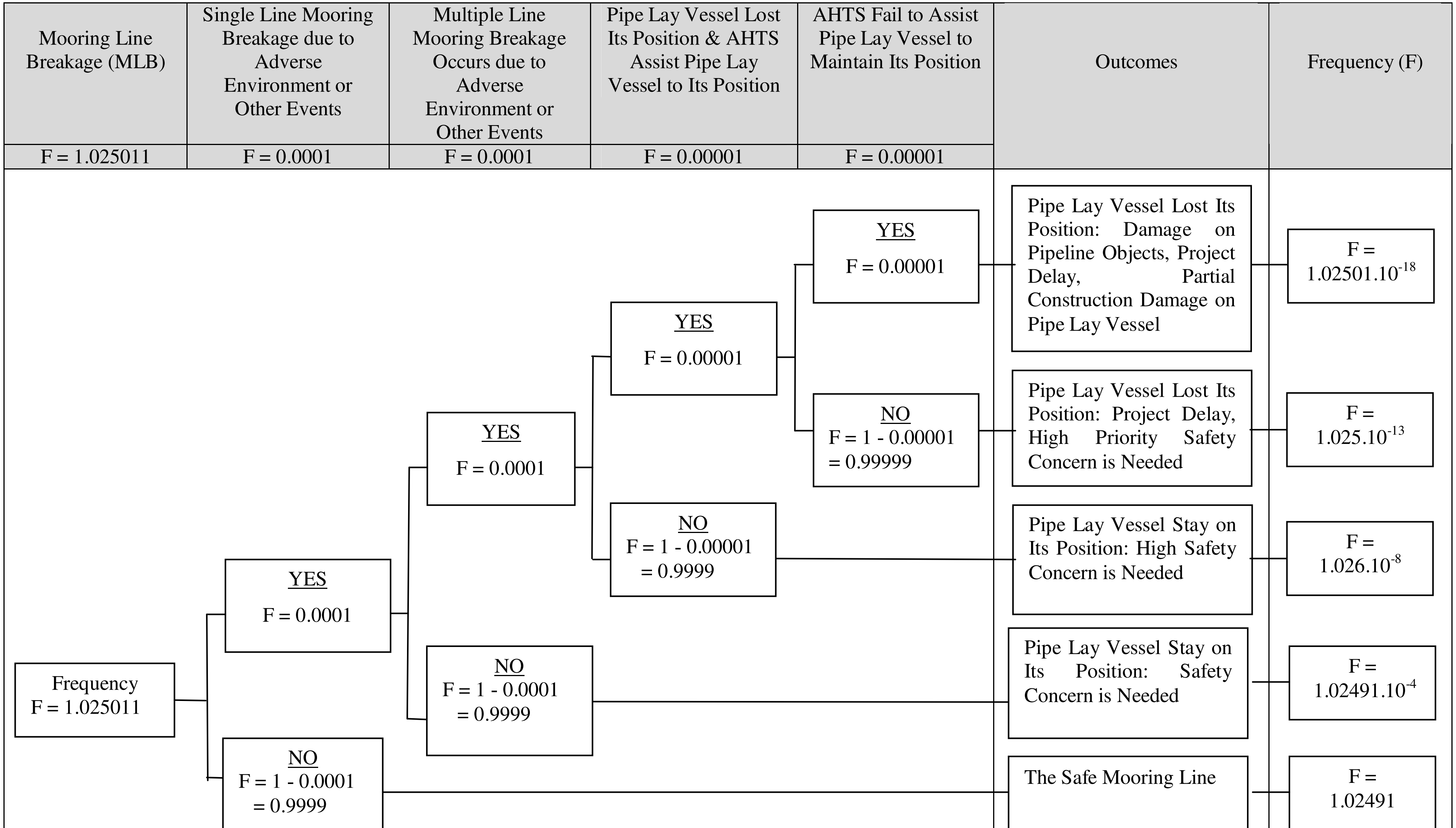

Figure 4.9. ETA for Mooring Line Breakage

4.1.17.2 Event Tree Diagram for Anchor Failure (AF)

Event tree diagram for AF is shown in Figure 4.10. The frequency of initiating event of AF derives from the result of the FTA, as seen in Table 4.6 that the frequency of AF is 1.026011 per year. This is then used as the frequency of AF as the initiating event in the diagram as seen in Figure 4.10.

The outcomes of AF consist of five outcome paths considered as the most possible combinations. For instance, the first path represents the yes path of every pivotal event resulting the pipe lay vessel lost its position with damage to pipeline objects, project delay, and partial construction damage on pipe lay vessel. The frequency of this outcome is $1.02601.10^{-17}$ per year obtained by multiplying the frequency of AF with all the frequencies of yes paths.

The last path represent the no path, resulting the possible outcomes namely the safe anchor with frequency of 1.025908399 per year. The same procedures are repeated to all possible paths of AF in the event tree diagram associated with all their frequencies of pivotal event paths. Each path will result the potential outcomes with the frequency based on their frequency of yes and no paths.

The other three paths of AF outcomes consist of mixed yes and no paths of pivotal events. As seen in Figure 4.10 the frequency of five AF outcomes has the result as follows:

(i) Frequency of the first outcomes of AF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(Y)} =$$

$$1.026011 \times 0.0001 \times 0.0001 \times 0.0001 \times 0.00001 = 1.02601.10^{-17} \text{ per year.}$$

(ii) Frequency of the second outcomes of AF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(N)} =$$

$$1.026011 \times 0.0001 \times 0.0001 \times 0.0001 \times 0.99999 = 1.026.10^{-12} \text{ per year.}$$

(iii) Frequency of the third outcomes of AF is:

IE x $PE_{1(Y)}$ x $PE_{2(Y)}$ x $PE_{4(N)}$ =

1.026011 x 0.0001 x 0.0001 x 0.9999 = $1.02591.10^{-8}$ per year.

(iv) Frequency of the fourth outcomes of AF is:

IE x $PE_{1(Y)}$ x $PE_{2(N)}$ =

1.026011 x 0.0001 x 0.9999 = $1.02591.10^{-4}$ per year.

(v) Frequency of the fifth outcomes of AF is:

IE x $PE_{1(N)}$ =

1.026011 x 0.9999 = 1.025908399 per year.

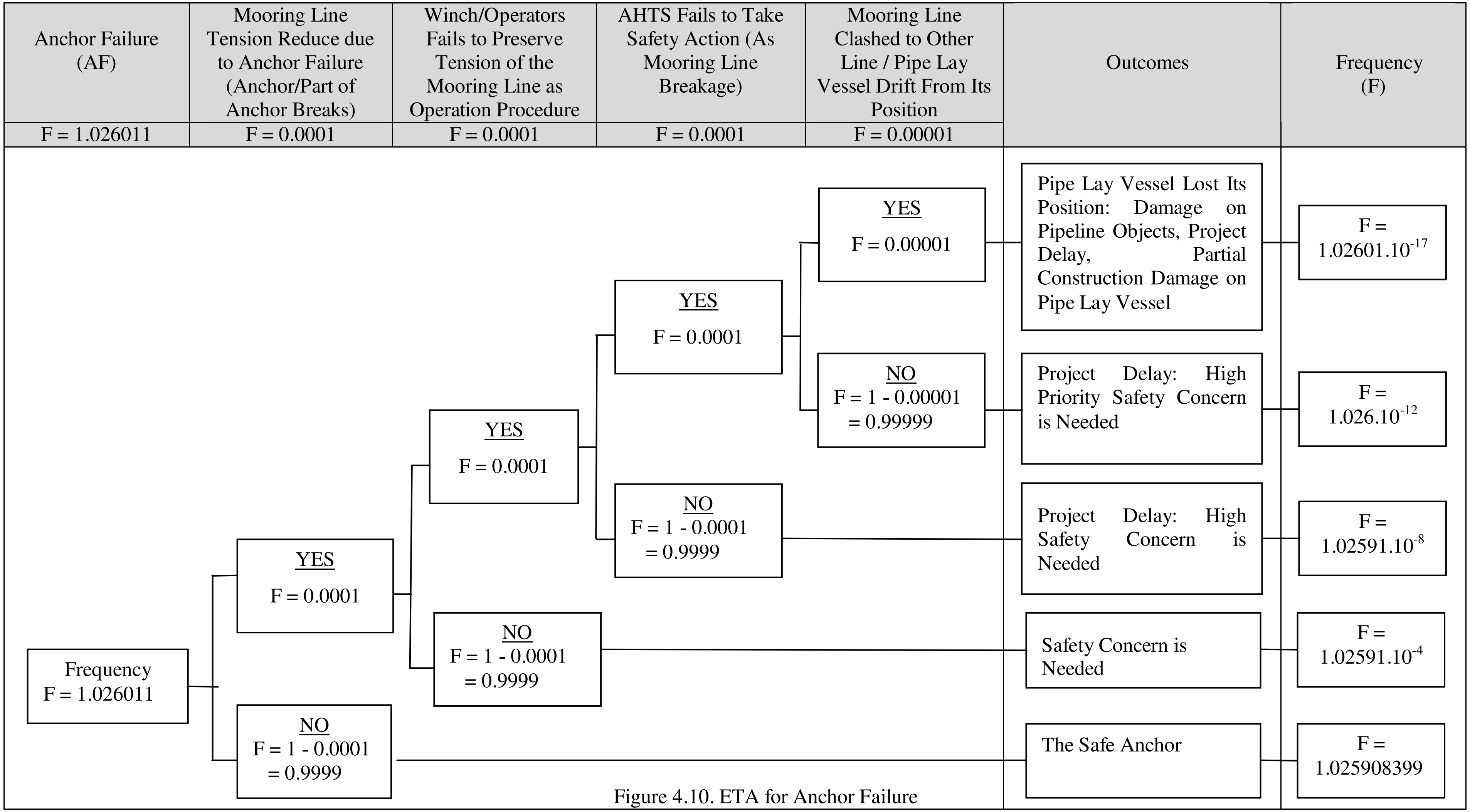

Figure 4.10. ETA for Anchor Failure

4.1.17.3 Event Tree Diagram for Appurtenances Connection Failure (ACF)

Figure 4.11 shows the event tree diagram for ACF. The frequency of initiating event of ACF derives from the result of the FTA, as seen in Table 4.7 that the frequency of ACF is 1.01764 per year. This value is then used as the frequency of ACF for the initiating event in the diagram as seen in Figure 4.11.

The outcomes of ACF also consist of five outcome paths considered as the potential path combinations. The first path in ACF represents the yes path of every pivotal event resulting the pipe lay vessel drift from its design path causing damage to the pipeline objects, project delay, and partial construction damage on pipe lay vessel. The frequency of this outcome is $1.01764.10^{-18}$ per year obtained by multiplying the frequency of ACF with all the frequencies of yes paths.

The fifth path represents the no path resulting the possible outcomes namely the safe appurtenances connection with frequency 1.017538226 per year. The same procedures are repeated to all potential paths of ACF in the event tree diagram associated with all their frequencies of pivotal event paths. Each path will result the possible outcomes based on their frequency of yes and no paths.

The other three paths of ACF outcomes consist of mixed yes and no paths of pivotal events. As shown in Figure 4.11 the frequency of five ACF outcomes gives the result as follows:

(i) Frequency of the first outcomes of ACF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(Y)} =$$

$$1.01764 \times 0.0001 \times 0.0001 \times 0.00001 \times 0.00001 = 1.01764.10^{-18} \text{ per year.}$$

(ii) Frequency of the second outcomes of ACF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(N)} =$$

$$1.01764 \times 0.0001 \times 0.0001 \times 0.00001 \times 0.99999 = 1.01764.10^{-18} \text{ per year.}$$

(iii) Frequency of the third outcomes of ACF is:

$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{4(N)} =$

$1.01764 \times 0.0001 \times 0.0001 \times 0.99999 = 1.01763.10^{-8}$ per year.

(iv) Frequency of the fourth outcomes of ACF is:

$IE \times PE_{1(Y)} \times PE_{2(N)} =$

$1.01764 \times 0.0001 \times 0.9999 = 1.01754.10^{-4}$ per year.

(v) Frequency of the fifth outcomes of ACF is:

$IE \times PE_{1(N)} =$

$1.01764 \times 0.9999 = 1.017538236$ per year.

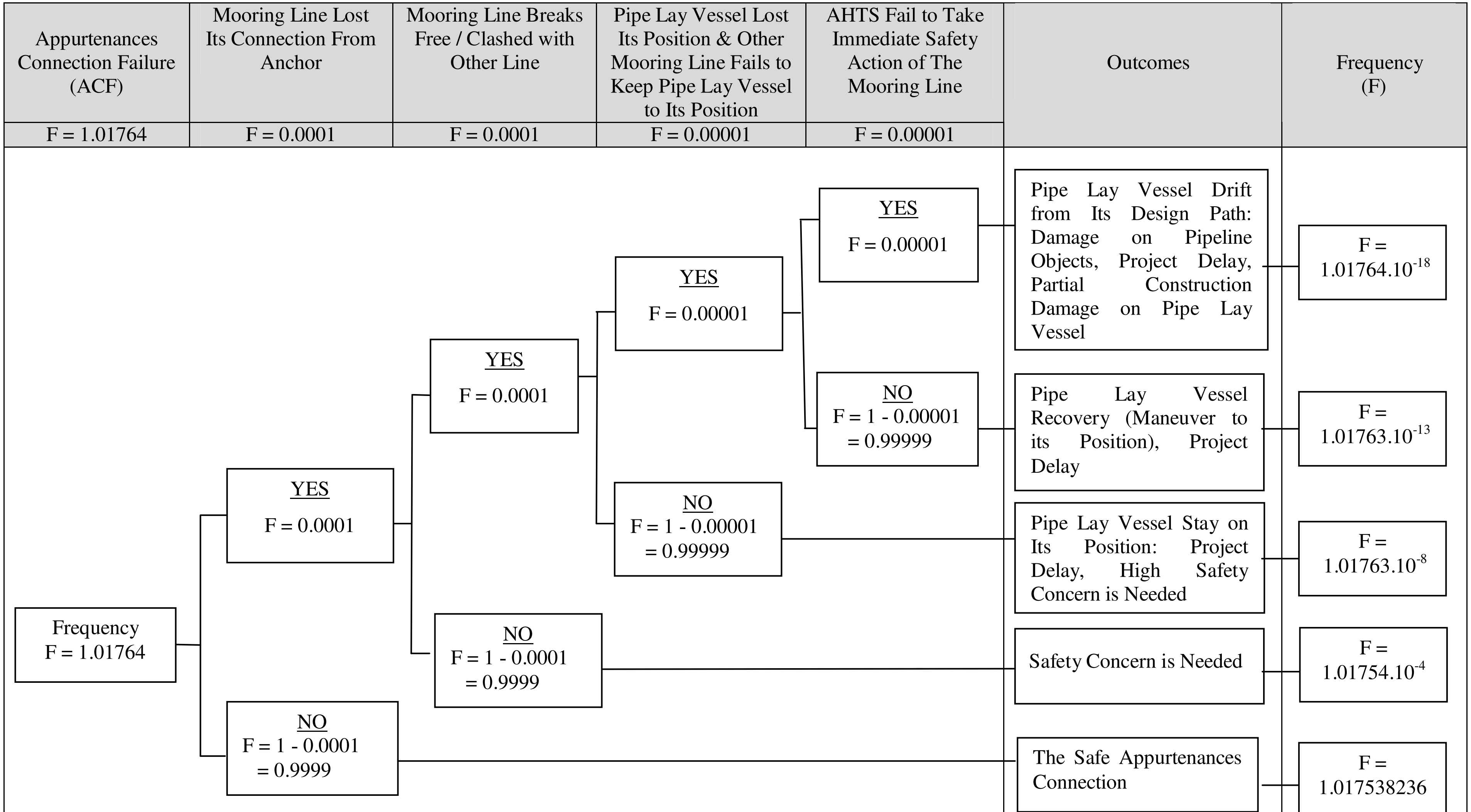

Figure 4.11. ETA for Appurtenances Connection Failure

4.1.17.4 Event Tree Diagram for Anchor Handling Failure (AHF)

Figure 4.12 shows the event tree diagram for AHF. The FTA result for the AHF as seen in Table 4.8 is used as the frequency of initiating event of AHF in the event tree diagram which is 0.0034 per year as shown in Figure 4.12. There are five outcomes of AHF considered all the potential path combinations. The upper path in AHF represents the yes path of every pivotal event resulting the project delay with partial damage to the mooring line and high priority safety concern is needed. This outcome has frequency of $3.4.10^{-21}$ per year obtained by multiplying the frequency of AHF with all the frequencies of yes paths.

The lower path represents the no path resulting the possible outcomes, namely the safe anchor handling with frequency of $3.39966.10^{-3}$ per year. The same procedures are repeated to all potential paths of AHF in the event tree diagram associated with all their frequencies of pivotal event paths. Every path will carry out the potential outcomes based on their frequency of yes and no paths.

The other three paths of AHF outcomes consist of mixed yes and no paths of pivotal events. As shown in Figure 4.12 the frequency of five AHF outcomes gives the result as follows:

(i) Frequency of the first outcomes of AHF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(Y)} =$$

$$0.0034 \times 0.0001 \times 0.0001 \times 0.00001 \times 0.00001 = 3.4.10^{-21} \text{ per year.}$$

(ii) Frequency of the second outcomes of AHF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{3(Y)} \times PE_{4(N)} =$$

$$0.0034 \times 0.0001 \times 0.0001 \times 0.00001 \times 0.99999 = 3.39997.10^{-16} \text{ per year.}$$

(iii) Frequency of the third outcomes of AHF is:

$$IE \times PE_{1(Y)} \times PE_{2(Y)} \times PE_{4(N)} =$$

$$0.0034 \times 0.0001 \times 0.0001 \times 0.99999 = 3.39997.10^{-11} \text{ per year.}$$

(iv) Frequency of the fourth outcomes of AHF is:

$IE \times PE_{1(Y)} \times PE_{2(N)} =$

$0.0034 \times 0.0001 \times 0.9999 = 3.39966.10^{-7}$ per year.

(v) Frequency of the fifth outcomes of AHF is:

$IE \times PE_{1(N)} =$

$0.0034 \times 0.9999 = 3.39966.10^{-3}$ per year.

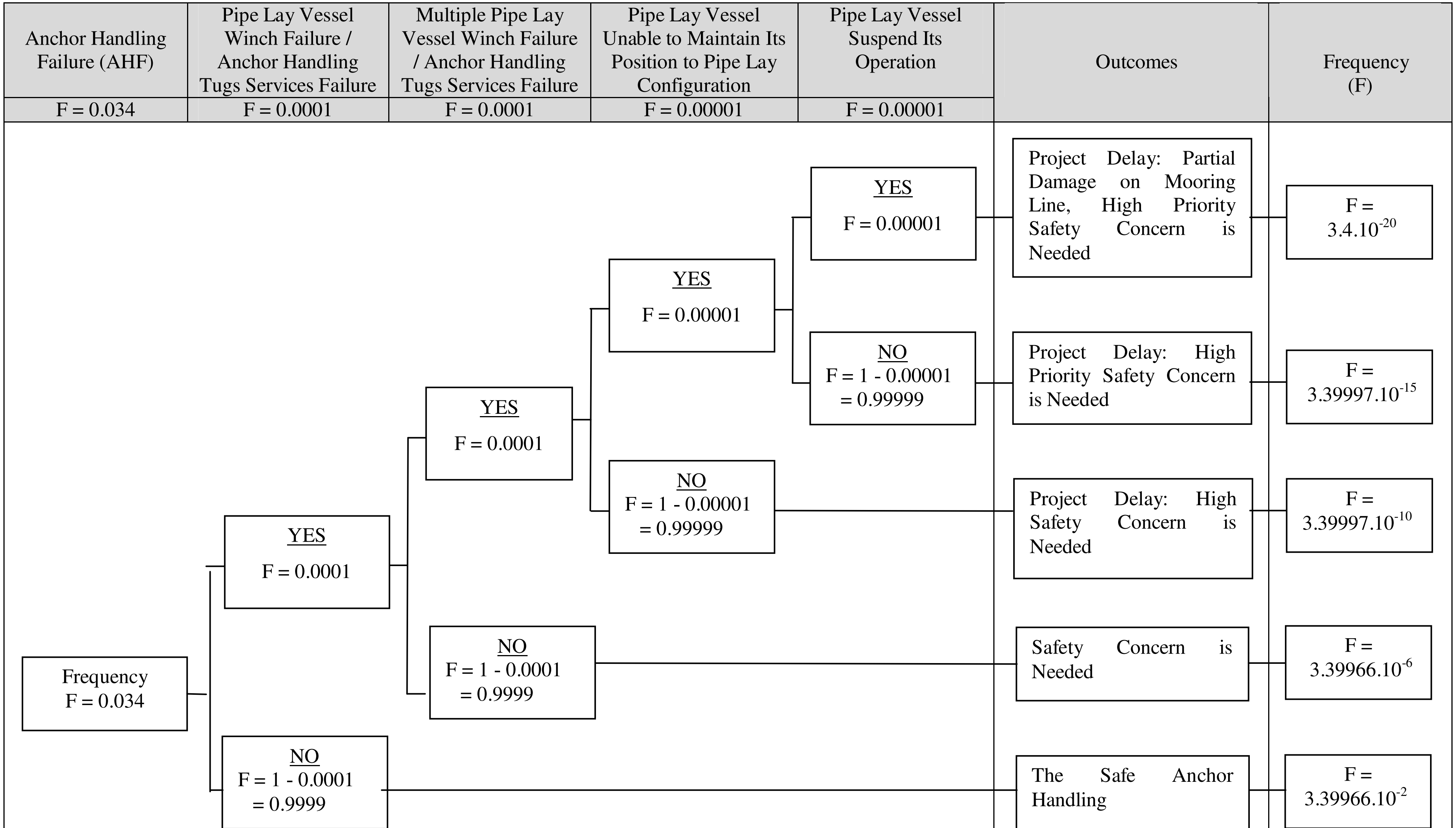

Figure 4.12. ETA for Anchor Handling Failure

4.2 Summary of the Application of MIVTA

This research applies three types of risk assessment approaches namely HAZOP, FTA and ETA to develop MIVTA. HAZOP is useful for preliminary risk analysis of the mooring system. The HAZOP result is tabulated in a systematic method that covers up important information about the system. The important information deriving from the HAZOP includes the component, guide words, deviation, potential causes, possible consequences, safeguards and the action needed to handle the risk. HAZOP is a qualitative analysis useful as a guidance to conduct further analysis which is quantitative analysis.

There are two types of quantitative analysis used in this study namely FTA and ETA. FTA is helpful to determine the root causes of mooring system failure described in logical diagram. The fault tree diagram starts with the top event or the critical hazardous event then broken down into the root causes until the undesired or basic events are identified. The critical hazardous events of mooring system failure are divided into four major events, namely mooring line breakage (MLB), anchor failure (AF), appurtenance connection failure (ACF) and anchor handling failure (AHF).

The FTA results show that the frequency of failure of mooring system is 3.103662 per year classified as probable event. The highest contribution of mooring system failure is caused by anchor failure (AF) with the frequency of failure of 1.026011 per year classified as probable event, the second highest is caused mooring line breakage (MLB) with the frequency of failure 1.025011 per year classified as probable event. The third highest contribution of mooring system failure is caused by appurtenance connection failure (ACF) with the frequency of failure of 1.01764 per year classified as probable event. The other contributions derive from anchor handling failure (AHF) with the frequency of failure of $3.4.10^{-2}$ per year classified as occasional events.

The next analysis to develop MIVTA is by conducting ETA. ETA is useful to model the sequence of all possible outcomes of mooring system failure in a systematic way. For each critical hazardous event that had been identified in FTA, an

ETA is constructed in order to determine the consequences. Therefore the frequency of failure derives from the FTA is then used as frequency of initiating events in ETA. There are two path phenomenons for each sequence of events which are yes or no of the systems. There are five possible consequences of each critical hazardous event which can be seen on the right side in Figure 4.9-4.12.

The findings in MIVTA consist of frequency and consequence of the mooring system which then used to develop MIRBA. MIRBA is useful to determine the risk level, risk mitigation and select the best maintenance strategy. MIRBA will be discussed further in the next chapter.

CHAPTER FIVE
APPLICATION OF METHODOLOGY FOR INVESTIGATION OF RISK BASED MAINTENANCE (MIRBA)

As discussed in the previous chapter, the result of MIVTA will be used in the MIRBA in order to determine the risk matrix and risk level of mobile mooring system failure.

5.1 MIRBA Application

Potential causes of mooring system failure and their possible outcomes have been determined in the previous chapter using the MIVTA application. The next thing to do in order to establish complete risk based decision making of the mobile mooring system is by conducting MIRBA. MIRBA is important to be investigated as the continuity of MIVTA result which is to determine the mitigation plan and maintenance strategy for the mobile mooring system.

Mitigation plan is useful to minimize the risk failure so that the risk level can be controlled. Selecting the best maintenance strategy is important in order to maintain and manage the risks using AHP. AHP is very helpful in deciding subjective and objective, tangible and intangible evaluation measurements in a quantitative approach. AHP has been applied successfully in many areas to help the decision makers evaluate the problem's solution with multi criteria to be considered.

The application of MIRBA starts by developing the complete bow tie. The Steps of MIRBA can be seen in Figure 3.6, the detail of each Step of MIRBA will be discussed in the next section. The development of complete bow tie is obtained by the connection of a critical event, associated with fault tree on the left and associated with an event tree on the right. Each bow tie corresponds to a critical accident hazard that can occur on the system with assumptions that the safety systems are ineffective.

5.1.1 MIRBA Step 1: Building the Complete Bow Tie

A bow tie is the combination method of fault tree analysis on the left and event tree analysis on the right. These bow ties are the basis for the application of the MIRBA methodology.

Bow tie analysis is developed for each critical event investigated in mooring system failure which are MLB, AF, ACF and AHF. The bow tie diagrams help to understand clearly through graphical visualization the relationship between the potential causes and their possible consequences.

5.1.1.1 Bow Tie for MLB

Figure 5.1 shows the bow tie diagram of MLB which derives from the fault tree of MLB as seen in Figure 4.4a-4.4e in the left part and event tree of MLB as seen in Figure 4.9 in the right part.

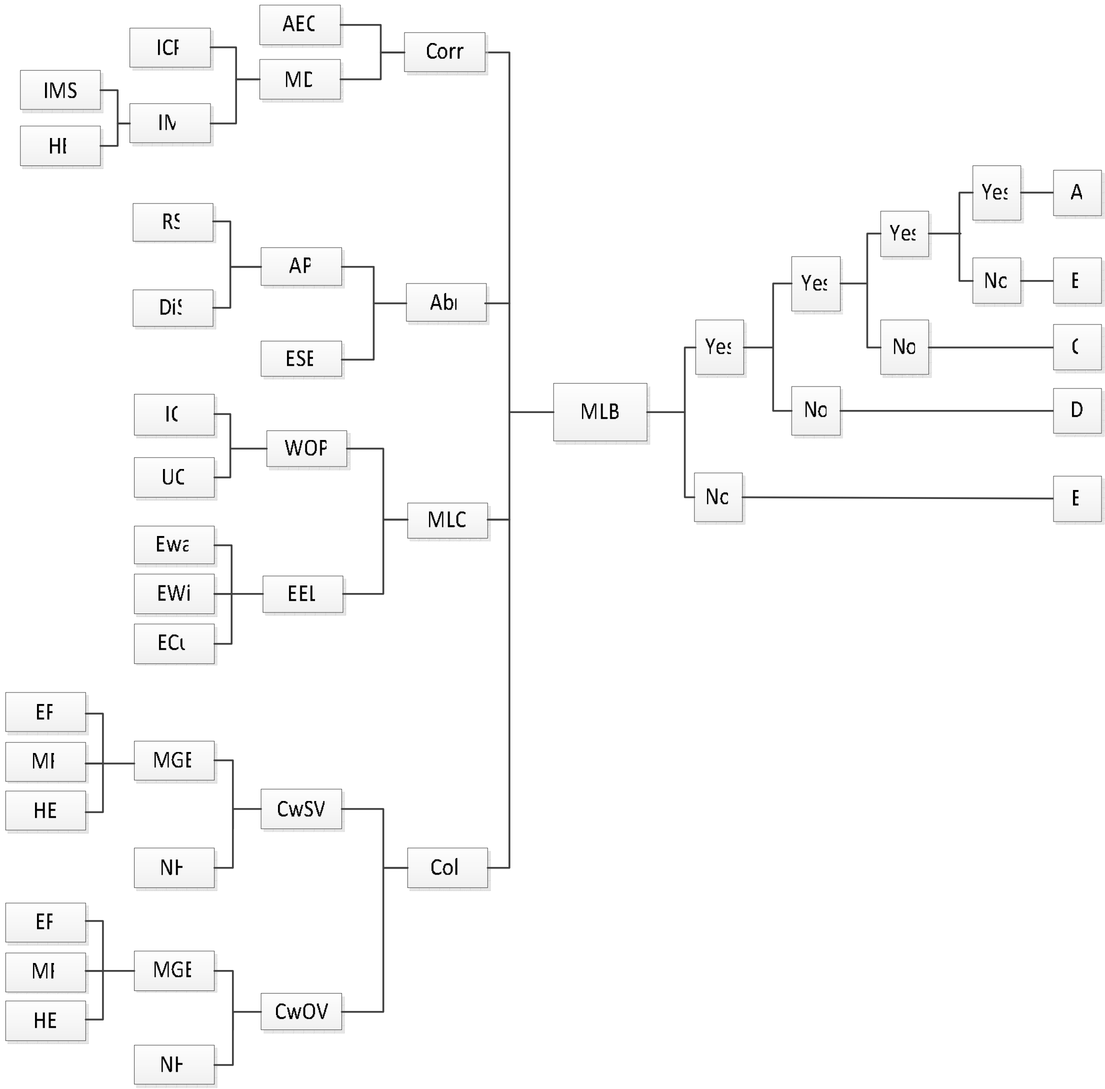

Figure 5.1 Bow Tie Diagram of MLB

5.1.1.2 Bow Tie for AF

Figure 5.2 illustrates the bow tie diagram of AF summarizing the fault tree of AF as seen in Figure 4.5a-4.5e in the left part and event tree of AF as seen in Figure 4.10 in the right part.

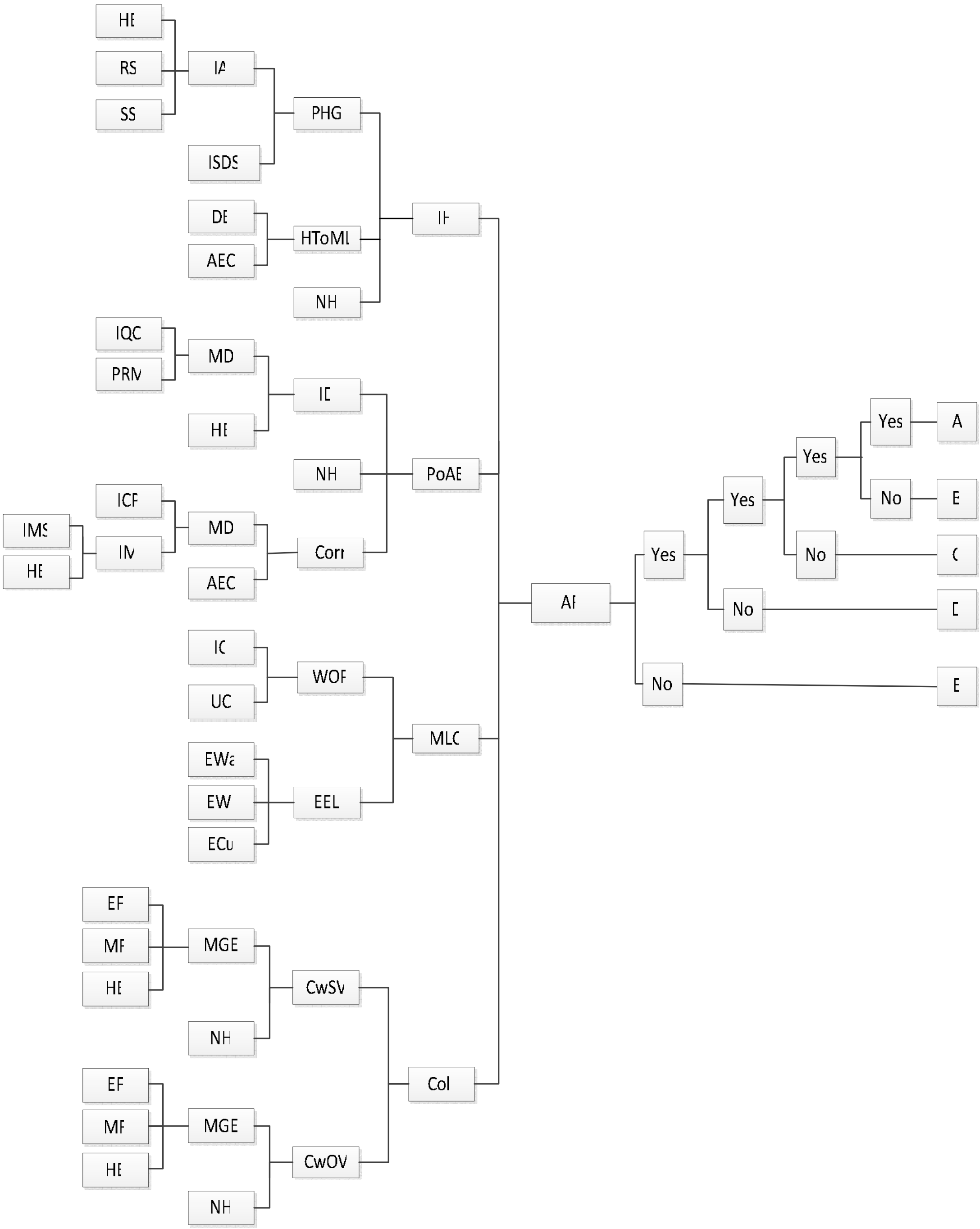

Figure 5.2 Bow Tie Diagram of AF

5.1.1.3 Bow Tie for ACF

The bow tie diagram of ACF is shown in Figure 5.3 which is obtained from the fault tree ACF as seen in Figure 4.6a-4.6c on the left part and event tree ACF as seen in Figure 4.11 on the right part.

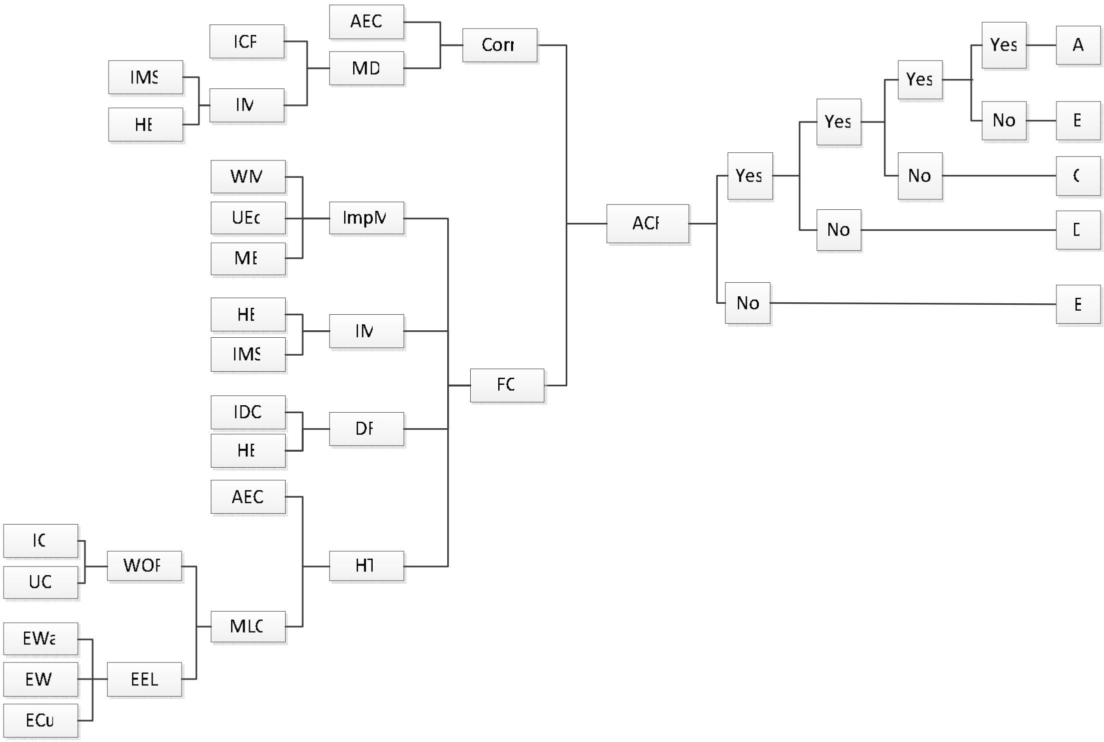

Figure 5.3 Bow Tie Diagram of ACF

5.1.1.4 Bow Tie for AHF

The bow tie diagram of AHF is shown in Figure 5.4 which is obtained from the fault tree AHF as seen in Figure 4.7a-4.7d on the left part and event tree AHF as seen in Figure 4.12 on the right part. The frequency of occurrence of each failure event in the fault tree is estimated then combined with the potential consequences of the critical event in the event tree. The potential consequences of the critical event are described as the path of an event tree.

Once the bow tie has been generated for all the critical events for mooring system failure then the next Step is to map the risk index based on the bow tie analysis. The frequency of both FTA and ETA are then incorporated into the risk matrix in order to determine the risk level. The following section will discuss the risk matrix mapping and risk level of mooring system in more detail.

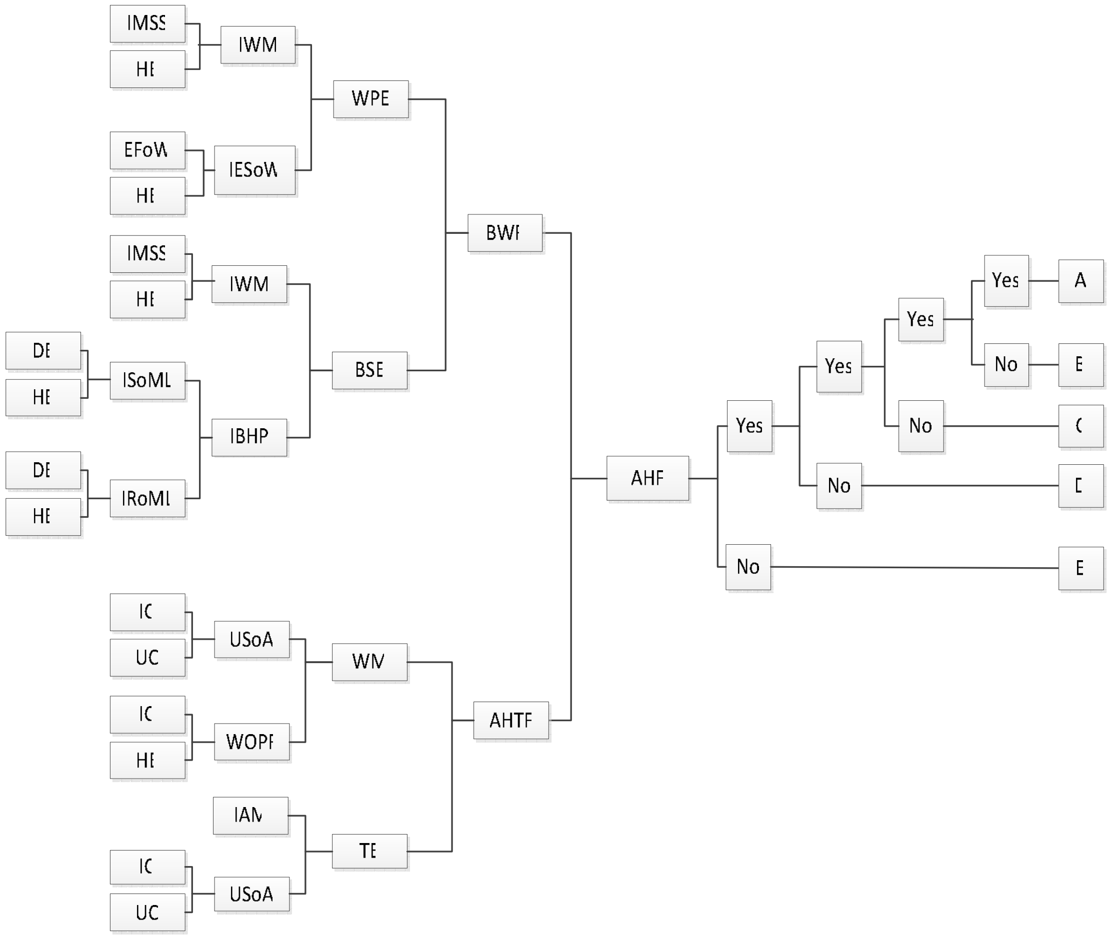

Figure 5.4 Bow Tie Diagram of AHF

5.1.2 MIRBA Step 2: Determining Frequency of Occurrence.

The frequency of occurrence derives from the result of FTA which is then used as the frequency of initiating event in ETA. The frequency of initiating events multiplied by the pivotal events will result the frequency of occurrence of the outcomes. Generally, there are several possible outcomes deriving from the initiating event followed by the pivotal events which include the success or failure possibility. The frequency of pivotal events is obtained from the experts judgments based on their knowledge and experiences. Once the event tree diagram is constructed, the frequency of occurrence can be applied to the diagram for each path.

5.1.3 MIRBA Step 3: Calculating the Class of Outcomes

Once the frequency of the outcome has been identified, the next Step is to determine the class of the outcomes based on the DNV standards. There are four points of view to determine the class of outcome involving aspects of people, assets, environment and reputation. Each aspect has six levels to be chosen by the expert judgment in order to identify the outcome class.

5.1.4 MIRBA Step 4: Developing the Risk Matrix

The risk matrix graph is constructed based on the frequency as x axis and outcome as the y axis. Four zones of risk level are classified in the risk matrix. Risk graphs describe the risk level for each event which shows the impact ratings.

Risk matrix is developed based on bow tie diagram and class of consequence categorization. As discussed previously in the literature review that the risk index (RI) is developed according to the frequency index (FI) as shown in Table 5.1 developed by IMO (1997) and the severity index (SI) as seen in Table 5.2 developed by DNV (2002). Since the frequency in ISO 17776 developed by DNV are descriptive in nature, therefore this study adopts both standards, namely the frequency based on IMO and the consequence based on ISO. The risk matrix used in this study is a 7 by 6 risk matrix which useful to increase the visibility of risk level.

Table 5.1. Frequency Index

FI	Frequency	Definition	F (per ship year)
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of ships, i.e. likely to occur several times during a ships life	10^{-1}
3	Remote	Likely to occur once per year in a fleet of 1000 of ships, i.e. 10% chance of occurring in the life of 4 similar ships	10^{-3}
1	Extremely remote	Likely to occur once in 100 years in a fleet of 1000 ships, i.e.1% chance of occurring in the life of 40 similar ships	10^{-5}

Class of consequences is divided into four criteria consisting of people, assets, environment and reputation of the company. All the possible outcomes of the bow tie analysis are estimated using this class of consequences and places in the risk matrix.

Table 5.2. Class of Consequences

Severity Rating	Consequences				Class Ranking
	People	**Assets**	**Environment**	**Reputation**	
0	Zero Injury	Zero Damage	Zero Effect	Zero Impact	C1
1	Slight Injury	Slight Damage	Slight Effect	Slight Impact	C2
2	Minor Injury	Minor Damage	Minor Effect	Minor Impact	C3
3	Critical Injury	Critical Damage	Critical Effect	Critical Impact	C4
4	Single Fatality	Critical Damage	Critical Effect	Critical National Impact	C5
5	Multiple Fatalities	Extensive Damage	Massive Effect	Critical International Impact	C6

Based on both frequency index and class of consequence, the risk matrix mapping reveals the decision classes as being very high, high, medium and low. Table 5.3 explains the risk matrix classes that will be useful to generate the graphs of risk level.

Table 5.3. Risk Matrix Classes

Frequency \ Severity	Negligible	Slight	Minor	Critical	Critical	Catastrophic
Frequent	High	Very High	Very High	Very High	V ery High	Very High
Probable	Medium	High	High	Very High	Very High	Very High
Reasonably Probable	Medium	High	High	Very High	Very High	Very High
Occasional	Medium	Medium	Medium	High	High	Very High
Remote	Low	Medium	Medium	Medium	High	High
Improbable	Low	Low	Low	Medium	Medium	High
Extremely Remote	Low	Low	Low	Low	Medium	Medium

The next Step is to describe the risk level into risk graph. The risk graph characterizing both frequency and consequences of an event is helpful to serve as a communication tool to describe the risk level. The frequency of occurrence has been developed through the FTA and ETA resulting several potential outcomes of the mooring system. Furthermore, the class of consequences of the potential outcomes of mooring system needs to be found. Currently there are insufficient data to determine the class of consequence, hence it can be estimated through the Expert Opinion Survey (EOS). The fourth EOS is distributed to the nine experts in order to determine the class of consequence. The fourth EOS for the outcome of MLB can be seen in Table 5.4. The expert estimates the class of consequence for each of the possible outcomes based on Table 5.2.

Table 5.4. Fourth EOS for MLB

Systems	**Outcomes**	**Class of Consequences**					
		C1	C2	C3	C4	C5	C6
Mooring Line Breakage (MLB)	Pipe Lay Vessel Lost Its Position: Damage on Pipeline Objects, Project Delay, Partial Construction Damage on Pipe Lay Vessel	C1	C2	C3	C4	C5	C6
	Pipe Lay Vessel Lost Its Position: Project Delay, High Priority Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Pipe Lay Vessel Stay on Its Position: High Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Pipe Lay Vessel Stay on Its Position: Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	The Safe Mooring Line	C1	C2	C3	C4	C5	C6

Table 5.5 shows the result of fourth EOS for possible MLB outcomes corresponding to the frequency and class of consequences. The frequency of occurrence and the outcomes of MLB derives from the ETA of MLB as shown in Figure 4.9. The class of consequences of ACF is resulted from the fourth EOS for ACF as shown in Table 5.4.

