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Decision Making for Safety Assessment of Mobile Mooring System

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Graphical abstract

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					

Abstract

Floating structures use mooring system for station keeping in any water depths. Mooring system is a vital component for the safety of floating structures. Mooring accidents can cause serious injury or damage to the vessel, and hence it is necessary to establish a systematic risk-based decision making for safety assessment of mobile mooring system. This study uses the mobile mooring system of a semi submersible pipe laying barge as a case study. The aim of this study is to develop a Methodology for Investigation of Critical Hazards (MIVTA), which is carried out by the development of preliminary risk analysis using HAZOP (Hazard and Operability), to generate the root causes using FTA (Fault Tree Analysis) and to construct the sequence of the consequences using ETA (Event Tree Analysis). HAZOP is a systematic examination of a system helpful to identify and evaluate the risks related to accidents/incidents in mooring system. FTA is a deductive method useful to generate the potential causes of mooring system failure into undesired events. ETA is an inductive method helpful to define all possible outcomes of accidental events. This study conducts risk-based decision making coupled with the knowledge of the experts of mooring system to identify the root causes, to evaluate the frequency of failure and to classify their class of consequences. This study provides a systematic methodology guideline for the risk-based decision making useful to identify the risk of accidents occurring in offshore platforms.

Keywords: Assessment; fault; hazard; safety; tree

Abstrak

Sistem mooring digunakan dalam struktur apungan untuk menjaga kestabilan dalam setiap kedalaman air. Sistem mooring adalah komponen penting sebagai sistem keselamatan dalam struktur apungan. Kemalangan yang disebabkan mooring boleh mengakibatkan kecederaan parah atau kerosakan yang teruk pada kapal. Maka sistem tersebut perlu diselerasakan melalui kaedah keputusan yang berasaskan risiko bersistematik untuk mengurangkan risiko kegagalan. Kajian ini mengunakan sistem mooring mudah alih yang terdiri daripada semi submersible yang meletakkan pipa sebagai kes kajian. Tujuan utama dalam kajian ini adalah untuk mengembangkan kaedah dalam penyiidikan untuk bencana yang kritical (MIVTA), yang diawali pembangungan risiko awal menggunakan HAZOP (bencana dan pengoperasian), untuk mencetuskan masalah awal dengan menggunakan FTA (Analisis Pokok Kesalahan) dan untuk menjanakan akibat mengikuti urutan menggunakan ETA (Analisis Pokok Kejadian). HAZOP merupakan pengujian secara sistematis dalam sistem yang membantu untuk mengenal pasti dan mentafsir risiko-risiko yang berkaitan dengan kemalangan dalam sistem mooring. FTA merupakan kaedah deduktif yang berguna untuk mencetuskan masalah potensi dalam kegagalan sistem mooring dalam kejadian yang tidak diingini. ETA merupakan kaedah induktif yang membantu dalam pentakrifan segala hasil kemungkinan dari kejadian kemalangan. Kajian ini juga menyediakan kaedah garis panduan yang sistematik untuk membuat keputusan berdasarkan risiko yang mana berguna untuk mengenal risiko berlakunya kemalangan dalam pelantar-pelantar minyak.

Kata kunci: Taksiran; kesalahan; bahaya; keselamatan; pokok

1.0 INTRODUCTION

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 (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). Offshore installations are hazardous places because incidents in these environments can lead to enormous consequences (Deacon *et al.*, 2010). A hazard is a condition with the potential to cause harm, while risks depend on the likelihood of the harm, the severity of the harm and the number of people who might get injury or illness (Authority, 2006). This paper explains the hazards that occur in a semi submersible column stabilized pipe lay barge which used mobile mooring system for the positioning. The vessel has a hull with two pontoons and four columns fitted with 12 point mooring system in order to control movement during pipe lay operations. The main objective of this study is to develop an integration of risk assessment approaches consisting of HAZOP, FTA and ETA called MIVTA (Methodology for Investigation of Critical Hazards). Developing MIVTA consists 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

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. The hazard risk analysis methods used in this study are based on ((API), 1993) which described the characteristics of hazard analysis as shown in Table 1. From this table it can be seen that the methods used involve the qualitative and quantitative methods and it can be used in all types of facilities.

Table 1. 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.

