RISK-BASED FRAMEWORK FOR SAFETY MANAGEMENT OF ONSHORE TANK FARM OPERATIONS

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Abstract

The onshore tank farm operations has become more useful and handy, as a result of increased international sea-borne trade, particularly, the unprecedented higher volume of petroleum products and hazardous chemicals traffic globally. The onshore tank farm is a facility used for safe discharge, loading and storage of petroleum products and other hazardous chemicals at the ports. It has become an important element in the supply chain system because of the increased universal energy demand and the fact that large number of modern tanker vessel is busy and efficiently moving cargo to different destinations around the world. The tank farm serves as a back-up facility to the ports. However, it has high degree of system-wide challenges of potential major incidents/accidents, as evidenced in various tank farm recorded accidents, which occurred at different times with estimated losses valued in millions of US dollars. The accidents could be catastrophic, leading to deaths, extensive damages and adverse impact on environment. To eliminate or minimize the risk of major incident/accidents, as well as minimize the magnitude and severity, it is acutely urgent to uncover and assess all potential hazards, with a view to adopt the best preventive/mitigative policy direction in the management of this strategic facility.

This thesis presents multiple safety/risk assessment approaches, uncertainties treatments and decision making techniques that are capable of finding optimal solutions that will ensure safety of tank farm operations. The standard tools of analysis employed in this tank farm operational risk assessment are Failure Mode Effect Analysis (FMEA), Faulty Tree Analysis (FTA), fuzzy logic, Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). Firstly, the FMEA-Fuzzy Rule Based (FRB) is applied in Hazard Identification (HAZID) and risk evaluation of tank farm operations. The methodology is utilized to discover five possible causes of catastrophic accidents in tank farm operations. The causes/hazards are described as the automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device system failure, and secondary containment monitoring system failure. In the risk assessment conducted, the leak detection system failure was identified as the riskiest hazard using expected utility theory.

Consequent upon the need for further investigation, another technique, Fuzzy Fault Tree (FFT), as novel model is used successfully to investigate and understand the causes of the leak detection system failure. The main aim of these two exercises is to assess risks and facilitate proper manage of these risks in tank farm operations, in order to forestall accidents that could cause damage to the facility, workers and the port environment. Nevertheless, the tank farm operations need to be optimized by ensuring the efficiency and safety of all systems and sub-systems through the adoption of best safety management decisions, which is achieved by employing AHP-TOPSIS model. This method is used to solve a complex multi-criteria decision-making problem such as selection of best Safety Control Design (SCD) among various SCDs identified. Finally, the results produced from the developed models and frameworks are summarized and other areas where they can effectively make impacts in HAZID, risk assessment and safety improvement are defined.

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Abbreviations

AIChE	American Institute of Chemical Engineers
AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
AST	Aboveground Storage tanks
BEs	Basic Event
BN	Bayesian Network
DoBs	Degree of Belief
CA	Criticality Analysis
CCA	Cause-Consequence Analysis
CI	Consistency Index
CoA	Centre of Area
CR	Consistency Ratio
CSH	Consequence Severity of Hazard
DEA	Data Envelopment Analysis
DH	Detectability of Hazard
DWT	Dead Weight Tonnage
EFMEA	Expanded Failure Mode and Effects Analysis
ESD	Emergency Shutdown
ET	Event Tree
ETA	Event Tree Analysis
ER	Evidential Reasoning
FPs	Failure Possibility
FPr	Failure Probability
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effects and Criticality Analysis

FTs	Fault Trees
FTA	Fault Tree Analysis
FSA	Formal Safety Assessment
F-VIM	Fussell-Vesely Importance Measure
FFTA	Fuzzy-Fault Tree Analysis
FRB	Fuzzy Rule Base
FRB-FMEA	Fuzzy Rule Base-Failure Mode and Effect Analysis
FST	Fuzzy Set Theory
HAZID	Hazard Identification
HAZOP	Hazard Operability Study
IMEA	Infection Mode Effect Analysis
IMO	International Maritime Organization
LPG	Liquefied Petroleum Gas
MSA	Maritime Safety Agency
MCS	Minimal Cut Set
MCDM	Multi-criteria Decision Making
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
NFPA	National Fire Protection Association
NGL	Natural Gas Liquid
NIRP	Negative Ideal Reference Point
NIS	Negative Ideal Solution
OLH	Occurrence Likelihood of Hazard
PAH	Priority for Attention of Hazard
PHA	Preliminary Hazard Analysis
PIRP	Positive Ideal Reference Point
PIS	Positive Ideal Solution
PRA	Probabilistic Risk Assessment
RCO	Risk Control Option
RI	Random Index
RPN	Risk Priority Number

SCR	Safety Case Regulations
SCDs	Safety Control Designs
TEs	Top Events
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
UST	Underground Storage Tanks
UVI	Ultra-Violet Irradiation
WMoM	Weighted Mean of Maximum

Chapter 1 - Introduction

Summary

In this chapter, the background analysis, aim, objectives, hypothesis and challenges of conducting the research are discussed. The research methodology, justification of research and scope of the thesis are detailed, followed by the research contributions and descriptions of the structure of the thesis for better understanding of how to address and investigate tank farm risk-based problems.