Table 5.5. The MLB Frequency and Class of Consequences

No	Outcomes	Frequency	Class of Consequences
1.	Pipe Lay Vessel Lost Its Position: Damage on Pipeline Objects, Project Delay, Partial Construction Damage on Pipe Lay Vessel	$1.02501.10^{-18}$	C6
2.	Pipe Lay Vessel Lost Its Position: Project Delay, High Priority Safety Concern is Needed	$1.025.10^{-13}$	C5
3.	Pipe Lay Vessel Stay on Its Position: High Safety Concern is Needed	$1.026.10^{-8}$	C4
4.	Pipe Lay Vessel Stay on Its Position: Safety Concern is Needed	$1.02491.10^{-4}$	C3
5.	The Safe Mooring Line	1.02491	C1

The result shows that the safe mooring line with the frequency of 1.02491 per year classified as probable event and the class of consequence is categorized in the C1 class ranking with zero impact. Figure 5.5 illustrates the risk matrix of MLB with all the possible outcomes corresponding to the frequency of occurrence in the y axis and class of consequences in the x axis. The safe mooring line is categorized in the medium level, hence it has to be determined for the mitigation plans. The others outcomes of MLB are located in the lower level which can be neglected.

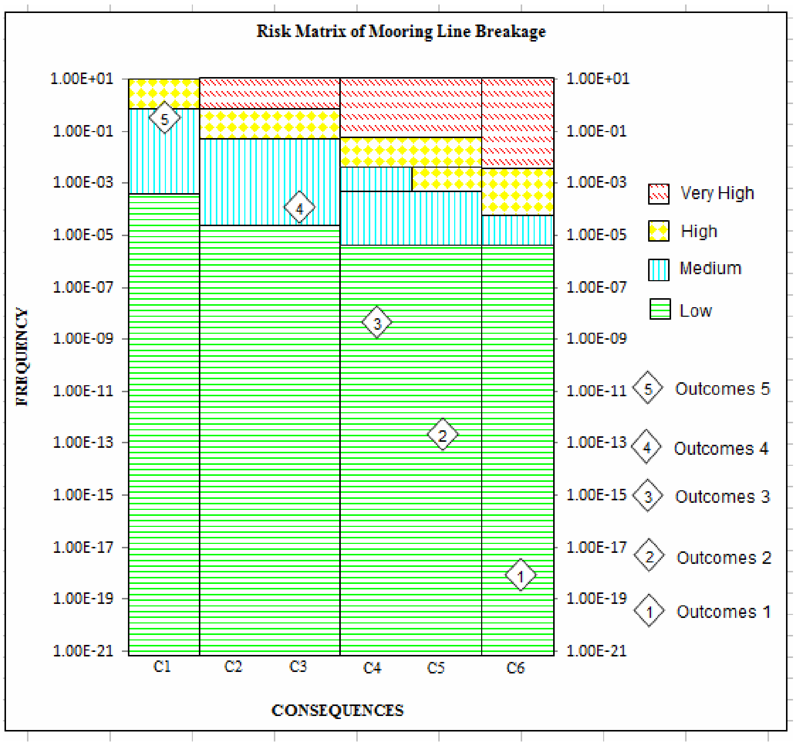

Figure 5.5. Risk Matrix of MLB

The same procedure is repeated by distributing the fourth EOS for AF outcomes. The fourth EOS for AF outcomes is shown in Table 5.6. The experts are asked for classification of the consequence for each of the AF outcome.

Table 5.6. Fourth EOS for AF

Systems	**Outcomes**	**Class of Consequences**					
		C1	C2	C3	C4	C5	C6
Anchor Failure (AF)	Pipe Lay Vessel Lost Its Position: Damage on Pipeline Objects, Project Delay, Partial Construction Damage on Pipe Lay Vessel	C1	C2	C3	C4	C5	C6
	Project Delay: High Priority Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Project Delay: High Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	The safe Anchor	C1	C2	C3	C4	C5	C6

The frequency of occurrence and the AF outcomes derives from the ETA result of AF as shown in the Figure 4.10. The class of consequence of AF is resulted from the fourth EOS for AF as shown in Table 5.7. For instance, the safe anchor has the frequency of occurrence of 1.025908399 per year which is classified as probable event and the class of consequences is grouped into C1 as zero impact.

Table 5.7. The AF Frequency and Class of Consequences

No	Outcomes	Frequency	Class of Consequences
1.	Pipe Lay Vessel Lost Its Position: Damage on Pipeline Objects, Project Delay, Partial Construction Damage on Pipe Lay Vessel	$1.02601.10^{-17}$	C6
2.	Project Delay: High Priority Safety Concern is Needed	$1.026.10^{-12}$	C5
3.	Project Delay: High Safety Concern is Needed	$1.02591.10^{-8}$	C4
4.	Safety Concern is Needed	$1.02591.10^{-4}$	C3
5.	The Safe Anchor	1.025908399	C1

Figure 5.6 shows the risk matrix of anchor failure with all the possible outcomes. The safe anchor is classified as medium level in the risk matrix graphs. Since the anchor is located in the medium level, it is important to develop the mitigation plans. The other outcomes of AF are located in lower level which can be neglected.

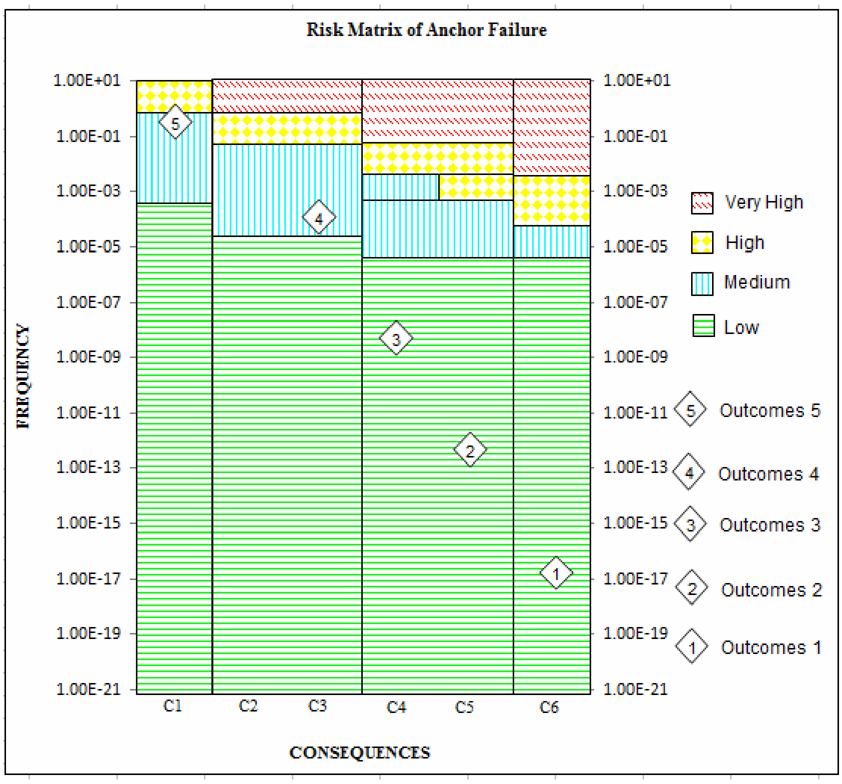

Figure 5.6. Risk Matrix of AF

In order to determine the class of consequences for ACF, the fourth EOS of ACF is distributed to the experts. Table 5.8 shows the fourth EOS for ACF again distributed to the nine experts. The experts need to give their classification on the consequence for each of the possible outcomes of ACF.

Table 5.8. Fourth EOS for ACF

Systems	Outcomes	Class of Consequences					
		C1	C2	C3	C4	C5	C6
Appurtenances Connections Failure (ACF)	Pipe Lay Vessel Drift from Its Design Path: Damage on Pipeline Objects, Project Delay, Partial Construction Damage on Pipe Lay Vessel	C1	C2	C3	C4	C5	C6
	Pipe Lay Vessel Back to Design Path: Project Delay, High Priority Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Pipe Lay Vessel Stay on Its Position: Project Delay, High Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	The Safe Appurtenances Connections	C1	C2	C3	C4	C5	C6

Table 5.9 shows the frequency of occurrence and class of consequences of ACF events. The frequency of occurrence of ACF is tabulated based on ETA result for ACF as seen in Figure 4.11. The class of consequences of ACF is resulted from the fourth EOS for ACF as shown in Table 5.8.

Table 5.9. The ACF Frequency and Class of Consequences

No	Outcomes	Frequency	Class of Consequences
1.	Pipe Lay Vessel Drift from Its Design Path: Damage on Pipeline Objects, Project Delay, Partial Construction Damage on Pipe Lay Vessel	$1.01764.10^{-18}$	C6
2.	Pipe Lay Vessel Back to Design Path: Project Delay, High Priority Safety Concern is Needed	$1.01763.10^{-13}$	C5
3.	Pipe Lay Vessel Stay on Its Position: Project Delay, High Safety Concern is Needed	$1.01763.10^{-8}$	C4
4.	Safety Concern is Needed	$1.01754.10^{-4}$	C3
5.	The Safe Appurtenances Connections	1.017538236	C1

The safe appurtenances connection with the frequency of occurrence of 1.017538236 which is classified as probable event and the class of consequence is categorized into C1 class as zero impact. Risk matrix of ACF is shown in Figure 5.7, the graphs show that the safe appurtenances connections is in the medium level, so that the mitigation plans need to be established. The other outcomes of the ACF are located in the lower level which can be neglected.

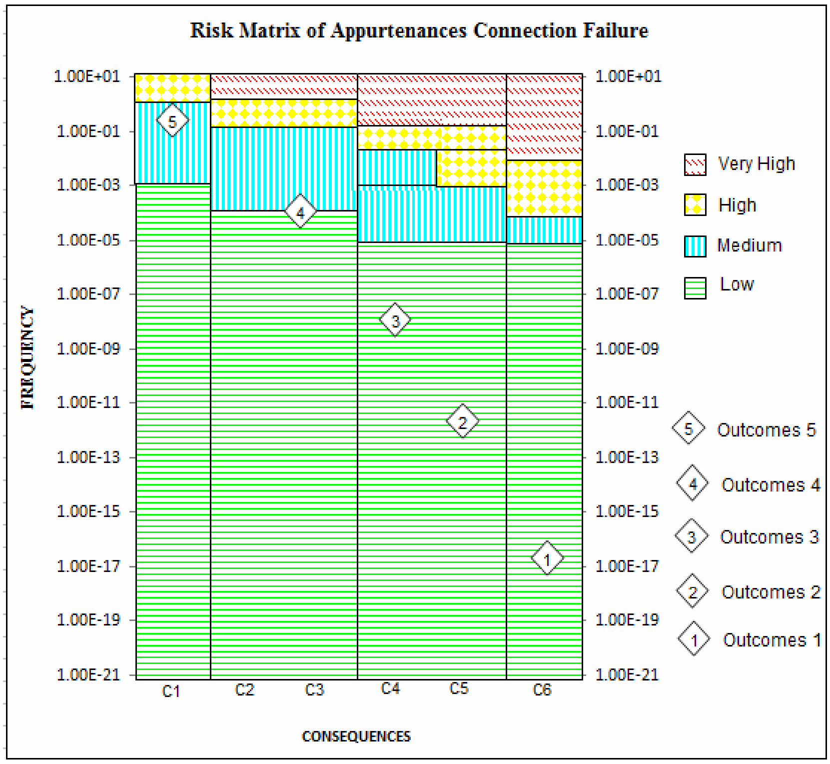

Figure 5.7. Risk Matrix of ACF

The fourth EOS for AHF are distributed to the nine experts in order to find the classification for each of the AHF outcomes. There are five outcomes of AHF which need to be classified for the class of consequences by the experts. Table 5.10 shows the fourth EOS for AHF.

Table 5.10. Fourth EOS for AHF

Systems	Outcomes	Class of Consequences					
		C1	C2	C3	C4	C5	C6
Anchor Handling Failure (AHF)	Project Delay: Partial Damage on Mooring Line, High Priority Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Project Delay: High Priority Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Project Delay: High Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	Safety Concern is Needed	C1	C2	C3	C4	C5	C6
	The Safe Anchor Handling	C1	C2	C3	C4	C5	C6

Table 5.11 shows the frequency of occurrence and class of consequence of the AHF. The frequency of the outcomes of AHF derives from the ETA of ACH as seen in Figure 5.12. The class of consequences for AHF is tabulated based on the fourth EOS for AHF as shown in Table 5.10. The frequency of the safe anchor handling is $3.39966.10^{-2}$ per year considered as occasional event and the class of consequence is located at C1 with zero impact.

Table 5.11. The AHF Frequency and Class of Consequences

No	Outcomes	Frequency	Class of Consequences
1.	Project Delay: Partial Damage on Mooring Line, High Priority Safety Concern is Needed	$3.4.10^{-20}$	C6
2.	Project Delay: High Priority Safety Concern is Needed	$3.39997.10^{-15}$	C5
3.	Project Delay: High Safety Concern is Needed	$3.39997.10^{-10}$	C4
4.	Safety Concern is Needed	$3.39966.10^{-6}$	C3
5.	The Safe Anchor Handling	$3.39966.10^{-2}$	C1

The risk matrix of AHF is illustrated in Figure 5.8, the graphs show that the safe anchor handling is located in the medium level which also needs to be developed for mitigation plans. The others outcomes of AHF are located in the lower level which can be neglected.

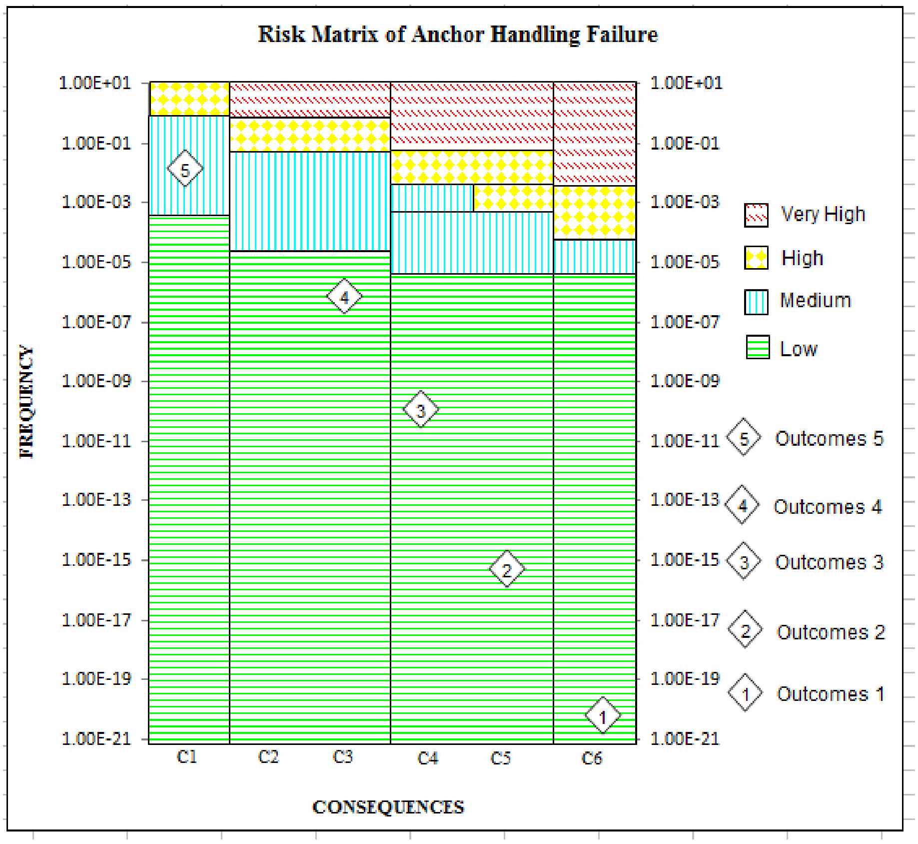

Figure 5.8. Risk Matrix of AHF

Generally, both FTA and ETA results on critical event of mooring system obtained in this study are classified into the operational and maintainability categories. Previously, there were no significant records of potential causes that may lead to an accident. The risk matrix graphs that derive from the bow tie analysis is essentially not a guide for the acceptability of risk level. This graph is only a guide to select the mitigation plans. The mitigation plans have to be established in order to minimize the risk of damages that may occur as result of destruction caused by a major hazardous event. The following section will discuss the mitigation plans in more detail.

5.1.5 MIRBA Step 5: Determining the Mitigation Plan

Developing the mitigation plan is based on the risk level. It is useful to minimize the failure. Mitigation plan is established for each of the undesired events on how to handle and manage the risk. The bow tie framework helps to identify all the related causes of an event and their consequences. By identifying all the causes of possible failure, the list of mitigation plans can be established. Mitigation plans are developed based on the result of the risk level of the bow tie analysis. With regard to the risk level classification the four critical events of mooring system failure MLB, AF, ACF and AHF are located in the medium level. Therefore, it is important to establish mitigation plans for each of undesired events.

The mitigation plans are obtained based on all the critical basic events in mooring system failure. At the beginning the mitigation plans are obtained from the literature review. The next Step is by distributing the fifth EOS to the experts in order to add or revise the mitigation plan obtained on the literature review. After the responses from the experts have been gathered, the next Step is to compile and arrange the mitigation plans for each of the basic events. The result from fifth EOS for mitigation plan is tabulated in Table 5.12.

Table 5.12. Fifth EOS for Mitigation Plans

Basic Events	Code	Mitigation Code	Mitigation Plans
Adverse Environmental Condition	AEC	M1	Conduct mooring analysis to ensure the moorings are fit for purpose
		M2	Have the metocean data be reviewed & validated by independent party
		M3	Rescheduling special task when necessary
		M4	Insure all the assets of company
		M5	Visual inspect all mooring components
Debris in Seabed	DiS	M1	Conduct comprehensive survey on sea bed location
		M2	Perform a trawl sweep across the working area
Design Error	DE	M1	Carry out pre project arrangement to reduce design errors
		M2	Design to be reviewed and validated by 3rd party certification (ABS or DNV or Lloyds, etc)
		M3	Review the design plan with independent engineering/the consultant
		M4	Obtain design liability insurance
Electrical Failure of Winch	EFoW	M1	Check electrical condition of the winches
		M2	Monitor the winch speed
		M3	Ensure the winch wire length
Electrical Failure	EF	M1	Maintain the electrical condition
		M2	Uses stand by system for control system
		M3	Have an alarm system to detect power failure
Excessive Waves	EWa	M1	Record roll and pitch in degrees
		M2	Check heave in feet
		M3	Have the metocean data be reviewed & validated by independent party
Excessive Winds	EWi	M1	Verify wind direction and velocity
		M2	Have the metocean data be reviewed & validated by independent party
Excessive Currents	ECu	M1	Monitor the current drawn
		M2	Have the metocean data be reviewed & validated by independent party
Human Error	HE	M1	Trained the crew regularly to maintain the skills
		M2	Hired the certified and credible crew
		M3	Employ competent crew with the certification
Incomprehensive Data Collection	IDC	M1	Conduct comprehensive survey on operation location
		M2	Hired the certified and credible crew
		M3	Perform the verification data with other company/consultant
Improper Quality Control	IQC	M1	Implement proper quality control procedures and supervision
		M2	Employ all regulatory documentation including vessel classification, equipment and personnel certification
		M3	Engage 3rd party inspection
Inadequate Winch Maintenance Schedule	IWMS	M1	Examine electrical and mechanical condition of the winches
		M2	Inspect that sheaves and fairleaders are free and properly greased

Basic Events	Code	Mitigation Code	Mitigation Plans
		M3	Obtain that shackles and pins are properly secured and connected
		M4	Ensure proper & periodical maintenance program
Inadequate Coating Protection	ICP	M1	Protect chain from corrosion by increasing the chain diameter
		M2	Additional coating protection by adding sacrificial anodes
		M3	Ensure adequate corrosion allowance in the design of the mooring chain
Inadequate Maintenance Schedule	IMS	M1	Investigate any marked reduction in wire diameter
		M2	Maintain a permanent record of the equipment history and status
		M3	Ensure proper & periodical maintenance program
		M4	Remove from service any wire with insufficient conditions
Improper Soil Data Sampling	ISDS	M1	Ensure capability /credibility of the lab conducting the soil sample testing and evaluation
		M2	Carry out sufficient soil data sampling of operation location
		M3	Hired the certified and credible crew
		M4	Conduct the soil test properly
Incompetence Crews	IC	M1	The crew regularly trained to maintain the skills
		M2	Hired the certified and credible crew
		M3	Employ competent crew with the certification
Manufacturing Error	ME	M1	Highly supervision during the manufacturing or field processes
		M2	Ensure that design & construction specifications are complete and verified
Mechanical Failure	MF	M1	Conduct the verification test to examine the performance of mechanical mooring hardware
		M2	Ensure mechanical condition of the winches
Natural Hazard	NH	M1	Conduct mooring analysis to ensure the moorings are fit for purpose
		M2	Visual inspect all mooring components
Poor Raw Material	PRM	M1	Revisit /verify correctness of design & construction specifications
		M2	Engage 3rd party verification during manufacturing and construction
		M3	Verify all mill certificates
		M4	Ensure proper NDT program & adequate record procedure for traceability
Rocky Seabed	RS	M1	Conduct comprehensive survey on sea bed location
		M2	Review & verify adequacy/suitability of anchoring design
Soft Clay	SC	M1	Conduct comprehensive survey on sea bed location
		M2	Review & verify adequacy/suitability of anchoring design
Uncertified Crews	UC	M1	Hired the certified and credible crew
		M2	Employ competent crew with the certification

Basic Events	Code	Mitigation Code	Mitigation Plans
Irregular AHT	IAM	M1	Establish the capability of AHT whether it still maintain adequate holding capacity and tension.
		M2	Ensure the AHT performance in order to moor the vessel in a working pipe lay configuration.
		M3	Ensure proper & periodical maintenance program
Uncertified Equipment	UE	M1	Obtain the equipment certification
		M2	Record the inspection in certificate of thorough examination to maintain a permanent record of the equipment history and status.
		M3	Engage 3rd party verification during manufacturing and construction
Wrong Material	WM	M1	Revisit /verify correctness of design & construction specifications
		M2	Engage 3rd party verification during manufacturing and construction
		M3	Verify all mill certificates
		M4	Ensure proper NDT program & adequate record procedure for traceability
		M5	Improve the quality control in manufacturing process

The mitigation plans are established through the risk assessment in qualitative linguistic terms. In order to avoid uncertainty and vagueness, the effectiveness of mitigation is measured through seven degree rating system. The seven degree rating systems are adopted to develop the preciseness and reliability of the survey for the criticality of risks and the effectiveness of mitigation measures as shown in Table 5.13.

Table 5.13. Risk Criticality and Mitigation Measure Effectiveness (Wang, 2004)

Rating	Risk Criticality	Mitigation Measure Effectiveness
1	Not critical at all	Not effective at all
2	Slightly critical	Slightly effective
3	Somehow critical	Somehow effective
4	Critical	Effective
5	Very critical	Very effective
6	Very much critical	Very much effective
7	Exceptionally critical	Exceptionally effective

In an attempt to investigate the risk criticality and mitigation measure effectiveness, sixth EOS is distributed to the experts as shown in Table 5.14. The experts have been asked the risk criticality of each basic event using the seven degree rating system.

Table 5.14. Sixth EOS Risk Criticality

Basic Events	Code	Risk Criticality						
		1	2	3	4	5	6	7
Adverse Environmental Condition	AEC	1	2	3	4	5	6	7
Debris in Seabed	DiS	1	2	3	4	5	6	7
Design Error	DE	1	2	3	4	5	6	7
Electrical Failure of Winch	EFoW	1	2	3	4	5	6	7
Electrical Failure	EF	1	2	3	4	5	6	7
Excessive Waves	EWa	1	2	3	4	5	6	7
Excessive Winds	EWi	1	2	3	4	5	6	7
Excessive Currents	ECu	1	2	3	4	5	6	7
Human Error	HE	1	2	3	4	5	6	7
Incomprehensive Data Collection	IDC	1	2	3	4	5	6	7
Improper Quality Control	IQC	1	2	3	4	5	6	7
Inadequate Winch Maintenance S.	IWMS	1	2	3	4	5	6	7
Inadequate Coating Protection	ICP	1	2	3	4	5	6	7
Inadequate Maintenance Schedule	IMS	1	2	3	4	5	6	7
Improper Soil Data Sampling	ISDS	1	2	3	4	5	6	7
Incompetence Crews	IC	1	2	3	4	5	6	7
Manufacturing Error	ME	1	2	3	4	5	6	7
Mechanical Failure	MF	1	2	3	4	5	6	7
Natural Hazard	NH	1	2	3	4	5	6	7
Poor Raw Material	PRM	1	2	3	4	5	6	7
Rocky Seabed	RS	1	2	3	4	5	6	7
Soft Clay	SS	1	2	3	4	5	6	7
Uncertified Crews	UC	1	2	3	4	5	6	7
Irregular AHT Maintenance	IAM	1	2	3	4	5	6	7
Uncertified Equipment	UE	1	2	3	4	5	6	7
Wrong Material	WM	1	2	3	4	5	6	7

The result of sixth EOS obtained from nine experts in order to determine the risk criticality of the basic events is tabulated in Table 5.15. The total criticality index is obtained from the summation for all the judgments of each basic event. For instance, in term of adverse environmental condition, five experts give the risk criticality on 4 degree rating. And the other four experts give the risk criticality for adverse environmental condition on 5 degree rating. Therefore the total criticality for adverse environmental condition is the summation of the total judgments four experts multiplied by 5 degree rating equals to 20, and plus four experts multiplied by 4 degree rating equals to 20. Hence the total criticality index for adverse environmental condition is 40. This procedure is repeated for each of the basic events and the result of total criticality index is shown in Table 5.15.

Table 5.15. Judgments on Sixth EOS

Basic Events	Risk Criticality Judgments on Sixth EOS							Total Criticality Index
	1	2	3	4	5	6	7	
Adverse Environmental Condition	-	-	-	5	4	-	-	40
Debris in Seabed	-	-	3	3	3	-	-	36
Design Error	-	5	4	-	-	-	-	22
Electrical Failure of Winch	-	5	4	-	-	-	-	22
Electrical Failure	-	-	-	6	3	-	-	39
Excessive Waves	-	-	-	-	-	5	4	58
Excessive Winds	-	-	-	-	-	5	4	58
Excessive Currents	-	-	-	-	-	5	4	58
Human Error	-	-	-	5	4	-	-	40
Incomprehensive Data Collection	-	-	-	5	4	-	-	40
Improper Quality Control	-	-	-	5	4	-	-	40
Inadequate Winch Maintenance S.	-	-	9	-	-	-	-	27
Inadequate Coating Protection	-	-	6	3	-	-	-	30
Inadequate Maintenance Schedule	-	-	-	8	1	-	-	37
Improper Soil Data Sampling	-	-	6	3		-	-	30
Incompetence Crews	-	-	-	5	4	-	-	40
Manufacturing Error	-	5	4	-	-	-	-	22
Mechanical Failure	-	-	-	6	3	-	-	39
Natural Hazard	-	-	-	5	4	-	-	40
Poor Raw Material	-	-	-	8	1	-	-	37
Rocky Seabed	-	-	-	5	4	-	-	40
Soft Clay	-	-	-	5	5	-	-	40
Uncertified Crews	-	-	-	9	-	-	-	36
Irregular AHT Maintenance	-	-	-	-	9	-	-	36
Uncertified Equipment	-	5	4	-	-	-	-	22
Wrong Material	-	-	-	8	1	-	-	37

Table 5.16 shows the statistical results on the criticality of risks deriving from the sixth EOS which represent the total criticality index, mean index, risk rank and standard deviation. The total criticality index is obtained from the sum of all rated indexes scales from 1 to 7 for each basic event by all respondents as shown in previous Table 5.15.

In order to measure more precise value, the expert opinions obtained from this study are measured in the 95th percentile of the aggregate series (Dimitopoulos, 2009; Gyarmati, 2012; Stanojevic, 2010). The 95th percentile is typically between the average and the maximum balancing. By using the parameter of 95th percentile precise value can be achieved and an accurate estimate of the 95th percentile can be applied based on small number of samples (Oakley, 2004). Therefore this thesis used the 95th percentile for the data analysis.

The 95th percentile is gained through the risk criticality judgments consisting of 9 respondents. For instance the 95th percentile for adverse environmental condition is obtained from the result of risk criticality of the judgments which is 4. The basic events rank is directly based on the 95th percentile rank from the highest to the lowest. Here the 95th percentile of adverse environmental condition namely 4 is categorized into rank 4. These procedures are repeated for all the basic events in order to determine the 95th percentile and the rank of basic events.

Table 5.16. Statistical Results on the Criticality of Basic Events

Basic Events	Code	Total Criticality Index	95th Percentile	Basic Events Rank
Adverse Environmental Condition	AEC	40	4	4
Debris in Seabed	DiS	36	3	19
Design Error	DE	22	2	23
Electrical Failure of Winch	EFoW	22	2	23
Electrical Failure	EF	39	4	4
Excessive Waves	EWa	58	6	1
Excessive Winds	EWi	58	6	1
Excessive Currents	ECu	58	6	1
Human Error	HE	40	4	4
Incomprehensive Data Collection	IDC	40	4	4
Improper Quality Control	IQC	40	4	4
Inadequate Winch Maintenance S.	IWMS	27	3	19
Inadequate Coating Protection	ICP	30	3	19
Inadequate Maintenance Schedule	IMS	37	4	4
Improper Soil Data Sampling	ISDS	30	3	19
Incompetence Crews	IC	40	4	4
Manufacturing Error	ME	22	2	23
Mechanical Failure	MF	39	4	4
Natural Hazard	NH	40	4	4
Poor Raw Material	PRM	37	4	4
Rocky Seabed	RS	40	4	4
Soft Clay	SS	40	4	4
Uncertified Crews	UC	36	4	4
Irregular AHT Maintenance	IAM	36	4	4
Uncertified Equipment	UE	22	2	23
Wrong Material	WM	37	4	4

The results of criticality basic events as seen in Table 5.16 show that 19 out of 26 basic events having 95th percentile index between 4 meaning critical and 6 meaning very much critical. In general the respondents define about 70 % of identifying basic events within critical to very much critical. The most critical basic events are excessive wave, winds and currents with criticality index very much critical.

The effective measure is useful to dictate the implementation sequence of mitigation measures. In order to measure the effectiveness of mitigation, the experts fill up the seventh EOS which uses the seven degree rating system for each of the basic events as shown in Table 5.13. The experts need to give their judgment on the effectiveness of mitigation (M) based on the mitigation plan given for each of basic events as seen in Table 5.17.

Table 5.17. Seventh EOS Mitigation Measure Effectiveness

Basic Events	Code	Mitigation Plans (Refer Table 5.12)	Risk Criticality						
			1	2	3	4	5	6	7
Adverse Environmental Condition	AEC	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
		M5	1	2	3	4	5	6	7
Debris in Seabed	DiS	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Design Error	DE	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
Electrical Failure of Winch	EFoW	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Electrical Failure	EF	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Excessive Waves	EWa	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Excessive Winds	EWi	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Excessive Currents	ECu	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Human Error	HE	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Incomprehensive Data Collection	IDC	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Improper Quality Control	IQC	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Inadequate Winch Maintenance Schedule	IWMS	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
Inadequate Coating Protection	ICP	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Inadequate	IMS	M1	1	2	3	4	5	6	7

Basic Events	Code	Mitigation Plans (Refer Table 5.12)	Risk Criticality						
			1	2	3	4	5	6	7
Maintenance Schedule		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
Improper Soil Data Sampling	ISDS	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
Incompetence Crews	IC	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Manufacturing Error	ME	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Mechanical Failure	MF	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Natural Hazard	NH	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Poor Raw Material	PRM	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
Rocky Seabed	RS	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Soft Clay	SC	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Uncertified Crews	UC	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
Irregular AHT Maintenance	IAM	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Uncertified Equipment	UE	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
Wrong Material	WM	M1	1	2	3	4	5	6	7
		M2	1	2	3	4	5	6	7
		M3	1	2	3	4	5	6	7
		M4	1	2	3	4	5	6	7
		M5	1	2	3	4	5	6	7

The results of mitigation measures indicate that the higher effectiveness value should be implemented with higher priority than that with less effectiveness. The judgments from nine experts based on seventh EOS are tabulated in Table 5.18. As seen in Table 5.12 there are five mitigation plans for adverse environmental condition (AEC), hence the nine experts give their mitigation measure effectiveness for each mitigation plan. For mitigation one (M1), three experts give their judgments on 3 degree rating system and six experts give their judgments on 4 degree rating system. For mitigation two (M2), five experts give their judgments on 5 degree rating system and four experts give their judgments on 6 degree rating system. Then, with mitigation three (M3), 3 degree rating system is chosen by three experts, and the other four experts choose 4 degree rating system and other two experts choose 5 degree rating system. The fourth mitigation (M4) plan for AEC is judged as 4 degree rating system by the three experts and other six experts give 5 degree rating system. The fifth mitigation (M5) of AEC is given 3 degree rating system by three experts and 4 degree rating system by other six experts. This procedure is repeated for each mitigation plan of all basic events

.

Table 5.18. The Result of Mitigation Measure Effectiveness

Basic Events	Code	Mitigation Plans (Refer Table 5.12)	Mitigation Measure						
			1	2	3	4	5	6	7
Adverse Environmental Condition	AEC	M1	-	-	3	6	-	-	-
		M2	-	-	-	-	5	4	-
		M3	-	-	3	4	2	-	-
		M4	-	-	-	3	6	-	-
		M5	-	-	3	6	-	-	-
Debris in Seabed	DiS	M1	-	-	4	5		-	-
		M2	-	-	1	6	2	-	-
Design Error	DE	M1	-	-	1	7	1	-	-
		M2	-	-		3	6	-	-
		M3	-	-	1	5	3	-	-
		M4	-	-	2	5	2	-	-
Electrical Failure of Winch	EFoW	M1	-	-	-	7	2	-	-
		M2	-	-	3	5	-	-	-
		M3	-	-	2	7	-	-	-
Electrical Failure	EF	M1	-	-	1	5	3	-	-
		M2	-	-		3	6	-	-
		M3	-	-	3	6		-	-
Excessive Waves	EWa	M1	-	-	-	4	5	-	-
		M2	-	-	-	3	6	-	-
		M3	-	-	-	6	3	-	-
Excessive Winds	EWi	M1	-	-	2	4	3	-	-
		M2	-	-	-	2	7	-	-
Excessive Currents	ECu	M1	-	-	-	3	6	-	-
		M2	-	-	-	2	7	-	-
Human Error	HE	M1	-	-	-	2	7	-	-
		M2	-	-	2		7	-	-
		M3	-	-	-	3	6	-	-
Incomprehensive Data Collection	IDC	M1	-	-	-	6	3	-	-
		M2	-	-	-	6	3	-	-
		M3	-	-	2	-	7	-	-
Improper Quality Control	IQC	M1	-	-	2	7	-	-	-
		M2	-	-	3	4	2	-	-
		M3	-	-	-	3	6	-	-
Inadequate Winch Maintenance Schedule	IWMS	M1	-	-	2	5	2	-	-
		M2	-	-	4	3	2	-	-
		M3	-	-	3	6	-	-	-
		M4	-	-	-	3	6	-	-
Inadequate Coating Protection	ICP	M1	-	-	1	7	1	-	-
		M2	-	-	-	5	4	-	-
		M3	-	-	-	3	6	-	-

Basic Events	Code	Mitigation Plans (Refer Table 5.12)	Mitigation Measure						
			1	2	3	4	5	6	7
Inadequate Maintenance Schedule	IMS	M1	-	-	-	6	3	-	-
		M2	-	-	-	3	6	-	-
		M3	-	-	3	4	2	-	-
		M4	-	-	-	7	2	-	-
Improper Soil Data Sampling	ISDS	M1	-	-	1	1	7	-	-
		M2	-	-	-	2	7	-	-
		M3	-	-	1	2	6	-	-
		M4	-	-	7	2		-	-
Incompetence Crews	IC	M1	-	-	1	2	6	-	-
		M2	-	-	-	1	8	-	-
		M3	-	-	1	6	2	-	-
Manufacturing Error	ME	M1	-	-	2	7		-	-
		M2	-	-	-	5	4	-	-
Mechanical Failure	MF	M1	-	-	3	6	-	-	-
		M2	-	-	-	7	2	-	-
		M3	-	-	-	7	2	-	-
Natural Hazard	NH	M1	-	-	2	7	-	-	-
		M2	-	-	1	6	2	-	-
Poor Raw Material	PRM	M1	-	-	-	1	5	3	-
		M2	-	-	-	3	6	-	-
		M3	-	-	2	7	-	-	-
		M4	-	-	1	7	1	-	-
Rocky Seabed	RS	M1	-	-	1	6	2	-	-
		M2	-	-	-	3	6	-	-
Soft Clay	SC	M1	-	-	1	4	4	-	-
		M2	-	-	-	2	7	-	-
Uncertified Crews	UC	M1	-	-	2	3	4	-	-
		M2	-	-	-	6	3	-	-
Irregular AHT Maintenance	IAM	M1	-	-	-	6	3	-	-
		M2	-	-	-	4	5	-	-
		M3	-	-	-	2	7	-	-
Uncertified Equipment	UE	M1	-	-	2	4	3	-	-
		M2	-	-	-	6	3	-	-
		M3	-	-	2	-	7	-	-
Wrong Material	WM	M1	-	-	-	-	8	1	
		M2	-	-	3	-	6	-	-
		M3	-	-	2	1	6	-	-
		M4	-	-	1	1	7	-	-
		M5	-	-	2	7	-	-	-

Once all the effectiveness of mitigation measures from nine experts have been identified, the next Step is to calculate the mean index for each of mitigation plan. Table 5.19 shows the mean index for each of the mitigation plans. The examples of AEC the mitigation measure effectiveness deriving from nine experts as seen in Table 5.19 as follows:

a. Mitigation one (M1) for AEC is 3 degree rating system by three experts equals to 9, plus 4 degree rating system by six experts equals to 24. Hence the total effectiveness is 9 plus 24 equals to 33 and the mean index for AEC is 33 divided by 9 equals to 3.67.

b. Mitigation two (M2) of AEC is 5 degree rating system by five experts equals to 25, plus 6 degree rating system by four experts equals to 24. The total effectiveness for M2 is 25 plus 24 equals to 49, and the mean index for M2 AEC is 49 divided by 9 equals to 5.44.

c. Mitigation three (M3) of AEC is 3 degree rating system by three experts equals to 9, 4 degree rating system by four experts equals to 16 and 5 degree rating by two experts equals to 10. Hence, the total effectiveness is 9 plus 16 plus 10 equal to 36 and the mean index for AEC is 35 divided by 9 equals to 3.89.

d. The fourth mitigation (M4) for AEC is 4 degree rating system by the three experts equals to 12 plus 5 degree rating system by six experts give equal to 30. The total effectiveness for M4 is 12 plus 30 equal to 42, and the mean index for M4 AEC is 42 divided by 9 equals to 4.67.

e. The fifth mitigation (M5) of AEC is given 3 degree rating system by three experts equals to 9 and 4 degree rating system by another six experts equals to 24. The total effectiveness for M5 is 9 plus 24 equals to 33, and the mean index for M4 AEC is 33 divided by 9 equals to 3.67.

This procedure is repeated for each mitigation plan of all basic events. The mitigation measure effectiveness has been rated between 3 to 5 as shown in Table 5.19. Thus all respondents have defined the proposed mitigation measures as effective to very effective.

Table 5.19. Effectiveness of Mitigation Measures for Each Basic Events

Basic Events	Code	M1	M2	M3	M4	M5
Adverse Environmental Condition	AEC	3.00	5.00	3.00	4.00	3.00
Debris in Seabed	DiS	3.00	3.00	N/A	N/A	N/A
Design Error	DE	3.00	4.00	3.00	3.00	N/A
Electrical Failure of Winch	EFoW	4.00	3.00	3.00	N/A	N/A
Electrical Failure	EF	3.00	4.00	3.00	N/A	N/A
Excessive Waves	EWa	4.00	4.00	4.00	N/A	N/A
Excessive Winds	EWi	3.00	4.00	N/A	N/A	N/A
Excessive Currents	ECu	4.00	4.00	N/A	N/A	N/A
Human Error	HE	4.00	3.00	4.00	N/A	N/A
Incomprehensive Data Collection	IDC	4.00	4.00	3.00	N/A	N/A
Improper Quality Control	IQC	3.00	3.00	4.00	N/A	N/A
Inadequate Winch Maintenance S.	IWMS	3.00	3.00	3.00	4.00	N/A
Inadequate Coating Protection	ICP	3.00	4.00	4.00	N/A	N/A
Inadequate Maintenance Schedule	IMS	4.00	4.00	3.00	4.00	N/A
Improper Soil Data Sampling	ISDS	3.00	4.00	3.00	3.00	N/A
Incompetence Crews	IC	3.00	4.00	3.00	N/A	N/A
Manufacturing Error	ME	3.00	4.00	N/A	N/A	N/A
Mechanical Failure	MF	4.00	4.00	4.00	N/A	N/A
Natural Hazard	NH	3.00	3.00	N/A	N/A	N/A
Poor Raw Material	PRM	4.00	4.00	3.00	3.00	N/A
Rocky Seabed	RS	3.00	4.00	N/A	N/A	N/A
Soft Clay	SC	3.00	4.00	N/A	N/A	N/A
Uncertified Crews	UC	3.00	4.00	N/A	N/A	N/A
Irregular AHT Maintenance	IAM	4.00	3.00	4.00	N/A	N/A
Uncertified Equipment	UE	3.00	4.00	3.00	N/A	N/A
Wrong Material	WM	5.00	3.00	3.00	3.00	3.00

5.1.6 MIRBA Step 6: Determining the Maintenance Strategy

Maintenance strategy is developed in order to maintain the risk failure. Selecting the best maintenance strategy is cost saving, because it will be more efficient and effective. The method used to select the best maintenance strategy is AHP. It is one of the most widely used of multi criteria decision making methods (Xu, 2001). In order to apply the analytic hierarchy process, few Steps need to be taken which include construction of hierarchical tree, evaluation of hierarchy and sensitivity analysis. This study uses AHP to select the best maintenance strategy for mooring system on the basis of the likelihood of failure shown in Figure 5.9. The second hierarchy is developed to select the best maintenance strategy for mooring system on the basis of the consequences of failure as shown in Figure 5.10.

5.1.7 MIRBA Step 6.1: Starting AHP by Selecting the Goal/Objective

AHP starts by selecting the goal/objective through the hierarchical structure. Hierarchical structure is used to model the problem which contains the decision goal, the alternative to achieve it and the criteria to evaluate the alternatives. The goal of this study is to select the best maintenance strategy for the mobile mooring system.

5.1.8 MIRBA Step 6.2: Developing the Hierarchy Tree

The hierarchical structure is used to model the decision in a systematic way. The design of the hierarchical structure is based on knowledge, judgments and opinion of the experts involved in decision making process. Hierarchical structure is visualized through a diagram tree showing the goal at the first level, criteria at the second level, sub criteria at the third level and the alternative at last level.

5.1.8.1 Construction of The Hierarchy Tree

Construction of hierarchy in AHP is started from system identification and hierarchical structure. System identification in AHP helps the decision maker understand their problem and find the best solutions suitable for their goal. Hierarchical structure composes the decision problem into a hierarchy in order to comprehend sub problems easily, and to evaluate its various elements by comparing them using AHP scale.

5.1.8.2 System Identification

The first Step in executing the AHP is to identify the systems to be employed in the maintenance strategy selection. This Step includes the brainstorming with the experts aimed to acquire knowledge with the help of expert opinion survey and interviews.

5.1.8.3 Hierarchical Structure

Based on the system identification, the information can be constructed to a hierarchy as shown in Figure 5.9 and 5.10. The hierarchy of AHP generally consists of four levels, as follows:

a. First level is the goal that needs to be achieved
b. Second level is criteria of the factor to enable the goal to be achieved
c. The third level is sub factor of the factor in the previous level
d. The fourth level is alternatives of the maintenance strategies.