HAZOP is a useful approach for safety analysis and it is important to identify problems by conducting brainstorming with the expert (Dhillon, 2003). To develop HAZOP for mobile mooring system, was done initially a brainstorming with the team members about all possible potential hazards in mooring system (Silvianita, 2011). 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):

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

FTA has been widely used to develop a framework for safety assessment because of its systematic and logical approach (Stamatelatos, 2002). FTA is a deductive approach that consists of symbols and gates in order to describe the process of system failure. In order to analyze the fault tree, the evaluations use the rules of Boolean Algebra. A fault tree is translated into an equivalent set of Boolean equations. FTA is useful to describe the root cause of an accident logically. Quantitative analysis of fault trees usually perform two cases of fault tree with repeated events and without repeated events (Metin, 2010).

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). 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. ETA is an inductive method that defines all potential consequences resulting from an accidental (initiating) event, named as consequence spectrum (Rausand, 2005b). 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.

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 1. IMO (International Maritime

Organization) also developed risk ranking matrix with the frequency index as described in Table 2 ((IMO), 1997).

Deacon *et al.* (Deacon *et al.*, 2010) explains that the qualitative frequencies of ISO standard 17776 developed by DNV as shown in Figure 1 can be compared with the frequency index from IMO as can be seen in Table 2. 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.

Table 2 Frequency Index ((IMO), 1997)

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}

Consequence					Increasing Probability				
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Figure 1 ISO 17776 Risk Ranking ((DNV), 2002)

2.0 MIVTA APPLICATION

The idea of this study is to integrate or combine four methods which are HAZOP, FTA, and ETA into comprehensive risk based decision making (RBDM). Integrating approach framework as shown in Figure 2 consists of MIVTA that means Methodology for Investigation of Critical Hazardous. 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
   Defines the objective of the research and helps to maintain the focus of the research. Most importantly it will affect the tools that are going to be analyzed.
3. MIVTA step 3: Determining the scope
   Determines 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
6. MIVTA step 5.1: Defining problems of interest
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 as shown in Table 3.
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 proceeding to the higher level, 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.

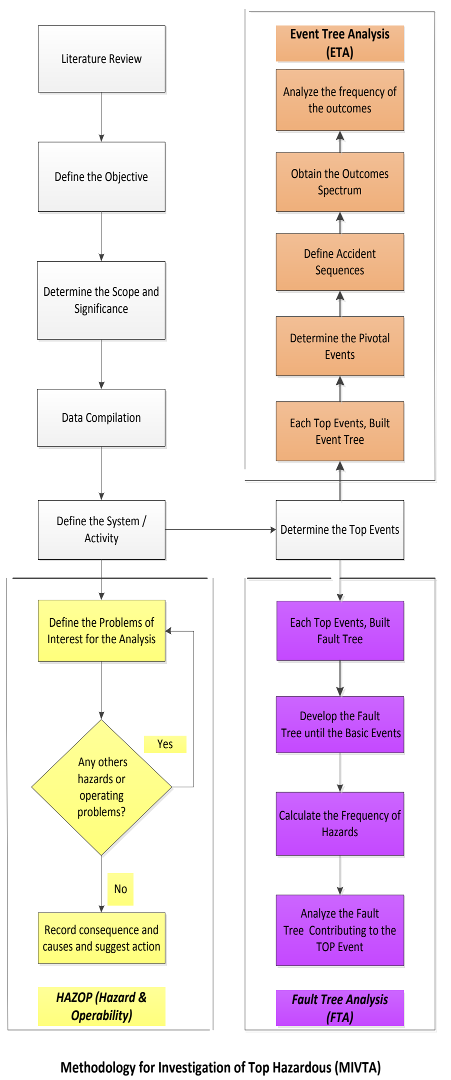

Figure 2 MIVTA application

3.0 RESULT & DISCUSSION

3.1 HAZOP Result

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. Table 3 shows the HAZOP result of a mobile mooring system.

3.2 FTA Result

The top event of this study is mooring system failure. This top event is then divided into four major events which are mooring line breaks, anchor failure, anchor handling failure and appurtenances connection failure. Each of the major events is broken down in order to define the basic event. This paper discusses only the root causes of anchor failure using fault tree analysis (FTA) as can be seen in Figure 3 – 7. The fault tree was developed using the computational tool DPL software belonging to the Syncopation Software Corporation (Chris, 2005).