1.1. Background Analysis

The safety of tank farms cannot be compromised because of its importance and strategic positions in storage of the petroleum, chemical and hazardous flammable liquid. The main function of tank farm is to store transported petroleum and chemical products from pipelines, ships or refineries in a cost effective manner. Petroleum products demand is on the high side and will continue being high in the future. This will result in a continuous increase in constructions and use of tank farms for storage of petroleum products. There should be continuous review and assessment of the safety of tank farm operations, evidenced from various major accidents that have occurred.

These accidents are still shocking the world due to system, environmental and personnel loss. The values of these losses are in millions of dollars. For instance, in 1997, 37 people died, 100 injured and 15 loaded storage tanks destroyed, when LPG ignited during loading operations of a tank from a ship in Vishakhapatnam, India (Chang and Lin, 2006). Also in Naples, Italy, 24 tanks farms at a marine petroleum products terminal were lost due to fire inferno caused by overfilling of the tank. This further destroyed the terminal buildings, industrial and residential structures (Chang and Lin, 2006; Clark *et al*., 2001). This is another important and bitter lesson. Other catastrophic tank farm accidents can be found in Chang and Lin (2006).

These accidents have attracted questions on how safety is reviewed in tank farm operations. Every safety regulations should aim at ensuring that risk associate with any operations under investigation has been reduced to the level of As Low As Reasonably Practicable (ALARP) and cost effective control measure recommended and implemented. Notable organizations such as American Petroleum Institute (API), International Maritime Organisation (IMO), American Institute of Chemical Engineers (AIChE), American Society of Mechanical Engineers (ASME) and National Fire Protection Association (NFPA) have been improving on tank farm safety via recommendation of rules and regulations aimed at addressing previous accidents. However, accidents still happen and will continue to occur if proactive risk assessment is not practiced in tank farm operations. Therefore, the way tank farm safety is assessed and managed should be proactive manner rather than reactive manner.

This approach is facilitated in marine and oil industries by the introduction of safety regulations such as Safety Case Regulations (SCR) and Formal Safety Assessment (FSA). Use of the proactive approach is the advantage of this thesis. In this study, there is focus on major hazards of the tank farm operations for the risk/safety assessment processes. The risk/safety assessment processes are HAZID and risk evaluation, risk analysis and management/control. A generic tank farm is used to facilitate an understanding of the subject under study and can help identify major hazards, since various tank farms (i.e. fixed or cone roof tank, open top floating roof tank and fixed roof tanks with internal floating roof) have similar operational features.

The work proactively tackled risk assessment of major tank farm operational hazards under uncertainty using advanced computing techniques. The step by step risk/safety assessment processes are used in this study. Firstly, the Failure Mode Effect Analysis – Fuzzy Rule Based (FMEA-FRB) models are used in tank farm HAZID and risk evaluation. The second step is the use of Fuzzy Fault Tree (FFT) model in further risk analysis of riskiest tank farm hazard (s). The final step is the use of the Analytical Hierarchical Process-Technique for Order Preference by Similarity to the Ideal Solution (AHP-TOPSIS) technique for selection of tank farm safety/risk control measure.

1.2. Research Objectives and Hypothesis

The primary aim of this research is to generate a methodology for risk assessment of tank farms under uncertainties and test with case studies. This will be beneficial to the industries because it ensure oversight of safety on tank farm operations and pollution prevention to the environment. The proactive nature of this research in the investigation and management of the major tank farm operational hazards can only be successful if the objectives described below are met.

- Carry out a comprehensive literature search on various tank farm accidents, regulations, standards and codes related to tank farm safety and constructions.
- Carry out literature search and adoption of a brainstorming technique to reveal major hazards of the tank farm operations.
- Conduction of risk evaluation and ranking of automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure and secondary containment monitoring system failure, which are the identified major tank farm operational hazards under uncertainties using the FMEA-FRB methodology.
- Carry out investigation of the causes of the leak detection system failure using the Fault Tree Analysis (FTA) method. The leak detection system failure is the riskiest hazard of the tank farm operations.
- Conduction of the investigation of the failure probabilities of the leak detection system failure and their causes under uncertainties using the FFT model.
- Conduction of the identification of the best safety improvement measure that can ensure optimal operations of the tank farm using the AHP-TOPSIS technique and experts' judgement.