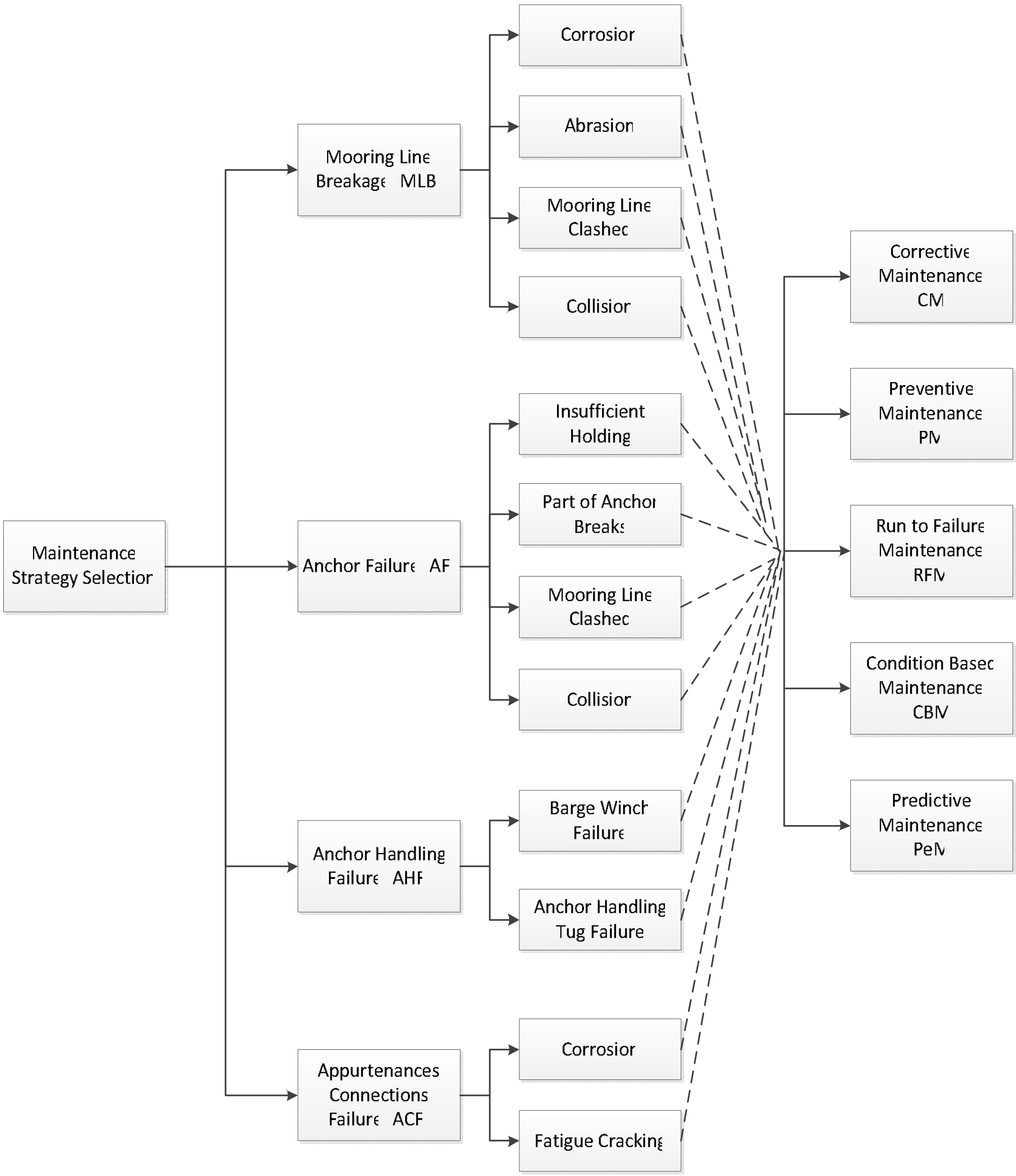

Figure 5.9. Maintenance Strategy for Mooring System on the Basis of Likelihood of Failure

Figure 5.9 shows the hierarchical structure for maintenance strategy for mooring system on the basis of likelihood of failure. The first level is the goal which is maintenance strategy selection on the basis of likelihood. The second level is the factors that need to be considered in likelihood of mooring failure, consisting of MLB, AF, AHF, and ACF. The third level is the sub factor that can contribute to the each of the factor of the likelihood of mooring failure. Based on the brainstorming with the experts the four factors and their sub factor that need to be considered in the likelihood of mooring failure are similar with the critical events that have been identified in FTA namely:

a. MLB due to corrosion, abrasion, mooring line clashed and collision.
b. AF due to insufficient holding, part of anchor breaks, mooring line clashed and collision.
c. AHF due to barge winch failure and anchor handling tug failure.
d. ACF due to corrosion and fatigue cracking.

The fourth level or last level is the alternative maintenance policies evaluated in this study, namely CM, PM, RFM, CBM and PeM.

With regards to the hierarchy of maintenance strategy for mooring system on the basis of the likelihood of failure, the eighth EOS is developed in order to investigate the best maintenance strategy. Appendix B shows the eighth EOS to select the best maintenance strategy for mooring system on the basis of the likelihood of failure. Nine respondents are involved and give their judgments through the eighth EOSs.

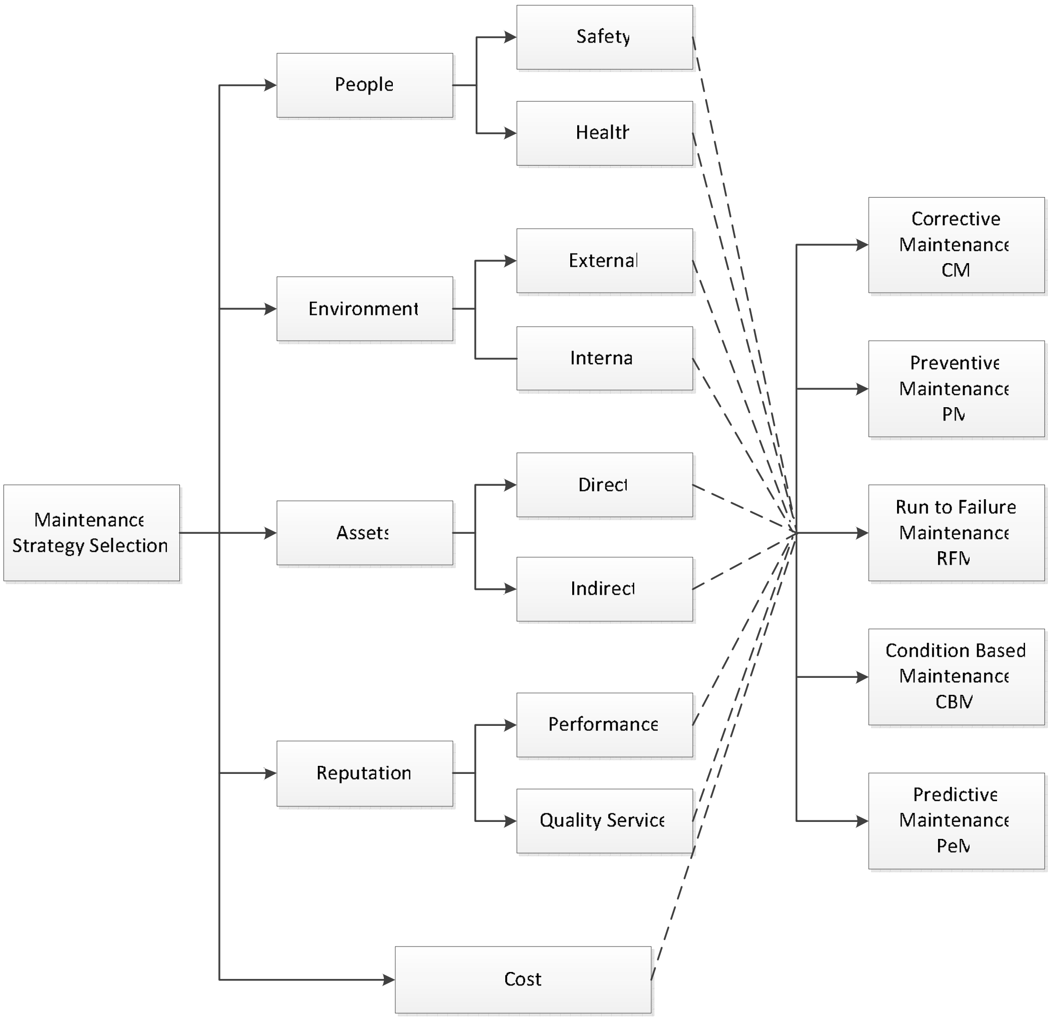

Figure 5.10. Maintenance Strategy for Mooring System on the Basis of Consequence of Failure

Figure 5.10 describes the hierarchical structure for maintenance strategy for mooring system on the basis of consequence of failure. The first level is the goal which is maintenance strategy selection on the basis of consequence. The second level is the factors that need to be considered in the consequence of mooring failure consisting of people, environment, assets, reputation and cost. The third level is the sub factor that can contribute to each factor of the consequence of mooring failures. The four factors and their sub factor on the basis of consequence are obtained based on the interview with the experts consisting of:

a. People considering the safety and health of the personnel.
b. Environment, by taking into account the external damage and internal damage of the platform.

c. Assets, by considering the direct damage having tangible effects of the failure and indirect damage into account the possible reduction of the failure on the working life of the platform.
d. Reputation, by considering the performance and quality service.
e. Costs, that can include the crew cost and spare past cost.

With regards to the hierarchy of maintenance strategy for mooring system on the basis of the consequences of failure, the ninth EOS is developed in order to investigate the priority of the best maintenance strategy. Appendix C shows the ninth EOS to select the best maintenance strategy for mooring system at the point of view of the consequences of failure. Nine respondents are also involved and they give their judgments through the ninth EOS.

5.1.9 MIRBA Step 6.3: Calculating the Matrix Pair Wise Comparison

The hierarchy evaluation starts with the calculation of the matrix pair wise comparison. The judgment is made on a numerical scale ranging from 1 to 9. The judgments of the relative importance of the elements with respect to the overall goal of the hierarchy tree are made. Elements at each level of the hierarchy are compared to each other in pairs with their respective parents in the next higher level.

Hierarchy evaluations consist of calculation of matrix pair wise comparison, priority vector completed with the consistency ratio then investigate the result with the sensitivity analysis. For example, for comparing the factors mooring line breakage and anchor failure, a judgment level is chosen as 4 which means that the anchor failure is 4 times (moderately to strongly) more important than the mooring line breakage. The same procedure is repeated for the next elements in each level of the hierarchy. Here is the example:

In order to select an appropriate maintenance strategy, the respondents are asked through the eighth EOS. The eighth EOS derives from the hierarchy based on the Figure 5.9. The eighth EOS uses AHP scale from 1 to 9 in order to determine the pair wise comparison. Table 5.20 shows the questions comparing two criteria, for example: Which of these two criteria elements is of greater importance (priority) to you and how much? If the respondents choose the scale on the left part of 1, then in mathematic calculation it will become 1/x, and if the respondents choose the scale on the right part 1, then the calculation will become x.

Table 5.20. Matrix Pair wise Comparison on Criteria

Factors	AHP Scale																	Factors
MLB	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**AF**
MLB	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**AHF**
MLB	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**ACF**
AF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**AHF**
AF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**ACF**
AHF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**ACF**

Table 5.21 shows the judgments of the nine respondents (R). As seen in Table 5.21 the first comparison is between MLB and AF. Therefore first row of Table 5.21 derives from:

- R1 chooses the AHP scale 1,
- R2 chooses the AHP scale 2 on the left part of 1 therefore the calculation becomes 1/x=1/2,
- R3 also chooses the AHP scale 2 on the left part of 1 therefore the calculation becomes 1/x=1/2,
- R4 chooses the AHP scale 3 on the left part of 1 therefore the calculation becomes 1/x=1/3,
- R5 also chooses the AHP scale 3 on the left part of 1 therefore the calculation becomes 1/x=1/3,
- R6 chooses the AHP scale 2 on the left part of 1 therefore the calculation becomes 1/x=1/2,
- R7 also chooses the AHP scale 2 on the left part of 1 therefore the calculation becomes 1/x=1/2,
- R8 also chooses the AHP scale 2 on the left part of 1 therefore the calculation becomes 1/x=1/2,
- R9 also choose the AHP scale 2 on the left part of 1 therefore the calculation becomes 1/x=1/2.

Once all the judgments have been identified, the next Step is to calculate the 95th percentile of aggregate series of expert opinions. For instance, the first row on the average of MLB compared to AF (MLB VS AF) derives from the nine judgments of respondents which are : (1 + 1/2 + 1/2 + 1/3 + 1/3 + 1/2 + 1/2 + 1/2)/9 = 0.520. These procedures are repeated for every factor until the average is obtained.

Table 5.21. Pair Wise Comparison Result from the Experts Judgments

Factors	R1	R2	R3	R4	R5	R6	R7	R8	R9	95th Percentile
MLB VS AF	=1/3	=1/3	=1/3	=1/3	=1/3	=1/3	=1/3	=1/4	=1/3	0.333
MLB VS AHF	2	2	2	2	2	2	1	2	1	2
MLB VS ACF	2	2	2	2	2	2	2	1	1	2
AF VS AHF	2	2	2	2	2	2	1	2	1	2
AF VS ACF	2	2	2	2	2	2	2	2	1	2
AHF VS ACF	=1/3	=1/3	=1/3	=1/4	=1/4	=1/3	=1/3	=1/3	=1/3	0.333

Process pair wise comparison is used to make judgments regarding relative importance of the elements in each level with respect to the higher level of the hierarchy, using the AHP pair wise comparison scale, as given in table 5.22. The result of eighth EOS is tabulated as pair wise comparison with row element is x (or 1/x) times more (or less) important than column element.

Table 5.22. Pair wise Comparison Respect to Goal on the Basis of Likelihood Failure

Factors	Mooring line breakage	Anchor Failure	Anchor Handling Failure	Appurtenance Connection Failure
Mooring line breakage	1	0.333	2	2
Anchor Failure	$1/0.3333$	1	2	2
Anchor Handling Failure	$1/2$	$1/2$	1	0.333
Appurtenances Connection Failure	$1/2$	$1/2$	$1/0.333$	1
Total	5	2.333	8	5.333

From the table 5.22 above an n x n matrix is a square matrix, because n is the number of rows and columns, in this level n is 4. An element is equally important when compared to itself therefore the main diagonal must be 1. The reverse comparisons produce the reciprocal of the basic comparison this is called a reciprocal matrix. The next Step is to normalize the matrix by dividing each value by the column sum. For example:

- First column (MLB) and first row (MLB), the normalization is obtained from the value 1 divided by the total value 3.658, and the result is $\frac{1}{5} = 0.2$. This value is inserted into Table 5.23 in the first column and first row.

- Second column (AF) and first row (MLB), the same way the normalization is obtained from the value 0.520 divided by the total value 2.212, and the result is $\frac{0.333}{2.333} = 0.143$. Again this value is inserted into Table 5.23 for the second column and first row.

- First column (MLB) and second row (AF), the normalization is obtained from the value $1/0.333$ divided by the total value 3.658, and the result is $\frac{1/0.333}{5} = 0.6$. Again this value is inserted into Table 5.23 for the first column and first row.

The same procedure of calculation is repeated for the whole factors as summarized in table 5.23.

Table 5.23. Normalize Matrix Respect to Goal of Maintenance Strategy

Criteria	Mooring line breakage	Anchor Failure	Anchor Handling Failure	Appurtenance Connection Failure	Total
Mooring line breakage	0.2	0.143	0.250	0.375	0.968
Anchor Failure	0.6	0.429	0.250	0.375	1.654
Anchor Handling Failure	0.1	0.214	0.125	0.063	0.502
Appurtenances Connection Failure	0.16	0.214	0.375	0.188	0.877
Total					4

5.1.10 MIRBA Step 6.4: Calculating the Priority Vector

The priority vector describes the preference, importance or the likelihood of its elements with respect to a certain criteria. The priority vector is obtained from normalized eigenvector of the matrix. The next Step is to calculate the synthesis judgments by multiplying the vectors of priority by the weight of the criteria, and taking the sum over all weighted priority entries corresponding to those in the next lower level, and so on. From Table 5.24, it can be obtained that anchor failure is the highest with 43.1%. The priority vector of the criteria derives from;

- Mooring line breakage : 0.968/ 4 = 0.387
- Anchor Failure: 1.654/ 4 = 0.413
- Anchor Handling Failure: 0.502/ 4 = 0.125
- Appurtenance Connection Failure: 0.877/ 4 = 0.219

The next Step is measuring the consistency ratio. The AHP provides a theory for checking the inconsistency throughout the matrix, first to compute $A.w = \lambda.w$, then to find the eigen vector and it will get λ_{max};

$$\underset{A}{\begin{pmatrix} 1 & 0.333 & 2 & 2 \\ 1/0.333 & 1 & 2 & 2 \\ 1/2 & 1/2 & 1 & 0.333 \\ 1/2 & 1/2 & 1/0.333 & 1 \end{pmatrix}} \times \underset{w}{\begin{pmatrix} 0.968 \\ 1.654 \\ 0.502 \\ 0.877 \end{pmatrix}} = \underset{A.w}{\begin{pmatrix} 1.214 \\ 2.264 \\ 0.599 \\ 0.996 \end{pmatrix}}$$

Eigen Vector

$A.w = \lambda.w$ therefore $\lambda = A.w / w$

$$\begin{pmatrix} 1.214 \\ 2.264 \\ 0.599 \\ 0.996 \end{pmatrix} : \begin{pmatrix} 0.968 \\ 1.654 \\ 0.502 \\ 0.877 \end{pmatrix} = (3.136 ; 5.477 ; 4.773 ; 4.543)$$

$$\lambda_{max} = \frac{3.136 + 5.477 + 4.773 + 4.543}{4} = 4.482$$

After finding the λ_{max} = 4.482 then calculate the consistency index (CI), with n = 4.

CI = $(\lambda_{max} - n)/(n-1)$

= (4.482 – 4) / (4-1)

= 0.16

To find the Consistency Ratio (CR), must know the random index for n = 4 is 0.89 (refer table 2.17).

$$CR = \frac{CI}{RI}$$

$$CR = \frac{0.16}{0.89}$$

= 0.1 (The CR ≤ 0.1 indicating sufficient consistency)

Based on the calculation above, it can be summarized the priority of each factor below as shown in Table 5.24.

Table 5.24. Comparison of Criteria With Respect To Goal of Maintenance Strategy

Criteria	Mooring line breakage	Anchor Failure	Anchor Handling Failure	Appurtenance Connection Failure	Priority
Mooring line breakage	1	0.333	2	2	0.387
Anchor Failure	$1/0.333$	1	2	2	0.413
Anchor Handling Failure	$1/2$	$1/2$	1	0.333	0.125
Appurtenances Connection Failure	$1/2$	$1/2$	$1/0.333$	1	0.219
Consistency Index : 0.161					
Random Index : 0.89					
Consistency Ratio : 0.1					

The above evaluations are manual calculation of AHP based on the Saaty (Saaty, 1988) formulation for weighing the priority of risk matrix comparison. The above evaluations procedures are repeated for the higher level of hierarchy until the best maintenance strategy is found. This study uses Expert Choice software to evaluate the weight of priority of the maintenance strategy. The following section discusses the result deriving from the Expert Choice software.

5.1.11 MIRBA Step 6.5: Selecting the Alternative of Choice

AHP result gives the list of alternatives with the weight of priority to be chosen. Selecting the best alternative or choice is based on the highest priority of AHP result. Weight of priority is obtained for each element of the hierarchy that is possible for each element to be compared in a rational and consistent approach. The weight of priority shows the relative meaning and importance in order to achieve the goal. Final decision is based on this process therefore it is important to check the consistency of the judgments. The consistency of the judgments known as consistency ratio must be or equal to 0.10.

5.1.11.1 AHP Output for Maintenance Strategy on the Basis of Likelihood

This study uses Expert Choice software in order to evaluate the matrix comparison based on the hierarchy. The hierarchical structure for maintenance strategy on the basis of likelihood as shown in Figure 5.9 is used to develop eighth EOS. The eighth EOS is distributed to the experts in order to find the best maintenance strategy on the basis of likelihood. Table 5.20 shows the example of questions in the eight EOS and the experts give their judgments based on AHP scale.

The AHP result in selecting the best maintenance strategy on the basis of the likelihood of failure is summarized in Table 5.25. The results are obtained from the expert judgments of the risk matrix comparison based on the eighth EOS. There are nine respondents giving their judgments based on their knowledge and experience on the maintenance strategy for mooring system. The results of the pair wise comparison of the first level of the hierarchy indicate that anchor failure (AF) has contributed highest frequency to mooring failure, namely 42.3%. The second highest frequency of the cause of mooring failure is mooring line breakage (MLB) of 24.4%. The third highest is appurtenances connection failure (ACF) of 21.1%, and the last criteria is an anchor handling failure of 12.2%.

Table 5.25 AHP Output on Maintenance Strategy on the Basis of Likelihood

Maintenance Factor				AHP Output on Maintenance Strategy				
Factor	Priority	Sub Factor	Priority	CM	PM	RTF	CBM	PeM
Mooring Line Breakage	0.244	Corrosion	0.098	0.008	0.017	0.008	0.020	0.046
		Abrasion	0.049	0.005	0.007	0.005	0.013	0.019
		Mooring Line C.	0.049	0.004	0.009	0.005	0.013	0.017
		Collision	0.049	0.004	0.010	0.005	0.012	0.018
Anchor Failure	0.423	Insufficient H.	0.107	0.011	0.024	0.011	0.027	0.032
		Part of Anchor B.	0.127	0.012	0.029	0.013	0.030	0.042
		Mooring line C.	0.101	0.010	0.019	0.010	0.027	0.035
		Collision	0.088	0.009	0.017	0.007	0.023	0.031
Anchor Handling F.	0.122	Barge Winch F.	0.031	0.003	0.003	0.003	0.008	0.013
		Anchor HTF.	0.092	0.009	0.017	0.012	0.024	0.030
Appurtenances Connection F.	0.211	Corrosion	0.106	0.010	0.020	0.013	0.026	0.037
		Fatigue cracking	0.106	0.011	0.024	0.011	0.025	0.035
Priority of Maintenance on the Basis of Likelihood				0.097	0.198	0.104	0.247	0.356
Ranking				5	3	4	2	1

As an example, Figure 5.11 shows the output from Expert Choice Software for the highest weight priority of factor is AF namely 42.3%. This value is then generated into weight priority for each sub factor of AF which are IH (Insufficient Holding) namely 10.7%, PoAB (Part of Anchor Breaks) namely 12.7%, MLC (Mooring Line Clashed) namely 10.1% and Colli (Collision) namely 8.8%. The other weights of priority are obtained in the same procedures from the Expert Choice software.

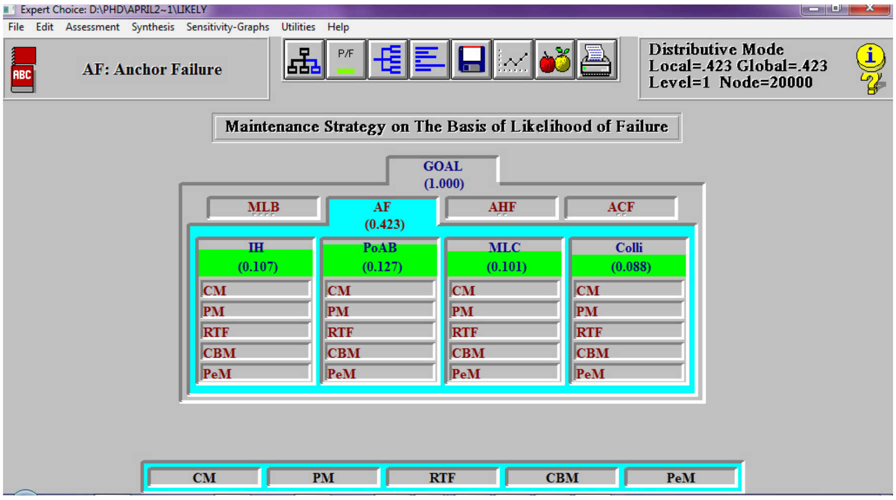

Figure 5.11. Weight Priority of AF

Sub criteria are the probable causes attributed to the main criteria, for example 42.3% likelihood of failure due to anchor failure is caused by 12.7% due to part of anchor breaks, 10.7% due to insufficient holding. 10.1% due to mooring lines clashed and 8.8% due to collision. The priority of mooring line breakage i.e. 24.4% is caused by corrosion 9.8%, abrasion 4.9%, mooring line clashed 4.9% and collision 4.9%. Sub criteria of appurtenances connection failure with priority 21.1% are due to corrosion 10.6% and fatigue cracking 10.6%. The last critical factor is the anchor handling failures i.e. 12.2% are caused by barge winch failure 3.1% and anchor handling tugs failure 9.2%.

Figure 5.12 shows the weight priority of sub factor of PoAB namely 12.7% broken down into the weight priority of each maintenance strategy, namely CM namely 1.2%, PM 2.9%, RTF 1.3%, CBM 3% and PeM 4.2%. This procedure are repeated for all the sub factors in order to determine the weight of priority for each maintenance strategy.

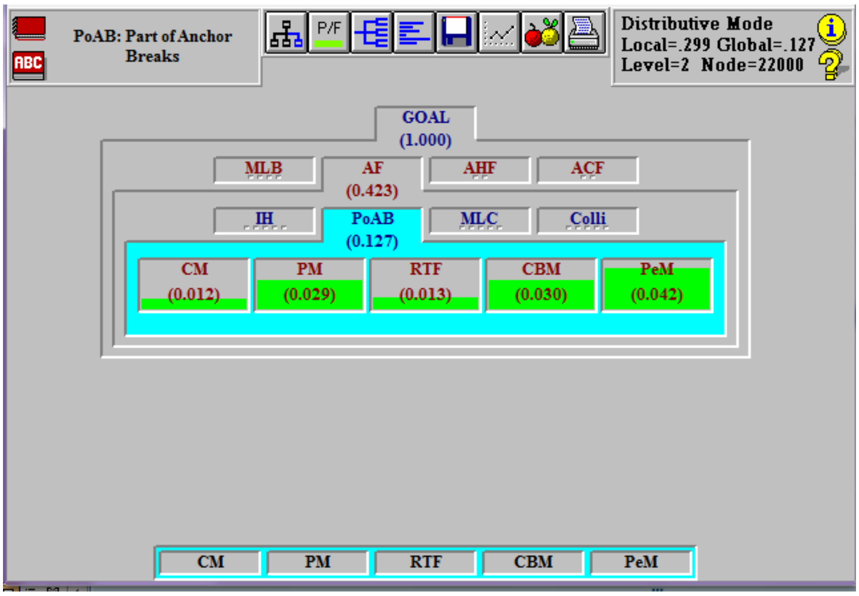

Figure 5.12. Weight Priority of PoAB

The Figure 5.13 shows the overall weight priority of the alternative for maintenance strategy. The overall inconsistency index or known as consistency ratio (CR) is 0.1 which means that the matrix pair wise comparison can be considered as having an acceptable consistency.

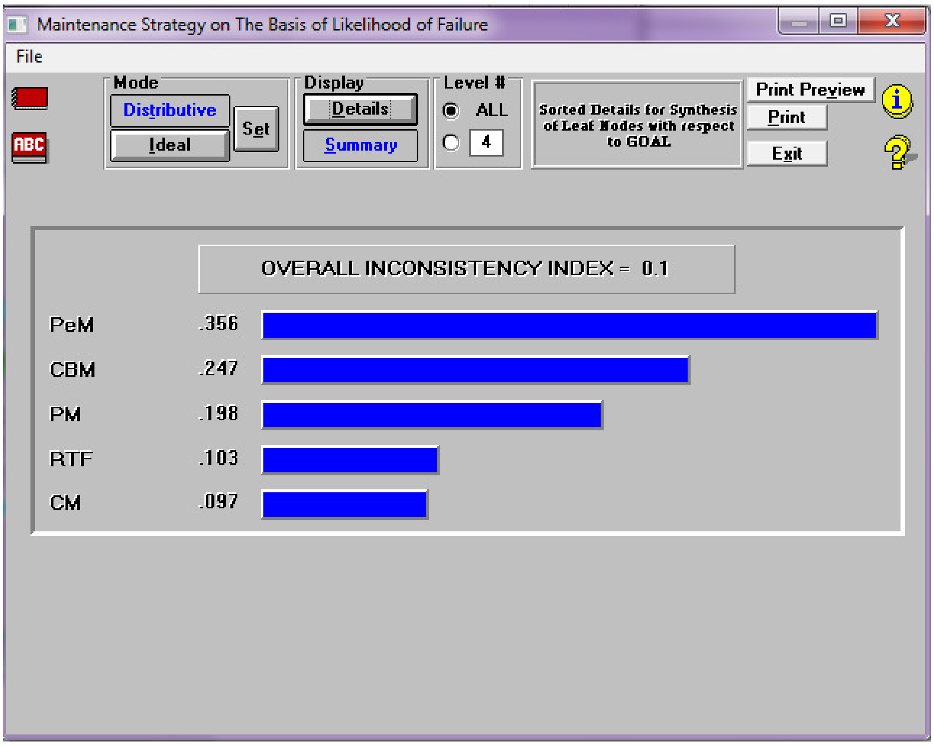

Figure 5.13. Overall Priority of Maintenance Strategy on the Basis of Likelihood

The priority vector of maintenance strategy on the basis of likelihood shows that the best maintenance strategy is PeM (Predictive Maintenance) with the priority of 35.6%. The value of priority maintenance strategy is obtained from the weight of priority of each sub factors in the hierarchy. For instance, the value of PeM of 35.6% or 0.356 is obtained from 0.046 + 0.019 + 0.017 + 0.018 + 0.032 + 0.042 + 0.035 + 0.031 + 0.013 + 0.030 + 0.037 + 0.035 = 0.356. This procedure is repeated for other maintenance strategy.

The second best maintenance is CBM (Condition Based Maintenance) with priority vector 23.3%, followed by PM (Preventive Maintenance) with priority vector of 23.1%, CM (Corrective Maintenance) with priority vector of 14.4% and the last maintenance strategy is RTF (Run to Failure Maintenance) with priority vector of 10.3%.

5.1.11.2 AHP Output for Maintenance Strategy on the Basis of Consequence

Table 5.26 shows AHP output for maintenance strategy on the basis of consequences. The hierarchical structure for maintenance strategy on the basis of consequence as shown in Figure 5.10 is used to develop ninth EOS. The results of the pair wise comparison of the first level of the hierarchy indicate that the highest consequences of mooring system will give impact to people namely 41.7%. The second highest consequence of mooring system will impact to assets of 16.3%. The third highest consequence will impact to environment of 12.6%, to the maintenance cost 18.4% and to the reputation, image of the company of 10.9%.

Table 5.26. AHP Output on Maintenance Strategy on the Basis of Consequences

Maintenance Factor				AHP Output on Maintenance Strategy				
Critical Factor	Priority	Sub Factor	Priority	CM	PM	RTF	CBM	PeM
People	0.417	Safety	0.208	0.018	0.044	0.014	0.041	0.091
		Health	0.209	0.028	0.032	0.018	0.043	0.088
Environment	0.126	External	0.042	0.004	0.011	0.004	0.008	0.014
		Internal	0.084	0.008	0.023	0.011	0.015	0.027
Assets	0.163	Direct	0.122	0.010	0.024	0.009	0.026	0.052
		Indirect	0.041	0.004	0.007	0.004	0.008	0.017
Reputation	0.109	Performance	0.055	0.004	0.012	0.004	0.011	0.023
		Quality S.	0.055	0.005	0.012	0.004	0.012	0.023
Cost	0.184			0.036	0.016	0.080	0.035	0.017
Priority of Maintenance on the Basis of Consequences				0.116	0.185	0.146	0.199	0.353
Ranking				5	3	4	2	1

As an example, Figure 5.14 shows the output from Expert Choice Software for the highest weight priority of factor, namely People of 41.7%. This value is then broken down into weight priority for each sub factor of People consisting of Safety namely 20.8%, and Health namely 20.9%. The other factors and sub factor are also generated in the same procedures from the Expert Choice software.

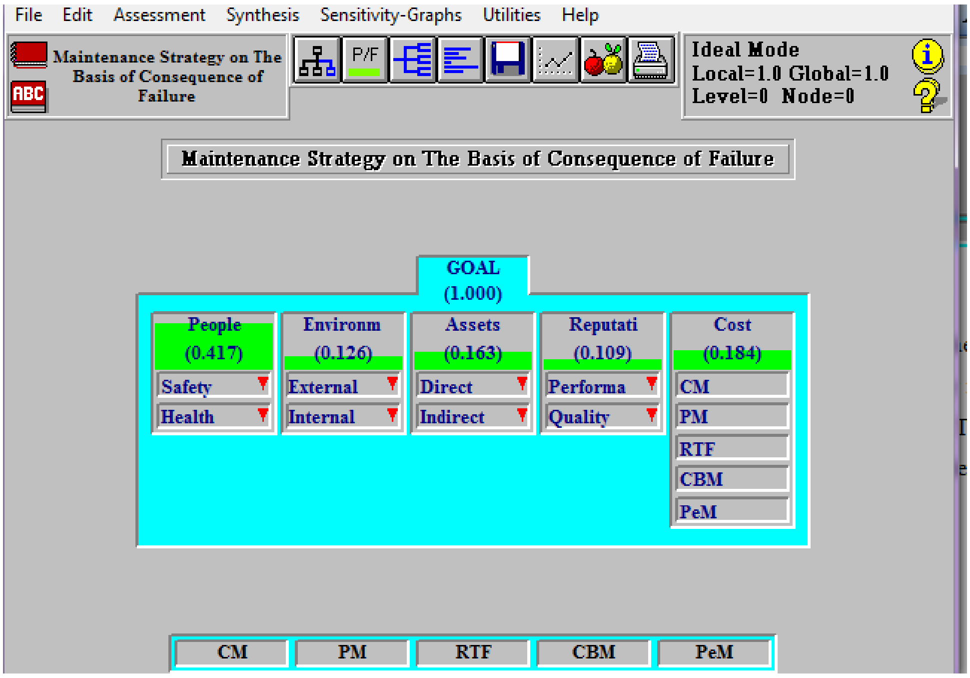

Figure 5.14. Weight Priority of People

Sub criteria of the attributed main criteria for maintenance strategy on the basis of consequence, for instance 41.7% consequence of failure will impact to people related to 20.8% safety and 20.9% health of the people. The second highest consequence of failure will impact to assets 16.3% due to the contribution of sub factors directly 12.2% and indirectly 4.1%. The third consequence of failure impact to environment i.e. 12.6% is due to external impact of 4.2% and internal impact of 8.4%. The fourth consequence of failure will impact on the cost of maintenance of 18.4%. The last consequence of failure will impact to reputation i.e. 10.9% that will affect the performance of 5.5% and quality service of 5.5%.

Figure 5.15 shows the weight priority of sub factor of Safety namely 20.8% generated into the weight priority of each maintenance strategy consisting of CM 1.8%, PM 4.4%, RTF 1.4%, CBM 4.1% and PeM 9.1%. This procedure is repeated for all the factors and their sub factors in order to determine the weight of priority for each maintenance strategy on the basis of consequence.

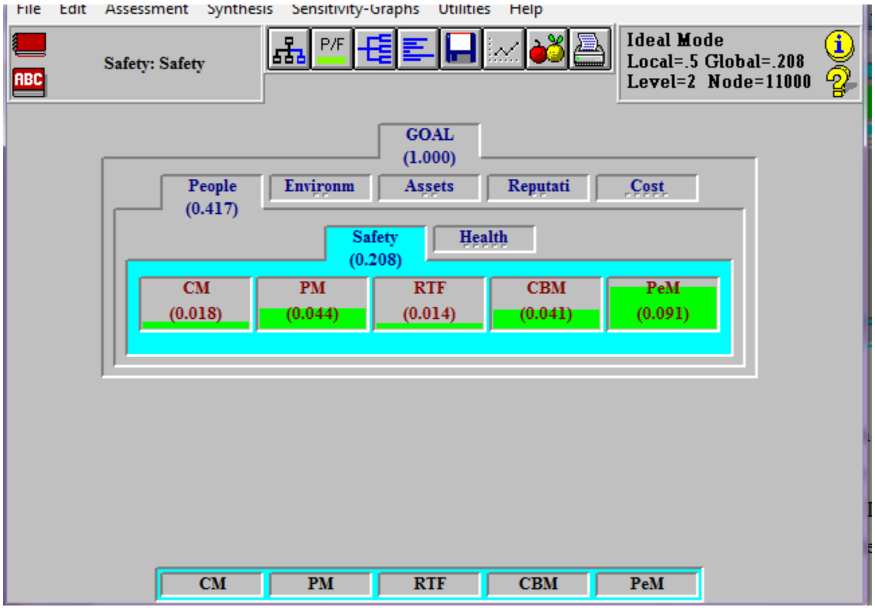

Figure 5.15. Weight Priority of Safety

Figure 5.16 shows the overall weight priority of the alternative for maintenance strategy on the basis of consequence. The consistency ratio (CR) is 0.04 suitable for the requirement of AHP which must be less than 0.1. The CR with value 0.04 shows that the matrix pair wise comparison can be considered as having an acceptable consistency.

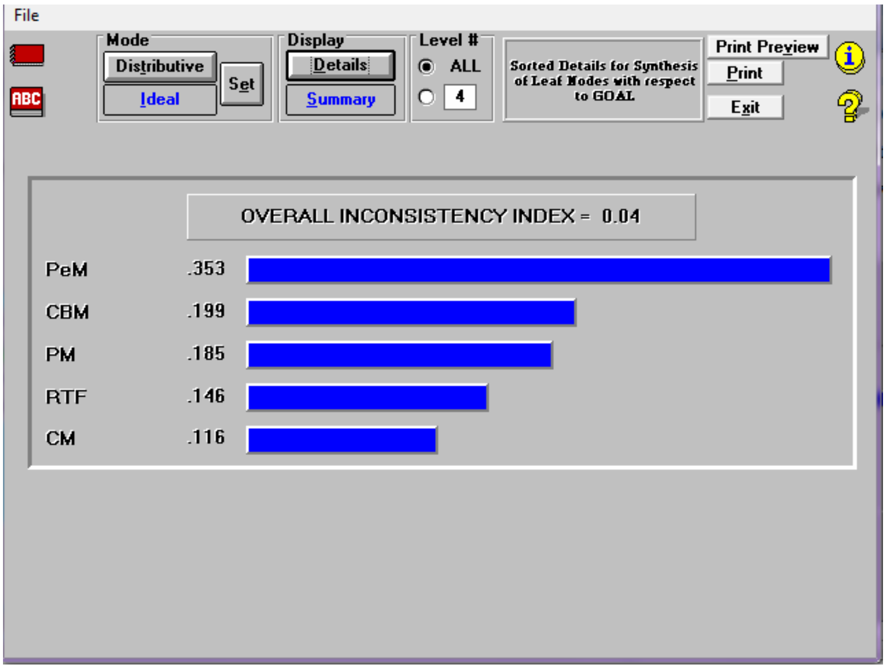

Figure 5.16. Overall Priority of Maintenance Strategy on the Basis of Consequence

The priority vector of maintenance strategy on the basis of consequences classifies that the best maintenance strategy is PeM (Predictive Maintenance) with the priority of 35.3%. The second best maintenance is CBM (Condition Based Maintenance) with priority vector of 19.9%, followed by PM (Preventive Maintenance) with priority vector of 18.5%, RTF (Run to Failure Maintenance) with priority vector of 14.6% and the last maintenance strategy is CM (Corrective Maintenance) with priority vector of 11.6%.

5.1.11.3 Sensitivity Analysis

Sensitivity analysis is used to eliminate the alternatives, to enhance a group decision process or in providing information as to the robustness of a decision (Erhan, 1991). The sensitivity analysis derives from Expert Choice software which is useful to determine sensitivity of the priority. There are five graphical sensitivity analyses, namely performance graphs, dynamic graphs, gradient graphs, two dimensional graphs and difference graphs. Concentrating to the highest priority of the criteria in the second hierarchy, three scenarios of interpretation are applied to define possible combinations of weights priority of the alternatives. Scenarios of interpretation consist of decreasing and increasing the initial weight priority of the highest criteria in the second hierarchy. Sensitivity analysis is applied on both maintenance strategy points of view, on the basis of likelihood and on consequences.

5.1.11.3.1 Sensitivity Analysis for Maintenance Strategy on the Basis of Likelihood

Based on the calculation shown in Table 5.25 the highest factor in maintenance strategy on the basis of likelihood is AF (anchor failure), hence the three scenarios of interpretations on the weight priority of AF are applied. The three scenarios interpretations are applied in an attempt to identify the significant changes of the maintenance strategies selection as seen in Figure 5.17 – 5.20.

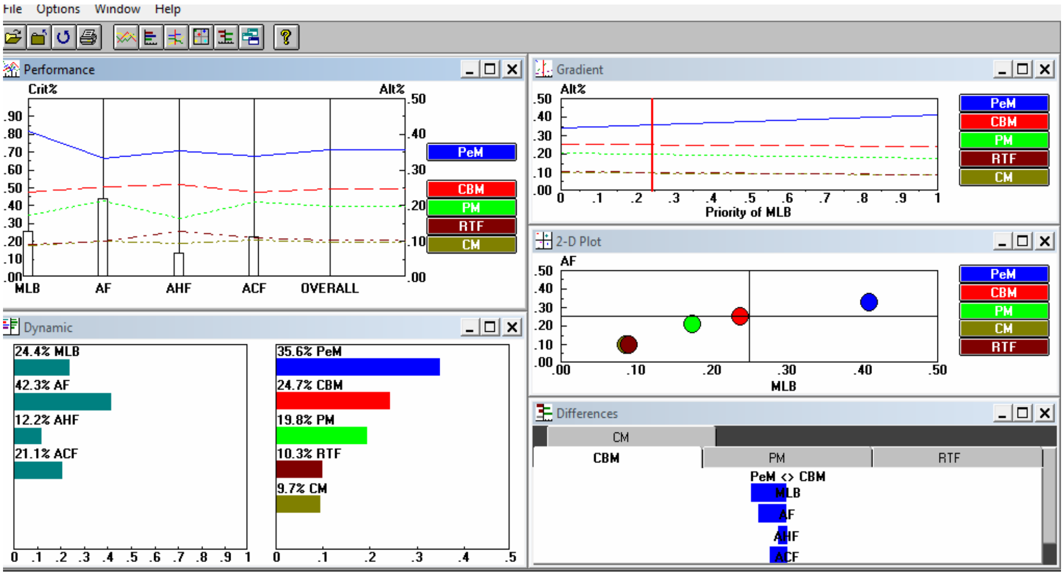

Figure 5.17. Sensitivity Analysis on the Basis of Likelihood

Figure 5.17 shows the initial weight of priority of AF namely 42.3%. The weight of alternatives shows 35.6% for PeM, 24.7% for CBM, 19.8% for PM, 10.3% for RTF and 9.7% for CM. Here the highest alternative is PeM of 35.6%. The first scenario of interpretations decreases 9.8% of the weight priority of AF from 42.3% to be 32.5% as seen in Figure 5.18. This figure shows the weight of alternatives which are 35.9% for PeM, 24.6 % for CBM, 19.5% for PM, 10.4% for RTF and 9.6% for CM. Here the highest alternative is still PeM with 35.9%.

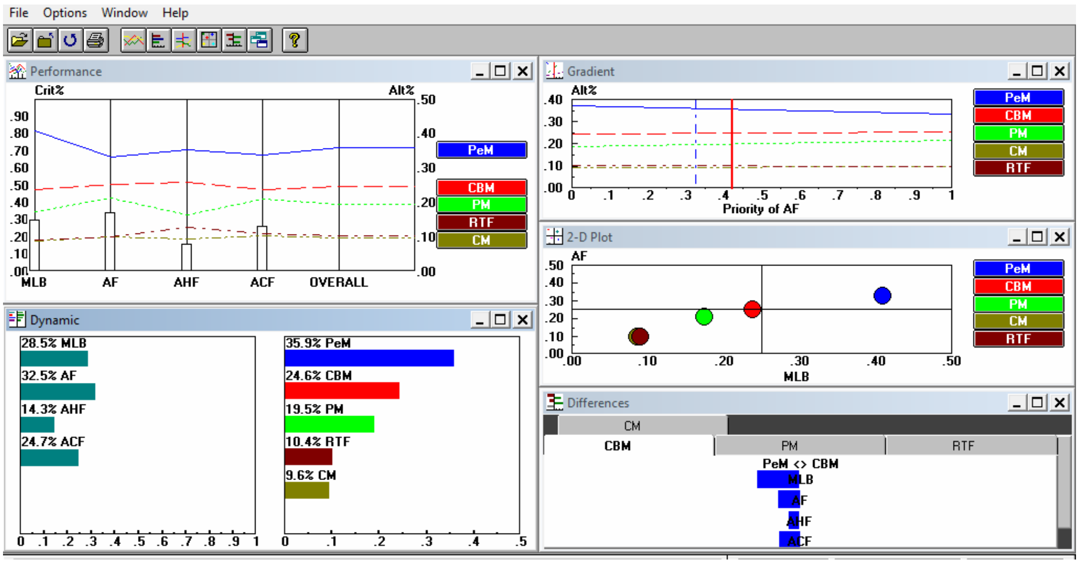

Figure 5.18. Sensitivity Analysis on the Basis of Likelihood (Decreasing 9.8% Intrepretations)

The second scenario of interpretations increases 10.4% of the weight priority of AF from 42.3% to be 52.7% as seen in Figure 5.19. This figure shows the weight of alternatives which are 35.1% for PeM, 24.8 % for CBM, 20.1% for PM, 10.2% for RTF and 9.7% for CM. Here the highest alternative is still PeM with 35.1%.

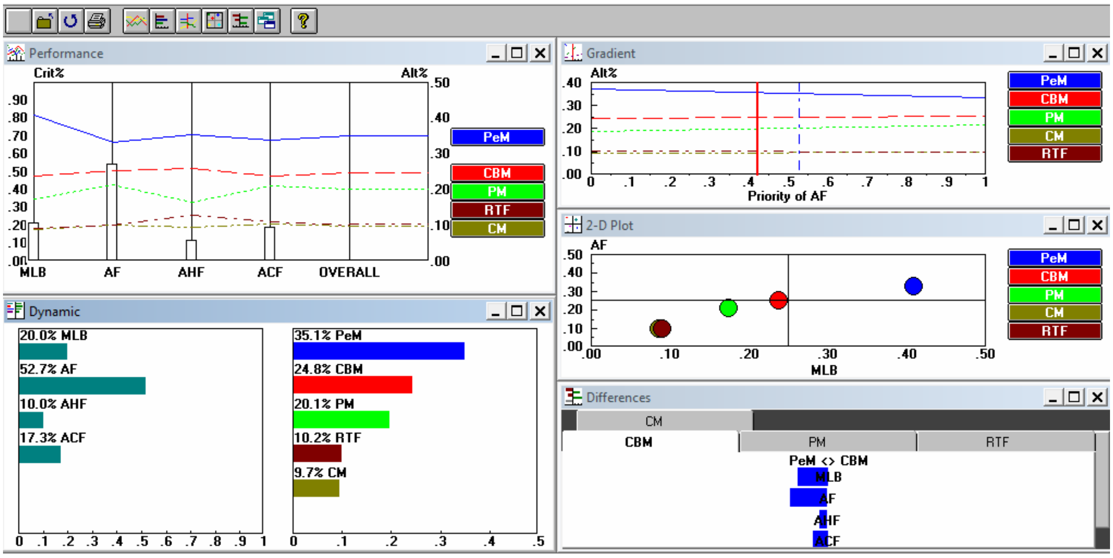

Figure 5.19. Sensitivity Analysis on the Basis of Likelihood (Inreasing 10.4% Intrepretations)

The third scenario of interpretations increases 53.4% of the weight priority of AF from 42.3% to be 95.7% as seen in Figure 5.20. This figure shows the weight of alternatives which are 33.5% for PeM, 25.3 % for CBM, 21.3% for PM, 10% for RTF and 10% for CM. Here the highest alternative is still PeM with 33.5%.