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 3. These events are connected with OR gate. Insufficient holding problems include poor holding ground, high tension on mooring line and natural hazard as seen in Figure 4. These problems are related by OR gate. 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 sand, 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 gate. Part of anchor breaks (fluke or shank) is due to problems caused by improper design, natural hazard, and corrosion as seen in Figure 5. These problems are related to OR gate. 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 developed using AND gate. Inadequate maintenance is broken down further with OR gate into inadequate maintenance schedule and human error.

Table 3 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
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

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 6. 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 7. 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.

In order to quantify the frequency of failure, the basic event in a system failure need to be found. But sometimes it is very difficult to gather the past record data for FTA, therefore we need the expert opinion and experience to determine the probabilities of the undesired events (Silvianita, 2012). In this study the experts gave their judgment based on the IMO (International Maritime Organization) standard as shown in Table 2 (Veritas, 2002).

FTA is a logical and diagrammatic approach which uses the rules of Boolean algebra to evaluate the occurrence probability of an accident resulting from sequence of faults and failure events (Metin, 2010). Mathematically the FT diagram of mooring system failure (MSF) can be expressed:

$$\begin{aligned} MSF &= MLB \cup AF \cup AHF \cup ACF \\ &= MLB + AF + AHF + ACF \end{aligned} \quad (1)$$

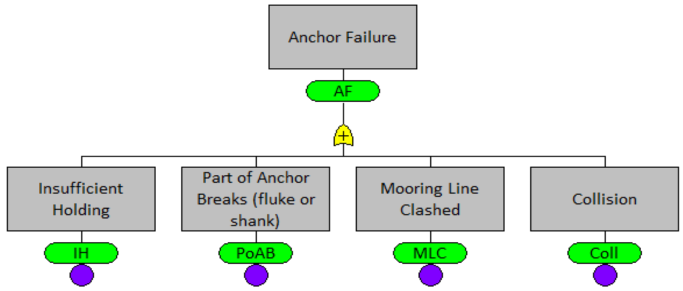

Figure 3 FT model anchor failure (AF)