Chapters 2, 3, 4 and 5 will be used to implement the objectives of this research. The literature review of this research is detailed in Chapter 2, to facilitate the development of other chapters. Application of the FMEA-FRB method in HAZID exercise and risk evaluation is illustrated in Chapter 3. Enabling of the FFT model is illustrated in Chapter 4 with case study, while Chapter 5 details how AHP-TOPSIS model reveals the best safety improvement measure.

The objectives are carried out on the hypothesis that an advanced computing technique such as fuzzy logic and decision making models such as AHP and TOPSIS methods can be explored in addressing challenges of obtaining optimal tank farm operations.

1.3. Challenges of Conducting the Research in Realm of Uncertainties (Statement of Problem)

Various challenges are encountered and subdued in the conduction of the HAZID and risk/safety evaluations, risk analysis and control of the tank farm operational hazards under uncertainties in this research. Advanced computing models are employed as tools that can address the challenges associated with the tank farm operational hazards. This will contribute immensely in the improvement of the tank farm operational safety. The notable challenges and how they can be addressed are described in Sub-sections 1.3.1 – 1.3.3.

1.3.1. Uncertainties Treatment in HAZID and Risk Evaluation of Tank Farm Operations

Revealing tank farm operational hazards and the associated risks, are not an easy task, especially when the process is proactively based. Proactive approach is used because the study is not all about investigation of a particular previous accident. Therefore, to overcome this challenge, thorough literature search in combination with experts' judgement in a brainstorming session are used to reveal major tank farm operational hazards. Risk evaluations and ranks of major tank farm operational hazards such as automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure and secondary containment monitoring system failure posed to be a challenge in realm of uncertainties. Use of the FMEA-FRB method and expert judgement in the investigation of each tank farm operational hazards revealed their riskiness and ranks.

1.3.2. Uncertainties Treatment in Risk Analysis of the Riskiest Tank Farm Operational Hazards

Leak detection system failure is the riskiest tank farm operational hazard and its cause is yet unknown and can only be identified by understanding its operation, use of experts' experiences and a thorough literature search. This challenge is addressed using the FTA method. Its failure logic mechanism facilitated the identification of the causes of the leak detection system failure and their relationships with one another. The unavailability of data for estimation of the failure probability of the leak detection system failure via its causes is also a big challenge in this research. This problem is addressed by using the FFT model. The FFT model can be used to estimate and facilitate the conversion of the failure possibilities of the leak detection system failure and its causes to their respective failure probabilities.

1.3.3. Multi-Criteria Decision Making (MCDM) on Safety Control Design (SCD) of the Tank Farm Operations

A novel model is developed for selection of the best Safety Control Design (SCD). The selection of the best SCD is addressed as a multi-criteria decision making problem. This difficult task is tackled by adoption of the AHP-TOPSIS model. The AHP-TOPSIS model is used to estimate the weights of the identified SCDs. A SCD associated with the highest relative closeness to ideal solution, RC^{+} value is classed as the best one and vice versa.

1.4. Research Methodology

The research methodology is centered on how to achieve optimal tank farm operations in the realm of uncertainties using the overall safety/risk assessment framework. In view of this, the research methodology of this study focused on HAZID and risk/safety evaluations, risk analysis and control of the tank farm operational hazards. In this study, uncertainties treatments and MCDM models have been developed for ensuring optimal tank farm operations. The success of the research methodology is described using various chapters. Thus, the research methodology is divided into three sections as evidenced in Fig. 1.1.