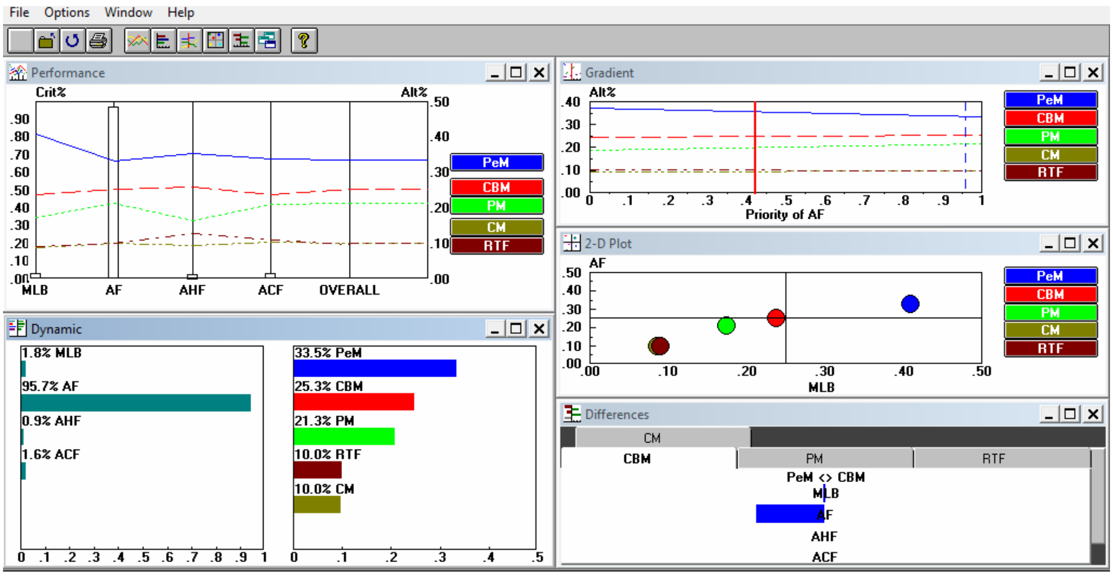

Figure 5.20. Sensitivity Analysis on the Basis of Likelihood (Inreasing 53.4% Intrepretations)

The interpretations scenarios consist of decreasing and increasing the priority value of the highest criteria AF as seen in Table 5.27. Based on the sensitivity analysis graphs it shows that there are no significant changes on the weight priority of the alternatives.

Table 5.27. Interpretations Obtained from Sensitivity Analysis on the Basis of Likelihood

Interpretations	Weight of Priority (%)						Sensitivity Changes (%)				
	AF	CM	PM	RTF	CBM	PeM	CM	PM	RTF	CBM	PeM
Decreasing 9.8%	32.5	9.6	19.5	10.4	24.6	35.9	1.03	1.52	0.97	0.40	0.84
Initial	42.3	9.7	19.8	10.3	24.7	35.6	N/A	N/A	N/A	N/A	N/A
Increasing 10.4%	52.7	9.7	20.1	10.2	24.8	35.1	0	1.52	0.97	0.40	1.40
Increasing 53.4%	95.7	10	21.3	10	25.3	33.5	3.09	7.58	2.91	2.43	5.90

Figure 5.21 shows the graphs of interpretation scenarios of maintenance strategies on the basis of likelihood. The best maintenance strategy on the basis of likelihood is always PeM (predictive maintenance), even though three scenarios of interpretation are applied. However there are few changes in the ranking of the alternatives for maintenance strategy as seen in Table 5.28. For instance the second ranking of maintenance strategy is changed from CBM to be PM by applying the third scenarios.

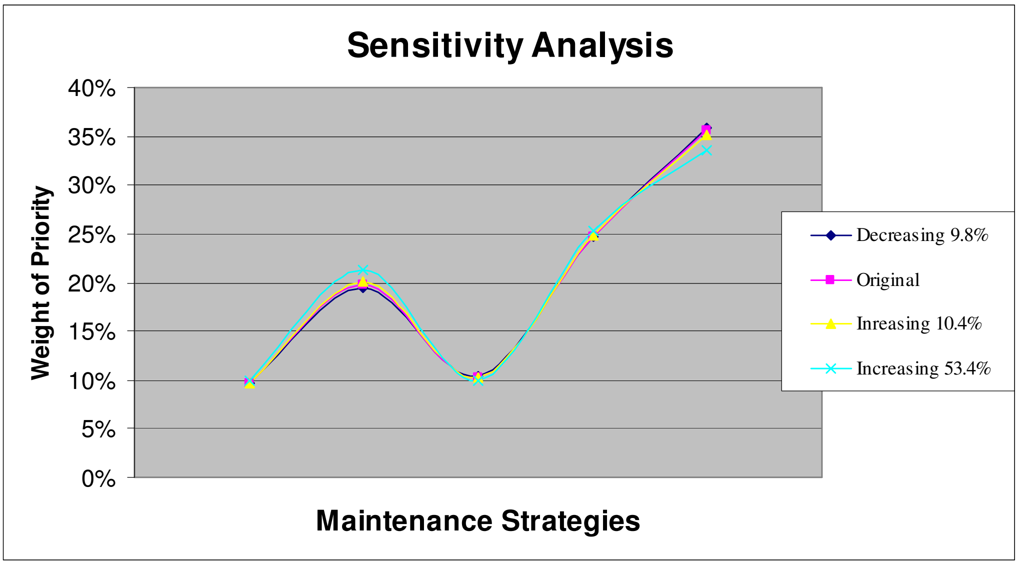

Figure 5.21. Sensitivity Analysis on the Basis of Likelihood Interpretations Scenarios

Table 5.28 defines the rank of maintenance strategy on the basis of likelihood with three interpretation scenarios in order to see the changes of the maintenance selection. The result shows PeM is always the best maintenance strategy in all interpretation scenarios. The second rank is CBM, third rank is PM, fourth rank is

RTF and the last rank is CM. Generally based on the sensitivity analysis, priority of maintenance strategy selection is constantly stable, there is no significant change of the priority unless the criteria and sub criteria of the hierarchy have been changed drastically.

Table 5.28. Rank of Maintenance Strategy on the Basis of Likelihood

Maintenance Strategy	Rank of Maintenance Strategy on the Basis of Likelihood			
	Initial	Decreasing 9.8%	Increasing 10.4%	Increasing 48.1%
CM	5	5	5	5
PM	3	3	3	3
RTF	4	4	4	4
CBM	2	2	2	2
PeM	1	1	1	1

5.1.11.3.2 Sensitivity Analysis for Maintenance Strategy on the Basis of Consequence

Based on the calculation in the previous section, the highest criterion for maintenance strategy on the basis of consequences is people, hence the interpretations of the people priority is applied. The interpretations apply three scenarios in an attempt to identify the significant changes of the maintenance strategies as seen in Figure 5.22 – 5.25. The interpretation scenarios consist of the decrease and increase of the priority value of the highest criteria of people as shown in Table 5.29.

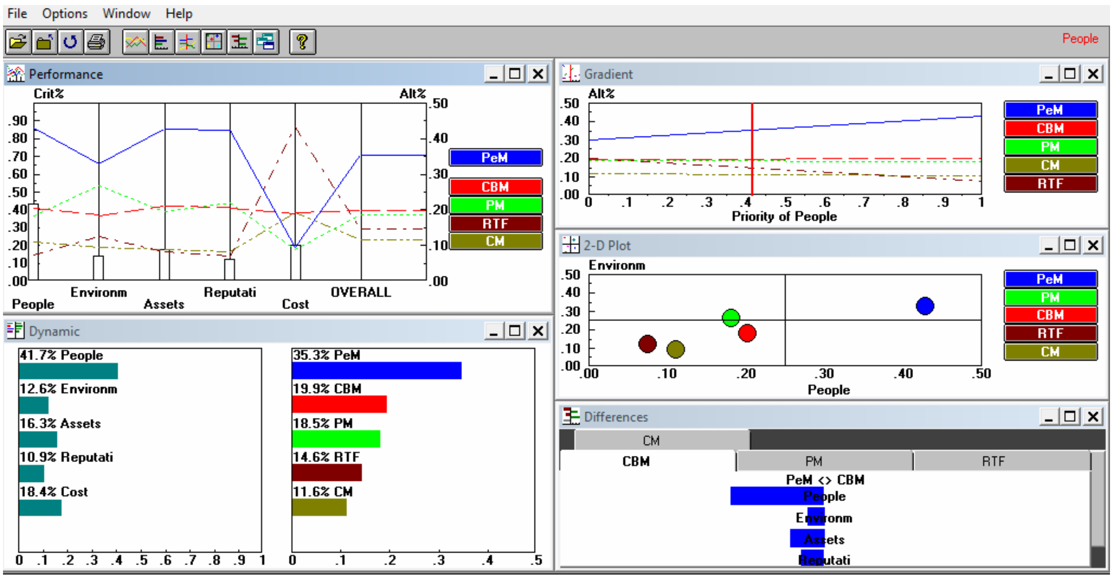

Figure 5.22. Sensitivity Analysis on the Basis of Consequences

Figure 5.22 shows the initial weight of priority of People, namely 41.7%. The weight of alternatives shows 35.3% for PeM, 19.9% for CBM, 18.5% for PM, 14.6% for RTF and 11.6% for CM. Hence the highest alternative is PeM with 35.3%.

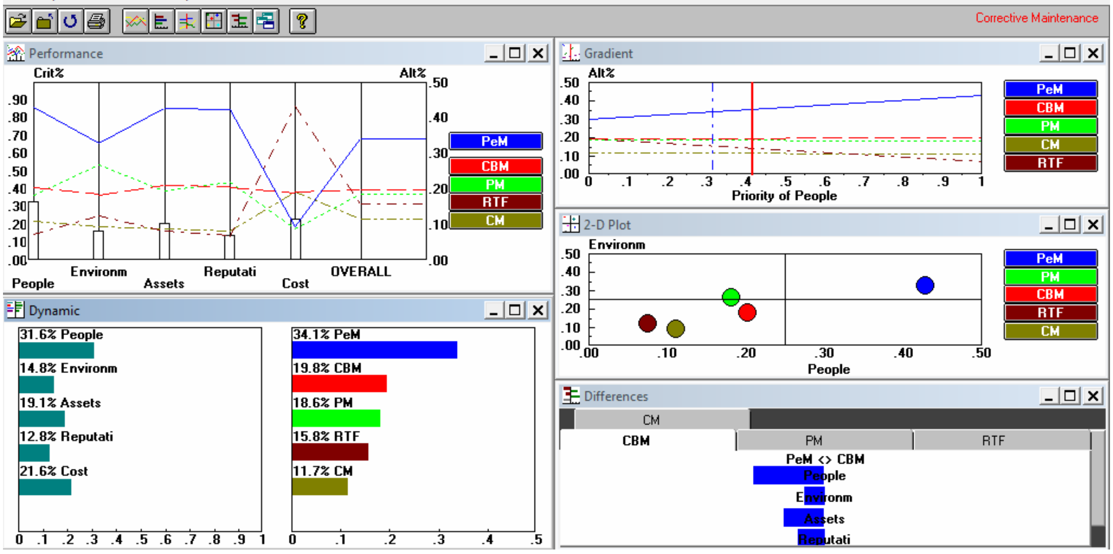

Figure 5.23 Sensitivity Analysis on the Basis of Consequences (Decreasing 10.1% Interpretations)

The first scenario of interpretations decreases 10.1% of the weight priority of people from 41.7% to be 31.6% as seen in Figure 5.23. This figure shows the weight of alternatives which are 34.1% for PeM, 19.8 % for CBM, 18.6% for PM, 15.8% for RTF and 11.7% for CM. Here the highest alternative is still PeM with 34.1%.

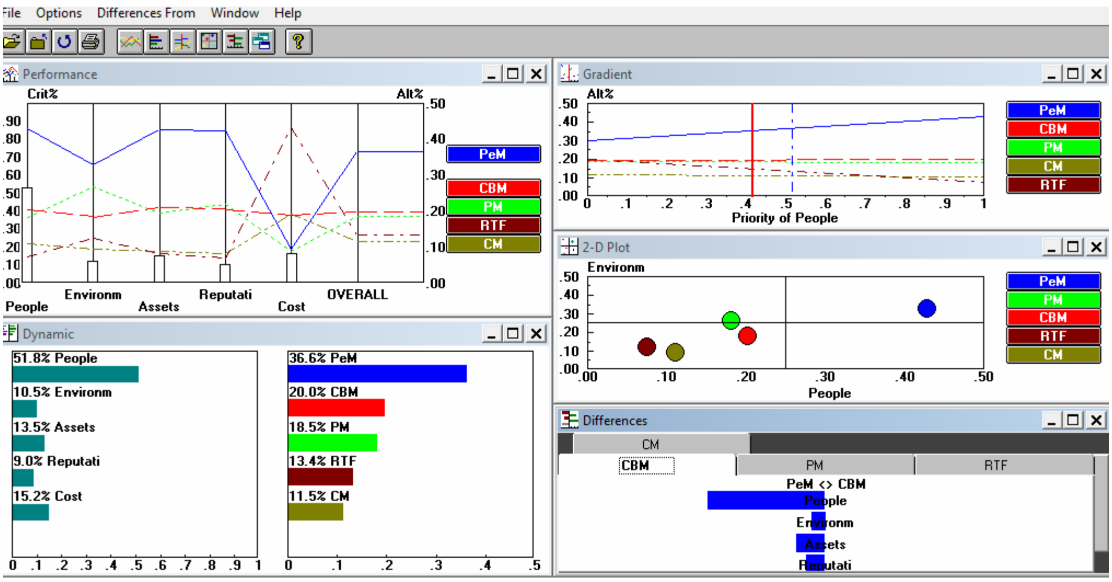

Figure 5.24. Sensitivity Analysis on the Basis of Consequences (Increasing 10.1% Interpretations)

The second scenario of interpretations increases 10.1% of the weight priority of people from 41.7% to be 51.8% as seen in Figure 5.24. This figure shows the weight of alternatives which are 36.6 for PeM, 20% for CBM, 18.5% for PM, 13.4% for RTF and 11.5% for CM. Here the highest alternative is still PeM with 36.6%.

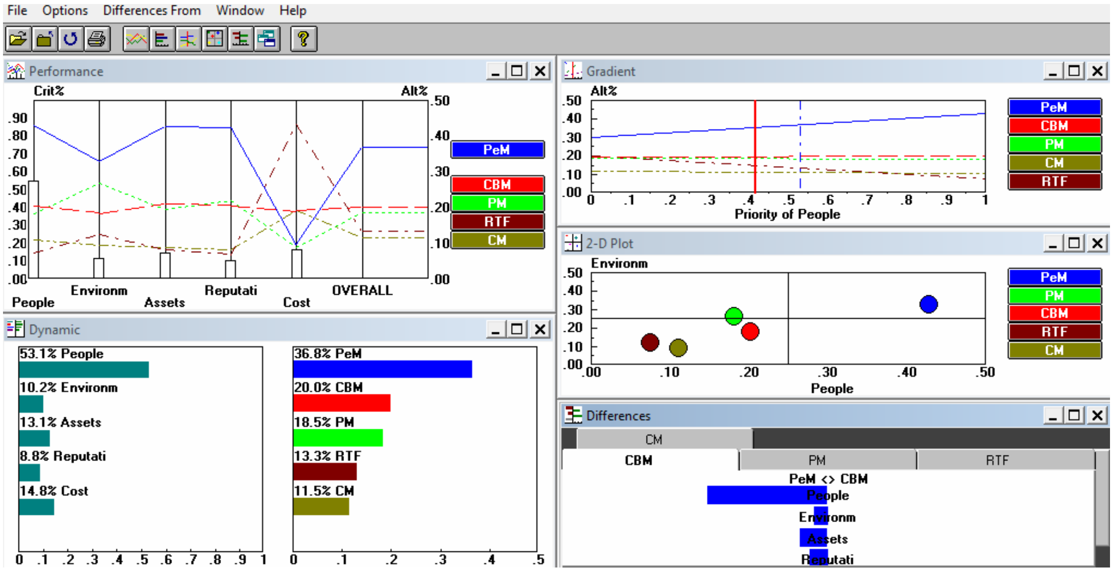

Figure 5.25. Sensitivity Analysis on the Basis of Consequences (Increasing 11.4% Interpretations)

The third scenario of interpretations increase 11.4% of the weight priority of people from 41.7% become 53.1% as can be seen in Figure 5.25. This figure show the weight of alternatives which are 42.236.8% for PeM, 20% for CBM, 18.5% for PM, 11.5% for CM and 13.3% for RTF. Here the highest alternative is still PeM with 42.2%.

Table 5.29. Interpretations Obtained from Sensitivity Analysis on the Basis of Consequences

Interpretations	Weight of Priority (%)						Sensitivity Changes (%)				
	People	CM	PM	RTF	CBM	PeM	CM	PM	RTF	CBM	PeM
Decreasing 10.1%	31.6	11.7	18.6	15.8	19.8	34.1	0.86	0.54	8.22	0.50	3.40
Initial	41.7	11.6	18.5	14.6	19.9	35.3	N/A	N/A	N/A	N/A	N/A
Increasing 10.1%	51.8	11.5	18.5	13.4	20	36.6	0.86	0	8.22	1.12	3.68
Increasing 11.4%	53.10	11.5	18.5	13.3	20	36.8	0.86	0	8.90	0.50	4.25

Figure 5.26 shows the graphs of interpretation scenarios of maintenance strategies on the basis of consequences. Based on the interpretations obtained from the sensitivity analysis, the best maintenance is still PeM (predictive maintenance) even though it has been applied to several interpretations.

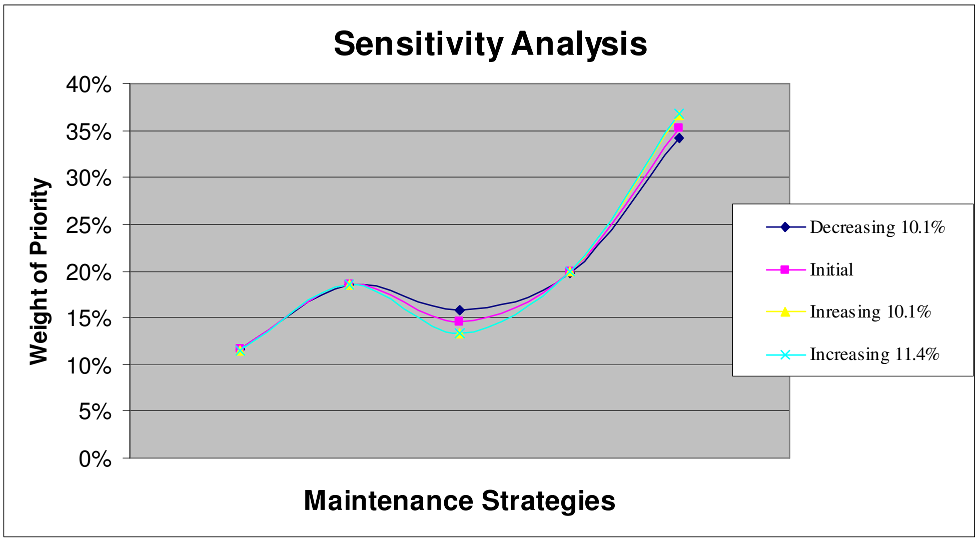

Figure 5.26. Sensitivity Analysis on the Basis of Consequences Interpretations Scenarios

Table 5.30 defines the rank of maintenance strategy on the basis of consequence with three interpretation scenarios in order to see the changes of the maintenance selection. The result shows PeM is the best maintenance strategy in all interpretation scenarios decreasing 10.1%, increasing 10.1% and increasing 11.4%, the best maintenance strategy is still PeM (predictive maintenance). CBM, PM, RTF and CM remains in the same ranking for maintenance strategy on the basis of consequence for all the interpretation scenarios. Generally based on the sensitivity analysis the priority of maintenance strategy selection is constantly stable, there are no significant changes of the priority unless the criteria and sub criteria of the hierarchy have been changed drastically.

Table 5.30. Rank of Maintenance Strategy on the Basis of Consequences

Maintenance Strategy	Rank of Maintenance Strategy on the Basis of Consequences			
	Initial	Decreasing 10.1%	Increasing 10.1%	Increasing 11.4%
CM	5	5	5	5
PM	3	3	3	3
RTF	4	4	4	4
CBM	2	2	2	2
PeM	1	1	1	1

5.1.12 MIRBA Step 7: Establish the Maintenance Strategy

The last Step in MIRBA is to establish the maintenance strategy and action. This is important to control and manage the risk by understanding their individual risks and knowing the alternatives. Formulating an appropriate inspection and maintenance strategy for mooring system is a part of the risk based decision making. The AHP helps develop a maintenance plan for the mobile mooring system under study. The AHP has been applied to select the best maintenance strategy for mooring system in two points of view, namely on the basis of likelihood and consequences. Based on the AHP result the best maintenance strategy on the basis of likelihood and consequence for mooring system is predictive maintenance (PeM). Predictive maintenance conducts process efficiency, heat loss or nondestructive techniques in an attempt to quantify the operating efficiency of non mechanical plant equipment or systems. Table 5.31 summarizes the maintenance strategy with regard to the failure of mechanisms of mooring system in term of predictive maintenance.

Table 5.31. Predictive Maintenance Strategy

Criteria	Sub Criteria	Techniques
Mooring Line Breakage	Corrosion	➢ Ultrasonic ➢ Radiographs ➢ Cathodic Potential ➢ Visual inspections.
	Abrasion	➢ Ultrasonic ➢ Radiographs ➢ Cathodic Potential ➢ Visual inspections
	Mooring Line C.	➢ Vibration monitoring and analysis ➢ Ultrasonic ➢ Visual inspections
	Collision	➢ Vibration monitoring and analysis ➢ Ultrasonic ➢ Visual inspections
Anchor Failure	Insufficient H.	➢ Vibration monitoring and analysis ➢ Visual inspections
	Part of Anchor B.	➢ Vibration monitoring and analysis ➢ Visual inspections
	Mooring line C.	➢ Vibration monitoring and analysis ➢ Ultrasonic ➢ Visual inspections
	Collision	➢ Vibration monitoring and analysis ➢ Ultrasonic ➢ Visual inspections
Anchor Handling F.	Barge Winch F.	➢ Vibration monitoring and analysis ➢ Ultrasonic ➢ Visual inspections
	Anchor HTF.	➢ Vibration monitoring and analysis ➢ Ultrasonic ➢ Visual inspections
Appurtenances Connection F.	Corrosion	➢ Ultrasonic ➢ Radiographs ➢ Cathodic Potential ➢ Visual inspections.
	Fatigue cracking	➢ Vibration monitoring and analysis ➢ Wear Particle Analysis

5.2 Validation Framework

The validation process involves 5 different respondents from the previous respondents consisting of the senior engineers, operational managers, and consultants. Five experts are minimum recommended for an expert panel content validity assessment (Yaghmale, 2003). The respondents profiles can be seen in Appendix D2 and the validation questionnaire can be seen in Appendix G. They are all of high management levels in their respective companies and have broad experience in handling the mooring systems worldwide. In addition, all of them have shown great commitment to this research, have filled up the tenth EOS carefully and provided a lot of valuable feedbacks. In the tenth EOS the experts were asked the relative important index (RII) and an open ended question related to the MIVTA and MIRBA framework. The result of the validation process is shown in Table 5.32, the respondents have been asked to indicate how much they agree or disagree to each of the following statements.

Table 5.32. The Result of Tenth EOS for Validation Framework

No	**Statement**	**Likert Scale**					**RII**	**Rank**
		1	**2**	**3**	**4**	**5**		
1	**Hazard Operability Analysis (HAZOP) with regards to Table 4.2**							
1a	Anchor is one of the main components of mobile mooring system	-	-	-	1	4	**0.96**	1
1b	Mooring line is one of the main components of mobile mooring system	-	-	1	1	3	**0.88**	3
1c	Anchor Handling Tugs is one of the main components of mobile mooring system	-	-	3	1	1	**0.72**	7
1d	Appurtenances Connections is one of the main components of mobile mooring system	-	-	-	2	3	**0.92**	2
1e	The information gathered in HAZOP as preliminary risk analysis is sufficient	-	-	1	2	2	**0.84**	4
1f	The HAZOP approach for mobile mooring system is systematic	-	-	1	1	3	**0.88**	3
1g	The HAZOP framework for mobile mooring system are easily to understand	-	-	-	1	4	**0.96**	1
1h	The HAZOP framework for mobile mooring system has identified all the factors sufficiently	-	-	2	2	1	**0.76**	6
2	**Fault Tree Analysis (FTA) with regards to Figure 4.4 – 4.7**							
2a	The root causes of mobile mooring system failure in FTA are acceptable	-	-	3	1	1	**0.72**	7
2b	The undesired/basic events identified in FTA for mobile mooring system are correct	-	-	1	2	2	**0.84**	4
2c	The FTA approach for mobile mooring system is systematic	-	-	1	2	2	**0.84**	4

No	Statement	Likert Scale					RII	Rank
		1	2	3	4	5		
2d	The FTA framework for mobile mooring system is easily to understand	-	-	2	1	2	**0.8**	5
2e	The FTA framework for mobile mooring system has identified all the factors sufficiently	-	-	2	3	-	**0.72**	7
3	**Event Tree Analysis (ETA) with regards to Figure 4.9 – 4.12**							
3a	The accidents sequences of the outcome of mobile mooring system failure is acceptable	-	-	2	-	3	**0.84**	4
3b	The ETA for mobile mooring system approach is systematic	-	-	2	1	2	**0.8**	5
3c	The ETA frameworks of mobile mooring system are easily to understand	-	-	1	2	2	**0.84**	4
3d	The ETA framework of mobile mooring system has identified all the factors sufficiently	-	-	3	1	1	**0.72**	7
4	**Analytic Hierarchy Process (AHP) with regards to Figure 5.9 – 5.10**							
4a	The maintenance strategies options for mobile mooring system are acceptable	-	-	1	2	2	**0.84**	4
4b	The criteria and sub criteria for mobile mooring system in order to select the best maintenance strategy are acceptable	-	-	2	1	2	**0.8**	5
4c	The AHP approach for mobile mooring system is systematic	-	-	2	1	2	**0.8**	5
4d	The AHP framework for mobile mooring system easily to understand	-	-	2	2	1	**0.76**	6
4e	The AHP framework for mobile mooring system has identified all the factors sufficiently	-	-	2	2	1	**0.76**	6
5	**Integration of HAZOP-FTA-ETA-AHP as MIVTA & MIRBA with regards to Figure 3.6**							
5a	The MIVTA and MIRBA framework is interrelated to each other and can be seen as one integrated framework	-	-	1	1	3	**0.88**	3
5b	MIVTA and MIRBA is an innovative approach	-	-	1	3	1	**0.8**	5
	Mean Relative Importance Index						**0.82**	

The thesis validations have been defined using a Likert Scale with their RII in order to rank the framework validation and an open ended question to support the judgments of Likert scale. Table 5.32 shows the highest relative ranking consisting of ranking 1 with value of 0.96 and ranking 2 with value of 0.9 respectively. The RII for each of the statements is more than 0.72 which is considered as important, and the mean RII for all the statements is 0.82. Based on the findings from MIVTA and MIRBA, it is found that the risk based decision making (RBDM) for mobile mooring system can be implemented into a comprehensive RBDM assessment. RBDM assessment can be useful as tools for oil and gas industry in order to evaluate the risk and manage the risk in daily routine.

5.3 Summary of MIRBA Application

The application of MIRBA (Methodology for Investigation of Risk Based Maintenance) is developed based on the result of previous analysis on MIVTA (Methodology for Investigation of Critical Hazardous). The first Step in MIRBA starts with developing complete bow tie analysis which is obtained from FTA on the left side and ETA on the right side. The critical hazards of mooring system which are MLB, AF, ACF, AHF are classified into the medium level as shown in Figure 5.27. The graph shows the fifth outcome of MLB is in medium level with the frequency of 1.025908399 per year classified as probable event and the class of consequence is categorized into the C1 class ranking with zero impact. The fifth outcome of AF is also in the medium level with the frequency of occurrence of 1.025908399 per year classified as probable events and the class of consequences is grouped into C1 as zero impact. The fifth outcome of ACF is also in medium level with the frequency of occurrence of 1.017538235 classified as probable events and the class of consequence is categorized into C1 class as zero impact. The fifth outcome of AHF is in medium level with the frequency of $3.39966.10^{-2}$ per year considered as occasional event and the class of consequence is located at C1 with zero impact.

Based on the result of analysis that all the critical hazards of mobile mooring system are in medium level of risk, it is needed to develop mitigation plans. Mitigation plans are developed based on the literature review and brainstorming with the nine experts. The mitigation plans are constructed with regards to the undesired events or basic events of the critical hazard of mooring systems. In order to make sure the risk criticality and the mitigation measure effectiveness of mitigation plans, the seven degree rating system is developed. The results show that 70% of identified basic events are in the ranged of critical to very much critical. The mitigation measure effectiveness has been rated around 3 to 5 as shown in Table 5.19. Hence all respondents have defined the proposed mitigation measures as effective to very effective. The last Step of MIRBA is conducting AHP to select the best maintenance strategy for mooring systems. In order to select the best maintenance strategy, the

AHP is developed in two points of view which are maintenance strategy on the basis of likelihood and on the basis of consequences. The AHP result shows the best maintenance strategy on the basis of the likelihood of failure is PeM (Predictive Maintenance) with the priority vector of 35.6% as seen in Table 5.25, whereas for the basis of the consequences of failure the best maintenance strategy is PeM (Predictive Maintenance) with the priority of 35.3% as seen in Table 5.26.

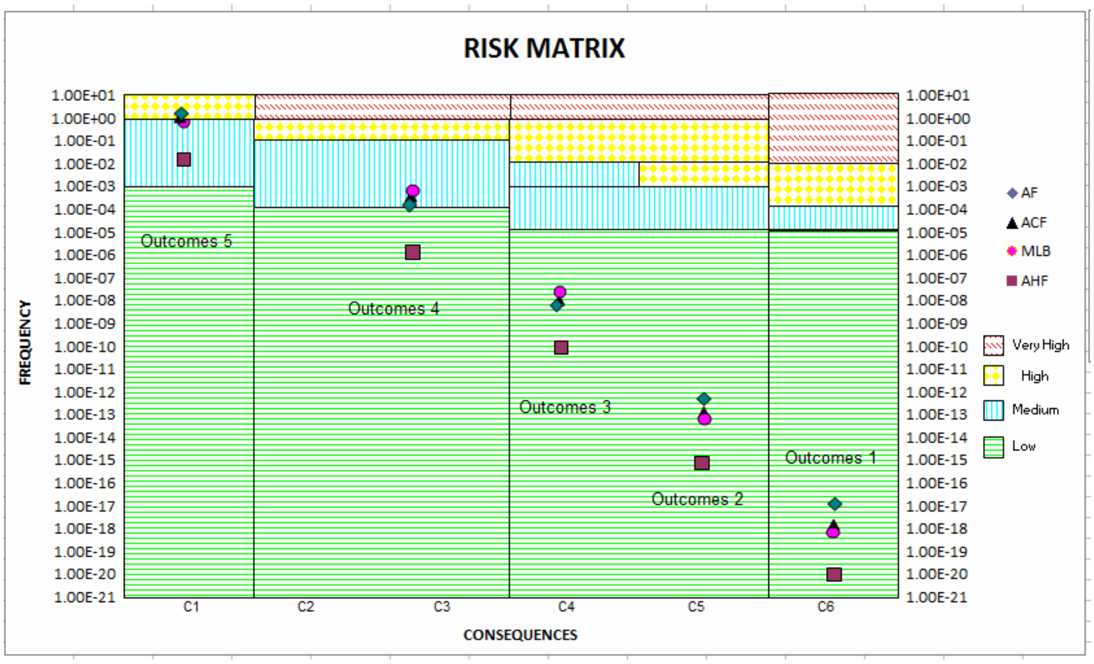

Figure 5.27. Risk Matrix of Critical Hazardous

MIVTA and MIRBA have been validated as an integrated method for risk based decision making for mobile mooring system. The validation process uses RII (Relative Important Index) to evaluate the criteria. The RII value of the validation framework is 0.82 which is considered as highly important. Therefore, this study develops a tool as the implementation of MIVTA and MIRBA. The tools can be useful as guidance for the oil and gas company to assess, to manage and to handle the risk on a daily basis. The next chapter will be discussing about conclusions, recommendations and the findings derived from this study.

CHAPTER SIX
CONCLUSIONS & RECOMMENDATIONS

As discussed earlier this chapter will be focus on the conclusion, recommendations and the finding of this study.

6.1 Conclusions

Mooring system is an important part of floating platform that may cause serious accident in oil and gas industry. However based on the literature review performed in this study, it is revealed that their causes and the ways to manage the risk of failure of mooring system have not yet been studied in detail. In order to mitigate the risk in the future, changes in industrial design standards need to be considered. For example the selection of the design return period of mooring the Mobile Offshore Drilling Unit (MODU) is no longer prescriptive but based on performing a suitable risk assessment (Petruska et al., 2009).

The aim of this study to integrate the risk based decision making (RBDM) for mobile mooring system has been successfully carried out. In order to achieve the aim of RBDM of mobile mooring system, three objectives need to be addressed. The following is the outline of the fundamental findings of this study in relation to its aim and objectives.

1. The first objective is to develop methodology for investigation of critical hazardous (MIVTA). The following are the main findings related to this objective:
   a. The critical hazards of mobile mooring system using HAZOP have been accomplished as seen in Table 4.2.
   b. The root causes of accident hazard of mobile mooring system failure using FTA have been determined namely MLB as seen in Figure 4.4a – 4.4e, AF as seen in Figure 4.5a – 4.5e, ACF as seen in Figure 4.6a – 4.6c, AHF as seen in Figure 4.7a - 4.7d.

c. The possible outcomes of an accident hazard of mobile mooring system failure using ETA have been established as seen in Figure 4.9 - 4.12.

2. The second objective is to develop methodology for investigation on risk based maintenance (MIRBA). The main findings related to this objective are as follows:
   a The risk matrix graphs for mobile mooring system failure have been presented in Figure 5.5-5.8.
   b. The mitigation plan have been determined as seen in Table 5.12 and the mitigation effectiveness have been measured as seen in Table 5.19.
   c. Best maintenance strategy selections on the basis of likelihood and consequence have been determined as seen in Table 5.25 and Table 5.26.

3. The validation framework of risk-based decision making consisting MIVTA and MIRBA have been validated as seen in Table 5.32.

6.2 Recommendations and Future Study

Based on the findings in this study on mobile mooring system, the recommendations are presented as follows:

1. Determining risk based decision making on two types of permanent mooring consisting of internal and external mooring systems should be carried out in order to make comparative analysis.
2. Developing a language programming or software for risk based decision making on mooring system that can be useful for oil and gas industry.
3. Generating risk based decision making for other types for offshore platform for instance spar platform, jack up, tlp and jacket etc.

6.3. The Findings

The findings of this research are an integrated methodology of risk based decision making (RBDM) which integrated four methods namely HAZOP, FTA, ETA and AHP which is called MIVTA and MIRBA. The current risk assessment practices in oil and gas industry can be enhanced by applying MIVTA and MIRBA. From theoretical point of view, the findings contribute to the understanding of mobile mooring system failure and how to handle the risk into daily routine. By applying the proposed method the risk failure of mobile mooring system failure can be reduced. Figure 6.1 shows the summary of the findings of this research. MIVTA is useful to determine the critical hazards of mooring system failure through investigating the root causes, the consequences, the frequency and severity index. The results of MIVTA are frequency index and severity which will be used in the MIRBA to determine the risk matrix and risk level. MIRBA is useful to determine the mitigation plan, risk criticality, measure the mitigation effectiveness and select the best maintenance strategy. The highest priority vector will be selecting as best maintenance strategy using AHP.

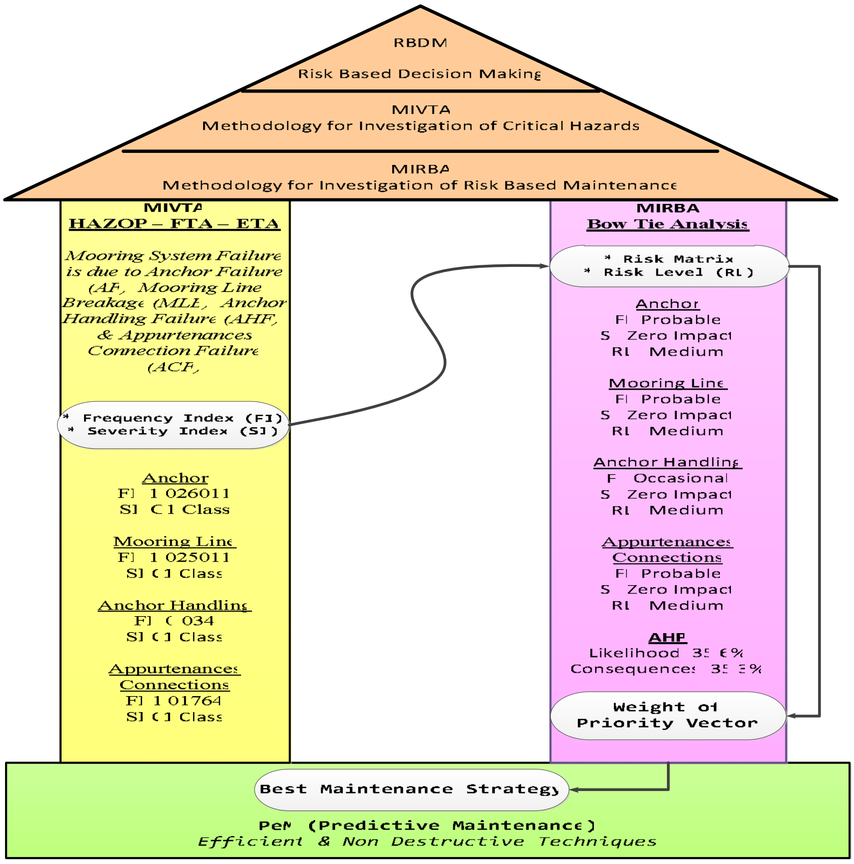

Figure 6.1. Research findings

Publications

Silvianita, Khamidi, M. F., Kurian, V. J. (2013). Decision Making for Safety Assessment of Mobile Mooring System. *Jurnal Teknologi, 61*(3), pp. 41-52.

Silvianita, Khamidi, M. F., Kurian, V. J. (2012a). Development of a Framework for Safety Assessment of Mobile Mooring System, *8th Asia Pacific Structural Engineering and Construction Conference 2012 (APSEC 2012) & 1st International Conference on Civil Engineering Research (ICCER 2012).* Surabaya, Indonesia.

Khamidi, M. F., Silvianita, Kurian V John. (2012b). Risk Based Decision Making of Mobile Mooring System, *International Conference on Statistics in Science, Business and Engineering 2012*. Langkawi, Malaysia.

Silvianita, Khamidi, M. F., Kurian, V. J. (2012c). An Application of Fault Tree Analysis for Mobile Mooring System. *International Conference on Civil, Offshore & Environmental Engineering*, Kuala Lumpur, Malaysia.

Silvianita, Khamidi, M. F., Kurian, V. J. (2011a) Critical Review of a Risk Assessments Method and its Applications, International Conference on Strategy Management and Research (ICSMR), Hongkong. pp. 83-87.

Silvianita, Khamidi, M. F., Kurian, V. J. (2011b) Operational Risk Assessment Framework of Mobile Mooring System, National Postgraduate Conference, Tronoh, Malaysia.

References

(ABS), A. B. S. (2001). *Principles of Risk Based Decision Making*. United States of America.

(API), A. P. I. (1993). Recommended Practice for Design and Hazards Analysis for Offshore Production Facilities, *API RP 14J*. Washington.

(API), A. P. I. (2005). Design and Analysis of Station Keeping Systems for Floating Structures, *Recommended Practive 2SK Third Edition*. Washington, D.C: API Publishing Services.

(DNV), D. N. V. (2002). *Marine Risk Assessment* (Offshore Technology Report No. 63).

(DNV), D. N. V. (2003). *Risk Management in Marine and Subsea Operations*. DNV-RP-H101: Det Norske Veritas.

(HSE), B. F. M. L. (2006a). *Review of Issues Associated with the Stability of Semi-submersibles* (Research Report No. 473).

(HSE), N. D. E. L. (2006b). *Floating Production System JIP FPS Mooring Integrity* (Research Report No. 444).

(HSE), H. S. E. (2009). *Accident Statistics for Offshore Units on the UKCS 1990-2007*. London: The United Kingdom Offshore Oil and Gas Industry Association Limited.

(IMO), I. M. O. (1997). *Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule Making Process.* London.

(KSU), K. S. U. (2010). *Maintenance Definition.* Available: http://www.ebookbrowse.com/lec1-maintenance-definition-ppt-d29519621

(NRC), N. R. C. (1997). *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Expert Use*: Senior Seismic Hazard Analysis Committee, Washington, D. C.

Arunraj, N. S., Maiti, J. (2010). Risk Based Maintenance Policy Selection Using AHP and Goal Programming. *Journal of Safety Science,* vol. 48, no. 2, pp. 238-247.

Ahmad, A. (2010). *Hazard and Operability (HAZOP).* Available: http://www.cheme.utm.my/staff/arshad/index.php/Process-Safety-Resources/HAZOP.html

Ali, H., Wedley, C. W. (2004). Maintenance Management An AHP Application for Centralization/Decentralization. *Journal of Quality in Maintenance Engineering,* vol. 10, no. 1, pp. 16-24.

Andrews, J. Tutorial Fault Tree Analysis. Paper presented at the *16th International System Safety Conference*, Seattle, Washington, September 14-19, 1998.

Apostolou, B., Hassel, J. M. (1993). An Empirical Examination of the Sensitivity of the Analytical Hierarchy Process to Departures from Recommended Consistency Ratios. *Journal of Mathematical and Computer Modelling,* vol. 17, no. 4, pp. 163-170.

Ayyub, B. M., Klir, G. J. *Uncertainty Modeling and Analysis in Engineering and the Sciences*: Chapman and Hall, 2006.

Badreddine, A., Amor, N. B. A. Dynamic Barriers Implementation in Bayesian Based Bow Tie Diagrams for Risk Analysis. Paper presented at the *International Conferences on Computer Systems and Applications,* Hammamet, Tunisia, May 16-19, 2010.

Balchin, K. (2005). *Process Safety Management (PSM)*. Mahshahr, Iran: Haward Technology Middle East.

Beck, N. (2006). *Proposed Risk Assessment Bulleting*. Washington, D.C.

Beer, M., Ferson, S., Kreinovich, V. (2013). Imprecise Probabilities in Engineering Analysis. *Journal of Mechanical Systems and Signal Processing*. In Press, Corrected Proof. Available: http://dx.doi.org/10.1016/j.ymssp.2013.01.024,

Bertolini, M., Bevilacqua, M. (2006). A Combined Goal Programming AHP Approach to Maintenance Selection Problem. *Journal of Reliability Engineering and System Safety,* vol. 91, no. 7, pp. 839-848.

Bevilacqua, M., Bragila, M. (2000). The Analytic Hierarchy Process. *Journal of Reliability Engineering and System Safety*, vol. 70, no. 1, pp. 71-83.

Birre, N., Soderholm, P. (2010). Selection of Maintenance Actions using the Analytic Hierarchy Process (AHP): Decision Making in Railway Infrastructure. *Journal of Structure and Infrastructure Engineering,* vol. 6, no. 4, pp. 467-479.

Brandsaester, A. (2002). Risk Assessment in the Offshore Industry. *Journal of Safety Science,* vol. 40, no. 4, pp. 231-269.

Burhanuddin, M.A., Halawani, S. M., Ahmad, A. R., Zulkifli, T. Contractor Selection for Maintenance in Small and Medium Industries Using Analytical Hierarchy Process. Paper presented at the *3rd IEEE International Conferece on Computer Science and Information Technology*, Chengdu, China, July 9-11, 2011.

Cavalli, R., Pellegrini, M., Grigolato, S. (2011). *Using GIS and AHP Tools to Define Maintenance Priorities of Primary Forest Road Networks Oan Alpine Case Study*. Forest Operations Management Unit, Department of Land and Agricultural and Forest Systems, University of Padova, Italy.

Celik, M., Lavasani, S. M., Wang, J. (2010). A Risk Based Modelling Approach to Enhance Shipping Accident Investigation. *Journal of Safety Science*, vol. 5, no. 1, pp. 18-27.

Chakrabarti, S. *Handbook of Offshore Engineering*: Elsevier Ltd, 2005.

Chang, C. S., Wang, Z., Yang, F., Tan, W. W. (2012). Hierarchical Fuzzy Logic System for Implementing Maintenance Schedules of Offshore Power Systems. *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 3-11.

Cheng, S. R., Lin, B., Hsu, B. M., Shu, M. H. (2009). Fault Tree Analysis for Liquefied Natural Gas Terminal Emergency Shutdown System. *Journal of Expert Systems with Applications*, vol. 36, no. 9, pp. 11918-11924.

Chelson, P. O. (1971). Reliability Computation Using Fault Tree Analysis. Institute of Technology, Pasadena, California.

Cockshott, J. E. (2005). Probability Bow Ties A Transparent Risk Management Tool. *Journal of Process Safety and Environmental Protection*, vol. 83, no. 4, pp. 307-316.