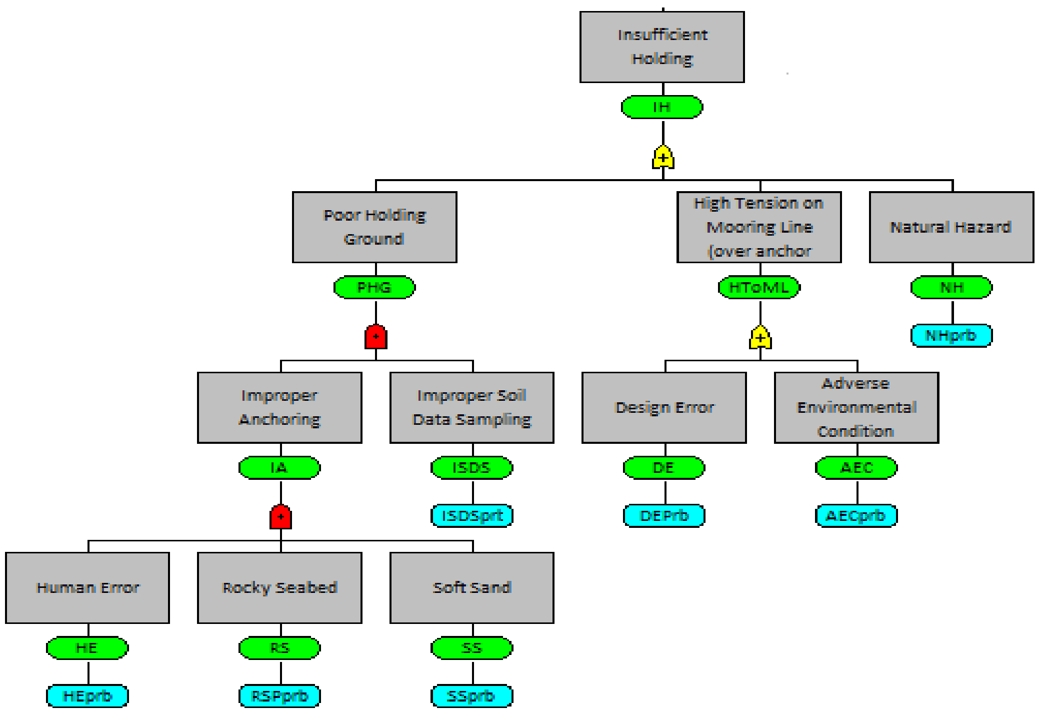

Figure 4 FT model insufficient holding with regards of AF

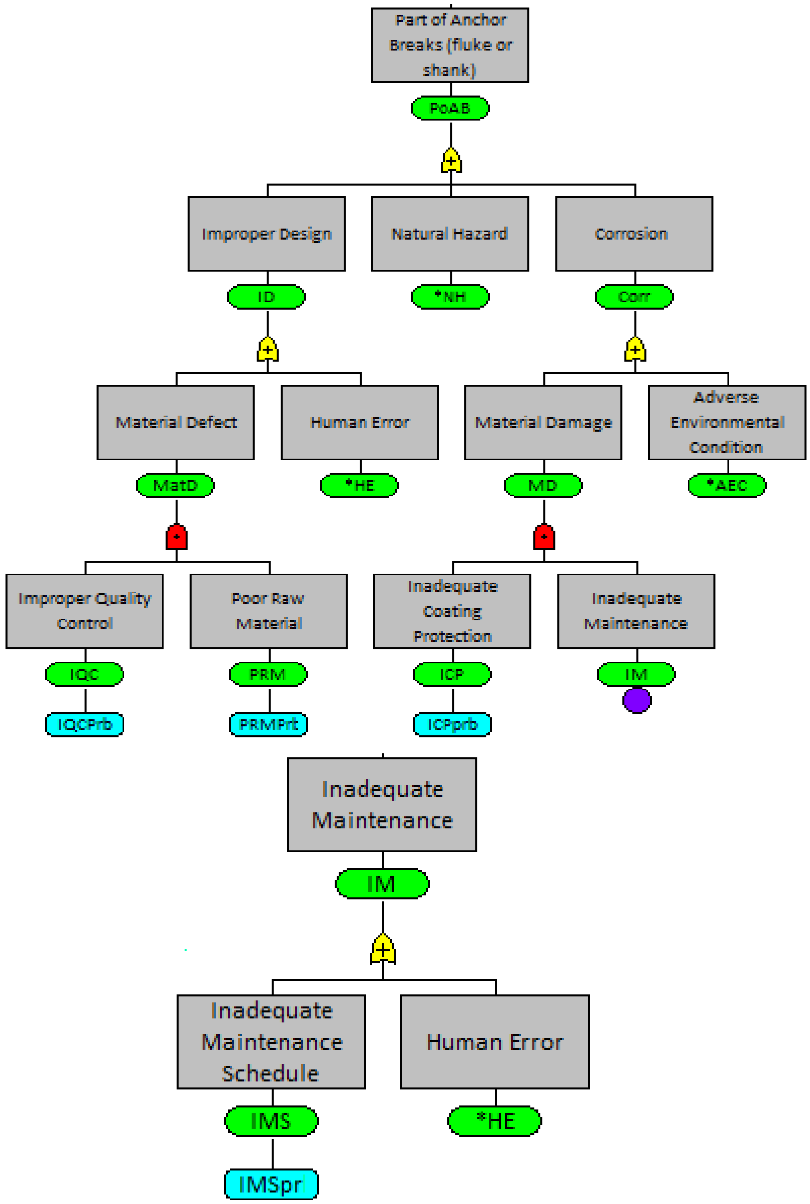

Figure 5 FT model part of anchor breaks with regards of AF

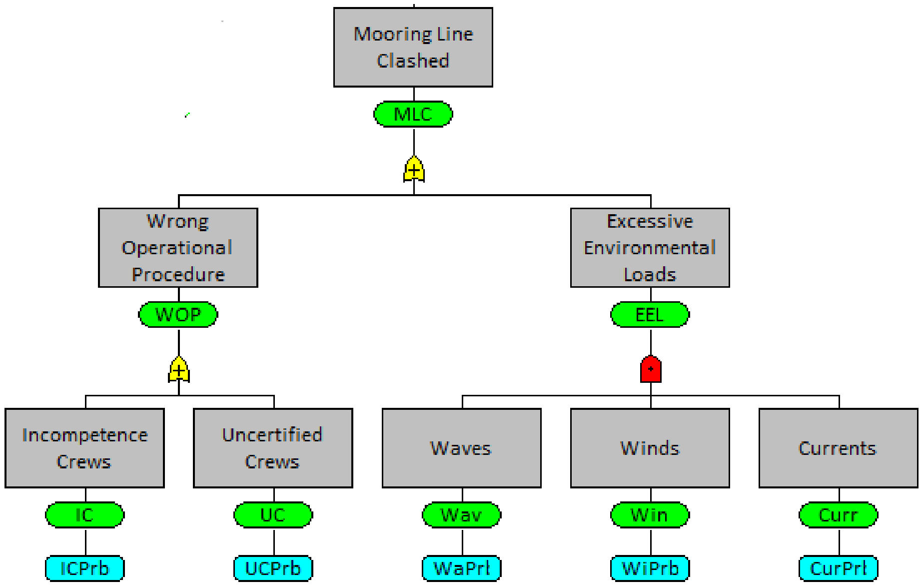

Figure 6 FT Model Mooring Line Clashed with regards of AF

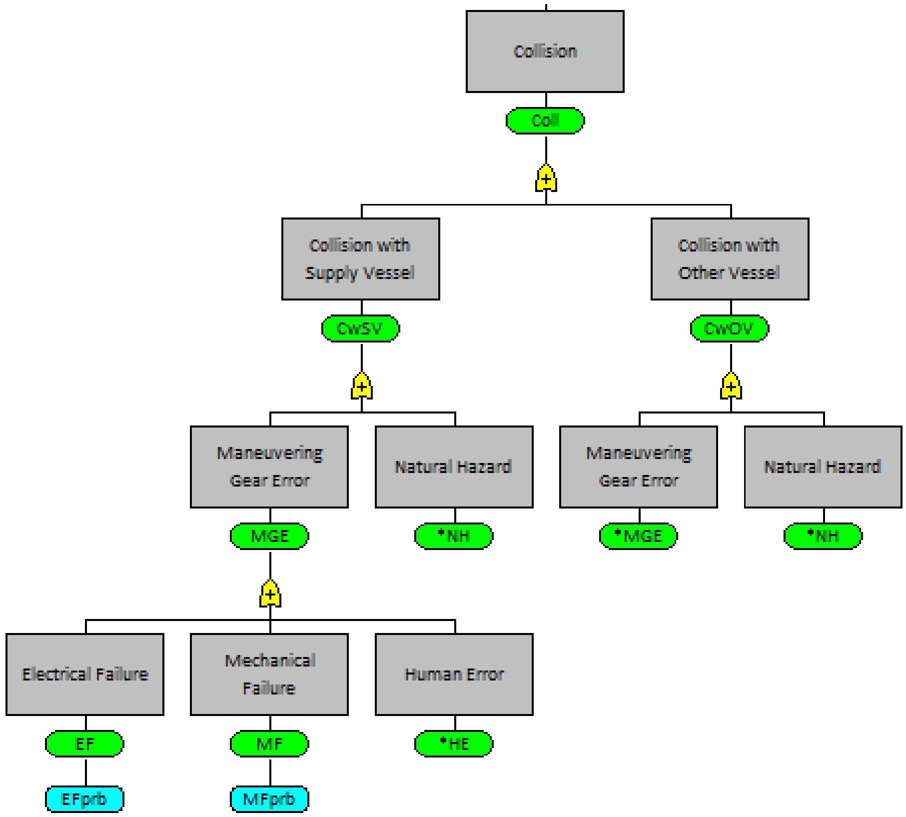

Figure 7 FT model collision with regards of AF

The FTA of mooring system failure is developed in Figure 1. and the description of top events, sub events and basic events are listed in Table 4 and 5. The evaluation of FTA begins with the calculation of the cut set. The smallest combinations of basic events that lead to the top event are called the minimal cut set. The minimal cut set of the mooring system failure is shown in Table 6.