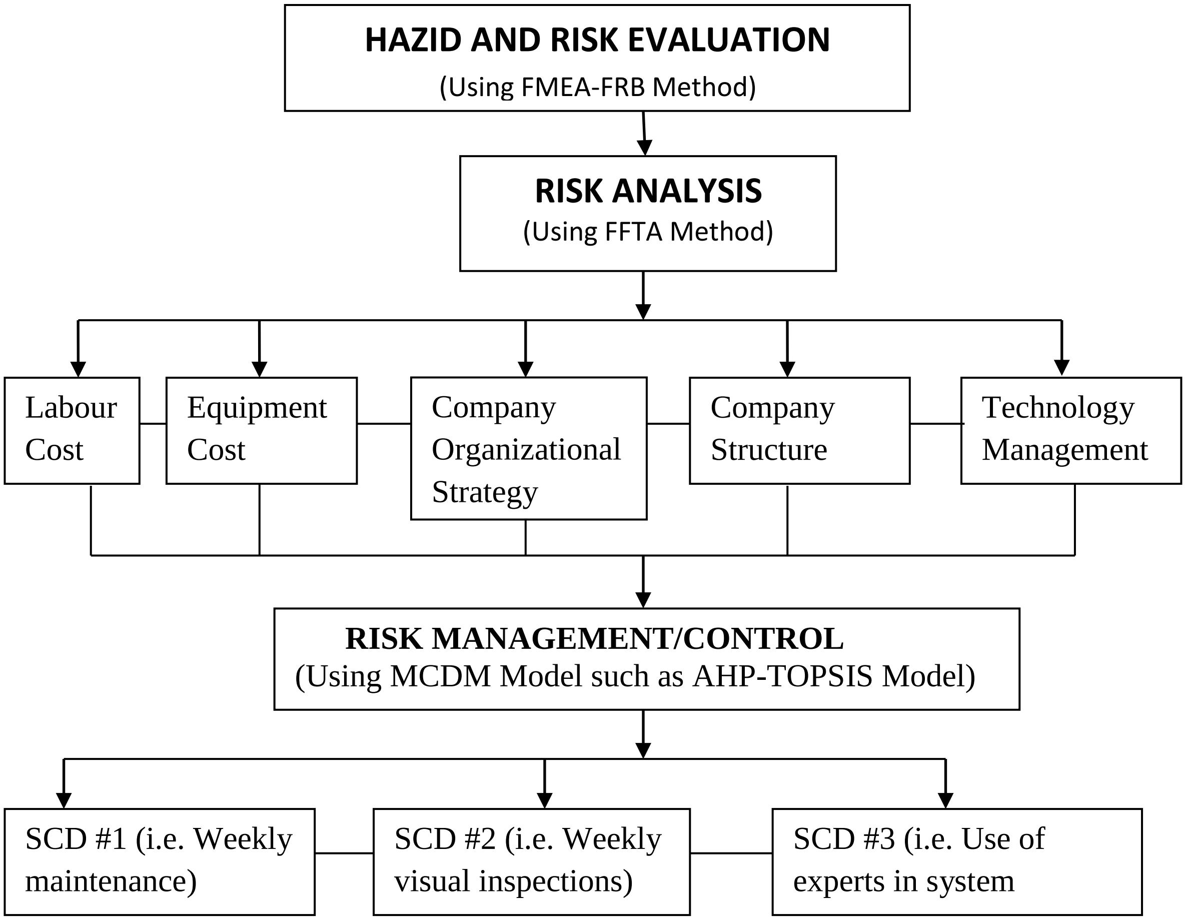

Figure 1.1: Thesis Research Methodology

1.4.1. Hazard Identification (HAZID) and Risk Evaluation

Major tank farm accidents and rules and regulations governing tank farm safety and constructions set by various organizations have been discussed in Chapter 2. Traditional safety/risk analysis, uncertainty treatments and decision making techniques are discussed and their impacts in risk assessment of various systems noted in Chapter 2, so as to facilitate adoption of some of them in the HAZID and risk evaluation of tank farm operational hazards. Experts' judgement, a brainstorming technique and conduction of literatures search exposed automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure and secondary containment monitoring system failure as major hazards of tank farm operations. A FMEA technique is used to risk evaluate the hazards. Due to uncertainties associated with the values/scores of the parameters of FMEA such as Occurrence Likelihood of Hazard (OLH), Consequence Severity of Hazard (CSH), Detection of Hazard (DH) and Priority for Attention of Hazard (PAH) (i.e. Risk Priority Number (RPN)), the FRB method is incorporated in the risk evaluation and ranking of the aforementioned major tank farm operational hazards. The OLH, the CSH, the DH and the PAH are described with five linguistic terms each in fuzzy environment, so as to facilitate their applications together with the FRB method in the subject being investigated. The linguistic descriptions of the OLH, CSH, DH and PAH are used to estimate fuzzy values of the major hazards of the tank farm operational hazards. The concept of FMEA-FRB methodology revealed the leak detection system failure as the highest priority tank farm operational hazard due to its riskiness.

1.4.2. Risk Analysis

In this safety/risk assessment phase, the concept of the FFT model is adopted in analyzing the causes of the riskiest tank farm operational hazards and estimations of their failure probabilities in Chapter 4. Revealing of the failure probabilities of the causes, will facilitate the estimation of the one of leak detection system failure. The FTA method is used to construct how leak detection system failed, thereby revealing the causes (i.e. BE and intermediate events) and the Top Event (TE) (i.e. leak detection system failure). Such a Fault Tree (FT) construction is effectively developed using experts' experiences and thorough literature search. Five linguistic terms in fuzzy environment is used to estimate the failure possibilities of the causes of the leak detection system failure, which are converted to their respective failure probabilities using mathematical concept of the FFT model. The failure probabilities of the causes are systematically combined in line with the principles of the FFT model to reveal the one of the TE. The failure probabilities of the BEs are used to rank them. The usefulness of the model is supported with result verification via sensitivity analysis.