Collins, H. M., Evans, R. *Rethinking Expertise*. University of Chicago Press, Chicago, 2007.

Commission, U. S. N. R. (1981). *Fault Tree Handbook*. Washington, D.C.

Coulter, E. D. (2005). *Setting Forest Road Maintenance and Upgrade Priorities Based on Environmental Effects and Expert Judgment.* Oregon State University, United States.

Cree, L. (2003). Risk Assessment - A Tool for Decision Making (Publication no. 10.1094/SOD-2003-LC). Available: http://www.apsnet.org/online/SOD

d'Hautefeuille. Floating Production Storage and Offloading: Discounnectable or Not? Paper presented at the *SPE Asia Pacific Conference*, Perth, Australia, November 4-7, 1991.

Dalton, C. T. M. (2005). Syncopation Software. Availabe: http://www.syncopation.com

Danial, M., Muniandy R., Hamid, H., Zainuddin, M. Y. (2011). The Use of Analytical Hierarchy Process in Priority Rating of Pavement Maintenance. *Journal of Scientific Research and Essays,* vol. 6, no. 12, pp. 2447-2454.

Dawotola, A. W., Gelder, P. H. A. J. M. V., Vrijling, J. K. (2011). Decision Analysis Framework for Risk Management of Crude Oil Pipeline System. *Journal of Advances in Decision Sciences,* vol. 1, no. 10. pp. 1-17.

Deacon, T., Amyotte, P. R., Khan, F. I. (2010). Human Error Risk Analysis in Offshore Emergencies. *Journal of Safety Science,* vol. 48, no. 6, pp. 803-818.

Delvosalle, C., Fievez, C., Pipart, A., Fabrega, J. C., Planas, E., Christou, M., Mushtaq, F. (2005). Identification of Reference Accident Scenarios is SEVESO Estabilshments. *Journal of Reliability Engineering and System Safety*, vol. 1, no. 90, pp. 238-246.

Demko, D. (2005). *Tools for Multi Objective and Multi Discplinary Optimization in Naval Ship Design.* Faculty of Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Dey, P. K. (2001). A Risk Based Model for Inspection and Maintenance of Cross Country Petroleum Pipeline. *Journal of Quality in Maintenance Engineering,* vol. 7, no. 1, pp. 25-41.

Dey, P. K. (2003). Analytic Hierarchy Process Analyses Risk of Operating Cross Country Petroleum Pipelines in India. *Journal of Natural Hazards Review,* vol. 4, no. 4, pp. 213-221.

Dey, P. K. (2004a). Analytic Hierarchy Process Helps Evaluate Project in Indian Oil Pipelines Industry. *International Journal of Operation & Production Management,* vol. 24, no. 6, pp. 588-604.

Dey, P. K. (2004b). Decision Support System for Inspection and Maintenance: A Case Study of Oil Pipelines. *Journal of Transactions on Engineering Management,* vol. 51, no. 1, pp. 47-57.

Dhillon, B. S. (2003). Methods for Performing Human Reliability and Error Analysis in Health Care. *International Journal of Health Care Quality Assurance*, vol. 16, no. 6, pp. 306-317.

Dipak, L., Pernendu, M. Handbook of Computational Intelligence in *Manufacturing and Production Management*. Information Science Reference, 2008, 516 pp.

Dimitopoulos, X., Hurley, P., Kind, A., Stoecklin, M. P. On the 95 Percentile Billing Method. Proceedings of the *10th International Conference on Passive and Active Network Measurement,* Seoul, Korea, April 1-3, 2009.

Dongjiao, W., Katory, M. Hydromechanics of Moored Offshore Structures: Prediction of Enviromental Loads, Motion Responses and Mooring Forces. Paper presented at the *11th Australasian Fluid Mechanics Conference,* University of Tasmania, Hobart, December 14-18, 1992.

Dong, Y. (2008). *Assessing Investment Analysis Strategies for Infrastructure Renewal In Regional Transportation Planning.* University of Delaware, United States.

Ellingwood, B. R., Kinali, K. (2009). Quantifying and Communicating Uncertainty in Seismic Risk Assessment. *Journal of Structural Safety,* vol. 31, no. 2, pp. 179-187.

Enshassi, A., Aziz, A. R. A., Abushaban, S. (2011). Performance of Construction Projects: Perception of Owners in Palestine. *Emirates Journal of Engineering Research,* vol. 16, no. 1, pp. 23-32.

Eni, S. (2010). *Construction Vessel*. Available: http://www.factbook.eni.com

Erhan, E., Tarimcilar, M. (1991). On Sensitivity Analysis in the Analytic Hierarchy Process. *Journal of Management Mathematics*, vol. 3, no. 1, pp. 61-83.

Ericson, C. A. (2000). *Fault Tree Analysis.* Available: http://www.fault-tree.net

Ericson, C. A. Event Tree Analysis in *Hazard Analysis Techniques for System Safety*: John Wiley & Sons, Inc, 2005.

Fennica, S., Coulter, E. D., Session, J., Wing, M. G. (2006). Scheduling Forest Road Maintenance Using the Analytic Hierarchy Process and Heuristics. *The Finnish Forest Research Institute,* vol. 40, no. 1, pp. 143-160.

Fenton, N., Radlinksi, L., Neil, M. Improved Bayesian Networks for Software Project Risk Assessment Using Dynamic Discretisation *in IEEE Transaction on Reliability,* April 2007, vol. 227, Springer, Boston.

Figuera, J., Greco, S., Ehrgott, S. M. *Multiple Criteria Decision Analysis, State of the Art Surveys*. New York: Springer, 2005.

Fitzgerald, J., Bergdahl, L. (2008). Including Moorings in the Assessment of a Generic Offshore Wave Energy Converter: A Frequency Domain Approach. *Journal of Marine Structure,* vol. 21, no. 1, pp. 23-44.

Fofonoff, N. P., Garret, J. (1968). *Mooring Motion*. Massachusetts: Woods Hole Oceanographic Institution.

Fouss, F., Saerens, M. (2004). *A Maximum Entropy Approach to Multiple Classifiers Combination* Technical Report, IAG, Universite Catholique de Louvain.

Fowler, D. (2003). *FHA Review Report*. EUR RVSM POSC Development.

Forman, E. *Decision By Objectives*, 1st ed. World Scientific Pub Co Inc, 2002.

Gao, Z. (2008). *Stochastic Response Analysis of Mooring Systems with Emphasis on Frequency-domain Analysis of Fatigue due to Wide-band Response Processes.* Norwegian University of Science and Technology, Trondheim, Norway.

Gas, N. (2011). *Offshore Drilling*. Available: http://www.naturalgas.org/naturalgas/extraction_offshore.asp

Gelman, A. (2008). Objections to Bayesian Statistics. *Journal of Bayesian Analysis,* vol. 3, no. 3, pp. 445-450.

Geum, Y., Seoul, H., Lee, S., Park, Y. (2009). Application of Fault Tree Analysis to the Service Process: Service Tree Analysis Approach. *Journal of Service Management,* vol. 20, no. 4, pp. 433-454.

Gerwick, B. C. *Construction of Marine and Offshore Structure,* 2nd ed. CRC Press, 2000.

Goulet, V., Jacques, M., Pigeon, M. (2009). Expert: Modeling Without Data Using Expert Opinion. *The R Journal, Contributed Research Article,* vol. 1, no. 1, pp. 31-36.

Gowland, R. (2006). The Accidental Risk Assessment Methodology for Industries (ARAMIS)/Layer of Protection Analysis (LOPA) Methodology: A Step

Forward Towards Convergent Practices in Risk Assessment? *Journal of Hazardous Materials,* vol. 130, no. 3, pp. 307-310.

Ghodrati, B., Akersten, P. A., Kumar, U. (2007). Spare Parts Estimastion and Risk Assessment Conducted at Choghart Iron Ore Mine A Case Study. *Journal of Quality in Maintenance Engineering,* vol. 13, no. 4, pp. 353-363.

Gifford, L. (1995). Pipeline Technology S Lay Vessels Can Be Convertedd to Install Oman India Pipeline. *Offshore Magazine*. vol. 55, no. 6, pp. 11.

Gregory, S. P., Smith, C. M., Frederick, I. M. (2010). Intelligent Adversary Risk Analysis: A Bioterrorism Risk Management Model. *Journal of Society for Risk Analysis*, vol. 30, no. 1, pp. 32-48.

Gyarmati, L., Sirivianos, M., Laoutaris, N. (2012). *Sharing the Cost of Backbone Networks: Simplicity vs Precision*. Workshop on the Economics of Networks, Systems and Computation (NetEcon). USA.

Haimes, Y. Y. *Risk Modelling Assessment and Management*. Harvard University Press Cambridge. New York: John Wiley and Sons, 2001.

Harris, R.E., Johanning, L., Wolfram, J. (2006). Mooring Systems for Wave Energy Converters: A Review of Design Issues and Choices. *Journal of Engineering for the Maritime Environment*, vol. 220, no. 4, pp. 159-174.

Harris, J. S., Shaffer, M., Schechter., A. (2009). Poor Maintenance Increases Risks of Offshore Accidents. Available: http://www.maintenanceandcure.com/Poor-Maintenance-Increases-Risks-of-Offshore-Accidents.html

Healy, M. J. R. (1990). Measuring Importance. *Journal of Statistic in Medicine,* vol. 9, no. 6, pp. 633-637.

Hemanta, D., Young, B. Achieving Cost Performance from the Clients, Consultants and Contractors Perspectives. Paper presented at *The Construction and Building Research Conference of the Royal Institution of Chartered Surveyors*, Cape Town, South Africa, September 10-11, 2009.

Jabareen, Y. (2009). Building a Conceptual Framework: Philosophy, Definitions, and Procedure. *International Journal of Qualitative Methods,* vol. 8, no. 4, pp. 49-62.

Jacinto, C., Silva, C. (2010). A Semi Quantitative Assessment of Occupational Risks Using Bow Tie Representation. *Journal of Safety Science,* vol. 48, no. 8, pp. 973-979.

Janos, F., Roth, D., Schweik, C. (2006). What is meant by "Decision Making" in the Context of Eco Informatics. Available: http://academic.evergreen.edu/projects/bdei/documents/decisionmakingsummary.pdf

Javed, F., Fwa, T. F. (2009). Pavement Maintenance Prioritization Using Analytic Hierarchy Process. *Journal of the Transportation Research Board,* vol. 1, no. 9, pp. 12-24.

Jean, C., Ericson, K. A., Madelyn, P. L. (2005). Tracing the Development of Athletes Using Retrospective Interview Methods: A Proposed Interview and Validation Procedure for Reported Information. *Journal of Applied Sport Psychology,* vol. 17, no. 1, pp. 1-19.

Jennifer, P., Tucker, L. (2003). *An Exploration of Triangulation of Methodologies: Quantitative and Qualitative Methodology Fusion In An Investigation of Perceptions of Transit Safety*. Center for Urban Transportation Research, University of South Florida.

Johnson, J. W., Lebreton, J. M. (2004). History and Use of Relative Importance Indices in Organizational Research. *Journal of Organizational Research Methods,* vol. 7, no. 3, pp. 238-257.

Johnson, R. M. (1966). The Minimal Transportation to Orthonormality. *Journal of Psychometrika,* vol. 31, no. 1, pp. 61-66.

Kaiser, K. M. A Simulation Study of Predictive Maintenance Policies and How They Impact Manufacturing Systems. MS Thesis, Dept. Industrial Engineering. The University of Iowa, Iowa City, Iowa, 2007.

Kaiser, M. J. (2007). World Offshore Energy Loss Statistics. *Journal of Energy Policy*, vol. 35, no. 6, pp. 3496-3524.

Khalil, M. A., Assaf, S., Anazi, F. A. (2005). Risk Based Maintenance Planning of Cross Country Pipelines. *Journal of Performance of Constructed Facilities,* vol. 43, no. 3, pp. 323-333.

Kiureghian, A. D., Ditlevsen, O. (2009). Alteatory or Epistemic? Does it Matter? *Journal of Structural Safety,* vol. 31, no. 2, pp. 105-112.

Kolmogorov, A. N. (1950). *Foundations of the Theory of Probability*: Chelsea Publishing Company, New York.

Koivisto, R., Wessberg, N., Eerola, A., Ahlqvist, T., Kivisaari, S., Myllyoja, J., Halonen, M. (2009). Integrating Future Oriented Technology Analysis and Risk Assessment Methodologies *Journal of Technological Forecasting & Social Change*, vol. 76, no. 6, pp. 1163-1174.

Kozine, I., Christensen, P., Jensen, M. W. (2000). *Failure Database and Tools for Wind Turbine Availability and Reliability Analysis*: Riso National Laboratory, Roskilde.

Koul, S., Kumar, P., Verma, R. Product Development Using AHP: Case on Small Car Segment in India. Paper presented at the *8th International Conference on Supply Chain Management and Information Systems (SCMIS),* Hongkong, October 6 - 8, 2010.

Labor, U. S. D. O. (1990). *Accident Investigation.* http://www.labtrain.noaa.gov/osha600/refer/menu16a.pdf

Lacasse, S. Event Tree Analysis of Aknes Rock Slide Hazard. *Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management,* Quebec, May 20-24, 2008.

Lassen, T., Syvertsen, K. (1997). Fatigue Reliabiity and Life Cycle Cost Analysis of Mooring Chains. *International Journal of Offshore and Polar Engineering,* vol. 7, no. 2, pp. 135-140.

Lawson, K. (2005). Pipeline Corrosion Risk Analysis - An Assessment of Deterministic and Probabilistic Methods. *Journal of Anti Corrosion Methods and Materials*. vol. 52, no. 1, pp. 3-10.

Lin, Z., Gao, L., Zhang, D., Ren, P., Li, Y. Application of Analytic Hierarchy Process in Power Lines Maintenance. Paper presented at the *6th World Congress on Intelligent Control and Automation*, Dalian, China, June 21-23, 2006.

Ligaarden, O. S., Refsdal, A., Stolen, K. Experiences from Using Indicators to Validate Expert Judgments in Security Risk Analysis. Paper presented at the *Third International Worskhop on Security Measurements and Metrics,* Canada, September 19-23, 2011.

Liu, B. L., Berger, P., Zeng, A., Gerstenfeld, A. (2008). Applying the Analytic Hierarchy Process to the Offshore Outsourcing Location Decision. *Journal of Supply Chain Management: An International Journal,* vol. 13, no. 6, pp. 435-449.

Macesker, B., Myers, J. J., Guthrie, V. H., Walker, D. A., Schoolcraft, S. G. (2009). Quick Reference Guide to Risk Based Decision Making (RBDM): A Step by Step Example of the RBDM Process in the Field. *Journal of American Society of Civil Engineers*, vol. 2, no. 1, pp. 1-10.

Maragakis, I., Clark, S., Piers, M., Prior, D., Tripaldi, C., Masson, M., Audard, C. L. (2009). *Guidance on Hazard Identification*. European Strategic Safety Initiative.

Matsuoka, T., Mitomo, N., Kaneko, F. Evaluation of Occurence Frequencies of Marine Accidents in The FSA Framework. Paper presented at the *2nd International Maritime Conference on Design for Safety*, Japan, October 27-30, 2004.

Marimatech. (2009). *Offshore*. Available: http://www.marimatech.com/?show=offshore

Marine, Q. (2011). *Study of Critical Equipment & Systems on Offshore Service Vessels*. June 3, 2011. Available: http://www.marineq.no/files/documents/report_-_critical_equipment_study_public.pdf

Marissa, F. M., Burgman, M. A. What is Expert Knowledge, How Is Such Knowledge Gathered, and How Do We Use It To Address Questions in Landscape Ecology? in *Expert Knowledge and Its Application in Landscape Ecology*. Springer Science Business Media, 2012.

MCS, I. (2002). Vortex Induced Vibration Shear 7 and Modes 3D. *The Newsletter for MCS Software Users*. MCS International.

Mentes, A., Helvacioglu, I. H. (2011). An Application of Fuzzy Fault Tree Analysis for Spread Mooring System. *Journal of Ocean Engineering*, vol. 38, no. 3, pp. 285-294.

Mentes, A., Helvacioglu, I. H. (2012). Fuzzy Decision Support System for Spread Mooring System Selection. *Journal of Expert Systems with Applications,* vol. 39, no. 3, pp. 3283-3297.

Mishra, R. K., Anand, G., Kodali, R. (2007). An AHP Model for Quantification of Benefits of World Class Maintenance Systems. *International Journal of Industrial and Systems Engineering,* vol. 2, no. 2, pp. 166-194.

Mobley, R. K. (2002). *An Introduction to Predictive Maintenance,* 2^{nd}. United States of America: Elsevier Science.

Moorings, O. (2009). *Mooring System*. Available: http://www.offshoremoorings.org.

Moorings, O. (2007). *Mooring Systems for Semi Submersibles*. Available: http://www.offshoremoorings.org.

Moss, H. H., Kurty, M. W. Reliability Analysis of A Tension Leg Platform. *Proceedings of OCEAN' 83*, pp. 755-759, USA, August 29 - September 1, 1983.

Nataraj, S. (2005). Analytic Hierarchy Process As A Decision Support System in the Petroleum Pipeline Industry. *Journal of Information Systems,* vol. 6, no 2, pp. 16-21.

News, W. (2009). A World of Expertise: An In Depth Review of Wood Group's FPSO Experience. Available: http://www.woodgroupnews.com/WoodNewsQ12009/English/wn_quarter1_09_en_3.aspx

Niu, W., Huang, X., Gu, W., Chu, J. Fault Tolerant Tension Allocation of Ship Mobile Mooring System under Sea Wind. Paper presented at the *International Conference on Measuring Techonology and Mechatronics Automation.* Hunan, China, April 11-12, 2009.

Nilsen, T., Gudmestad, O, T., Dalane, J. I., Rettedal, W. K., Aven, T. (1998). Utilisation of Principles from Structural Reliability in Quantitative Risk Analysis: Example from an Offshore Transport Problem. *Reliability Engineering and System Safety,* vol. 61, no. 35, pp. 127-137.

Oakley, J. (2004). Estimating Percentiles of Uncertain Computer Code Outputs. *Journals of the Royal Statistical Society, 1*(53), pp. 83-93.

Oil, W. (2003). *Offshore LNG Transfer and Storage is Set to Fill the Global Gas Gap.* http://www.worldoil.com/July-2003-Offshore-LNG-transfer-and-storage-is-set-to-fill-the-global-gas-gap.html

Olsen, W. Qualitative and Quantitative Methods Can Really Be Mixed in *Developments in Sociology*, 2004, ed. M. Holborn, Ormskirk: Causeway Press.

Paik, J. K., Thayamballi, A. K. *Ship Shaped Offshore Installations: Design, Building and Operation*. Cambridge University Press, 2007.

Pearce, R. (2011). Risk Control For Asset Managers. Northfield Information Services, INC.

Penny, C. (2010). *Risk Assessment for Lifting of Cyclotron from Valut at ANSTO Camperdown*: Australian Government.

Petruska, D., Banon, H., Liagre, P., Leary, M. Moored MODU Risk Assessment. Paper presented at the *Offshore Technology Conference,* Houston, Texas, May 4-7, 2009.

Pitt, M. J. (1994). Hazard and Operability Studies : A Tool for Management Analysis. *Journal of Facilities,* vol. 12, no. 13, pp. 5-8.

Professional, E. C. (2000). Users Manual. Pittsburgh.

Program, P. W. A. S. S. (2002). *Accident Prevention Manual*. http://www.pws.gov.nt.ca/pdf/Accident_Prevention.pdf

Raman, J. R., Garget, A., Warner, D. C. Application of HAZOP Techniques for Maintenance Safety on Offshore Installations. Paper presented at the Proceedings of the *First International Conference on Health, Safety Environment in Oil and Gas Exploration and Production, Society of Petroleum Engineers,* Richardson, Texas, October 6-9, 1991.

Rausand, M. Hazard and Operability Study in *System Reliability Theory*, 2nd ed, Wiley, 2005a.

Rausand, M. System Analysis Event Tree Analysis in *System Reliability Theory*, 2nd ed, Wiley, 2005b.

Ramadhan, R. H., Wahhab, H. I. A., Duffuaa, S. O. (1999). The Use of An Analytical Hierarchy Process in Pavement Maintenance Priority Ranking. *Journal of Quality in Maintenance Engineering,* vol. *5*, no. 1, pp. 25-39.

Saaty, T. L. *The Analytic Hierarchy Process*. United States of America: Pittsburg University, 1988.

Saaty, T. L. The Seven Pillars of the Analytic Hierarchy Process in *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process,* vol. 34, Kluwer Academic Publishers, 2001.

Saaty, T. L. *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*, vol. 6. USA: Pittsburg University, 2003.

Saaty, T. L. (2008). Decision Making with the Analytic Hierarchy Process. *International Journal of Servies Sciences,* vol. 1, no. 1, pp. 83-98.

Salvi, O. B. D. (2006). A Global View On ARAMIS, A Risk Assessment Methodology for Industries In The Framework of The SEVESO II Directive. *Journal of Hazardous Material*, vol. 130, no. 3, pp.187-199.

Salem, M. S. M. (2010). An Application of the Analytic Hierarchy Process to Determine Benchmarking Criteria for Manufacturing Organisations. *International Journal of Trade, Economics and Finance,* vol. 1, no. 1, pp. 93-103.

Sambasivan, M., Soon, Y. W. (2007). Causes and Effects of Delays in Malaysian Construction Industry. *International Journal of Project Management,* vol. 25, no. 6, pp. 517-524.

Savage, L. *The Foundation of Statistics*: Wiley, New York, 1954.

Sethiya, S. K. (2006). Condition Based Maintenance (CBM). Available: http://www.irsme.nic.in/files/cbm-sethiya.pdf

Siu, N. O., Kelly, D. L. (1998). Bayesian Parameter Estimation in Probabilistic Risk Assessment. *Journal of Reliability Engineering and System Safety,* vol. 62, no. 2, pp. 89-116.

Sharon, L. T. N., Neil, B. J., Peterson, L. E., Palmer, R. H. (1998). Eliciting Expert Opinion Using the Delphi Technique: Identifying Performance Indicators for Cardiovascular Disease. *International Journal for Quality in Health Care,* vol. 10, no. 3, pp. 247-260.

Shewring, D. (2010). *HAZOP Study Report, Ammonia Plant Uprate Project, Orica Australia PTY LTD.* Australia: Pinnacle Risk Management Pty Limited.

Silvianita, Khamidi, M. F., Kurian, V. J. (2013). Decision Making for Safety Assessment of Mobile Mooring System. *Jurnal Teknologi, 61*(3), pp. 41-52.

Silvianita. (2009). Prioritizing the Maintenance of Pipeline Based on Risk Analysis. MS Thesis. Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak, Malaysia.

Souza, R. Q., Alvares, A. J. (2008). FMEA and FTA Analysis for Application of the Reliability Centered Maintenance Metholodgy: Case Study on Hydraulic Turbines. *ABCM Symposium Series in Mechanics,* vol. 3, no. 1, pp. 803-812.

Stamatelatos, M. W. V. *Fault Tree Handbook with Aerospace Applications*. NASA Headquarters Office of Safety and Mission Assurane, USA, 2002.

Stanojevic, R., Laoutaris, N., Rodriguez, P. On Economic Heavy Hitters: Shapley Value Analysis of 95th Percentile Pricing. Paper presented at the *Internet Measurement Conference,* Melbourne, Australia*,* November 1-3, 2010.

Stiff, J., Ferrari, J., Ku, A., Spong, R. Comparative Risk Analysis of Two FPSO Mooring Configurations. Paper presented at the *Offshore Technology Conference.* Houston, Texas, May 5-8, 2003.

Taylor, M. (2006). *Safety Services. Guidance on Accident, Incident and Near Miss Investigation.*. Safety Guidance Version 1.5. The University of Manchester.

Targoutzidis, A. (2010). Incorporating Human Factos Into A Simplified "Bow-Tie" Approach for Workplace Risk Assessment. *Journal of Safety Science*, vol. 48, no. 1, pp. 145-154.

Tahriri, F., Osman, M. R., Ali, A., Yusuff, R. M. (2008). A Review of Supplier Selection Methods in Manufacturing Industries. *Journal of Science Technology,* vol. 15, no. 3, pp. 201-208.

Tools, M. (2003). *Essential Skills for An Excellent Carrer*. Available: http://www.mindtools.com

Topics, E. O. E. (2010). *Deepwater Oil and Gas Systems*. Available: http://www.eoearth.org/articles/view/158865/

Tuzmen, S., Sipahi, S. A Multi Criteria Factor Evaluation Model for Gas Station Site Selection. Paper presented at the *2nd International Conference on Business and Economic Research*, Langkawi, Malaysia, March 14-16, 2011.

UKOOA. (1999). *A Framework for Risk Related Decision Support*: UK Offshore Operators Association, London.

UK, O. A. G. (2012). *Guidance on the Conduct and Management of Operational Risk Assessment for UKCS Offshore Oil and Gas Operations*: The United Kingdom Offshore Oil and Gas Industry Association Limited.

University, M. S. (2002). *Validation and Data Collection*: Department of Information Technology and Media Egonsdotter. Duke University, USA.

Vargas, C. A. M. S. (1998). *Investigating Construction Falls Using Fault Tree Analysis and Developing a Prototype Tool to Reduce Falls Using Expert System and Computer Assisted Instruction Methods*. PhD Thesis. The Ohio State University.

Wang, J. (2002). Offshore Safety Case Approach and Formal Safety Assessment of Ships. *Journal Of Safety Research,* vol. 33, no. 6, pp. 81-114.

Wang, S. Q., Dulami, M. F., Aguria, M. Y. (2004). Risk Management Framework for Construction Projects in Developing Countries. *Journal of Construction Management and Economics,* vol. 22, no. 1, pp. 237-252.

Wang, Y. An Application of the AHP in Supplier Selection of Maintenance and Repair Parts. Paper presented at *1st International Conference on Information Science and Engineering (ICISE)*. China, December 26-28, 2009.

Xie, M., Tan, K. C., Goh, K. H., Huang, X. R. (2000). Optimum Prioritization and Resource Allocation Based on Fault Tree Analysis. *Journal of Quality & Reliability Management,* vol. 17, no. 2, pp. 189-199.

Xu, L., Yang, J. B. (2001). *Introduction to Multi Criteria Decision Making and the Evidential Reasoning Approach*: University of Manchester Institure of Science and Techonology.

Yaghmale, F. (2003). Content Validity and Its Estimation. *Journal of Medical Education,* vol. 3, no. 1, pp. 25-27.

Young, K. D. (2006). *Application of the Analytic Hierarchy Process Optimization Algorithm in Best Management Practice Selection.* Virginia Polytechnic Institute and State University Blacksburg, Virginia.

Yurdakul, M., Tansel, Y. (2004). AHP Approach in The Credit Evaluation of The Manufacturing Firms in Turkey. *International Journal of Production Economics,* vol. 88, no. 3, pp.269-289.

Zavadskas, E. K., Vilutiene, T., Turskis, Z., Tamosaitiene, J. (2010). Contractor Selection for Construction Works by Applying SAW-G and TOPSIS Grey Techniques. *Journal of Business Economics and Management*, vol. 9, no. 1, pp. 79-86.

Zhaoyang, T., Jiangfeng, L., Zongzhi, W., Jianhu, Z., Weifeng, H. (2011). An Evaluation of Maintenance Strategy Using Risk Based Inspection. *Journal of Safety Science,* vol. 49, no. 6, pp. 852-860.

Zhai, Y. (2010). *Non Numerical Ranking Based on Pairwise Comparisons.* Mc Master University, Hamilton, Ontario, Canada.

APPENDICES

APPENDIX A Hazard and Operability (HAZOP)

A. HAZOP (Hazard and Operability)

The purposes of this questioning are to find safety hazards and operability problems in mooring system components and also used to review risk failure. Please filled up based on your knowledge and experience in mooring system.

System Identification					
Activity: Description of System Activity					
Component	Deviation	Possible Causes	Possible Consequence	Safeguard	Action
Mooring line					
Anchor					
Appurtenances Connection					
Anchor Handling Tug					

APPENDIX B

AHP Questionnaires
Maintenance Strategy for Mooring System on the Basis of Likelihood of Failure

LEVEL 1 – THE GOAL

Level 1 of the AHP structure describes the goal or the objective of the problem that are trying to solve. By knowing the goal it will helps the decision maker for structuring a decision problem by describing the criteria, sub criteria and the alternative solutions. The goal of this questionnaire is to select the best maintenance strategy for mooring system.

LEVEL 2 - CRITERIA

Referring to the instructions on page 3, please compare two Criteria and judge the relative importance in each pair in the table below (i.e. how much more important one of paired factors is than the other) by using the judgement scale of AHP scale. **Bold/Underline** the number in one box corresponding to your judgement on the side of the more important criteria than the other. If two criteria are equally important, **bold/underline** the number of “equally=1” in the centre of the scale.

In order to select the best maintenance strategy, we have identified four main criteria: mooring line break, anchor failure, anchor handling failure, appurtenances connection failure. Which of these two factors of criterias is greater importance in the maintenance strategy selection and how much?

A. Mooring Line Breakage (MLB)
B. Anchor Failure (AF)
C. Anchor Handling Failure (AHF)
D. Appurtenances Connection Failure (ACF)

Table B.1. Criteria

Criteria	AHP Scale																	Criteria
MLB	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**AF**
MLB	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**AHF**
MLB	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**ACF**
AF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**AHF**
AF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**ACF**
AHF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**ACF**

LEVEL 3 – SUB CRITERIA

Please compare the followong Sub Criteria in order of importance concerning Maintenance Strategy of Mooring System. **Bold/Underline** the number in one box corresponding to your judgement on the side of the more important criteria than the other.

A. Sub-Criteria of Mooring Line Breakage

Consider the sub criteria of **Mooring Line Breakage.** Which of these two sub criteria is greater importance/contribution to mooring line breakage and how much?

A1. Corrosion
A2. Abrasion
A3. Mooring Line Clashed
A4. Collision

Table B.2. Mooring Line Breakage

Sub Criteria	AHP Scale																	Sub Criteria
Corrosion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Abrasion**
Corrosion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Mooring Line Clashed**
Corrosion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Collision**
Abrasion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Mooring Line Clashed**
Abrasion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Collision**
Mooring Line Clashed	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Collision**

B. Sub-Criteria of Anchor Failure

Consider the sub criteria of **Anchor Failure.** Which of these two sub criteria is greater importance /contribution to anchor failure and how much?

B1. Insufficient Holding
B2. Part of Anchor Breaks
B3. Mooring Line Clashed
B4. Collision

Table B.3. Anchor Failure

Sub Criteria	AHP Scale																	Sub Criteria
Insufficient Holding	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Part of Anchor Breaks**
Insufficient Holding	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Mooring Line Clashed**
Insufficient Holding	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Collision**
Part of Anchor Breaks	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Mooring Line Clashed**
Part of Anchor Breaks	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Collision**
Mooring Line Clashed	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Collision**

C. Sub-Criteria of Anchor Handling Failure

Consider the sub criteria of **Anchor Handling Failure.** Which of these two criteria is greater importance/contribution to anchor handling failure and how much?

C1. Barge Winch Failure
C2. Anchor Handling Tugs Failure

Table B.4. Anchor Handling Failure

Sub Criteria	AHP Scale																	Sub Criteria
Barge Winch Failure	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Anchor Handling Tugs Failure**

D. Sub-Criteria of Appurtenances Connections Failure

Consider the sub criteria of **Appurtenances Connections Failure.** Which of these two criteria is greater importance/contribution to appurtenances connection failure and how much?

D1. Corrosion
D2. Fatigue Cracking

Table B.5. Appurtenances Connection Failure

Sub Criteria	AHP Scale																	Sub Criteria
Corro-sion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Fatigue Cracking**

LEVEL 4 – ALTERNATIVES

Please rank the followong alternative in order of importance concerning the maintenance strategy for mooring systems. Please give your assessment between two factors contribute to the objective whether equal importance, more imortance or less importance based on AHP scale as shown in Table 1.

A1. Alternatives of Corrosion associated with Mooring Line Breakage

In terms of **Corrosion associated with Mooring Line Breakage**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.6. Corrosion associated with Mooring Line Breakage

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

A.2. Alternatives of Abrasion associated with Mooring Line Breakage

In terms of **Abrasion associated with Mooring Line Breakage**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.7. Abrasion associated with Mooring Line Breakage

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

A3. Alternatives of Mooring Line Clashed associated with Mooring Line Breakage

In terms of **Mooring Line Clashed associated with Mooring Line Breakage**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.8. Mooring Line Clashed associated with Mooring Line Breakage

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

A4. Alternatives of Collision associated with Mooring Line Breakage

In terms of **Collision associated with Mooring Line Breakage**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.9. Collision associated with Mooring Line Breakage

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

B1. Alternatives of Insufficient Holding associated with Anchor Failure

In terms of **Insufficient Holding associated with Anchor Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.10. Insufficient Holding associated with Anchor Failure

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM

CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

B2. Alternatives of Part of Anchor Breaks associated with Anchor Failure

In terms of **Part of Anchor Breaks associated with Anchor Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.11. Part of Anchor Breaks associated with Anchor Failure

ALTV	**AHP Scale**																	**ALTV**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

B3. Alternatives of Mooring Line Clashed associated with Anchor Failure

In terms of **Mooring Line Clashed associated with Anchor Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.12. Mooring Line Clashed associated with Anchor Failure

ALTV	**AHP Scale**																	**ALTV**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

B4. Alternatives of Collision associated with Anchor Failure

In terms of **Collision associated with Anchor Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.13. Collision associated with Anchor Failure

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

C1. Alternatives of Barge Winch Failure associated with Anchor Handling Failure

In terms of **Barge Winch Failure associated with Anchor Handling Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.14. Barge Winch Failure associated with Anchor Handling Failure

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

C2. Alternatives of Anchor Handling Tug Failure associated with Anchor Handling Failure

In terms of **Anchor Handling Tug Failure associated with Anchor Handling Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.15. Anchor Handling Tug Failure associated with Anchor Handling Failure

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM

CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

D1. Alternatives of Corrosion associated with Appurtenances Connections Failure

In terms of **Corrosion associated with Appurtenances Connections Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.16. Corrosion associated with Appurtenances Connections Failure

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

D2. Alternatives of Fatigue Cracking associated with Appurtenances Connections Failure

In terms of **Fatigue Cracking associated with Appurtenances Connections Failure**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table B.17. Fatigue Cracking associated with Appurtenances Connections Failure

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

 # Thank you very much for your kind cooperation and greatly appreciates for your time

APPENDIX C
AHP Questionnaires
Maintenance Strategy for Mooring System on the Basis of Consequence of Failure

LEVEL 1 – THE GOAL

Level 1 of the AHP structure describes the goal or the objective of the problem that are trying to solve. By knowing the goal it will helps the decision maker for structuring a decision problem by describing the criteria, sub criteria and the alternative solutions. The goal of this questionnaire is to select the best maintenance strategy for mooring system.

LEVEL 2 - CRITERIA

Referring to the instructions on page 3, please compare two Criteria and judge the relative importance in each pair in the table below (i.e. how much more important one of paired factors is than the other) by using the judgement scale of AHP scale. **Bold/Underline** the number in one box corresponding to your judgement on the side of the more important criteria than the other. If two criteria are equally important, **bold/underline** the number of "equally=1" in the centre of the scale. In order to select the best maintenance strategy, we have identified five main criteria: people, environment, assets, reputation and cost. Which of these two factors of criterias is greater importance in the appropriate maintenance strategy selection and how much?

A. People
B. Environment
C. Assets
D. Reputation
E. Cost

Table C.1. Criteria

Criteria	AHP Scale																	Criteria
People	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environment
People	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Assets
People	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reputation
People	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Environment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Assets
Environment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reputation
Environment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Assets	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reputation
Assets	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Reputation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost

LEVEL 3 – SUB CRITERIA

Please compare the followong Sub Criteria in order of importance concerning Maintenance Strategy of Mooring System. **Bold/Underline** the number in one box corresponding to your judgments on the side of the more important criteria than the other.

A. Sub-Criteria of People

Consider the sub criteria of **People.** Which of these two criteria is greater importance in the appropriate of maintenance strategy selection and how much?

A1. Safety
A2. Health

Table C.2. People

Sub Criteria	AHP Scale																	Sub Criteria
Safety	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Health**

B. Sub-Criteria of Environment
Consider the sub criteria of **Environment.** Which of these two criteria is greater importance in the appropriate of maintenance strategy selection and how much?

B1. External
B2. Internal

Table C.3. Environment

Sub Criteria	AHP Scale																	Sub Criteria
External	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Internal**

C. Sub-Criteria of Assets
Consider the sub criteria of **Assets.** Which of these two criteria is greater importance in the appropriate of maintenance strategy selection and how much?

C1. Direct
C2. Indirect

Table C.4. Assets

Sub Criteria	AHP Scale																	Sub Criteria
Direct	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	Indirect

D. Sub-Criteria of Reputation
Consider the sub criteria of Reputation. Which of these two criteria is greater importance in the appropriate of maintenance strategy selection and how much?

D1. Performance
D2. Quality Service

Table C.5. Reputation

Sub Criteria	AHP Scale																	Sub Criteria
Performance	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	Quality Service

LEVEL 4 - ALTERNATIVES

Please rank the followong alternative in order of importance concerning the maintenance strategy for mooring systems. Please give your assessment between two factors contribute to the objective whether equal importance, more imortance or less importance based on AHP scale as shown in Table 1.

A1. Alternatives of Safety associated with People

In terms of **Safety associated with People**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.6. Safety associated with People

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**

CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

A2. Alternatives of Health associated with People

In terms of **Health associated with People**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.7. Health associated with People

ALTV	**AHP Scale**																	**ALTV**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

B1. Alternatives of External associated with Environment

In terms of **External associated with Environment**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.8. External associated with Environment

ALTV	**AHP Scale**																	**ALTV**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

B2. Alternatives of Internal associated with Environment

In terms of **Internal associated with Environment**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.9. Internal associated with Environment

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

C1. Alternatives of Direct associated with Assets

In terms of **Direct associated with Assets**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.10. Direct associated with Assets

ALTV	AHP Scale																	ALTV
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
CM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RFM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
PM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CBM
RFM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM
CBM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PeM

C2. Alternatives of Indirect associated with Assets

In terms of **Indirect associated with Assets**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.11. Indirect associated with Assets

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

D1. Alternatives of Performance associated with Reputation

In terms of **Performance associated with Reputation**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.12. Performance associated with Reputation

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

D2. Quality Service associated with Reputation

In terms of **Quality Service associated with Reputation**, which of the five alternatives of maintenance strategies offers better maintenance and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.13. Quality Service associated with Reputation

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

E. Cost

In terms of **cos**t, which of the five alternatives of maintenance strategies is costly and by how much?

A. Corrective Maintenance (CM)
B. Preventive Maintenance (PM)
C. Run to Failure Maintenance (RFM)
D. Condition Based Maintenance (CBM)
E. Predictive Maintenance (PeM)

Table C.14. Cost

ALTV	AHP Scale																	ALTV
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
CM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**RFM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
PM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**CBM**
RFM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**
CBM	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**PeM**

 # Thank you very much for your kind cooperation and greatly appreciates for your time #

APPENDIX D

Respondent Profile

D1. Experts for EOS 1 – EOS 9

No	Code	Education	Experience (years)	Institution
1	Expert 1	Bachelor	10	SBM Malaysia
2	Expert 2	Bachelor	15	SBM Malaysia
3	Expert 3	Bachelor	10	Powertium Marine
4	Expert 4	Bachelor	10	SBM Malaysia
5	Expert 5	Bachelor	10	GL Noble Denton
6	Expert 6	Bachelor	10	Plomo Sdn Bhd
7	Expert 7	Bachelor	10	Plomo Sdn Bhd
8	Expert 8	Bachelor	15	Powertium Marine
9	Expert 9	Bachelor	10	SDMPOPL

D2. Experts for EOS 10

No	Code	Education	Experience (years)	Institution
1	Expert 1	Master	15	Plomo Sdn Bhd
2	Expert 2	Master	15	SBM Malaysia
3	Expert 3	Bachelor	10	GL Noble Denton
4	Expert 4	Master	15	SBM Malaysia
5	Expert 5	Master	15	DNV

APPENDIX E

Weightage of the Experts and Quantitative Raw Data

The weightage of the experts is based on the information derived from the expert opinions. The information can be considered each expert expresses his opinion about the events (Fouss, 2004):

$$P(d(k) = i_k | x) = \pi(d(k) = i_k | x) \text{ for } k = 1 \ldots m,\ i_k = 1 \ldots n \qquad (1)$$

Where $\pi(d(k) = i_k | x)$, the likelihood of choosing alternative i_k is provided by expert k for each event $i_k \in \{1,2,...,n\}$. In other words, each expert provides his likelihood of observing event i_k according to his subjective judgments. It indicates that in average, expert k would choose alternative i_k with probability $\pi(d(k) = i_k | x)$ when he observes evidence x.

It is well known that experts opinions can be correlated. A possible choice for modeling experts correlations would be to provide (Fouss, 2004):

$$\sum_i P(d(k) = i, d(l) = i | x) = \sigma(k,l | x) \ for\ k,l = 1 \ldots m \qquad (2)$$

It corresponds to the probability that expert k and expert l agree. If $\sigma(k,l|x) = 1$, expert k and expert l always agree (they are totally correlated), while if $\sigma(k,l|x) = 0$, they always disagree.

Table 1 shows EOS 2 the likelihood for each basic events and their average based on the experts judgments. In order to give weightage to the nine experts for instance for the basic events in EOS 2, the first Step is to calculate the average of likelihood for each of the basic event given by all the experts. The next Step is to correlate the judgments of each expert for all basic events with the average.

Table E.1. Second EOS for Frequency Index

Code	E1	E2	E3	E4	E5	E6	E7	E8	E9	AVERAGE	95th
AEC	0.001	0.001	0.001	0.001	0.01	0.01	0.001	0.001	0.001	0.003	0.01
DiS	0.001	0.0001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.0009	0.001
DE	0.001	0.0001	0.0001	0.001	0.001	0.0001	0.001	0.0001	0.0001	0.0005	0.001
EFoW	0.001	0.001	0.001	0.001	0.01	0.01	0.01	0.001	0.001	0.004	0.01
EF	0.0001	0.0001	0.0001	0.001	0.001	0.0001	0.001	0.001	0.001	0.0006	0.001
EWa	1	1	1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	1
EWi	1	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	1
ECu	1	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	1
HE	0.001	0.0001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.0009	0.001
IDC	0.0001	0.0001	0.0001	0.001	0.001	0.001	0.001	0.001	0.001	0.0007	0.001
IQC	0.001	0.01	0.01	0.01	0.01	0.001	0.001	0.001	0.001	0.005	0.01
IWMS	0.001	0.001	0.001	0.001	0.01	0.01	0.01	0.001	0.001	0.004	0.01
ICP	0.001	0.0001	0.0001	0.0001	0.0001	0.001	0.0001	0.001	0.001	0.0005	0.001
IMS	0.001	0.0001	0.0001	0.001	0.001	0.0001	0.0001	0.001	0.0001	0.0005	0.001
ISDS	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	0.001	0.001	0.0004	0.001
IC	0.0001	0.001	0.001	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.001
ME	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.00064
MF	0.001	0.0001	0.0001	0.001	0.001	0.001	0.001	0.0001	0.0001	0.0006	0.001
NH	0.01	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.01	0.0023	0.01
PRM	0.001	0.0001	0.0001	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0003	0.001
RS	0.01	0.01	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.01
SC	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	0.001	0.001	0.001	0.0005	0.001
UC	0.0001	0.0001	0.0001	0.001	0.001	0.001	0.0001	0.0001	0.0001	0.0004	0.001
IAM	0.01	0.01	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.01
UE	0.001	0.0001	0.0001	0.0001	0.0001	0.001	0.001	0.0001	0.0001	0.0004	0.001
WM	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	0.0001	0.0001	0.0003	0.001

Table 2 shows the weightage of the nine experts that have been participated for EOS 1 to EOS 9. The highest weightage is expert no 2 whose judgments is closer to the average of all the experts opinion.

Table E.2. Weightage of Nine Experts for EOS 1 - EOS 9

Experts	Weightage	Rank
E1	0.988771359	2
E2	0.988801373	1
E3	0.767601594	9
E4	0.987546714	4
E5	0.984140824	8
E6	0.985020705	7
E7	0.98625702	6
E8	0.988757856	3
E9	0.987279744	5

Figure 1 shows the graphs of the experts opinion for EOS 2 and the average from all the experts for each of the basic events.

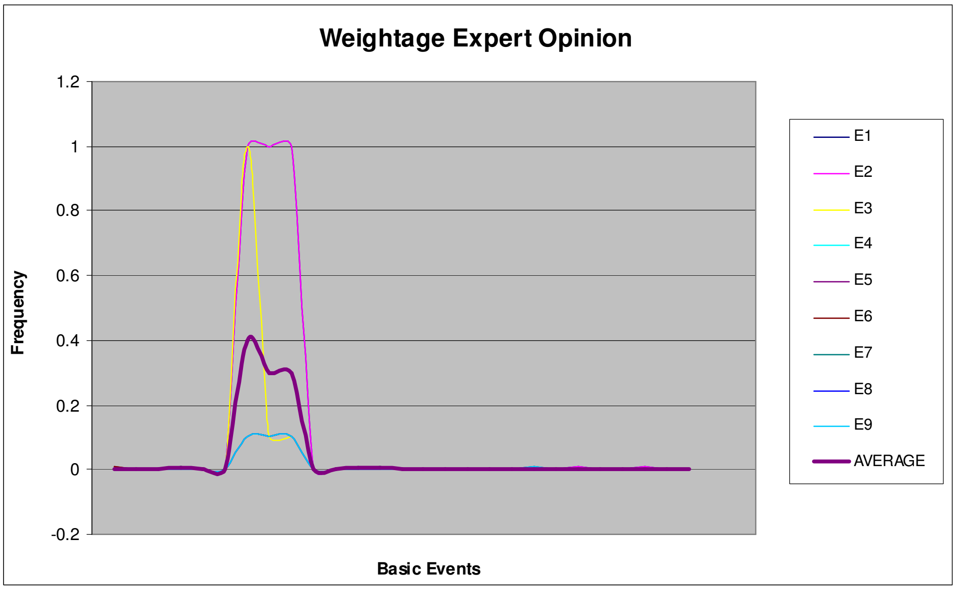

Figure E.1. Expert Opinion of EOS 2

The same procedure is repeated to the other five experts who are participated in EOS 10. Table 3 show the experts opinion for the validation framework in EOS 10. In order to give weightage to the six experts in EOS 10, the first Step is to calculate the average of each criteria in validation framework given by all the experts. The next Step is to correlate the judgments of each expert for all the criteria.