The formula of minimal cut set for the top event (Andrews, 1998) : $T = C_1 + C_2 + C_3 + ... + C_N$ (2)

Therefore the probability of mooring system failure is T = 0.0453027 + 0.0457015 + 0.0132 + 0.0438 = 0.1480042 per year, and based on Table 2 it is classified as reasonably probable.

Table 4 The descriptions of the sub events of mooring system failure (MSF)

No	Sub Events	Code
1	Mooring Line Breaks	MLB
2	Anchor Failure	AF
3	Anchor Handling Failure	AHF
4	Appurtenances Connection Failure	ACF

Table 5 The description of the basic events of mooring system failure

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	Exposed Sharp Edges	ESE
6	Electrical Failure	EF
7	Excessive Waves	EWa
8	Excessive Winds	EWi
9	Excessive Currents	ECu
10	Human Error	HE
11	Incomprehensive Data Collection	IDC
12	Improper Quality Control	IQC
13	Inadequate Winch Maintenance Schedule	IWMS
14	Inadequate Coating Protection	ICP
15	Inadequate Maintenance Schedule	IMS
16	Improper Soil Data Sampling	ISDS
17	Incompetence Crews	IC
18	Manufacturing Error	ME
19	Mechanical Failure	MF
20	Natural Hazard	NH
21	Poor Raw Material	PRM
22	Rocky Seabed	RS
23	Soft Sand	SS
24	Uncertified Crews	UC
25	Unregular AHT Maintenance	UAM
26	Uncertified Equipment	UE
27	Wrong Material	WM

Table 6 The minimal cut set of FT

Code	Order	ACF	AF	AHF	MLB
AEC	1st	0.003	0.003	N/A	0.003
DiS RS	2nd	N/A	N/A	N/A	0.0000027
DE	1st	N/A	0.0005	0.0005	N/A
EFoW	1st	N/A	N/A	0.004	N/A
ESE	1st	N/A	N/A	N/A	0.0001
EF	1st	N/A	0.0006	N/A	0.0006
EWa EWi ECu	3rd	0.037	0.037	N/A	0.037
HE	1st	0.0009	0.0009	0.0009	0.0009
IDC	1st	0.0007	N/A	N/A	N/A
IQC PRM	2nd	N/A	0.0000015	N/A	N/A
IWMS	1st	N/A	N/A	0.004	N/A
ICP	1st	N/A	N/A	N/A	N/A
IMS	1st	0.0005	N/A	N/A	N/A
ISDS	1st	N/A	N/A	N/A	N/A
IC	1st	0.0004	0.0004	0.0004	0.0004
ME	1st	0.0002	N/A	N/A	N/A
MF	1st	N/A	0.0006	N/A	0.0006
NH	1st	N/A	0.0023	N/A	0.0023
SS	1st	N/A	N/A	N/A	N/A
UC	1st	0.0004	0.0004	0.0004	0.0004
UAM	1st	N/A	N/A	0.003	N/A
UE	1st	0.0004	N/A	N/A	N/A
WM	1st	0.0003	N/A	N/A	N/A
Probability		0.0438	0.0457015	0.0132	0.0453027