1.4.3. Risk Management/Control

In the risk management/control phase, the AHP-TOPSIS model is used to identify the most efficient SCD among the three SCDs as evidenced in Chapter 5. The concept of the AHP model and experts judgement is used to estimate the weights of criteria associated with the SCDs. Eighteen linguistic terms are established but few relevance ones are used in the expert judgement of the pair-wise comparisons of the criteria. The revealed weights of the criteria are used to facilitate application of TOPSIS method in selection of the best SCD. Therefore, TOPSIS method revealed that the safety of tank farm operations can be improved by selection of a SCD with highest relative closeness to ideal solution, RC^{+} value as shown in Chapter 5. The one selected is SCD #1 (i.e. weekly maintenance). Other SCDs are SCD #2 (i.e. Daily Visual Inspections) and SCD #3 (i.e. Use of Experts in System Operations).

1.5. Justification of Research

Increasing use of tank farms for storage of various flammable liquids and the number of storage tanks accidents is giving stakeholders, various organizations and the public concern. The operations of tank farms are associated with hazards that pose to be a threat to the environment and public. Identification of those hazards and their associated risks in time can help experts to plan on how to prevent them or provide mitigative measures, thereby making tank farm operations safer and efficient in certain and uncertain environment. In view of this, there is need for this research, since the idea of the study is to identify these high risk hazards using tools capable of handling uncertainty in combination with traditional safety/risk methods and manage those hazards using a MCDM tool. This study will contribute in improving the low safety level of tank farm operations evidenced from the accidents in the industry. To address the problem, a proactive approach is used in the investigation, analysis and management of the risk associated with tank farm operational hazards under uncertainty.

A proactive approach is used in risk assessment of failure of tank farm operational systems. The systems are leak detection device/system, pipe corrosion protection system, automatic tank gauge system, automatic shut-down oil safety valve and secondary containment monitoring system. A combination of traditional safety/risk assessment technique such as FMEA and uncertainty treatment method such as FRB is used to facilitate the exercise. Such risk assessment exercise revealed leak detection device/system as the high risk one. Leak detection device/system is further investigated for detailed risk assessment exercise, so as to identify the causes of the system failures and quantify them, using a combination of another traditional safety/risk analysis technique (i.e. FTA) and fuzzy logic. The fuzzy logic addressed the problem associated with lack of failure rate data of the BEs. In addition, the challenges posed with improvement of the system safety, when various options are available were subdued using the AHP-TOPSIS model.

1.6. Scope of Thesis

In this research, overall safety/risk assessment processes is used to solve optimal operations challenges in tank farm. Step by step approach of safety/risk assessment processes such as HAZID and risk evaluation, risk analysis and risk control are fully utilized. This is because of the various accidents that have happened in tank farm operations. Risks of major hazards associated with the tank farm operations that could result to catastrophic consequences are estimated and controlled using the FMEA-FRB, FFTA and AHP-TOPSIS methodologies. The risk associated with the highest risk hazard is reduced to acceptable level.

1.7. Research Contributions

The uniqueness and novelty of this research makes it a vital and universal acceptable tool/platform for HAZID and risk/safety management of hazardous and dangerous systems/cargoes under uncertainty. In general, the main aim of this study was to conduct proactively a HAZID, risk/safety evaluation and control of tank farm operational hazards under uncertainty. It is achieved step by step as follows:

- Under uncertainty condition, a methodology of HAZID and risk evaluation of tank farm operational hazards is developed using the FMEA-FRB methodology and experts' judgements in Chapter 3. This methodology can be adopted by various industries in addressing HAZID and risk evaluation problems under uncertainty.
- An uncertainty treatment and failure investigation methodology is developed in Chapter 4. The causes of the failure of the high risk tank farm operational hazard are revealed using the FTA method and their failure probabilities are estimated by adoption of the FFT method under uncertainty. The TE failure probability is found and is reasonable and acceptable.
- A multi-criteria decision making model such as an AHP-TOPSIS model is developed in Chapter 5, for selection of most effective SCD. The AHP-TOPSIS model is used to facilitate risk reduction and safety improvement of tank farm operations via selection of the best SCD among the three SCDs. The SCD with the highest relative closeness to ideal solution, RC^{+} values is identified and revealed as the best one.

1.8. Structure of the Thesis

The understanding of this research lies on its structure. In view of this, the research is made up of seven core chapters, including this introduction (Chapter 1). The titles of the chapters are shown in Table 1.1 and how they are linked together is demonstrated in Figure 1.1. In the Figure 1.2, Chapter 1 being the introduction of the thesis, serves as the chapter where information about the thesis started. This is followed by Chapter 2, which serves as background analysis of other chapters (i.e. Chapters 3, 4 and 5) and other relevant information related to the subject matter. Chapter 2 is linked to Chapter 3 as shown in Figure 1.1 and Chapter 3 is purposely for HAZID and risk evaluations and ranking of tank farm operational hazards. Chapter 3 is linked to Chapter 4 and 5, while Chapter 4 is linked to Chapter 5. The primary aim of Chapter 4 is to investigate the causes of the riskiest hazard revealed in Chapter 3, while Chapter 5 provides the much needed solution for prevention of tank farm operational failures. Chapter 6 is linked to Chapters 3, 4 and 5. It discusses the results produced in Chapters 3, 4 and 5, and the merits and demerits of the models used in those chapters. It also concludes the thesis and is linked to the model applications (i.e. Chapters 3, 4 and 5).