Table E.3. Result of EOS 10

No	E1	E2	E3	E4	E5	RII	AVERAGE
1a	5	5	5	5	4	0.96	4.8
1b	5	5	4	5	3	0.88	4.4
1c	3	3	4	3	5	0.72	3.6
1d	5	5	4	5	4	0.92	4.6
1e	4	3	5	4	5	0.84	4.2
1f	4	5	5	3	5	0.88	4.4
1g	4	5	5	5	5	0.96	4.8
1h	4	3	4	3	5	0.76	3.8
2a	4	3	5	3	3	0.72	3.6
2b	4	5	5	3	4	0.84	4.2
2c	4	5	5	3	4	0.84	4.2
2d	3	3	4	5	5	0.8	4
2e	4	3	4	4	3	0.72	3.6
3a	5	3	5	3	5	0.84	4.2
3b	4	5	5	3	3	0.8	4
3c	4	5	4	3	5	0.84	4.2
3d	4	3	3	3	5	0.72	3.6
4a	4	4	5	3	5	0.84	4.2
4b	4	3	5	3	5	0.8	4
4c	4	3	5	3	5	0.8	4
4d	3	3	4	5	4	0.76	3.8
4e	4	3	5	3	4	0.76	3.8
5a	5	3	5	4	5	0.88	4.4
5b	4	3	4	5	4	0.8	4
AVERAGE RII						0.82	

Table 4 shows the weightage of the six experts that have been participated for EOS 10. The highest weightage is expert no 2 whose judgments is closer to the average of all the experts opinion. Figure 2 shows the graphs of the five experts judgments and the average from all the experts for each of the criteria.

Table E.4. Weightage of Five Experts for EOS 10

Experts	Weightage	Rank
E1	0.589506	2
E2	0.691619	1
E3	0.396868	4
E4	0.446599	3
E5	0.143674	5

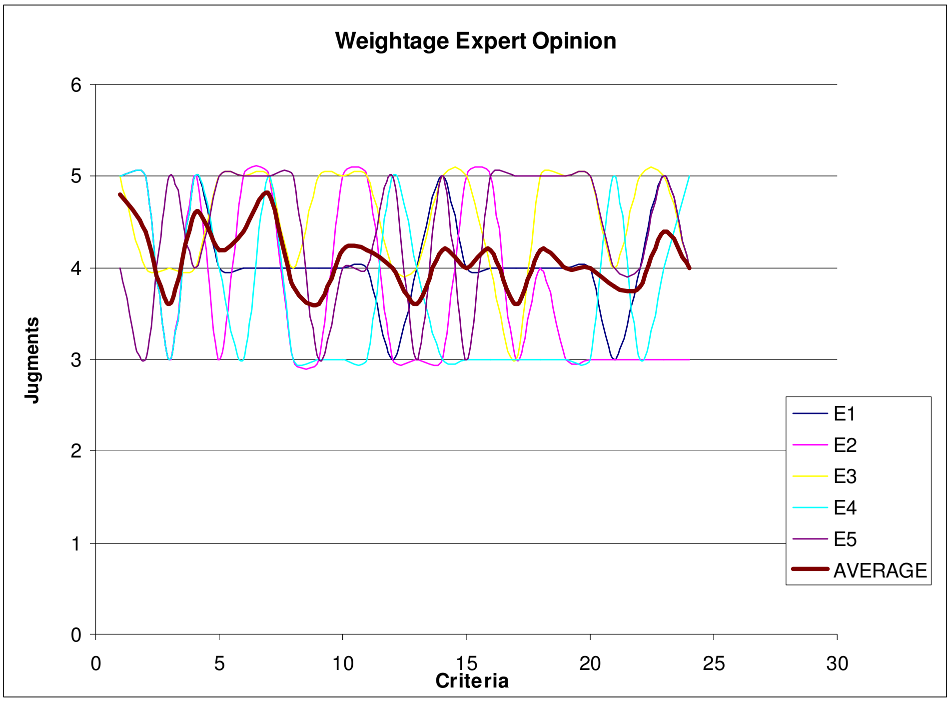

Figure E.2. Expert Opinion of EOS 10

The result of EOS 3 to 8 with nine experts is tabulated as the following. The weightage of the nine experts can be seen in Table 2.

Table E.5. Third EOS of Frequency Index for Outcomes Sequence

EVENTS MLB	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
QA	0.0001	0.0001	0.001	0.0001	0.0001	0.001	0.0001	0.001	0.001	0.0001
QB	0.0001	0.0001	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	0.0001
QC	0.0001	0.00001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.00001
QD	0.00001	0.00001	0.00001	0.00001	0.00001	0.0001	0.00001	0.0001	0.0001	0.00001

EVENTS AHF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
QA	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
QB	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	0.0001	0.0001	0.0001	0.0001
QC	0.0001	0.00001	0.0001	0.0001	0.0001	0.0001	0.00001	0.00001	0.00001	0.00001
QD	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001

EVENTS AF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
QA	0.001	0.0001	0.0001	0.0001	0.001	0.0001	0.001	0.001	0.001	0.0001
QB	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	0.001	0.0001
QC	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
QD	0.0001	0.00001	0.0001	0.00001	0.0001	0.00001	0.0001	0.0001	0.0001	0.00001

EVENTS ACF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
QA	0.0001	0.0001	0.0001	0.0001	0.001	0.0001	0.0001	0.001	0.0001	0.0001
QB	0.0001	0.001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
QC	0.0001	0.0001	0.00001	0.0001	0.00001	0.0001	0.0001	0.00001	0.0001	0.00001
QD	0.00001	0.0001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.0001	0.00001

Table E.6. Fourth EOS of Frequency Index for Class Outcomes

Outcome MLB	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
O1	5	5	5	5	5	5	5	5	5	5
O2	4	4	4	5	4	4	4	4	5	4
O3	3	3	3	3	3	3	4	3	3	3
O4	2	2	2	3	2	2	2	2	2	2
O5	0	0	0	0	0	0	0	0	0	0

Outcome AHF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
O1	5	5	5	5	5	5	5	5	5	5
O2	4	4	4	5	5	4	4	4	5	4
O3	3	3	3	4	3	3	4	3	3	3
O4	2	2	2	3	2	2	2	1	2	1
O5	0	0	0	0	0	0	0	0	0	0

Outcome AF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
O1	5	5	5	5	5	5	5	5	5	5
O2	4	4	5	3	5	4	4	4	5	3
O3	3	3	2	4	3	3	4	3	3	2
O4	2	2	3	3	3	2	2	2	2	2
O5	0	0	0	0	0	0	0	0	0	0

Outcome ACF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
O1	5	5	5	5	5	5	5	5	5	5
O2	4	4	4	5	5	4	4	4	5	4
O3	3	3	3	4	3	3	4	3	3	3
O4	2	2	2	3	2	2	2	2	2	2
O5	0	0	0	0	0	0	0	0	0	0

Table E.7. Sixth EOS Risk Criticality

Code	E1	E2	E3	E4	E5	E6	E7	E8	E9	Total Criticality Index	95th Percentile	Rank	Standard Deviation
AEC	5	4	4	5	5	5	4	4	4	40	4.00	4	0.53
DiS	4	4	4	5	5	5	3	3	3	36	3.00	19	1.58
DE	3	2	2	3	3	3	2	2	2	22	2.00	23	1.61
EFoW	3	2	2	3	3	3	2	2	2	22	2.00	23	1.54
EF	4	4	4	4	5	5	5	4	4	39	4.00	4	1.31
EWa	7	6	6	7	7	7	6	6	6	58	6.00	1	1.31
EWi	7	6	6	7	7	7	6	6	6	58	6.00	1	1.31
ECu	7	6	6	7	7	7	6	6	6	58	6.00	1	1.11
HE	5	4	4	5	5	5	4	4	4	40	4.00	4	0.83
IDC	5	4	4	5	5	5	4	4	4	40	4.00	4	0.81
IQC	5	4	4	5	5	5	4	4	4	40	4.00	4	0.81
IWMS	3	3	3	3	3	3	3	3	3	27	3.00	19	0.81
ICP	4	4	4	3	3	3	3	3	3	30	3.00	19	0.76
IMS	5	4	4	4	4	4	4	4	4	37	4.00	4	0.72
ISDS	3	3	3	3	3	4	4	4	3	30	3.00	19	0.86
IC	5	4	4	5	5	5	4	4	4	40	4.00	4	0.84
ME	3	2	2	3	3	3	2	2	2	22	2.00	23	0.85
MF	5	5	5	4	4	4	4	4	4	39	4.00	4	0.71
NH	5	4	4	5	5	5	4	4	4	40	4.00	4	0.73
PRM	4	4	4	5	4	4	4	4	4	37	4.00	4	0.74
RS	5	4	4	5	5	5	4	4	4	40	4.00	4	0.78
SC	5	4	4	5	5	5	4	4	4	40	4.00	4	0.79
UC	4	4	4	4	4	4	4	4	4	36	4.00	4	0.76

IAM	4	4	4	4	4	4	4	4	4	36	4.00	4	0.85
UE	3	2	2	3	3	3	2	2	2	22	2.00	23	0.96
WM	4	4	4	5	4	4	4	4	4	37	4.00	4	0.33

Table E.8. Seventh EOS Mitigation Measure Effectiveness

Code	R1	R2	R3	R4	R5	R6	R7	R8	R9	95th	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
	M1									M1	M2									M2
AEC	4	4	4	4	3	3	3	4	4	3.00	5	5	5	6	6	6	6	5	5	5.00
DiS	3	3	3	4	4	4	4	4	3	3.00	3	5	5	4	4	4	4	4	4	3.00
DE	4	4	4	3	5	4	4	4	4	3.00	5	5	5	4	4	4	5	5	5	4.00
EFoW	4	4	4	5	5	4	4	4	4	4.00	3	3	4	3	4	4	4	4	4	3.00
EF	4	4	5	5	5	4	3	4	4	3.00	4	4	4	5	5	5	5	5	5	4.00
EWa	5	5	5	4	4	5	5	4	4	4.00	5	5	5	4	4	4	5	5	5	4.00
EWi	5	5	5	4	4	4	3	3	4	3.00	5	5	4	4	5	5	5	5	5	4.00
ECu	4	5	5	5	5	5	5	4	4	4.00	5	5	5	4	4	5	5	5	5	4.00
HE	5	5	4	4	5	5	5	5	5	4.00	5	5	5	3	3	5	5	5	5	3.00
IDC	5	5	5	4	4	4	4	4	4	4.00	4	4	4	4	5	5	5	4	4	4.00
IQC	4	3	3	4	4	4	4	4	4	3.00	3	5	5	4	4	4	4	3	3	3.00
IWMS	5	5	4	4	4	3	3	4	4	3.00	3	3	3	4	4	4	5	5	3	3.00
ICP	5	4	4	4	4	4	4	4	3	3.00	4	4	5	5	5	5	4	4	4	4.00
IMS	4	4	4	5	5	5	4	4	4	4.00	5	5	4	4	4	5	5	5	5	4.00
ISDS	5	5	4	5	3	5	5	5	5	3.00	5	5	4	4	5	5	5	5	5	4.00
IC	5	4	4	3	5	5	5	5	5	3.00	5	5	5	4	5	5	5	5	5	4.00
ME	4	3	3	4	4	4	4	4	4	3.00	4	4	4	5	5	5	5	4	4	4.00
MF	4	4	4	5	5	5	5	5	5	4.00	4	4	4	4	5	5	4	4	4	4.00
NH	3	3	4	4	4	4	4	4	4	3.00	4	4	4	4	3	5	5	4	4	3.00
PRM	4	5	5	6	6	6	5	5	5	4.00	5	5	5	5	4	4	4	5	5	4.00
RS	3	4	4	5	5	4	4	4	4	3.00	5	5	5	5	4	4	4	5	5	4.00
SC	5	5	5	5	3	4	4	4	4	3.00	5	4	4	5	5	5	5	5	5	4.00
UC	5	5	5	5	3	3	4	4	4	3.00	4	4	5	5	5	4	4	4	4	4.00
IAM	4	4	4	4	5	5	5	4	4	4.00	3	3	4	4	4	4	3	3	3	3.00
UE	4	4	5	5	5	4	3	3	4	3.00	4	4	5	5	5	4	4	4	4	4.00
WM	5	5	5	5	6	5	5	5	5	5.00	5	3	3	3	5	5	5	5	5	3.00

Code	R1	R2	R3	R4	R5	R6	R7	R8	R9	95th
	M3									M3
AEC	3	3	3	4	4	4	4	5	5	3.00
DiS										
DE	5	5	5	4	4	3	4	4	4	3.00
EFoW	3	4	4	4	4	4	4	4	3	3.00
EF	4	4	3	3	3	4	4	4	4	3.00
EWa	4	5	5	5	4	4	4	4	4	4.00
EWi										
ECu										
HE	5	4	4	4	5	5	5	5	5	4.00
IDC	5	3	3	5	5	5	5	5	5	3.00
IQC	5	4	4	4	5	5	5	5	5	4.00
IWMS	3	3	4	4	4	4	4	4	3	3.00
ICP	5	5	4	4	4	5	5	5	5	4.00
IMS	4	4	3	3	3	5	5	4	4	3.00
ISDS	5	4	4	3	5	5	5	5	5	3.00
IC	5	5	4	4	3	4	4	4	4	3.00
ME										
MF	4	4	4	5	5	4	4	4	4	4.00
NH										
PRM	3	3	4	4	4	4	4	4	4	3.00
RS										
SC										

UC										
IAM	5	4	4	5	5	5	5	5	5	4.00
UE	5	3	3	5	5	5	5	5	5	3.00
WM	5	5	5	4	3	3	5	5	5	3.00

Code	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
	M4									M4	M5									M5
AEC	5	4	4	4	5	5	5	5	5	4.00	4	4	4	4	4	3	3	3	4	3.00
DiS																				
DE	5	5	3	3	4	4	4	4	4	3.00										
EFoW																				
EF																				
EWa																				
EWi																				
ECu																				
HE																				
IDC																				
IQC																				
IWMS	5	5	5	4	4	4	5	5	5	4.00										
ICP																				
IMS	4	4	4	4	5	5	4	4	4	4.00										
ISDS	3	3	3	4	4	3	3	3	3	3.00										
IC																				
ME																				
MF																				
NH																				
PRM	4	5	4	4	4	4	3	4	4	3.00										
RS																				
SC																				
UC																				
IAM																				
UE																				
WM	5	5	5	4	5	5	3	5	5	3.00	4	4	4	4	3	3	4	4	4	3.00

Table E.9. Eighth EOS Maintenance on the Basis of Likelihood

Level 1	Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
MLB	AF	0.333	0.33333	0.3333	0.3333	0.3333	0.3333	0.333	0.3333	0.33333	0.3333333
MLB	AHF	2	2	2	2	2	2	1	2	1	2
MLB	ACF	2	2	2	2	2	2	2	1	1	2
AF	AHF	2	2	2	2	2	2	1	2	1	2
AF	ACF	2	2	2	2	2	2	2	2	1	2
AHF	ACF	0.333	0.33333	0.3333	0.25	0.25	0.3333	0.333	0.3333	0.33333	0.3333333

MLB	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
Corrosion	Abrasion	2	2	2	2	2	3	2	2	2	2.6
Corrosion	ML Clashed	3	2	2	2	2	3	2	2	2	3
Corrosion	Collision	2	3	3	3	3	3	2	2	2	3
Abrasion	ML Clashed	2	2	2	1	1	1	1	1	2	2
Abrasion	Collision	2	2	1	2	2	2	2	2	2	2
ML Clashed	Collision	1	1	1	2	2	2	1	1	1	2

AF	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
Insuff holding	P A Breaks	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
Insuff holding	ML Clashed	2	3	3	1	2	2	2	2	2	3
Insuff holding	Collision	2	3	3	3	2	2	2	2	2	3
P A Breaks	ML Clashed	2	1	2	2	2	2	2	2	2	2
P A Breaks	Collision	3	2	2	3	3	2	1	1	1	3
ML Clashed	Collision	1	1	1	2	2	2	1	1	1	2

AHF	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
BW Failure	AHT Failure	0.5	0.5	0.3333	0.5	0.5	1	0.5	0.5	0.5	0.8

ACF	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
Corrosion	Fatigue Crack	2	2	2	3	1	1	1	1	1	2.6

Corrosion	MLB	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.25	0.5	0.5	0.5	0.5	0.5	0.333	0.3333	0.33333	0.5
CM	RTF	2	3	3	3	2	2	2	2	2	3
CM	CBM	0.333	0.33333	0.5	0.3333	0.3333	0.3333	0.333	0.3333	0.33333	0.4333333
CM	PeM	0.2	1	1	1	1	0.25	0.25	0.25	0.5	1
PM	RTF	1	1	1	2	1	1	2	2	1	2
PM	CBM	2	2	2	2	2	1	1	2	1	2
PM	PeM	1	1	0.5	0.5	0.5	0.5	0.5	0.333	0.5	1
RTF	CBM	0.2	0.2	0.3333	0.3333	0.3333	0.3333	0.333	0.2	0.2	0.3333333
RTF	PeM	0.2	0.2	0.2	0.2	0.3333	0.3333	0.25	0.25	0.25	0.3333333
CBM	PeM	0.333	0.33333	0.5	0.25	0.5	0.5	0.5	0.5	0.5	0.5

Abrasion	MLB	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.3333	0.5	0.333	0.3333	0.33333	0.5
CM	RTF	2	2	2	2	2	2	2	3	3	3
CM	CBM	0.5	0.5	0.5	0.25	0.25	0.25	0.333	0.25	0.25	0.5
CM	PeM	0.5	0.5	1	1	1	0.3333	0.333	0.5	0.5	1
PM	RTF	1	1	1	2	2	2	2	0.5	0.5	2
PM	CBM	2	2	2	0.5	1	1	1	2	2	2
PM	PeM	1	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	1
RTF	CBM	0.333	0.33333	0.25	0.25	0.25	0.25	0.25	0.3333	0.33333	0.3333333
RTF	PeM	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
CBM	PeM	0.333	0.33333	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

ML Clashed	MLB	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3333	0.33333	0.5
CM	RTF	2	1	1	2	2	2	2	2	2	2
CM	CBM	0.333	0.33333	0.3333	0.3333	0.3333	0.25	0.5	0.3333	0.33333	0.4333333
CM	PeM	0.5	0.5	0.5	0.5	1	1	1	1	1	1
PM	RTF	2	2	1	1	1	1	1	1	1	2
PM	CBM	1	1	1	1	1	0.5	0.5	0.5	0.5	1
PM	PeM	3	2	2	1	2	2	2	2	1	2.6
RTF	CBM	0.333	0.33333	0.3333	0.25	0.25	0.25	0.25	0.3333	0.33333	0.3333333
RTF	PeM	0.25	0.25	0.3333	0.3333	0.3333	0.25	0.25	0.25	0.25	0.3333333
CBM	PeM	0.333	0.33333	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Collision	MLB	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.25	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.8
CM	RTF	2	2	2	2	2	2	1	1	1	2
CM	CBM	0.5	0.33333	0.3333	0.5	0.3333	0.3333	0.333	0.3333	0.33333	0.5
CM	PeM	1	1	1	1	1	1	0.5	0.5	0.5	1
PM	RTF	1	1	1	1	1	1	1	1	2	1.6
PM	CBM	0.5	0.5	0.5	0.5	1	1	1	1	1	1
PM	PeM	2	2	2	2	2	2	1	1	1	2
RTF	CBM	0.333	0.33333	0.3333	0.3333	0.3333	0.3333	0.25	0.3333	0.33333	0.3333333
RTF	PeM	0.25	0.25	0.3333	0.3333	0.3333	0.3333	0.25	0.25	0.25	0.3333333
CBM	PeM	0.5	0.5	0.5	0.25	0.5	0.5	0.5	0.5	0.5	0.5

Insuff holding	AF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	1	1	1	1	0.5	0.5	0.5	0.5	0.5	1
CM	RTF	2	2	2	2	2	1	1	1	1	2
CM	CBM	1	1	1	0.5	0.5	0.5	0.5	1	1	1

CM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PM	RTF	2	2	2	1	1	1	1	1	1	2
PM	CBM	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8
PM	PeM	3	3	3	2	2	2	2	2	2	3
RTF	CBM	0.5	0.5	0.25	0.5	0.5	0.5	0.5	0.5	0.5	0.5
RTF	PeM	0.333	0.33333	0.3333	0.3333	0.3333	0.3333	0.333	0.3333	0.33333	0.3333333
CBM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.333	0.3333	0.5	0.5

P A Breaks	AF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	1	1	1	1	1	1	0.5	0.5	0.5	1
CM	RTF	1	1	2	2	2	1	1	1	1	2
CM	CBM	0.5	1	1	1	1	1	1	1	0.5	1
CM	PeM	1	0.33333	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8
PM	RTF	1	2	1	1	1	1	1	1	2	2
PM	CBM	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1
PM	PeM	2	2	2	2	2	2	2	3	2	2.6
RTF	CBM	0.333	0.33333	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
RTF	PeM	0.25	0.25	0.3333	0.5	0.5	0.5	0.333	0.3333	0.33333	0.5
CBM	PeM	0.333	1	0.5	0.5	0.5	0.5	0.5	0.3333	0.5	0.8

ML Clashed	AF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.3333	0.3333	0.5	0.5	0.5	0.33333	0.5
CM	RTF	1	2	2	2	2	2	2	2	2	2
CM	CBM	0.333	0.5	0.3333	0.3333	0.3333	0.3333	0.333	0.3333	0.33333	0.4333333
CM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1
PM	RTF	2	2	1	1	1	1	2	1	1	2
PM	CBM	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1
PM	PeM	1	2	2	1	2	2	2	2	2	2
RTF	CBM	0.25	0.25	0.25	0.3333	0.25	0.25	0.25	0.3333	0.33333	0.3333333
RTF	PeM	0.25	0.25	0.25	0.3333	0.3333	0.25	0.25	0.25	0.25	0.3333333
CBM	PeM	0.333	0.33333	0.3333	0.5	0.5	0.3333	0.5	0.5	0.5	0.5

Collision	AF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.8
CM	RTF	2	1	1	1	1	1	2	2	2	2
CM	CBM	0.333	0.33333	0.3333	0.3333	0.5	0.5	0.5	0.5	0.33333	0.5
CM	PeM	1	1	1	1	1	1	1	0.5	0.5	1
PM	RTF	2	2	1	1	1	1	1	1	0.5	2
PM	CBM	0.5	0.5	1	0.5	1	1	1	1	1	1
PM	PeM	1	1	1	2	2	2	2	1	1	2
RTF	CBM	0.25	0.33333	0.3333	0.3333	0.3333	0.3333	0.5	0.3333	0.33333	0.4333333
RTF	PeM	0.333	0.33333	0.3333	0.25	0.3333	0.3333	0.333	0.25	0.25	0.3333333
CBM	PeM	0.5	0.5	0.5	0.5	0.5	0.3333	0.333	0.3333	0.33333	0.5

BW Failure	AHF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0.8
CM	RTF	2	2	2	2	2	1	1	1	1	2
CM	CBM	0.333	0.33333	0.5	0.5	0.3333	0.3333	0.333	0.5	0.5	0.5
CM	PeM	1	1	1	1	1	0.5	0.5	0.5	0.33333	1
PM	RTF	1	1	0.5	0.5	1	2	2	2	1	2
PM	CBM	1	0.5	0.5	0.5	0.5	1	1	1	0.5	1
PM	PeM	0.333	0.33333	0.5	0.5	0.5	0.25	0.25	0.25	0.25	0.5
RTF	CBM	0.25	0.25	0.3333	0.25	0.25	0.25	0.5	0.3333	0.33333	0.4333333
RTF	PeM	0.5	0.25	0.3333	0.3333	0.3333	0.3333	0.333	0.3333	0.33333	0.4333333
CBM	PeM	0.5	0.33333	0.3333	0.3333	0.3333	0.5	0.5	0.5	0.5	0.5

AHT Failure	AHF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	1	1	1	1	1	1

CM	RTF	0.5	2	2	2	2	1	1	1	0.5	2
CM	CBM	1	1	1	1	1	1	0.5	0.5	1	1
CM	PeM	0.333	0.33333	0.3333	0.3333	1	1	0.5	0.5	0.5	1
PM	RTF	2	2	1	1	1	1	1	1	1	2
PM	CBM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
PM	PeM	2	2	2	1	3	3	2	2	2	3
RTF	CBM	0.5	0.5	0.5	0.5	0.5	0.3333	0.333	0.3333	0.33333	0.5
RTF	PeM	0.333	0.33333	0.3333	0.3333	0.3333	0.5	0.5	0.3333	0.33333	0.5
CBM	PeM	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8

Corrosion	ACF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3333	0.33333	0.5
CM	RTF	2	1	2	2	2	2	2	2	2	2
CM	CBM	0.333	0.33333	0.3333	0.3333	0.3333	0.5	0.333	0.3333	0.33333	0.4333333
CM	PeM	1	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1
PM	RTF	1	1	1	2	1	1	1	1	1	1.6
PM	CBM	2	2	2	1	1	2	1	1	1	2
PM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
RTF	CBM	0.25	0.25	0.3333	0.3333	0.3333	0.3333	0.333	0.25	0.25	0.3333333
RTF	PeM	0.2	0.2	0.2	0.2	0.3333	0.3333	0.333	0.3333	0.33333	0.3333333
CBM	PeM	0.333	0.5	0.5	0.5	0.5	0.5	0.5	0.3333	0.5	0.5

Fatigue Crack	ACF	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1
CM	RTF	1	1	1	1	2	2	2	2	2	2
CM	CBM	1	1	1	1	1	1	0.5	0.5	0.5	1
CM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.8
PM	RTF	2	1	1	1	1	1	1	2	2	2
PM	CBM	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8
PM	PeM	2	2	2	2	2	3	3	3	2	3
RTF	CBM	0.333	0.33333	0.3333	0.5	0.5	0.5	0.5	0.3333	0.33333	0.5
RTF	PeM	0.2	0.5	0.5	0.5	0.25	0.25	0.333	0.3333	0.33333	0.5
CBM	PeM	0.5	0.5	0.5	0.5	0.3333	0.3333	0.5	0.5	0.5	0.5

Table E.10. Ninth EOS Maintenance on the Basis of Consequence

Level 1	Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
People	Environment	4	4	3	3	3	4	4	4	3	4
People	Assets	3	3	4	4	4	4	4	4	4	4
People	Reputation	3	3	3	4	4	4	3	3	3	4
People	Cost	4	3	3	3	3	3	4	4	4	4
Environment	Assets	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.8
Environment	Reputation	2	3	2	2	2	2	2	3	3	3
Environment	Cost	0.5	0.5	0.5	1	1	1	1	1	1	1
Assets	Reputation	1	1	1	1	2	2	2	1	2	2
Assets	Cost	1	1	1	1	1	1	2	2	2	2
Reputation	Cost	0.5	0.5	0.5	1	1	0.5	0.5	0.5	0.5	1

People	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
Safety	Health	1	1	2	2	1	1	2	2	1	2

Environment	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
External	Internal	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	0.8

Assets	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
Direct	Indirect	3	3	3	4	4	3	3	4	4	4

Reputation	Sub Criteria	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
Performance	Quality Service	2	1	1	1	1	1	1	1	2	2

Safety	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.3333	0.3333	0.333	0.333	0.333	0.333	0.3333	0.3333	0.4333333
CM	RTF	2	2	2	3	2	2	2	2	2	2.6
CM	CBM	0.33333	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8
CM	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.333	0.2	0.2	0.3333333
PM	RTF	3	3	3	3	3	3	3	4	3	3.6
PM	CBM	1	2	2	2	1	1	1	2	2	2
PM	PeM	0.5	0.5	0.5	0.5	0.5	1	0.5	0.5	0.5	0.8
RTF	CBM	0.5	0.5	0.5	0.5	0.333	0.333	0.333	0.3333	0.3333	0.5
RTF	PeM	0.2	0.2	0.2	0.2	0.333	0.333	0.333	0.3333	0.3333	0.3333333
CBM	PeM	0.5	0.5	0.5	0.333	0.333	0.5	0.5	0.5	0.5	0.5

Health	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	2	3	3	3	3	2	2	3	3	3
CM	RTF	1	2	2	2	2	2	2	2	2	2
CM	CBM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CM	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.333	0.3333	0.2	0.3333333
PM	RTF	2	3	3	3	3	3	3	3	3	3
PM	CBM	1	1	1	1	2	1	2	2	1	2
PM	PeM	0.5	0.5	0.5	0.5	1	1	0.5	0.5	0.5	1
RTF	CBM	0.5	0.5	0.3333	0.5	0.5	0.5	0.5	0.3333	0.3333	0.5
RTF	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.2	0.2	0.2	0.3333333
CBM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5	0.8

External	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.333	0.333	0.333	0.3333	0.3333	0.5
CM	RTF	1	1	1	2	2	2	2	2	2	2
CM	CBM	0.5	0.5	0.5	0.5	0.333	0.333	1	0.5	0.5	0.8
CM	PeM	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8
PM	RTF	3	3	2	3	3	3	3	3	3	3
PM	CBM	2	2	3	3	3	3	3	3	3	3
PM	PeM	1	1	1	0.5	0.5	0.5	0.5	1	1	1
RTF	CBM	1	1	1	0.5	1	0.5	0.5	0.5	0.5	1
RTF	PeM	0.33333	0.3333	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CBM	PeM	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8

Internal	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.25	0.25	0.5
CM	RTF	1	1	1	1	0.5	0.5	0.5	1	1	1
CM	CBM	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1
CM	PeM	0.5	1	0.5	0.5	0.5	0.5	0.5	1	0.5	1
PM	RTF	3	3	2	2	2	2	2	3	3	3
PM	CBM	3	3	3	2	2	2	2	2	2	3
PM	PeM	0.5	0.5	1	1	1	1	1	1	1	1
RTF	CBM	0.5	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	0.8
RTF	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CBM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.8

Direct	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.333	0.333	0.333	0.3333	0.3333	0.5
CM	RTF	1	2	3	2	2	2	2	2	2	2.6
CM	CBM	0.5	0.5	0.5	0.5	0.333	0.333	0.333	0.3333	0.3333	0.5
CM	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.5	0.333	0.3333	0.3333	0.4333333
PM	RTF	3	3	3	3	3	4	3	3	3	3.6
PM	CBM	2	2	1	3	2	1	2	2	1	2.6
PM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.333	0.5	0.5	0.5
RTF	CBM	0.5	0.5	0.5	0.25	0.333	0.333	0.333	0.3333	0.3333	0.5
RTF	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.333	0.25	0.25	0.3333333

CBM	PeM	0.5	0.5	0.5	0.333	0.333	0.333	0.333	0.5	0.5	0.5

Indirect	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CM	RTF	1	1	2	2	2	2	2	2	2	2
CM	CBM	0.5	0.5	0.5	0.333	0.5	0.5	0.5	0.5	0.5	0.5
CM	PeM	0.5	0.5	0.5	0.333	0.5	1	0.5	0.5	0.5	0.8
PM	RTF	3	2	3	3	2	2	3	3	3	3
PM	CBM	2	1	2	1	2	1	1	1	1	2
PM	PeM	0.33333	0.3333	1	0.5	0.5	0.5	0.5	0.5	0.5	0.8
RTF	CBM	1	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5	1
RTF	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.5	0.5	0.5	0.5	0.5
CBM	PeM	0.5	0.3333	0.3333	0.5	0.5	0.5	0.5	0.5	1	0.8

Performance	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.333	0.25	0.25	0.3333333
CM	RTF	3	2	2	2	2	2	3	3	2	3
CM	CBM	0.33333	0.3333	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CM	PeM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.333	0.2	0.2	0.3333333
PM	RTF	3	3	3	3	3	3	3	3	3	3
PM	CBM	2	2	2	2	1	1	1	1	1	2
PM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
RTF	CBM	0.33333	0.3333	0.3333	0.333	0.333	0.333	0.333	0.5	0.5	0.5
RTF	PeM	0.2	0.2	0.2	0.2	0.25	0.333	0.333	0.3333	0.3333	0.3333333
CBM	PeM	0.5	0.5	0.5	0.333	0.333	0.333	0.333	0.5	0.5	0.5

Quality Service	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	0.33333	0.3333	0.3333	0.333	0.333	0.5	0.25	0.3333	0.3333	0.4333333
CM	RTF	2	2	2	2	2	2	3	2	2	2.6
CM	CBM	1	0.25	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8
CM	PeM	0.33333	0.3333	0.3333	0.25	0.25	0.333	0.333	0.3333	0.3333	0.3333333
PM	RTF	3	3	3	3	3	2	3	3	3	3
PM	CBM	2	2	2	1	1	2	2	2	2	2
PM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
RTF	CBM	0.5	0.5	0.5	0.5	0.333	0.333	0.333	0.3333	0.3333	0.5
RTF	PeM	0.2	0.25	0.25	0.25	0.25	0.2	0.333	0.3333	0.3333	0.3333333
CBM	PeM	0.5	0.5	0.5	0.5	0.5	0.5	0.333	0.5	0.3333	0.5

Cost	Alternatives	E1	E2	E3	E4	E5	E6	E7	E8	E9	95th
CM	PM	3	2	2	2	2	2	2	2	2	2.6
CM	RTF	0.5	0.5	0.3333	0.333	0.333	0.333	0.333	0.3333	0.3333	0.5
CM	CBM	1	1	2	1	2	2	2	2	2	2
CM	PeM	3	3	3	3	3	3	3	3	4	3.6
PM	RTF	0.33333	0.3333	0.3333	0.333	0.25	0.25	0.25	0.25	0.25	0.3333333
PM	CBM	0.5	0.5	0.5	0.333	0.5	1	0.5	0.5	0.5	0.8
PM	PeM	1	1	1	1	1	2	1	2	1	2
RTF	CBM	3	3	3	3	4	3	4	4	4	4
RTF	PeM	4	4	4	4	3	4	4	4	4	4
CBM	PeM	2	2	2	2	3	2	2	2	2	2.6