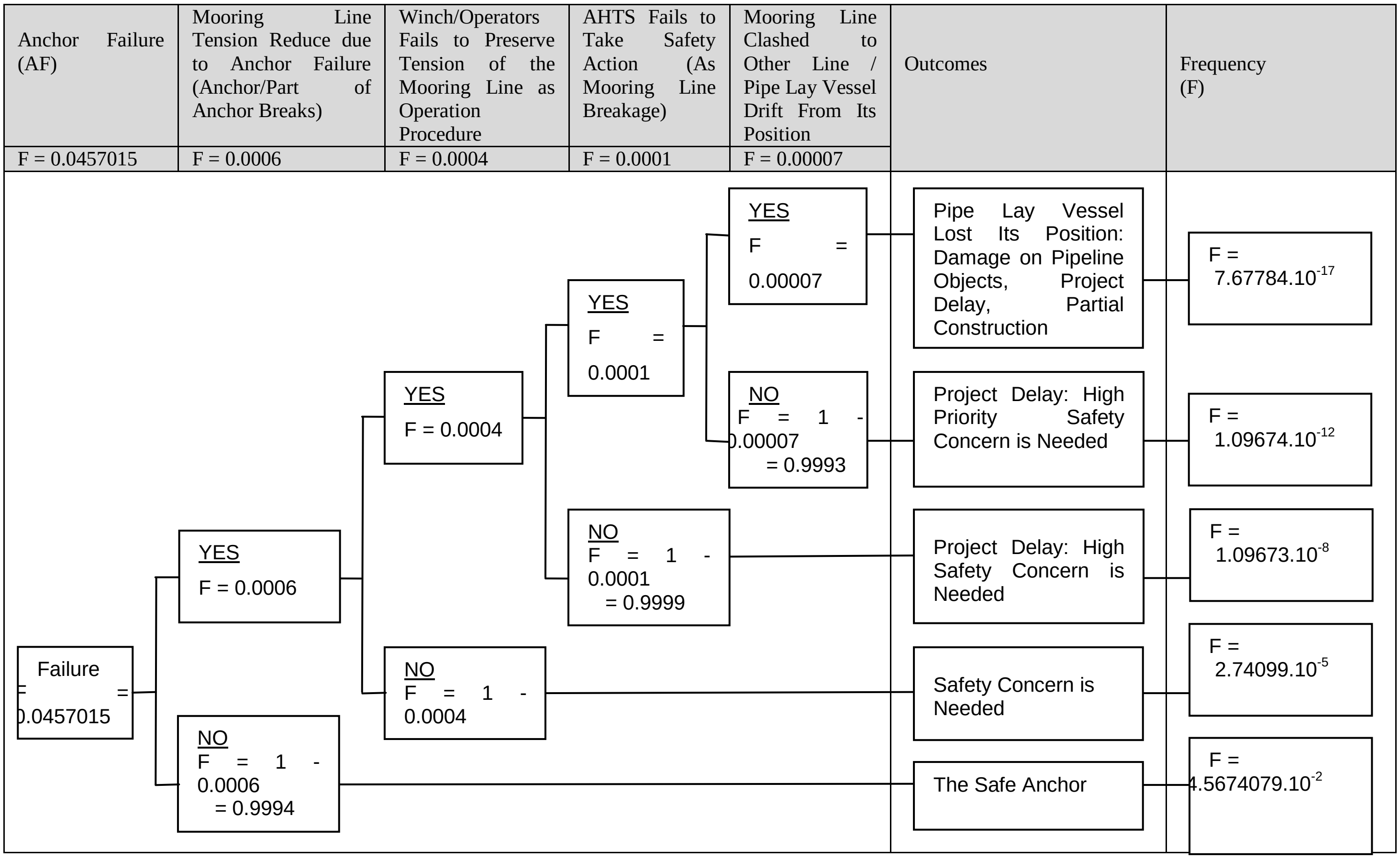

Figure 8 ETA for anchor failure

3.3 ETA Result

Event tree diagram for AF is shown in Figure 8. The frequency of initiating event of AF derived from the result of the FTA, as seen in Table 6 is 0.0457015 per year. This is then used as the frequency of AF for the initiating event in the left diagram as seen in Figure 8. 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 $7.67784.10^{-17}$ 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 $4.5280049.10^{-2}$ per year. The other three paths of MLB outcomes consist of mixed yes and no paths of pivotal events. 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.

4.0 CONCLUSION

1. The first objective is to develop methodology for investigation of critical hazardous (MIVTA). The following are the main findings related to this objective:

    i. Investigations of critical hazardous events that affect safety and operability in mooring systems show that there are four factors involved, namely mooring line breakage (MLB), anchor failure (AF), appurtenance connection failure (ACF) and anchor handling failure (AHF). Anchor failure is the major factor that imposes highest frequency of failure i.e. $4.57.10^{-2}$ per year classified as occasional events.

    ii. The potential causes of an accident hazard of mooring system are derived from each event of critical hazard. The direct causes of MLB are caused by corrosion, abrasion, mooring line clashed, and collision. The direct causes of AF are prompted by insufficient holding, part of anchor breaks, mooring line clashed and collision. The direct causes of AHF are caused by barge winch failure and anchor handling tug failure. The direct causes of the ACF are derived from corrosion and fatigue cracking.

    iii. The possible consequences of an accident hazard of mooring system are obtained from each event of critical hazard associated with all their frequencies of pivotal event paths.

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