Table 1.1: Summary of the Chapters in this Research

Chapter No.	Title
1	Introduction
2	Literature Review
3	Enabling Failure Mode Effect Analysis - Fuzzy Rule Based (FMEA-FRB) Methodology in Risk Evaluation and Prioritization of Tank Farm Operational Hazards
4	Incorporation of Fuzzy Fault Tree (FFT) Model to Failure Analysis of Leak Detection System of Tank Farm Operations
5	Optimal Safety Improvement of Tank Farm Operations using an Analytic Hierarchy Process-Technique for Order Preference by Similarity to the Ideal Solution (AHP-TOPSIS) Model
6	Discussions and Conclusions

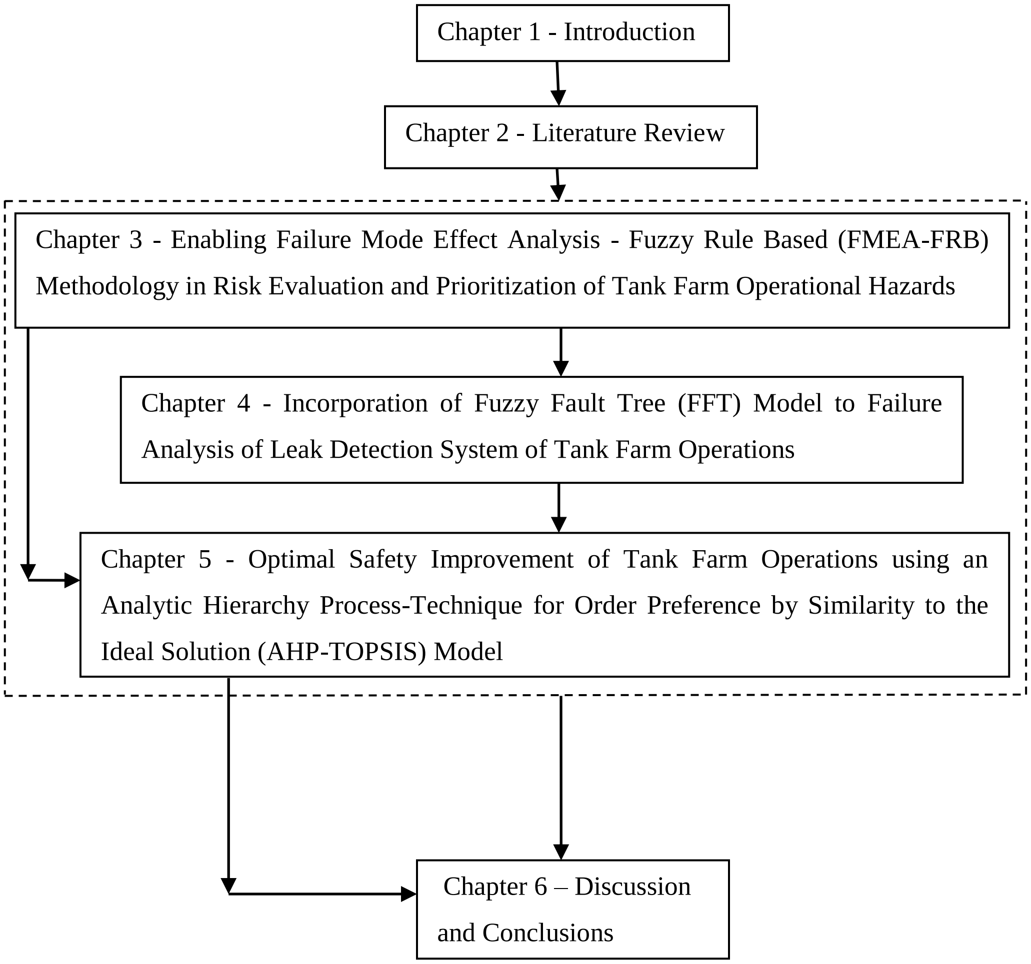

Figure 1.2: Structure of the Research

Chapter 2 - Literature Review

Summary

In this chapter, the literature related to the study is reviewed. The operations of tank farm in ports are discussed. The tank farm accidents, risk assessment of tank farm operations, rules and regulations governing tank farm operations and safety are detailed. Various safety/risk assessment techniques and uncertainty in risk assessment are explained. Uncertainty treatment and decision making techniques employed in the study are also described, and the need for the research is reported.