APPENDIX F

DPL Software Output

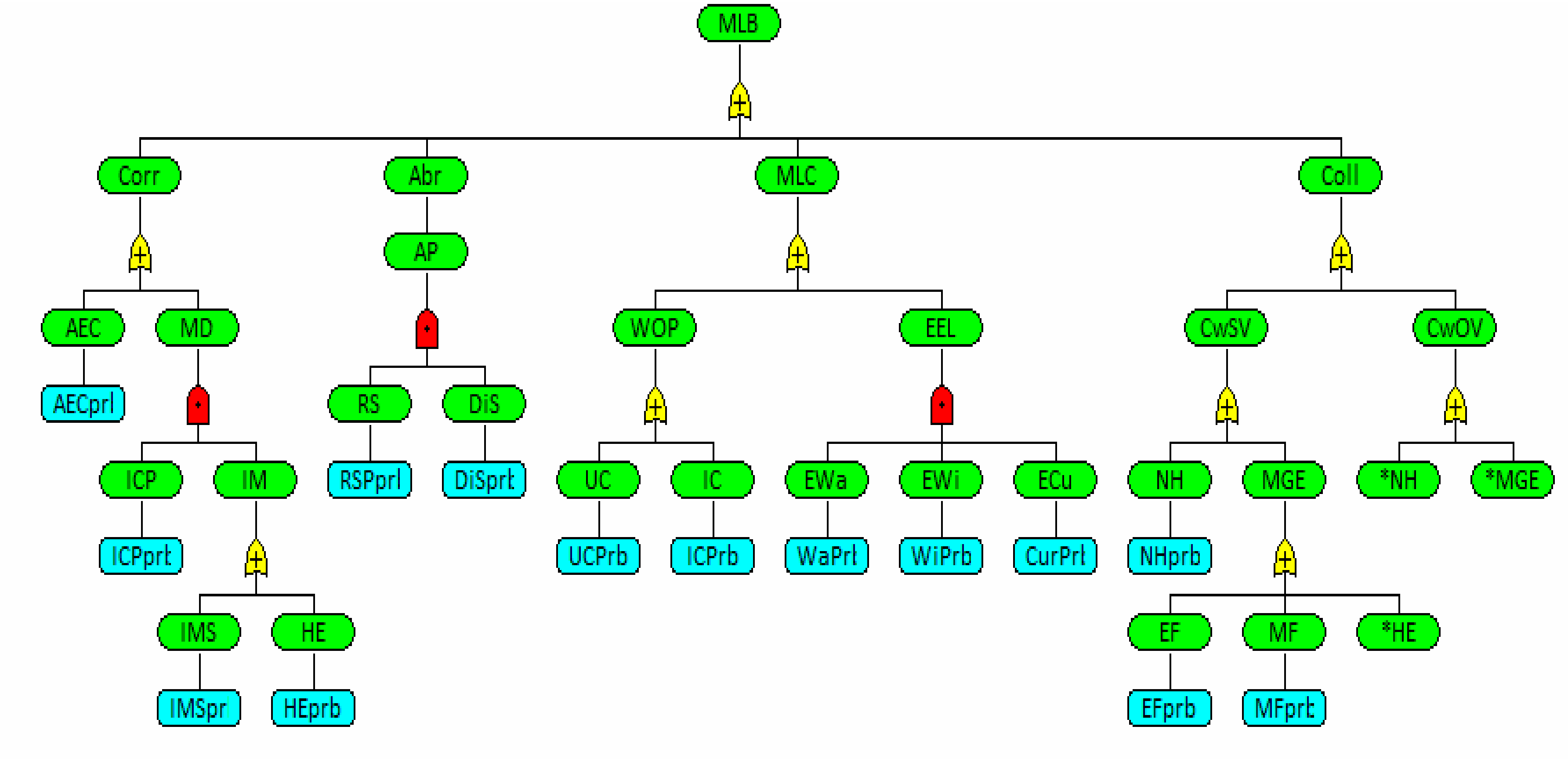

Figure F.1. Fault Tree Diagram of MLB

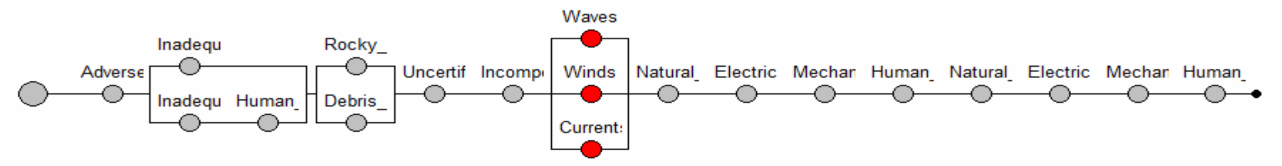

Figure F.2. Cut Set of MLB

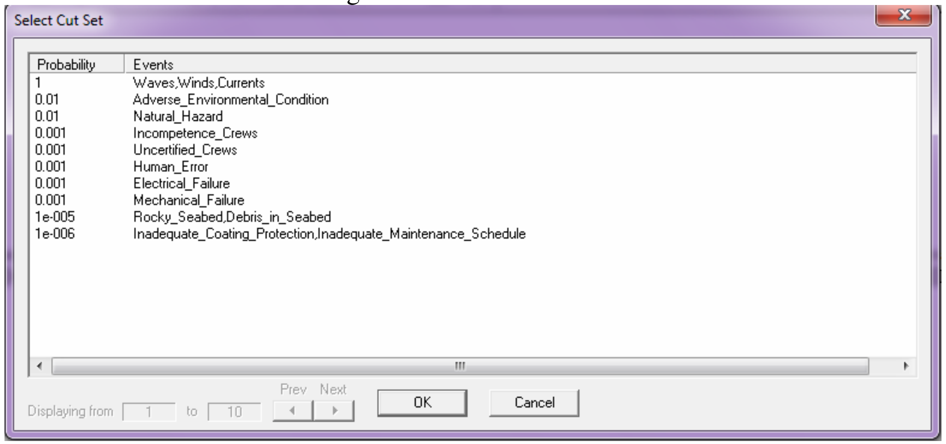

Figure F.3. Results of Minimal Cut Sets of MLB

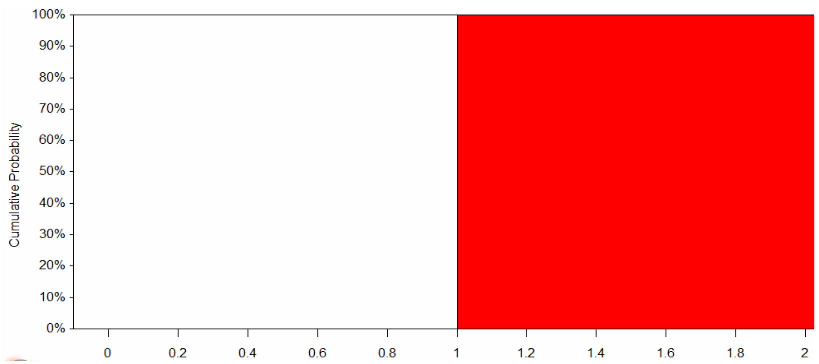

Figure F.4. Risk Profile Chart of MLB

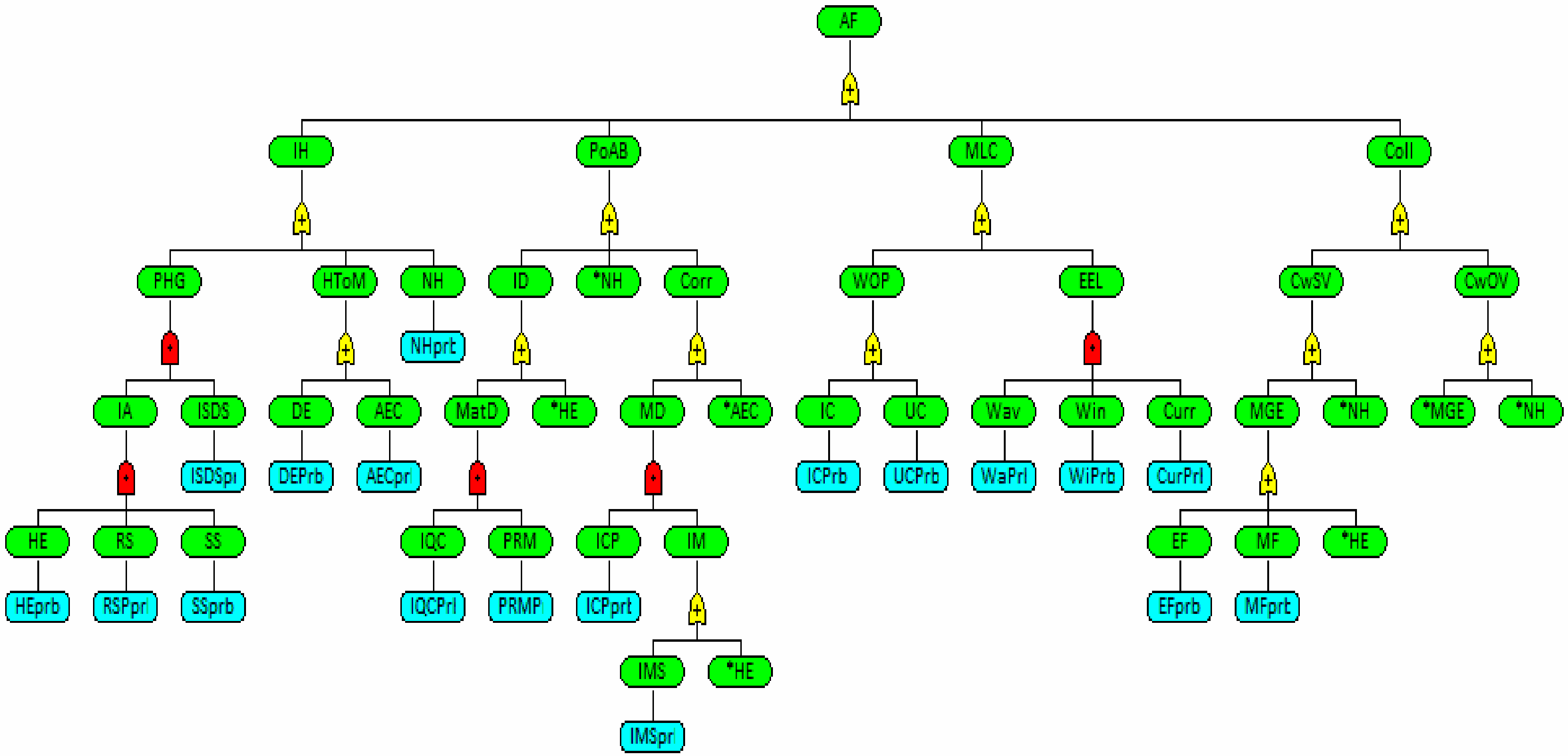

Figure F.5. Fault Tree Diagram of AF

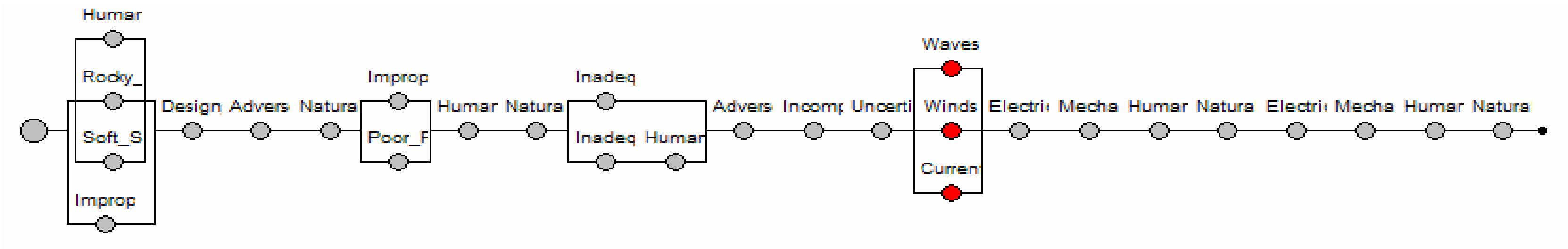

Figure F.6. Cut Set of AF

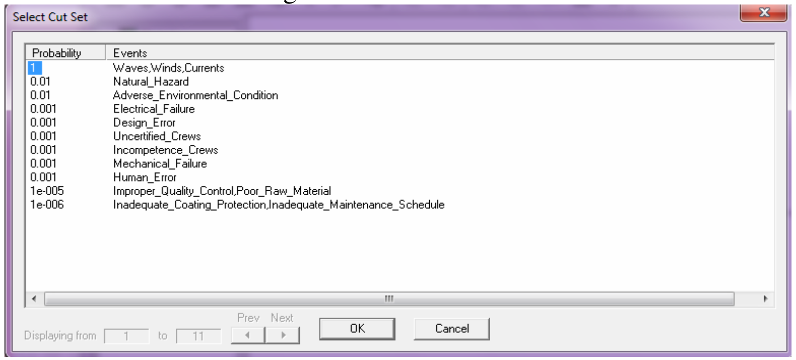

Figure F.7. Results of Minimal Cut Sets of AF

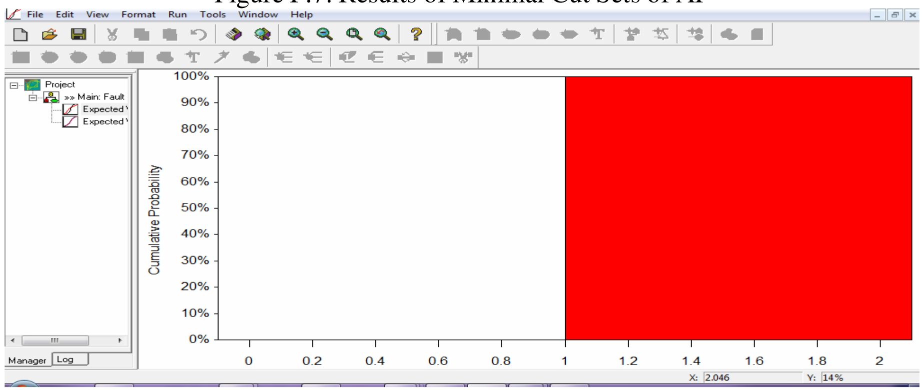

Figure F.8. Risk Profile Chart of AF

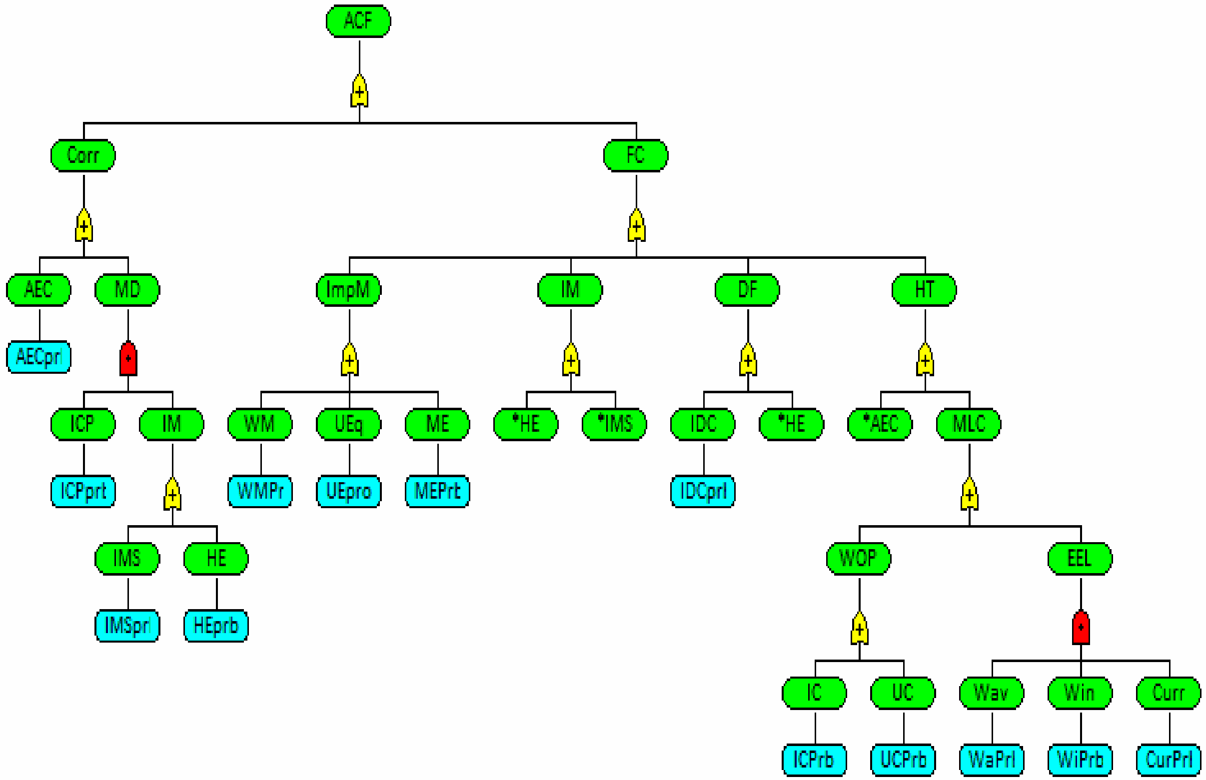

Figure F.9. Fault Tree Diagram of ACF

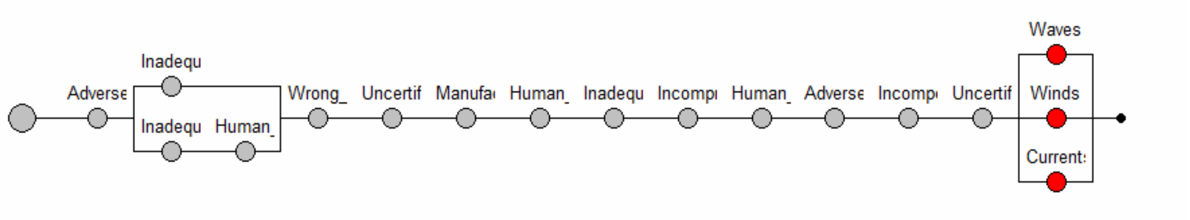

Figure F.10. Cut Set of ACF

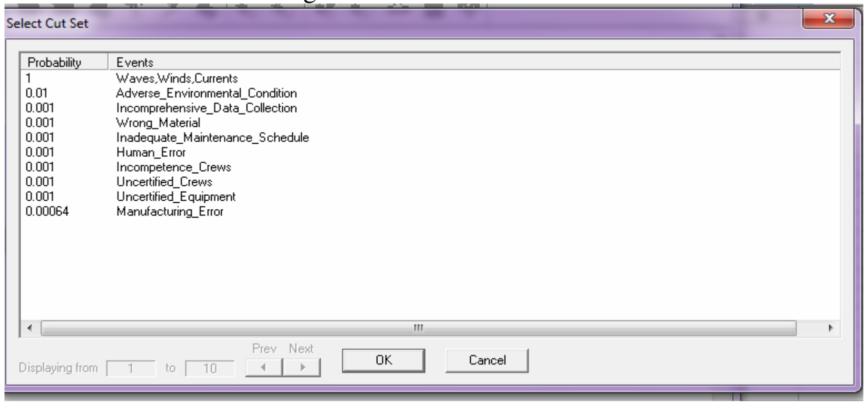

Figure F.11. Results of Minimal Cut Sets of ACF

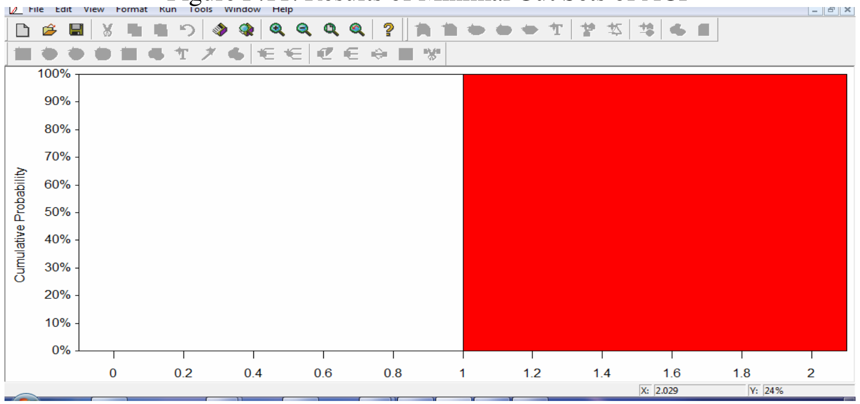

Figure F.12. Risk Profile Chart of ACF

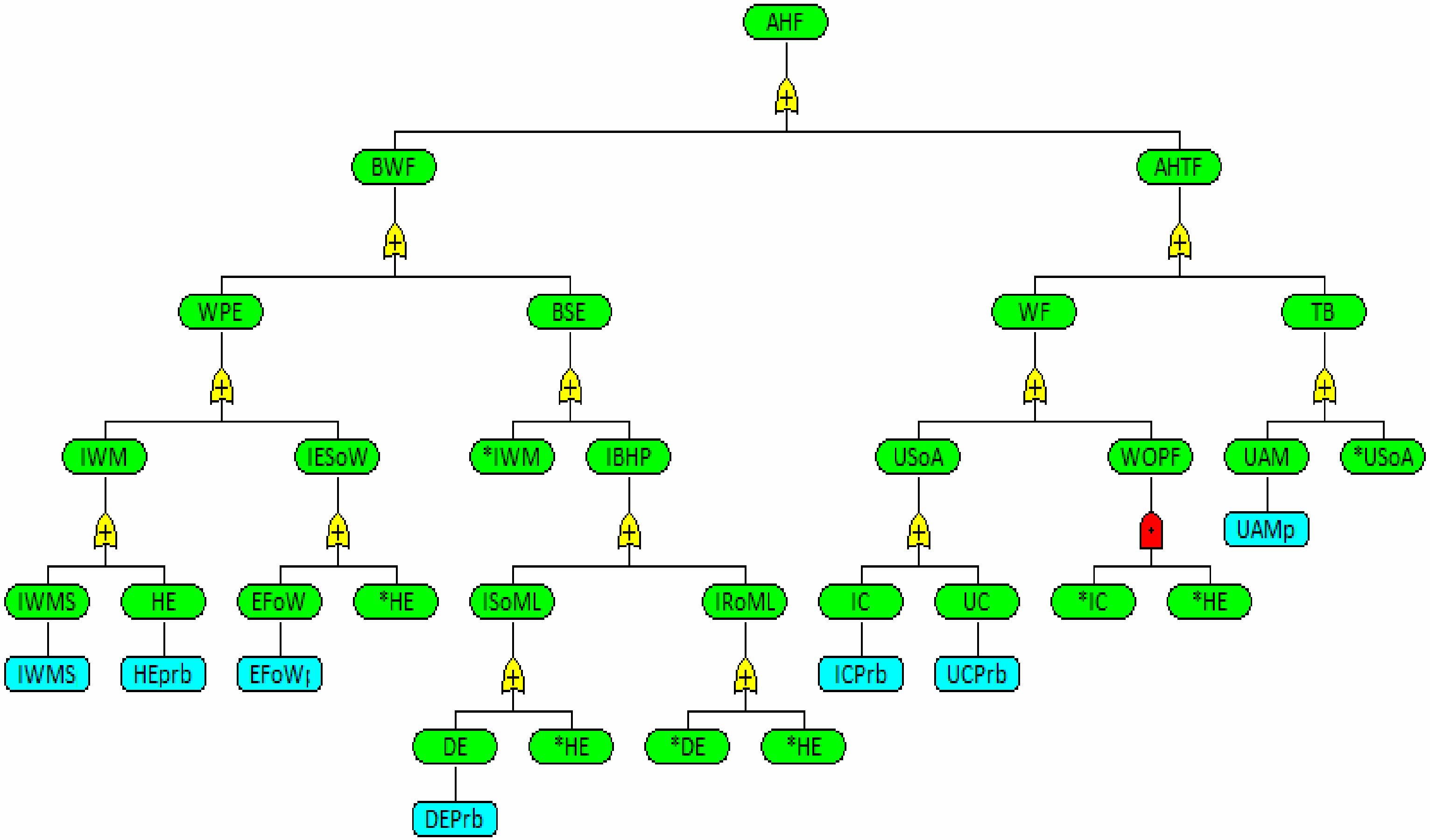

Figure F.13. Fault Tree Diagram of AHF

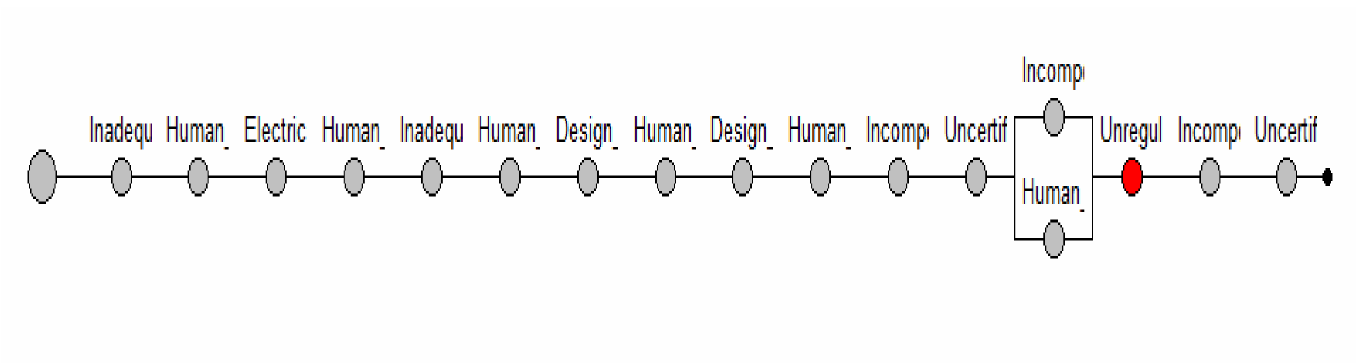

Figure F.14. Cut Set of AHF

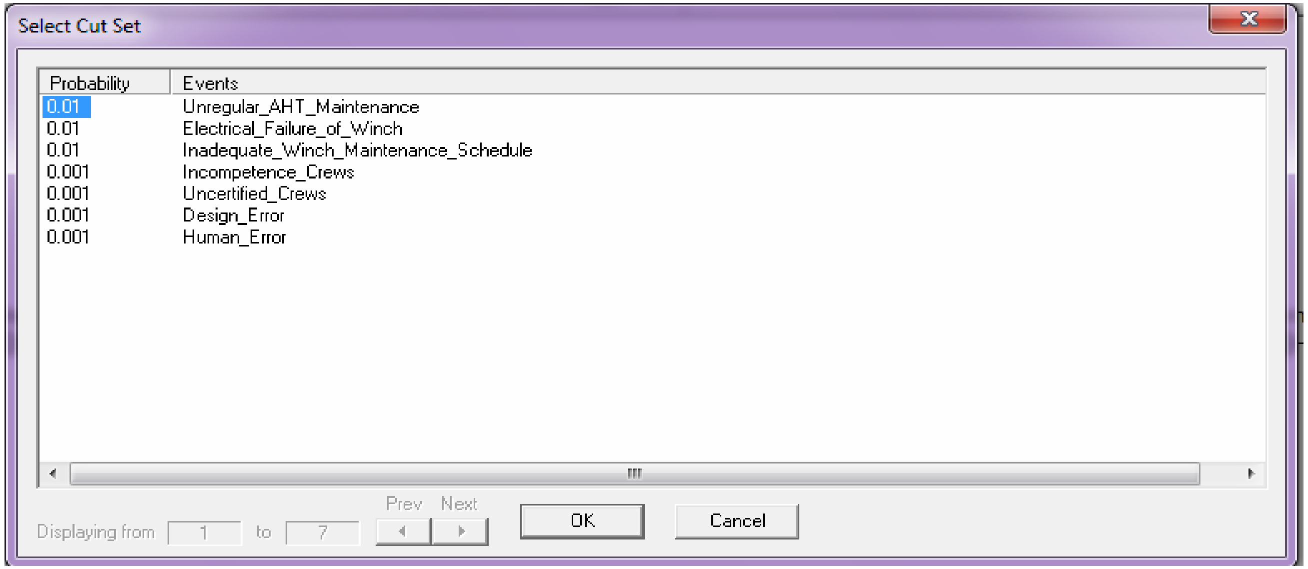

Figure F.15. Results of Minimal Cut Sets of AHF

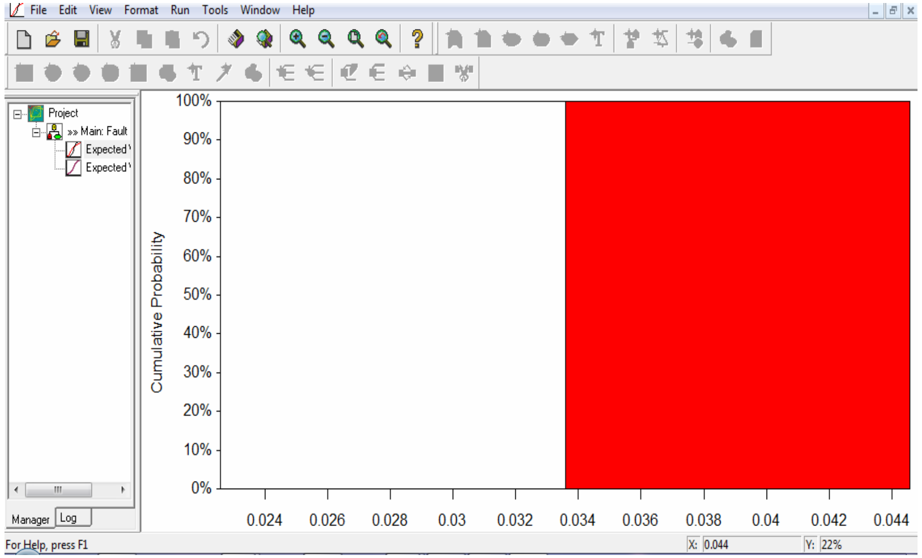

Figure F.16. Risk Profile Chart of AHF

APPENDIX G
Validation Questionnaire

HAZOP (HAZARD OPERABILITY)

HAZOP is helpful to identify and evaluate risk related to accidents/incidents in mooring system. HAZOP in terms of MIVTA framework is described in Figure G.1 followed with the HAZOP result that has been accomplished.

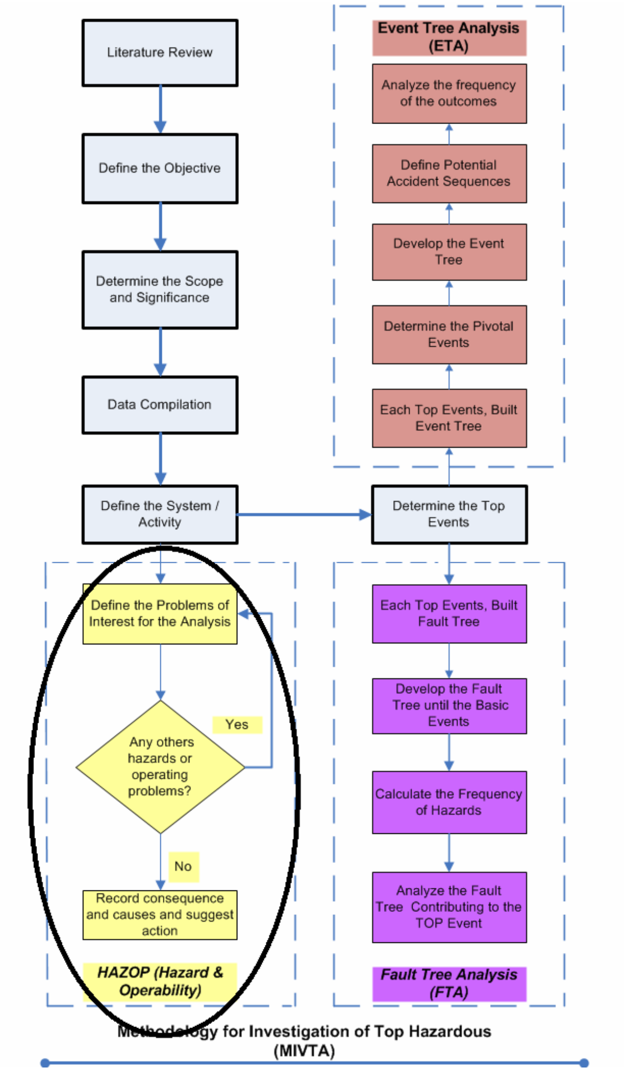

Figure G.1. HAZOP Framework

Table G.1 shows the HAZOP result for mobile mooring system **(Validity to be asked).**

Table G.1. HAZOP Result

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
Mooring Line	Unable to control the movement	Mooring Line Breakage	Corrosion	➢ Reduced the mooring capacities for example the moorings no longer meet their allowable loads ➢ Decrease the mooring line service life ➢ Broken wires ropes	➢ Uses heavier zinc coating to enhance corrosion protection properties ➢ The larger diameters of wires may use heavier zinc coatings to enhance the attainable design life ➢ An anti corrosion blocking compound should be applied during manufacture to increase corrosion prevention measure. ➢ Regular maintenance and inspection in order to avoid huge damage.	➢ Conduct visual inspection for example pitting inspection in order to determine the remaining life of the chain. ➢ Perform corrosion measurement using ROV to measure corrosion potential
			Abrasion	Decrease the service life of mooring lines	Uses braided jacket or sheathed spiral strand wire to minimize particle ingression that cause harmful abrasion of the ropes.	➢ In situ water inspection is needed to inspect the touchdown zone where rocks or debris on the sea bed can cause mooring line abrasion ➢ In situ water inspection of wire rope using ROV
			Mooring line clashed	➢ Operation activities delayed ➢ Vessel damage	Uses a mooring failure detector that can be attach with mooring chain or wire rope inculdes a power source which supply power to a transmitter to signal the failure by acoustic or radio frequency means.	ROV inspection in order to identify if the lines are intact and or suffer of breakage using inclinometers
			Collision	➢ Operation shutdown ➢ Vessel damage	➢ Checking the ARPA radar ➢ Checking the day vision radar	➢ Monitored the radar plant as a navigational aid and for weather surveillance in order to detect and to track weather fronts, storm clouds

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
						➢ Observe the radar with antenna arrays to define the anchor location match with target acquisition
Anchor	Loss of position	Anchor Failure	Insufficient holding	➢ Unable to penetrate at certain depth ➢ Incapable to provide sufficient resistance of applied load	Check as well all monitoring equipment before start the activities & make good coordination with project people	Checking and monitoring the equipment with Remotely Operated Vehicle (ROV)
			Part of anchor breaks	➢ Unable to hold the vessel on location ➢ The vessel moves or even breakaway	➢ Conduct NDT test on anchor in order to define flaws ➢ Awareness of extreme environmental condition especially in deep anchorages when to consider anchor and evacuate the anchorage	Monitoring of current weather conditions in order to maintain the safety of anchored vessels
			Mooring line clashed	➢ Operation activities delayed ➢ Vessel damage	Uses a mooring failure detector that can be attach with mooring chain or wire rope inculdes a power source which supply power to a transmitter to signal the failure by acoustic or radio frequency means.	ROV inspection in order to identify if the lines are intact and or suffer of breakage using inclinometers
			Collision	➢ Operation shutdown ➢ Vessel damage	➢ Checking the ARPA radar ➢ Checking the day vision radar	➢ Monitored the radar plant as a navigational aid and for weather surveillance in order to detect and to track weather fronts, storm clouds ➢ Observe the radar with antenna arrays to define the anchor location match with target acquisition
Mooring winches	Uable to shifting,	Winch handling failure	Barge Winch Failure	➢ Disruption of operations ➢ Damage or harm to life	Record and monitor the stability of vessel	Checking various parameters that effect the stability of the vessel

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
	holding & positioning			➢ Damage nearby installations		through stability control console such as pipe tension, anchor winch tension etc.
Anchor Handling Tugs (AHT)	Misconfiguration work	Anchor handling failure	Anchor Handling Tugs Failure	Unable to configure the working pipe lay	Radio and navigational warnings should be given to other traffic to keep safely away from the construction activities.	The positions of the AHT should be monitored when handling anchors, in order to ensure that they fulfill with the anchoring requirements in general and that lowering of an anchor does not start until the AHT is at the approved location.
Appurtenances Connection	Unable to connect together the main mooring line components	Appurtenances connection failure	Corrosion	➢ Reduced the connection equipment capacities for example the connecting no longer meet their allowable loads ➢ Decrease the connecting equipment service life ➢ Connecting equipment broken	➢ Uses heavier zinc coating to enhance corrosion protection properties ➢ The larger diameters of wires may use heavier zinc coatings to enhance the attainable design life ➢ An anti corrosion blocking compound should be applied during manufacture to increase corrosion prevention measure. ➢ Regular maintenance and inspection in order to avoid huge damage.	➢ Conduct visual inspection for example pitting inspection in order to determine the remaining life of the chain. ➢ Perform corrosion measurement using ROV to measure corrosion potential.

System Identification: Semi Submersible Column Stabilized Pipe Lay Barge						
Activity: Moor the vessel in a working pipe lay configuration						
Component	Guide Word	Deviation	Potential Causes	Possible Consequence	Safeguard	Action
			Fatigue Cracking	➢ Crack of connecting equipment such as shackles, swivels. ➢ Decrease the serviceability of the appurtenance connection such as shackle, ➢ The vessel breakaway	➢ All the arrangements for appurtenance connections should be strong enough and capable to endure fatigue loading over the life design and beyond ➢ Regular maintenance and inspection in order to avoid huge damage	➢ Conduct break testing to detect the presence of any fatigue cracks by doing magnetic particle inspection (MPI) ➢ Checking & monitoring the equipment with Remotely Operated Vehicle (ROV)

1. **<u>Questions with regards to HAZOP approach.</u>**

Please Bold/Underline the scale that indicates how much you agree or disagree with each of the following statements based on Table G.1.

No	Statement	Likert Scale				
		Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
		1	2	3	4	5
1a	Anchor is one of the main components of mobile mooring system	1	2	3	4	5
1b	Mooring line is one of the main components of mobile mooring system	1	2	3	4	5
1c	Anchor Handling Tugs is one of the main components of mobile mooring system	1	2	3	4	5
1d	Appurtenances Connections is one of the main components of mobile mooring system	1	2	3	4	5
1e	The information gathered in HAZOP as preliminary risk analysis is sufficient	1	2	3	4	5
1f	The HAZOP approach for mobile mooring system is systematic	1	2	3	4	5
1g	The HAZOP framework for mobile mooring system are easily to understand	1	2	3	4	5
1h	The HAZOP framework for mobile mooring system has identified all the factors sufficiently	1	2	3	4	5

FTA (Fault Tree Analysis)

FTA is a deductive method that is useful to generate the potential causes of mooring system failure into undesired events. FTA in terms of MIVTA framework is described in Figure G.2 followed with the FTA result that has been accomplished.

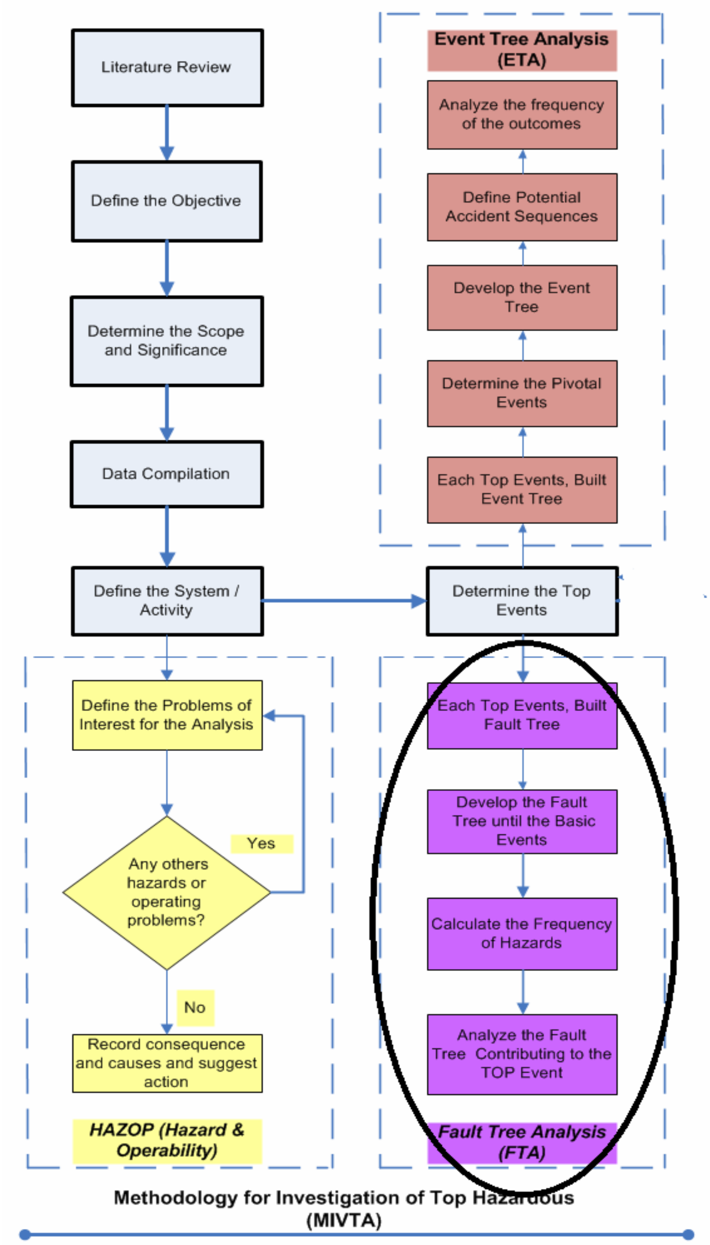

Figure G.2. FTA in terms of MIVTA Framework

Figure G.3 - G.6 shows the FTA mobile mooring system consist of mooring line breakage (MLB) namely G.3a - G.3e, anchor failure (AF) namely G.4a - G.4e, appurtenance connections failure (ACF) namely G.5a - G.5c and anchor handling failure (AHF) namely G.6a - G.6d. **(Validity to be asked).**

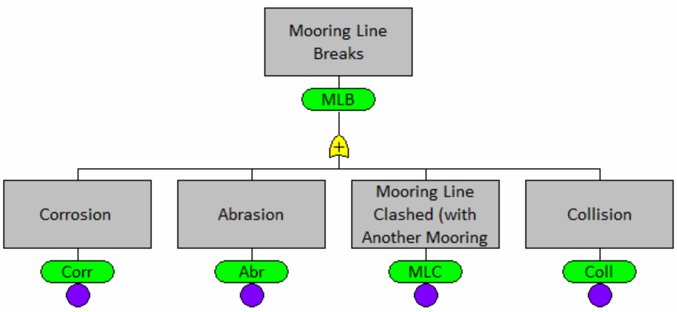

Figure G.3a. FT Model Mooring Line Breakage (MLB)

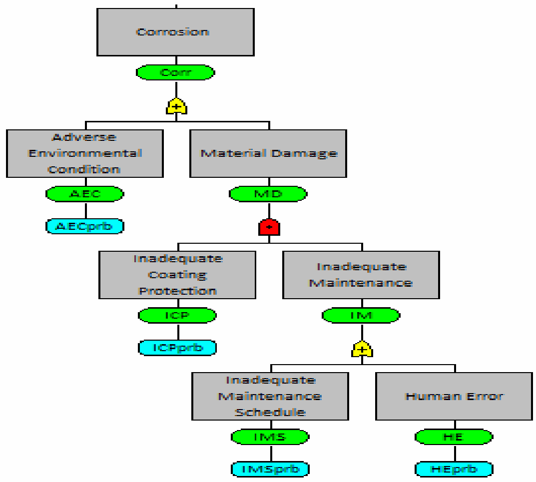

Figure G.3b. FT Model Corrosion with regards of Mooring Line Breakage (MLB)

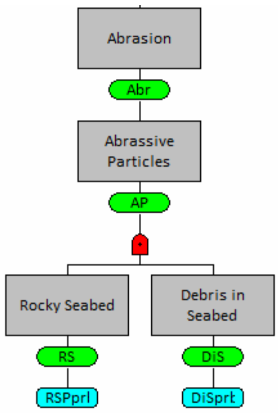

Figure G.3c. FT Model Abrasion with regards of Mooring Line Breakage (MLB)

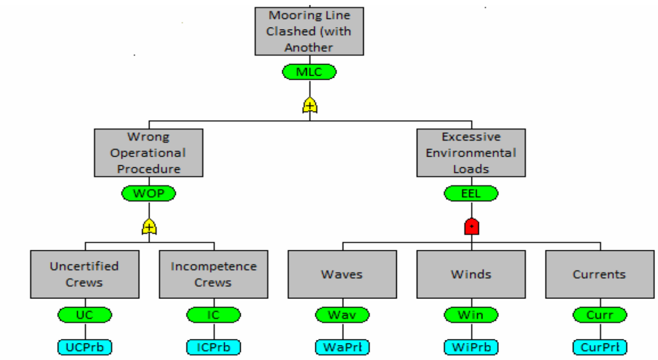

Figure G.3d. FT Model Mooring Line Clashed with regards of MLB

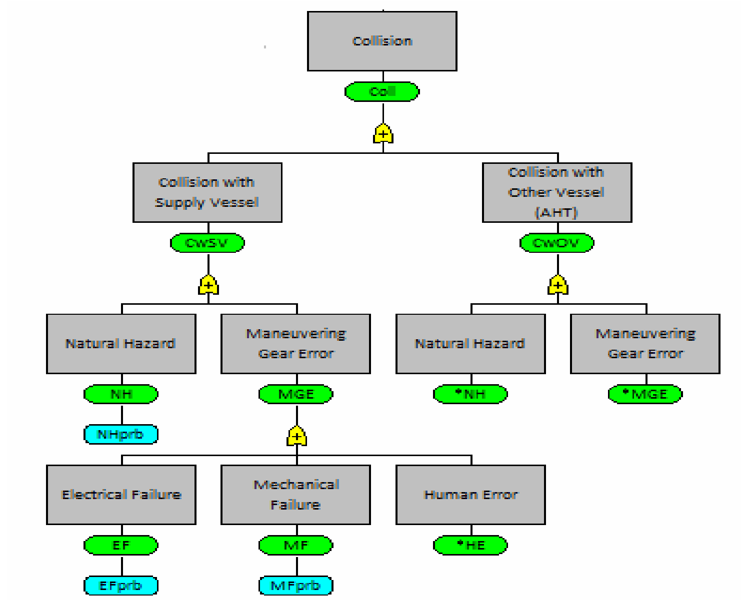

Figure G.3e. FT Model Collision with regards of MLB

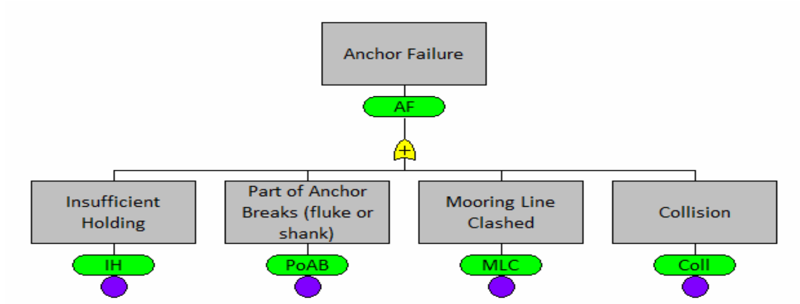

Figure G.4a. FT Model Anchor Failure (AF)

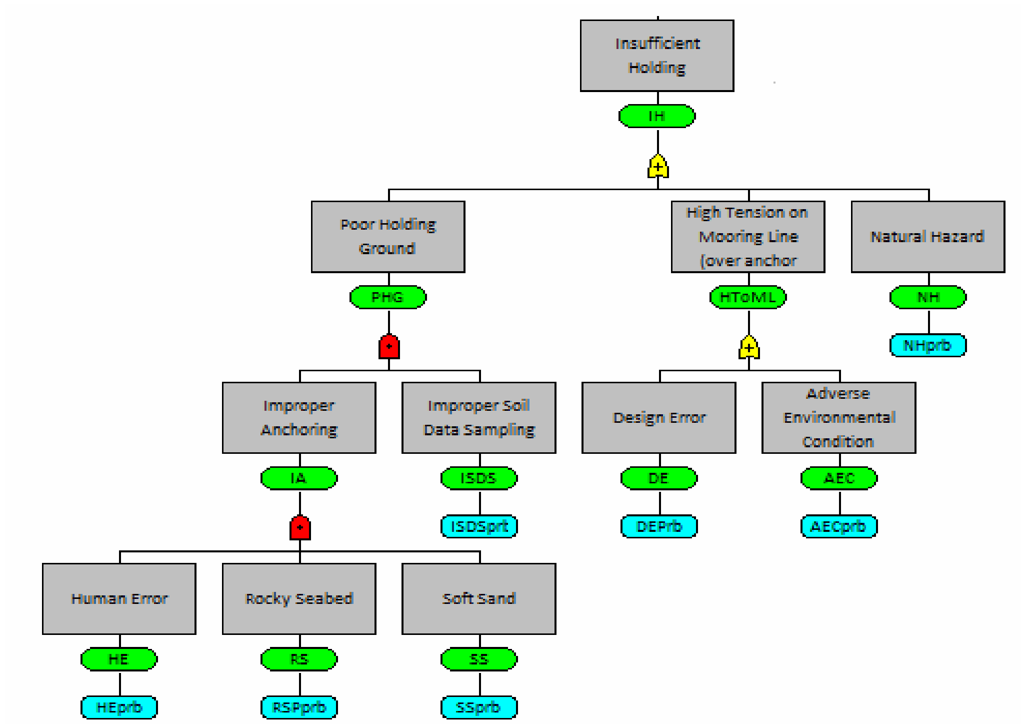

Figure G.4b. FT Model Insufficient Holding with regards of AF

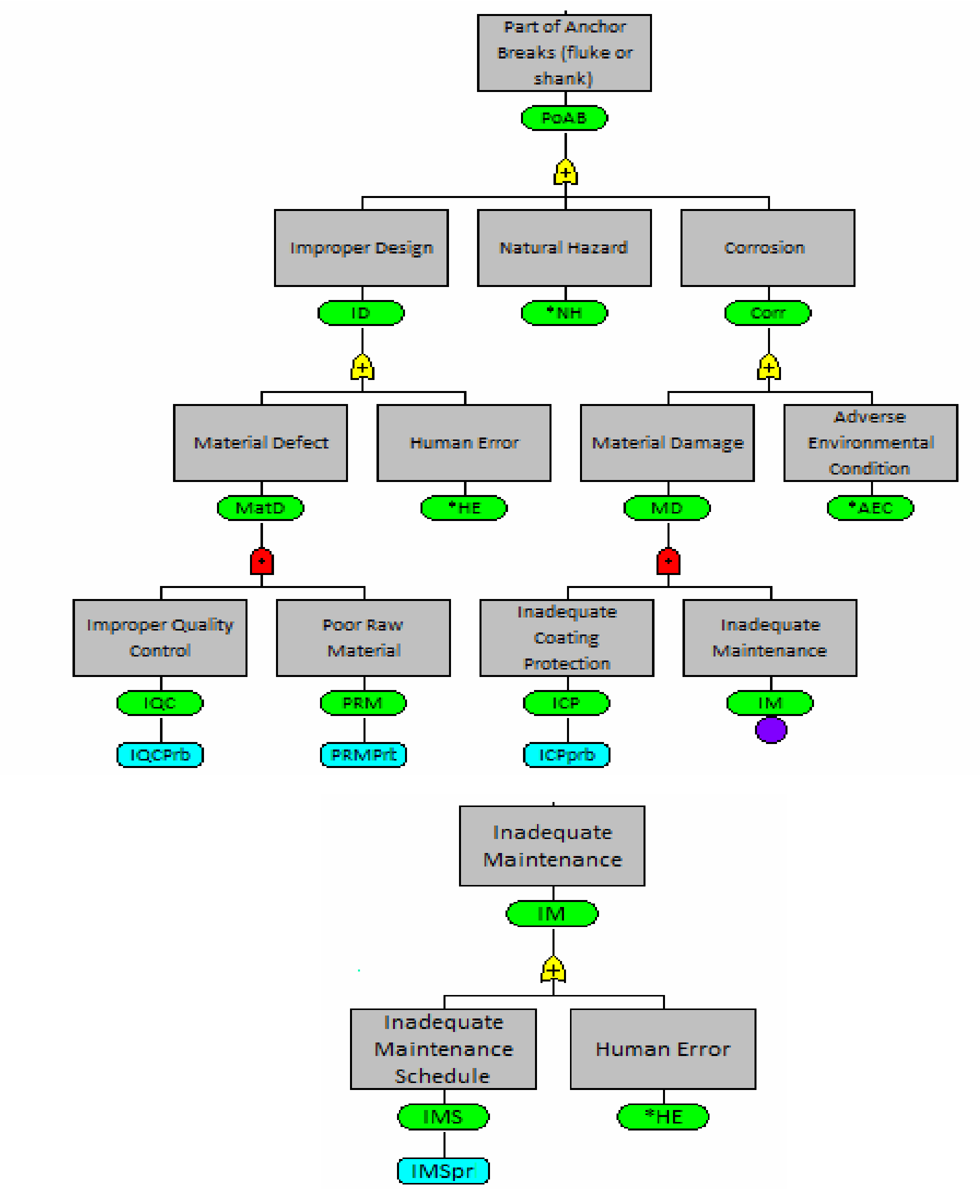

Figure G.4c. FT Model Part of Anchor Breaks with regards of AF

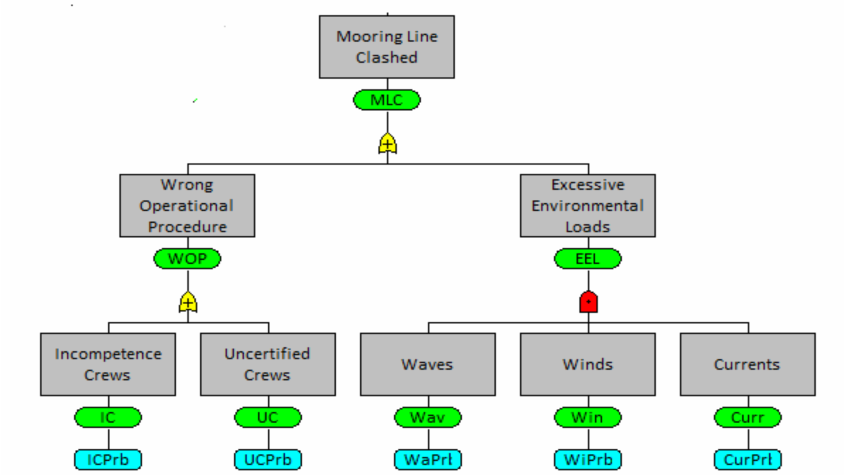

Figure G.4d. FT Model Mooring Line Clashed with regards of AF

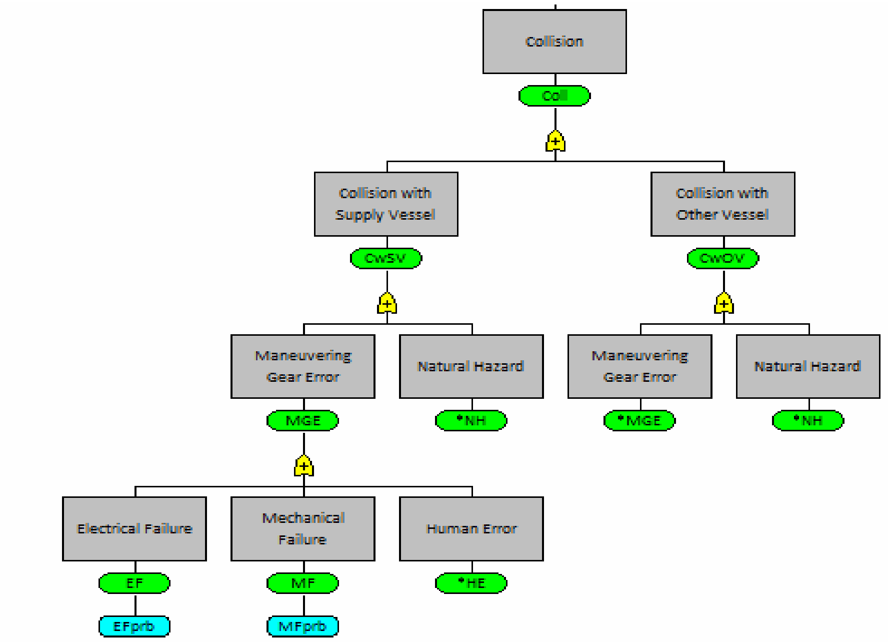

Figure G.4e. FT Model Collision with regards of AF

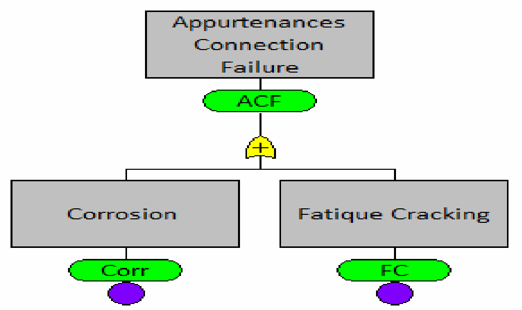

Figure G.5a. FT Model Appurtenances Connection Failure (ACF)