2.1. Introduction

Rapid development of petroleum and chemical industries has attracted the use of large-scale atmospheric storage tanks (Bai & Liu, 1995; Jiang & Li, 2005; Li, 1996; Shuai *et al.*, 2012). Safety of tank farms is very important, especially now the number of tank farms sited in port environment is increasing drastically. Tank farms are important storage facilities that can be used to store petroleum products and other hazardous chemicals in ports environment. These large-scale tanks filled with highly flammable liquid have high potential risk and once there is leakage, the consequences are serious environmental pollution, fire and casualties (Shuai *et al.*, 2012). Therefore, safety management of tank farms need urgent attention, in order to prevent catastrophic accidents. In this chapter, literature review is carried out to reveal the description of operations of tank farms in ports, and various tank farm accidents. Rules and regulation that contributed in tank farm safety is also discussed. The HAZID and risk assessment tools that can be used to ensure optimal tank farm operations are outlined and decision making techniques that can be employed for uncertainty treatment and safety design selection are detailed. Also, the literature review revealed why this research is necessary (i.e. justification of research).

Adoption of proactive approach in conduction of failure analysis of tank farm operations within the port environment under uncertainty and safety improvement of the systems and sub-systems of the tank farm are necessary. This will ensure optimal operations of the tank farm and reduction of catastrophic accident in port environment as low as reasonable practicable. Therefore, a combination of traditional safety/risk analysis and advanced computing techniques are adopted in this thesis, due to high level of uncertainties being addressed.

Proactive risk-based approaches for safety management of tank farm operations are employed. A FMEA-FRB methodology is used for hazard identification and risk evaluation of tank farm operations, while failure of leak detection system that posed to be a treat in ensuring optimal operations of the tank farms is investigated using FFT model. The safety improvement of tank farm operations is ensured using AHP-TOPSIS methodology to identify the most efficient SCD.

2.2. Operations of Tank Farm in Ports

Tank farm operations are associated with high risk due to its content. The volume of a tank farm is over 100,000m^3 (Shebeko *et al.,* 2007). The hazardous nature/quality of the cargo that the tank farm stores posed to be a treat to the system operational efficiency. The tank farm can store crude oil, oil products, gasoline/naphtha, petrochemicals, Liquefied Petroleum Gas (LPG), waste oil water, ammonia, hydrochloric acid, caustic soda, molten sulfur etc, classified as hazardous cargoes (Chang and Lin, 2006). Accidents may occur during loading of the tank content to a vessel or truck. It can also occur during the discharging of the vessel content to the tank farm or when there is no loading or discharging operations. Effective operations of the tank farm can be achieved by strictly adhering to the rules laid by API, AIChE, IMO, ASME and NFPA and local administration. To avoid risks in tank farm operations, the dynamics of the systems of tank farm need to be studied. Such studies can facilitate provision of mitigative measures for unforeseen hazards that can threaten proper operations of the tank farm. There are three main types of tank farms for storing combustible or flammable liquid hydrocarbon fuel. This includes (Argyropoulos *et al.,* 2012; IChemE, 2008):

- Fixed or cone roof tanks. It is designed in line with API standard (API, 2001). The tank is made of a vertical cylinder side and a fixed cone-shaped roof that is welded to each other as evidenced in Figure 2.1. This type of tank is designed with a weak seam at joint, where the roof and sides become one to cope with an internal explosion (API, 2001; Argyropoulos *et al.*, 2012). This makes the roof to separates from the tank without the containment and any fire accident is proliferated only on the surface of the fuel (Argyropoulos *et al.*, 2012). The tank type is mainly use for storage of fuel-oils, asphalt (bitumen) and vacuum or atmospheric residue, therefore, the use of insulation, steam or coil heating in these types of tanks is necessary for the keeping of its content in a liquid state (Argyropoulos *et al.*, 2012).

- Open top floating roof tank (simple pontoon or double deck). It is also designed in line with API standard and is made up of a vertical, cylindrical above ground shell similar to the conical roof tank, but with a pontoon type roof as shown in Figure 2.1. The roof has the ability to rise and fall on the stored-fuel surface, in order to prevent the large volumes emittance of fuel-vapours (Argyropoulos *et al.*, 2012). Moreover, there is a rim seal that covers the space between the floating roof and the tank shell, in the form of a rubber tube filled with kerosene, where most frequently a fire may start (Argyropoulos *et al.*, 2012). The tank is used for storage of volatile liquid hydrocarbons such as crude oil and “white” light products (i.e. jet, diesel and gasoline). The tank is constructed in a way that it can prevent the dissemination of the oil-leakage to the surrounding installations with a major probability of ignition.