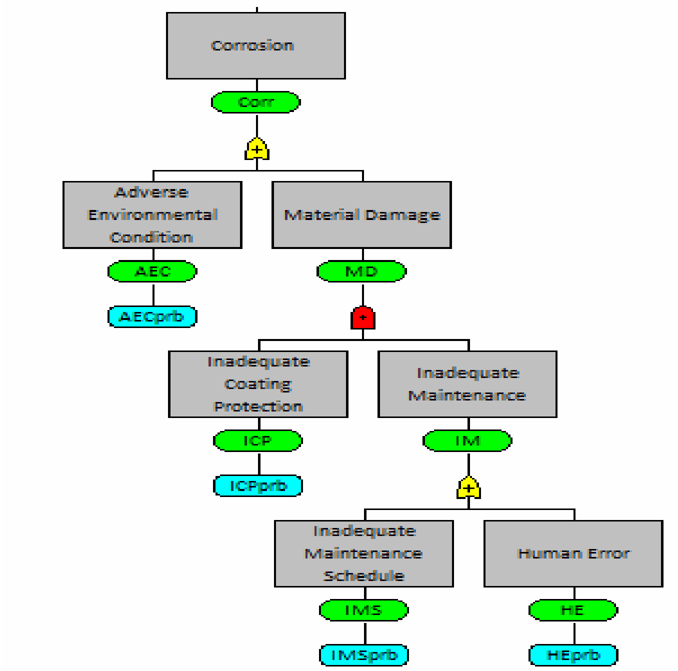

Figure G.5b. FT Model Corrosion with regards of ACF

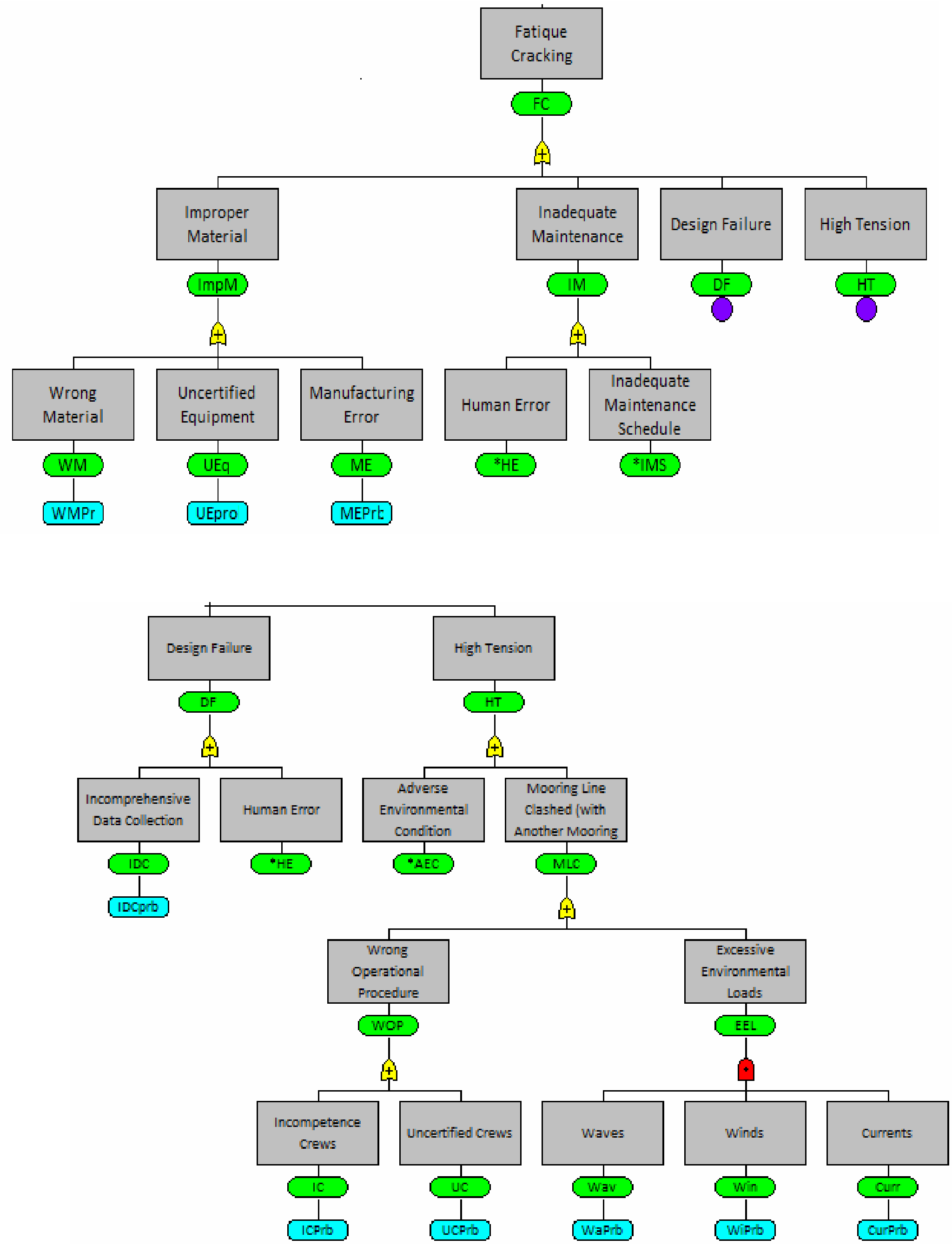

Figure G.5c. FT Model Fatigue Cracking with regards of ACF

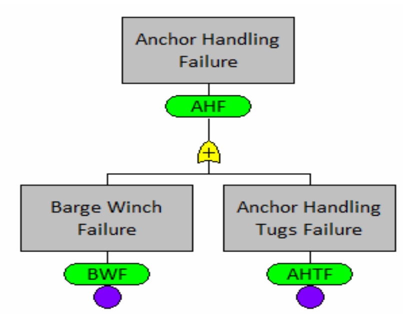

Figure G.6a. FT Model Anchor Handling Failure (AHF)

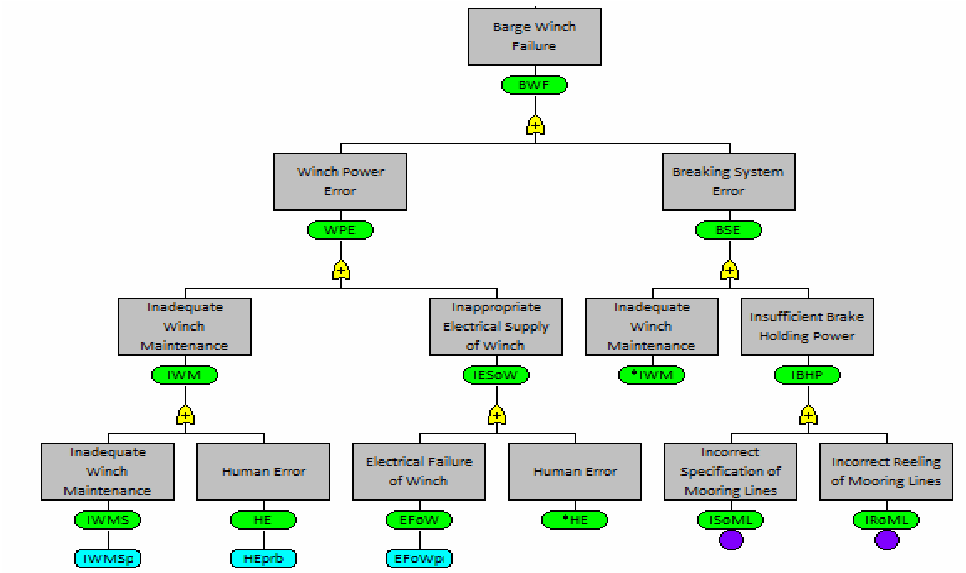

Figure G.6b. FT Model Barge Winch Failure with regards of AHF

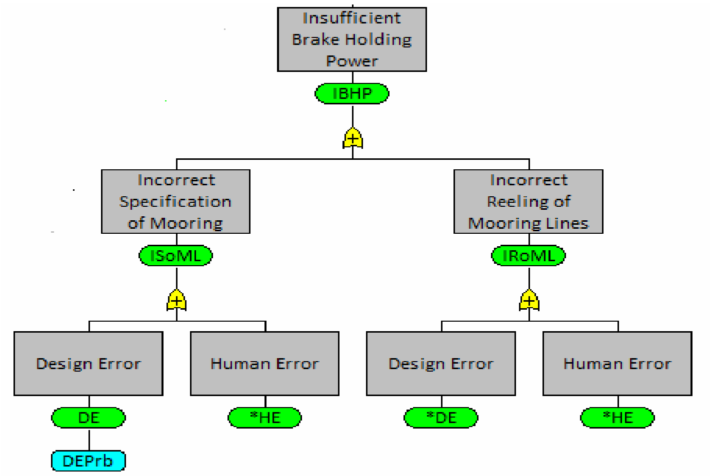

Figure G.6c. FT Model Insufficient Brake Holding Power with regards of AHF

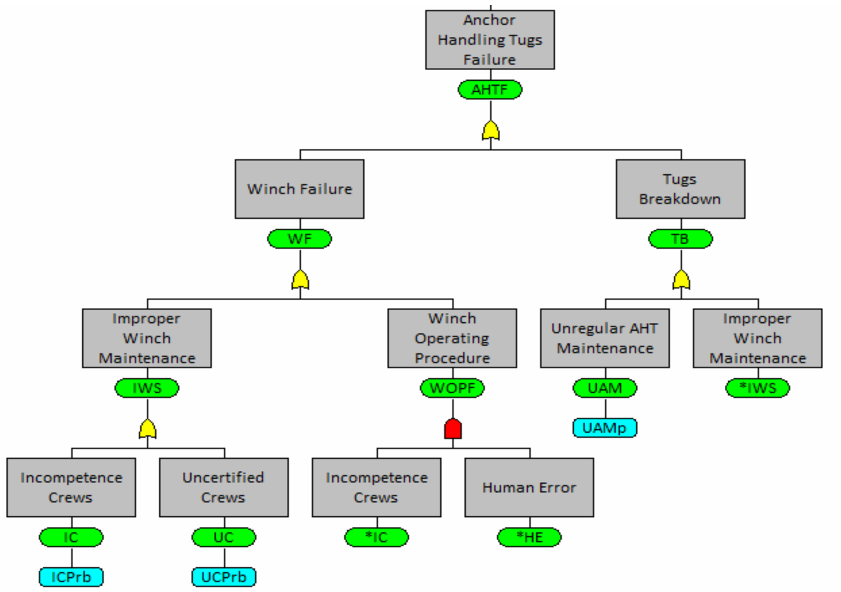

Figure G.6d. FT Model Anchor Handling Tugs Failure with regards of AHF

2. Questions with regards to FTA approach.

Please Bold/Underline the scale that indicates how much you agree or disagree with each of the following statements based on Figure G.3a-G.6d.

No	**Statement**	**Likert Scale**				
		Strongly Disagree	**Disagree**	**Neither Agree Nor Disagree**	**Agree**	**Strongly Agree**
		1	**2**	**3**	**4**	**5**
2a	The root causes of mobile mooring system failure in FTA are acceptable	1	2	3	4	5
2b	The undesired/basic events identified in FTA for mobile mooring system are correct	1	2	3	4	5
2c	The FTA approach for mobile mooring system is systematic	1	2	3	4	5
2d	The FTA framework for mobile mooring system is easily to understand	1	2	3	4	5
2e	The FTA framework for mobile mooring system has identified all the factors sufficiently	1	2	3	4	5

ETA (EVENT TREE ANALYSIS)

ETA is helpful to define all possible outcomes of accidental event. ETA in terms of MIVTA framework is described in Figure G.7 followed with the ETA result that has been accomplished.

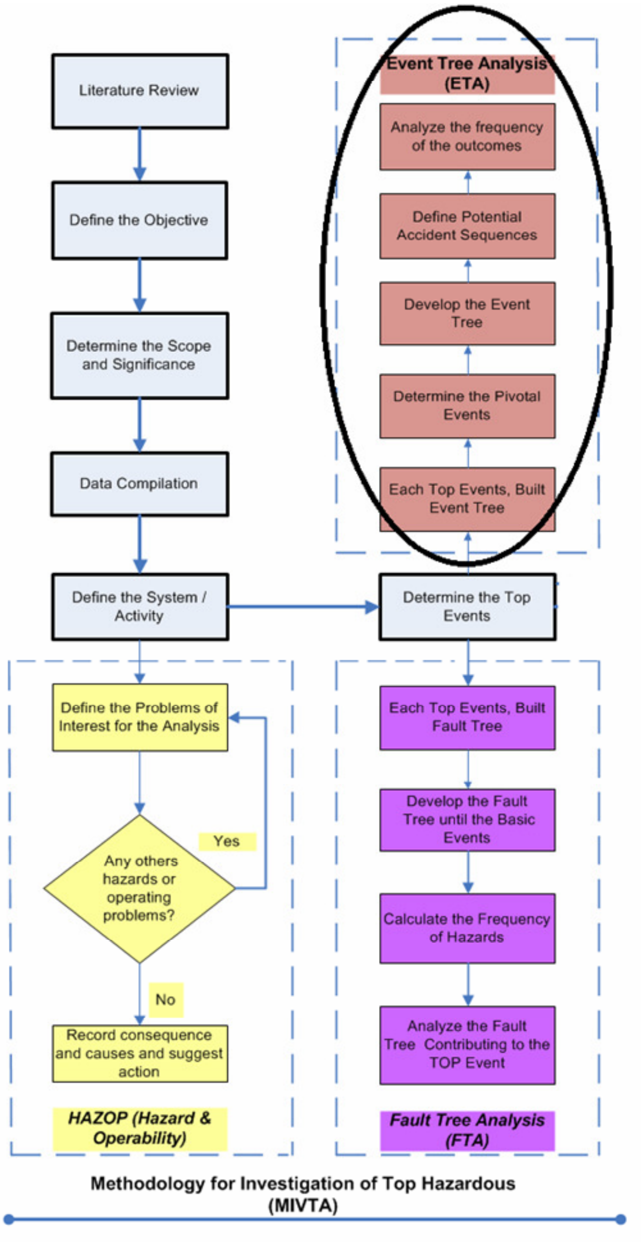

Figure G.7. ETA Result in terms of MIVTA Framework

ETA mobile mooring system consist of mooring line breakage (MLB) as seen in Figure G.8, anchor failure (AF) as seen in Figure G.9, appurtenance connections failure (ACF) as seen in Figure G.10 and anchor handling failure (AHF) Figure G.11. **(Validity to be asked).**

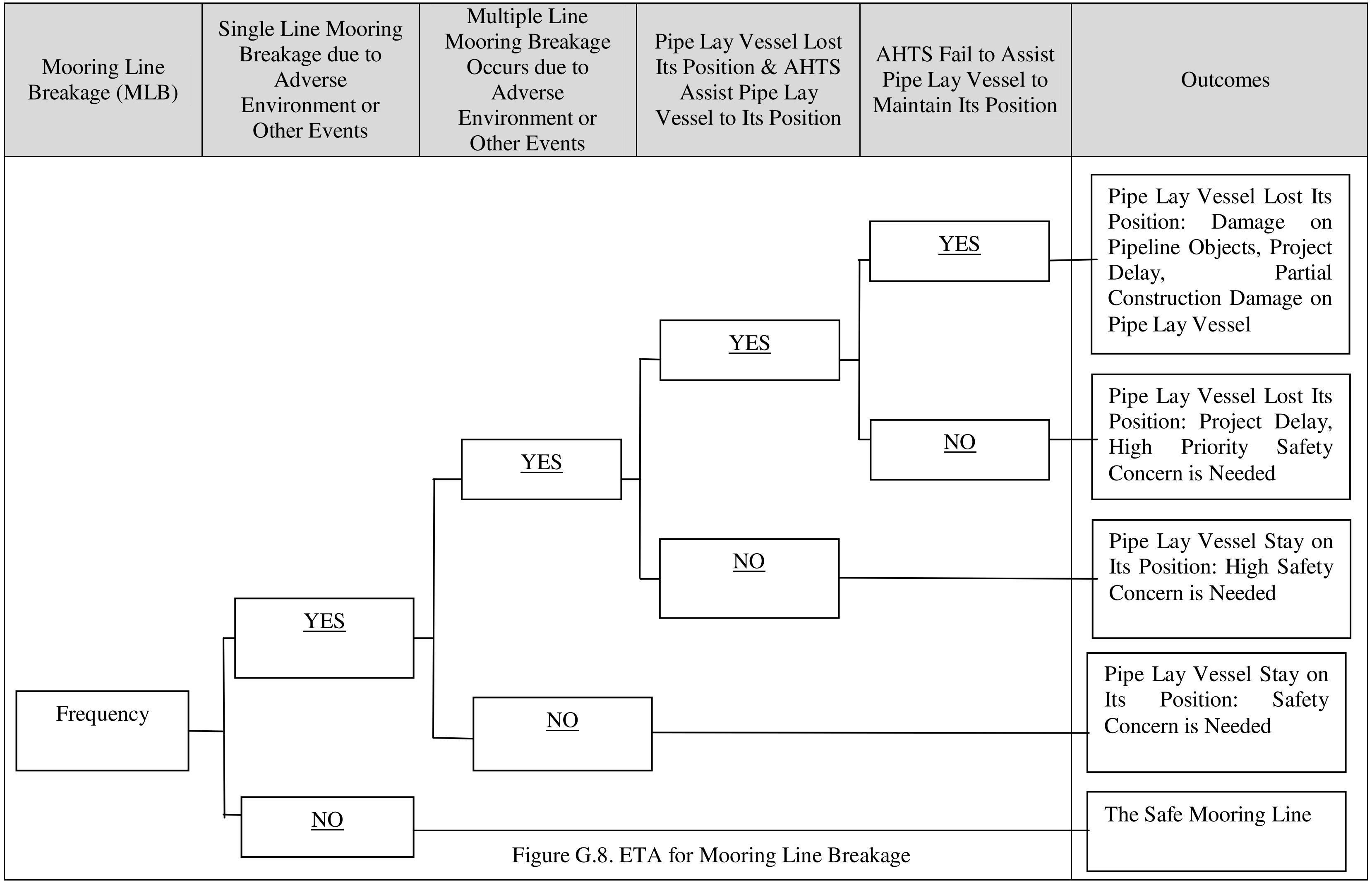

Figure G.8. ETA for Mooring Line Breakage

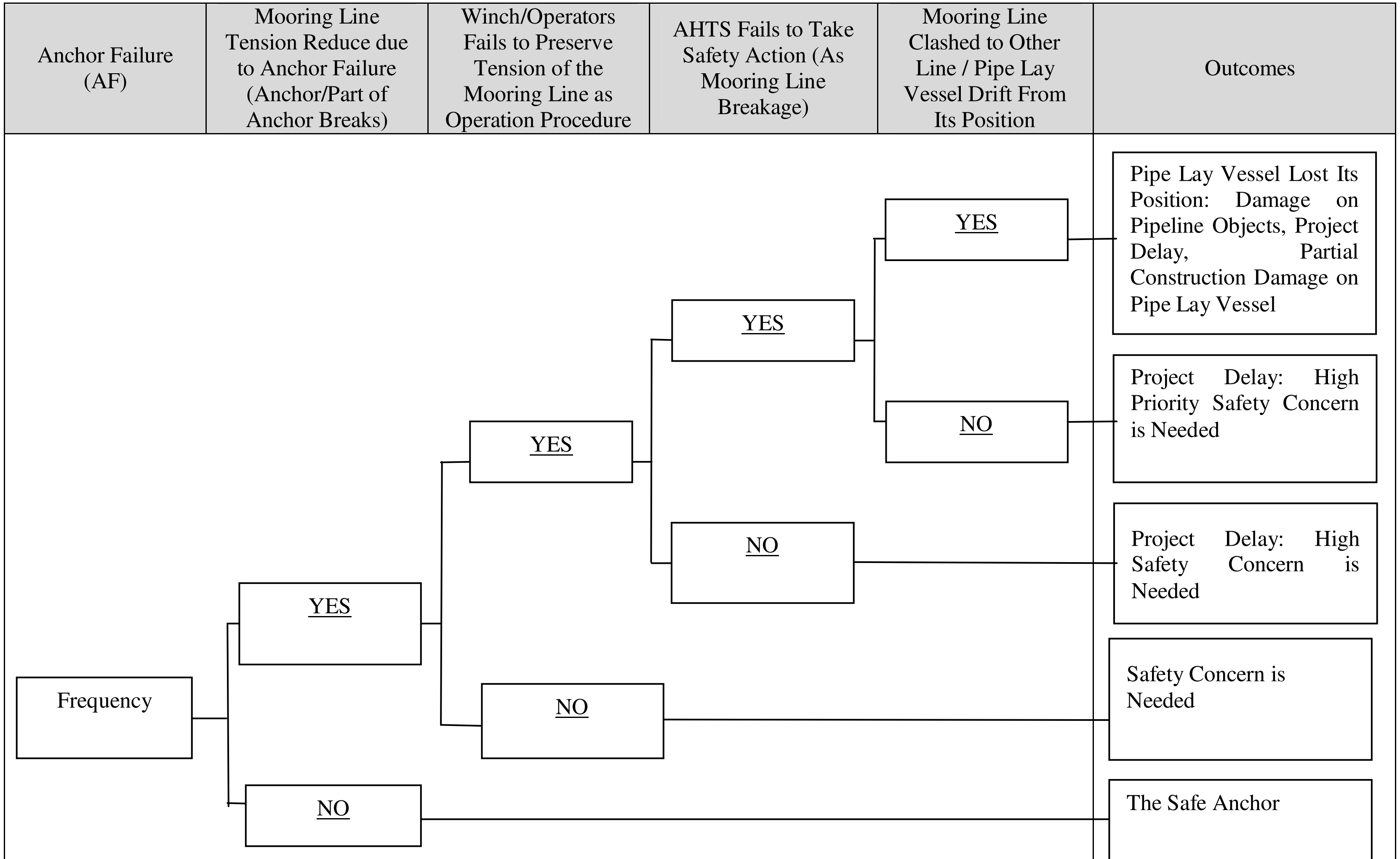

Figure G.9. ETA for Anchor Failure

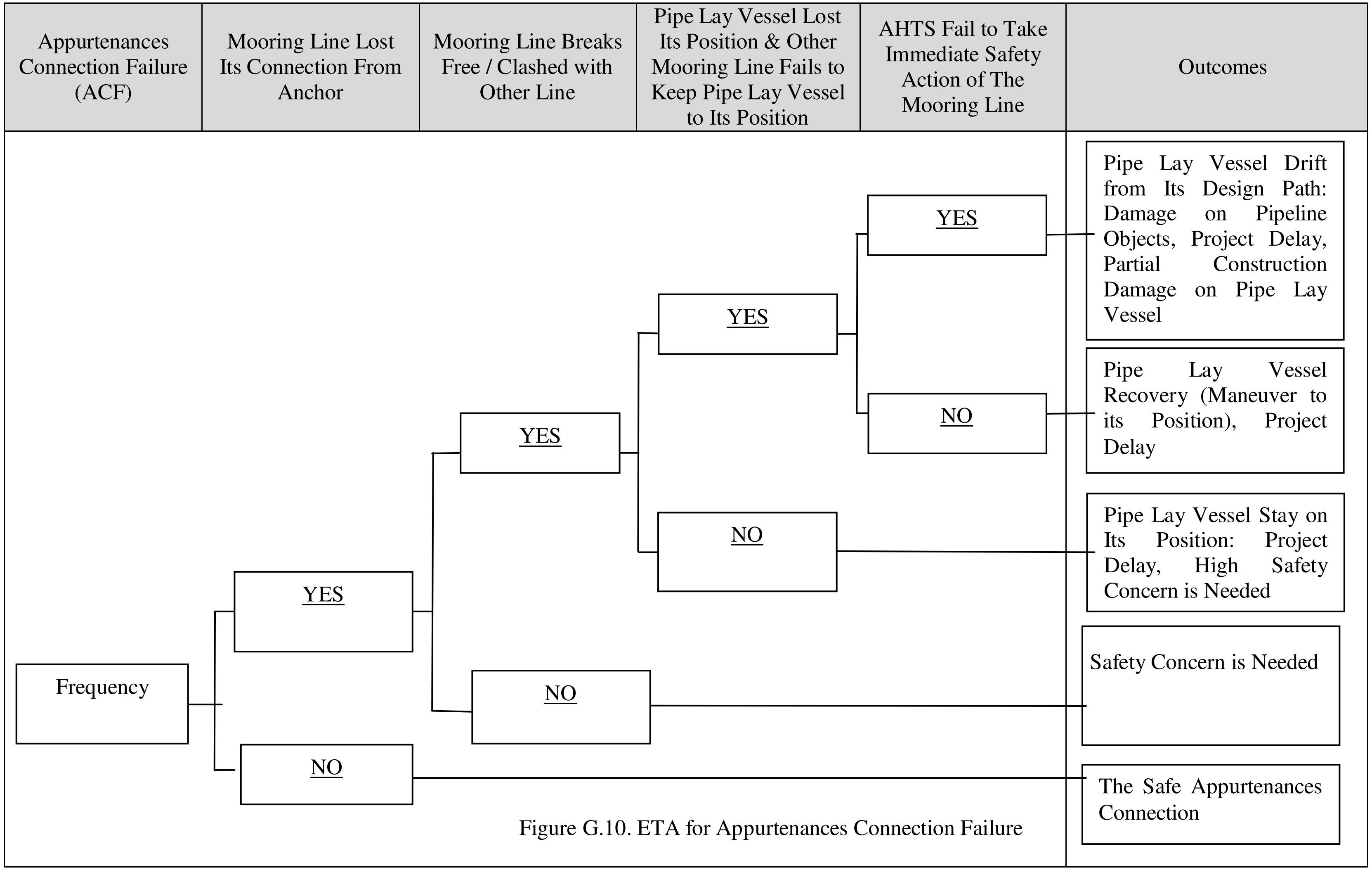

Figure G.10. ETA for Appurtenances Connection Failure

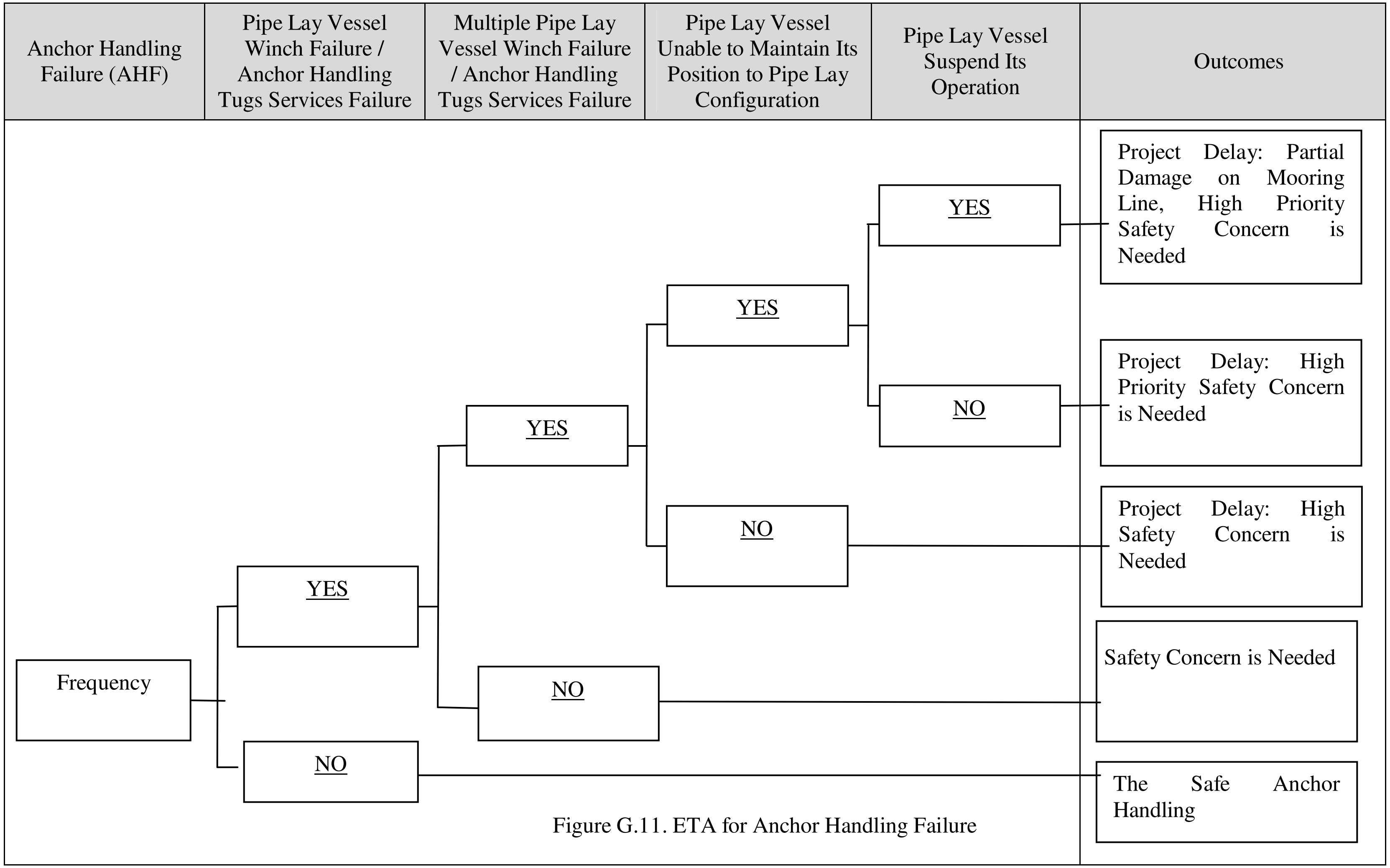

Figure G.11. ETA for Anchor Handling Failure

3. <u>Questions with regards to ETA approach.</u>

Please Bold/Underline the scales that indicate how much you agree or disagree with each of the following statements based on the Figure G.8-G.11.

No	Statement	Likert Scale				
		Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
		1	2	3	4	5
3a	The accidents sequences of the outcome of mobile mooring system failure is acceptable	1	2	3	4	5
3b	The ETA for mobile mooring system approach is systematic	1	2	3	4	5
3c	The ETA frameworks of mobile mooring system are easily to understand	1	2	3	4	5
3d	The ETA framework of mobile mooring system has identified all the factors sufficiently	1	2	3	4	5

AHP is applied to determine the best maintenance strategy of mooring system. AHP in terms of MIRBA framework is described in Figure G.12.

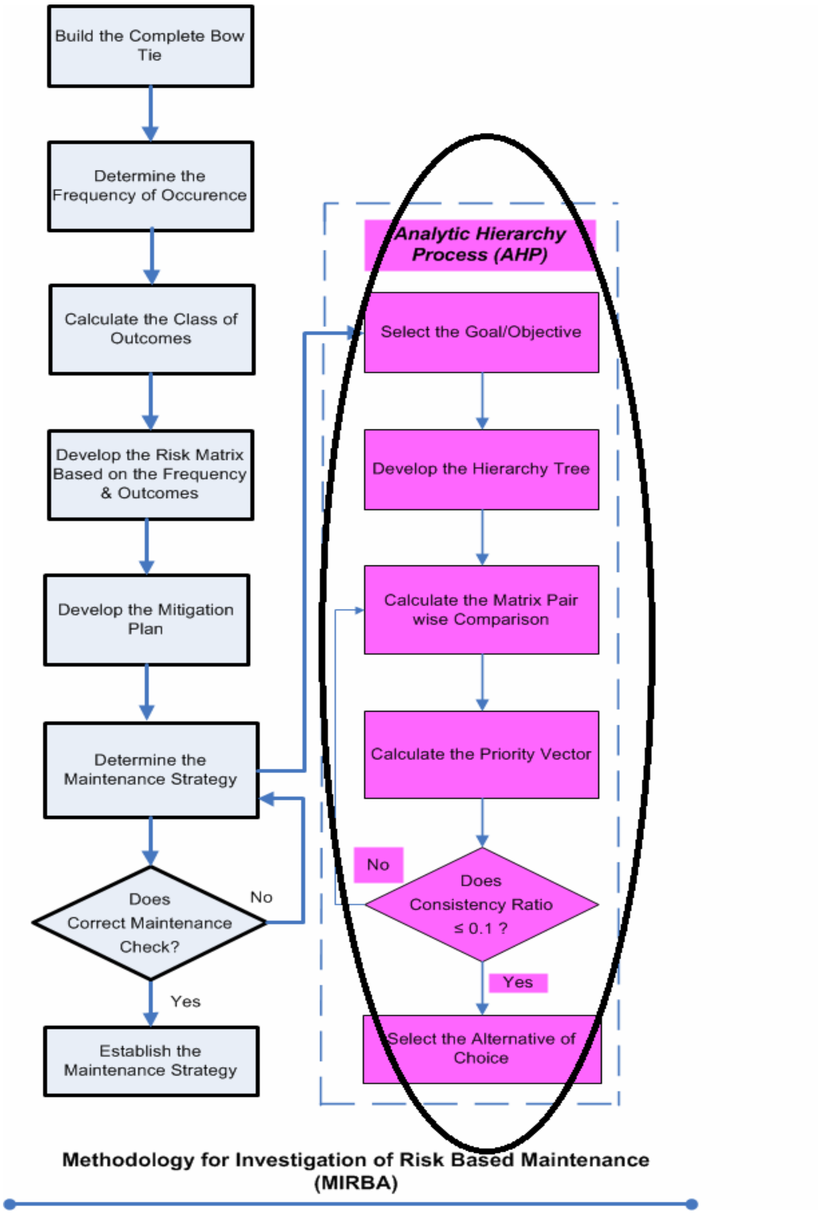

Figure G.12. AHP approach in terms of MIRBA Framework

Figure G.13 shows the AHP for selecting best maintenance strategy on the basis of likelihood for mobile mooring system and the AHP for selecting best maintenance strategy on the basis of consequence as seen in Figure G.14 **(Validity to be asked).**

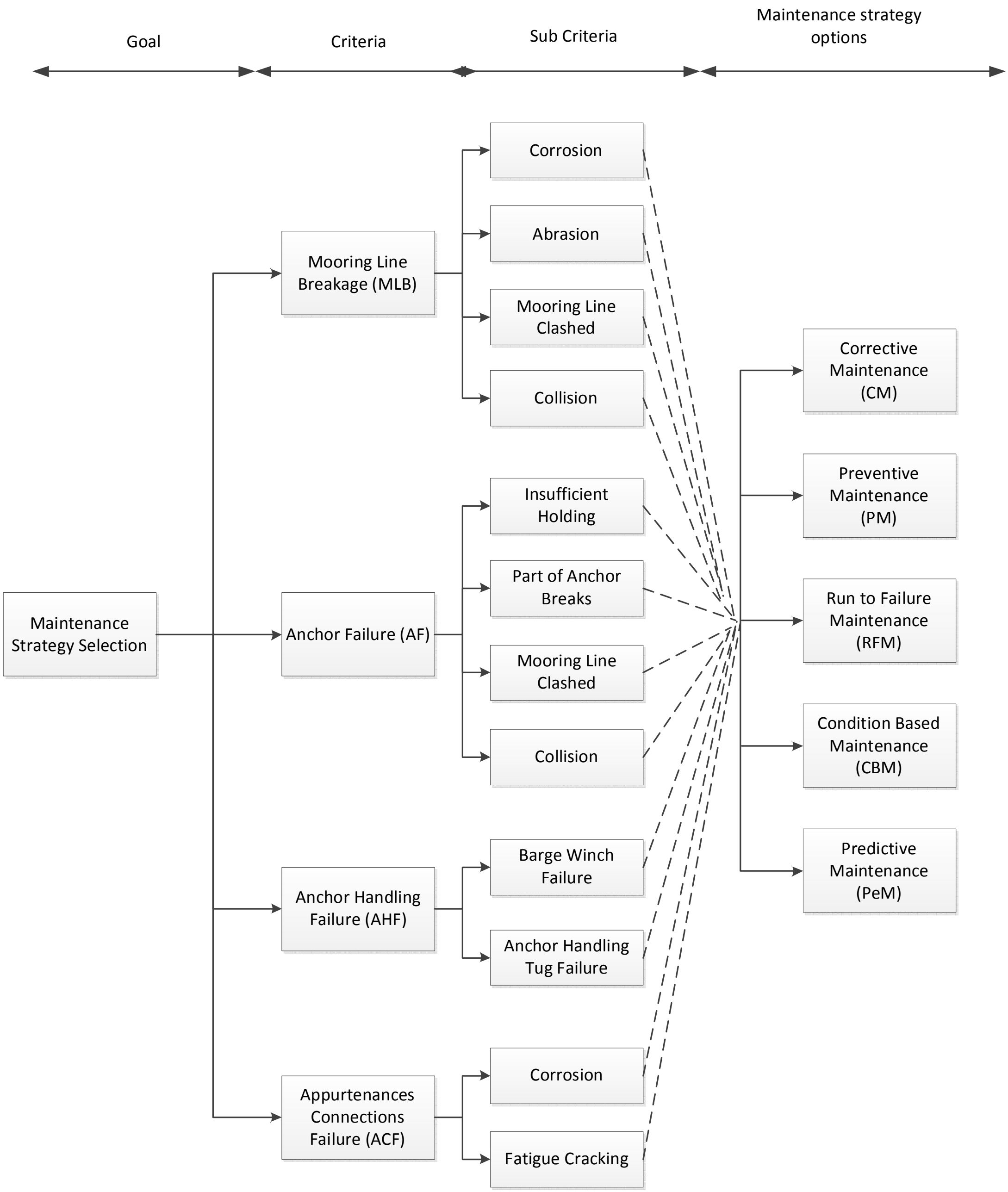

Figure G.13. Maintenance strategy on the basis of likelihood for mobile mooring system

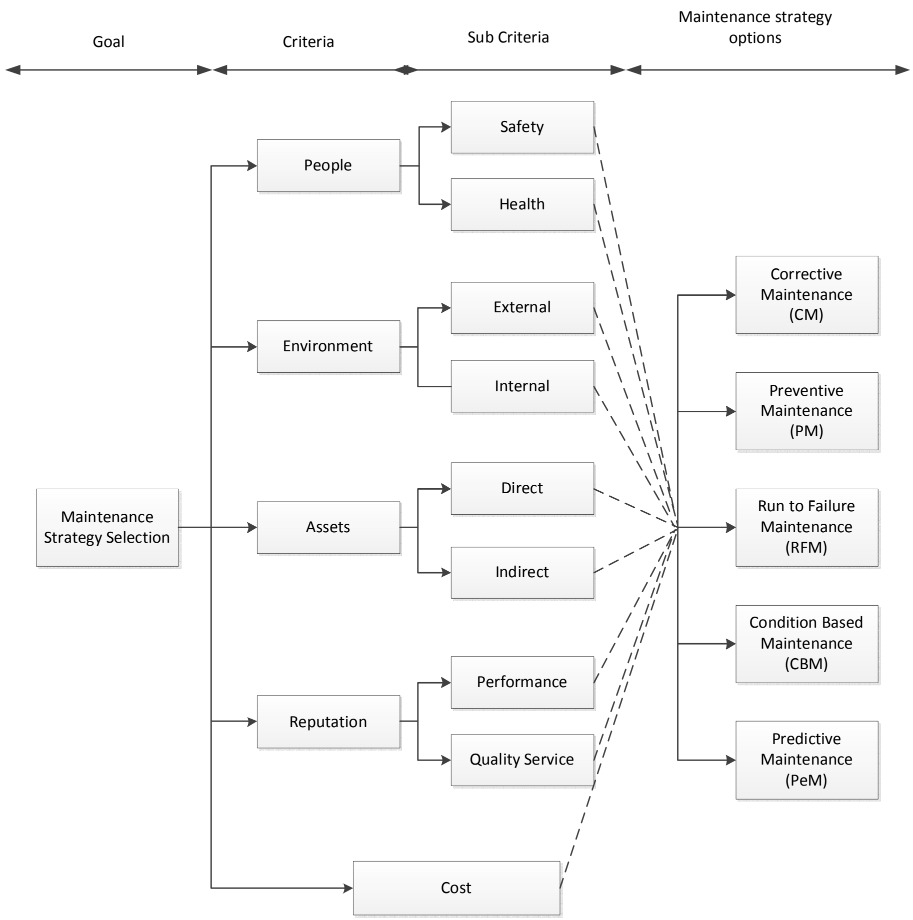

Figure G.14. Maintenance strategy on the basis of likelihood for mobile mooring system

4. <u>Questions with regards to AHP Framework</u>

Please Bold/Underline the scale that indicates how much you agree or disagree with each of the following statements with regards to Figure G.13 and G.14.

No	Statement	Likert Scale				
		Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
		1	2	3	4	5
4a	The maintenance strategies options for mobile mooring system are acceptable	1	2	3	4	5
4b	The criteria and sub criteria for mobile mooring system in order to select the best maintenance strategy are acceptable	1	2	3	4	5
4c	The AHP approach for mobile mooring system is systematic	1	2	3	4	5
4d	The AHP framework for mobile mooring system easily to understand	1	2	3	4	5
4e	The AHP framework for mobile mooring system has identified all the factors sufficiently	1	2	3	4	5

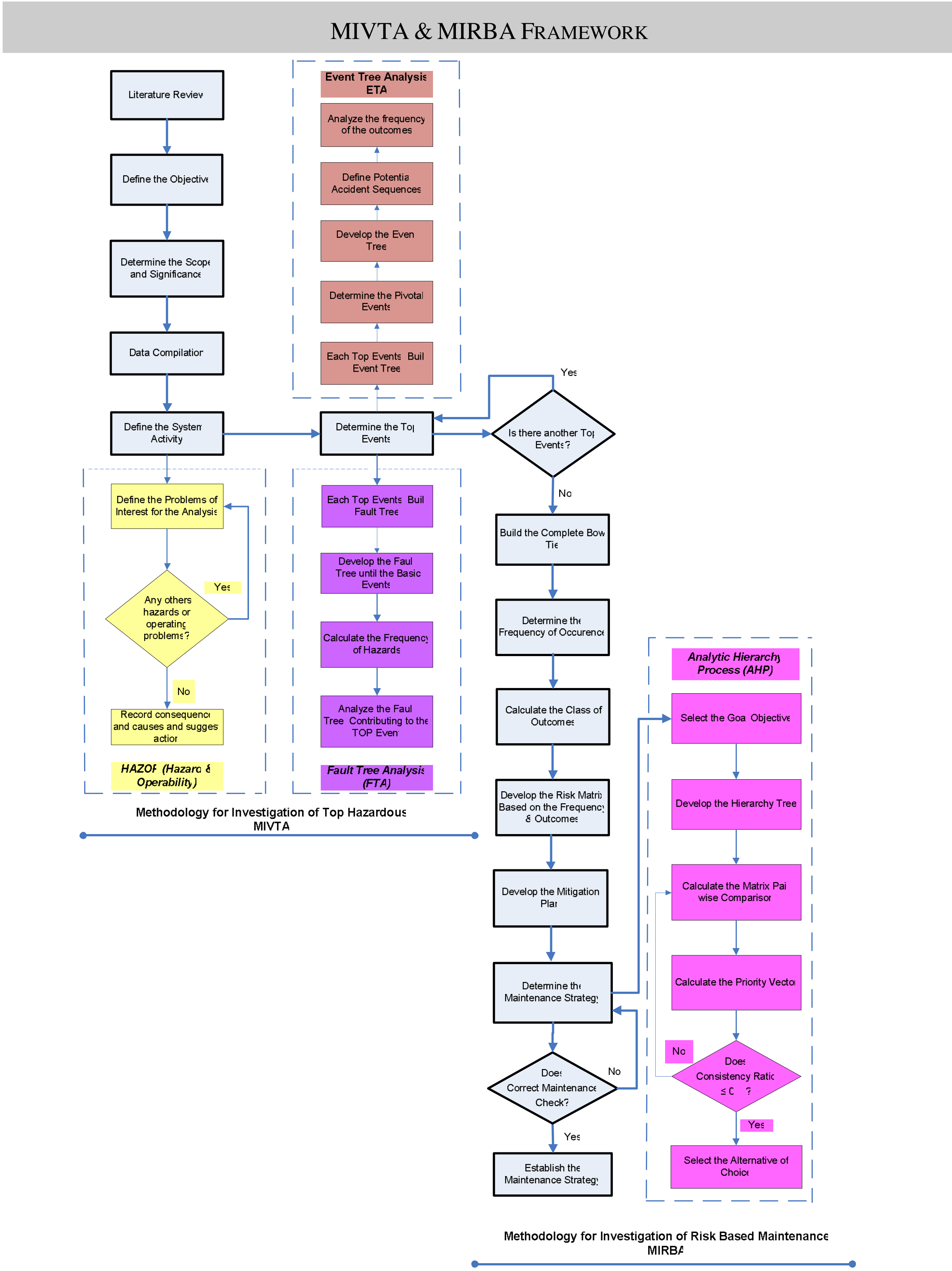

Figure G.15. MIVTA & MIRBA Framework

5. Questions with regards to MIVTA & MIRBA Framework

Please Bold/Underline the scale that indicates how much you agree or disagree with on the following statements based with regards to Figure G.15.

No	Statement	Likert Scale				
		Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
		1	2	3	4	5
5a	The MIVTA and MIRBA framework is interrelated to each other and can be seen as one integrated framework	1	2	3	4	5
5b	MIVTA and MIRBA is an innovative approach	1	2	3	4	5
	Is there any comments: Answer:……………………………………………………………………………………………… ……………………………………………………………………………………………… ……………………………………………………………………………………………… ……………………………………………………………………………………………… ……………………………………………………………………………………………… ………………………………………………………………………………………………					

 # Thank you very much for your kind cooperation #