- Fixed roof tanks with internal floating roof. This type of storage tank is a combination of cone roof tank and open top floating roof tank as illustrated in Figure 2.1. The tank consists of a conical roof with the addition of the internal floating roof or pan that floats directly on the fuel surface (Argyropoulos *et al.*, 2012). The tank has internal floaters that can decrease the potential of ignition and prevention of initiation of tank fires (Argyropoulos *et al.*, 2012). The tank can also be used to store volatile liquid hydrocarbons such as crude oil and “white” light products (i.e. jet, diesel and gasoline) and can prevent the dissemination of the oil-leakage to the surrounding installations with a major probability of ignition (Argyropoulos *et al.*, 2012).

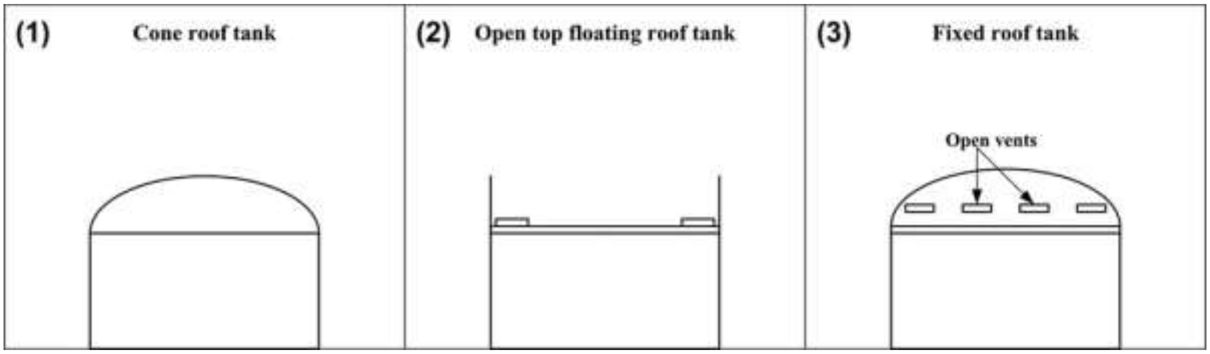

Figure 2.1: Types of Tank Farms (Argyropoulos et al., 2012)

2.2.1. Tank Farm Accidents

More than 242 tank farm accidents/incidents have happened since the use of tank farm in storage of flammable liquid (Chang and Lin, 2006). In this study, 11 most catastrophic tank farm accidents are outline in Table 2.1. These various tank farm accidents that have happened in the past necessitated the conduct of this research. In view of this, proactive approach is used to identify major tank farm operational hazards and risks assess and control them under uncertainties as evidenced in Chapters 3-5.

Table 2.1: Historical Largest Tank Farm Accidents

No.	Date	Location	Accident Description
1	24/2/1986	Thessaloniki Greece	Sparks from a flame cutting torch ignited fuel from a tank spill in a dyke of a fuel tank. The fire spread to other areas resulting in destruction of 10 out of 12 cruel oil tanks (Chang and Lin, 2006).

2	3/4/1977	Umm said, Qatar	A 260,000-barrel tank containing 236,000 barrels of refrigerated propane at -45^{o}F failure massively. An adjoining refrigerated butane tank and most of the process area were also destroyed by fire (Chang and Lin, 2006).
3	20/1/1968	Pernis, Netherlands	Frothing occurred when hot oil and water emulsion in a slop tank reacted with volatile slop, causing a violent vapour release an boil-over. The fire destroyed 3 hydrocarbon, a sulfur plant, and 80 storage tanks (Chang and Lin, 2006).
4	1/9/1979	Deer Park, Texas, USA	Nearly simultaneous explosions aboard a 70,000 Dead Weight Tonne (DWT) tanker off-loading and in an 80,000 barrel ethanol tank at a refinery occurred during a electric storm (Chang and Lin, 2006).
5	30/5/1978	Texas, USA	An unidentified failure led to the release of light hydrocarbons which spread to an ignition source. 11 tanks in this alkylation unit were destroyed (Chang and Lin, 2006).
6	20/8/1981	Kuwait	Fire destroyed 8 tanks and damaged several others. The cause of the fire has not been disclosed (Chang and Lin, 2006).
7	14/9/1997	Vishakhapatnam, India	LPG ignited during tank loading from a ship. A thick blanket of smoke spreading panic among the residents resulted in 37 people died and 100 injured. 15 storage tanks burned for two days (Chang and Lin, 2006).
8	21/12/1985	Naples, Italy	24 of the 32 tanks at a marine petroleum products terminal destroyed by fire that began

			with a tank overfill. Explosion caused complete destruction of the terminal buildings and nearby industrial and residential structures (Chang and Lin, 2006; Clark *et al.*, 2001).
9	7/1/1983	Newark, New Jersey, USA	A overfilling of a floating roof tank spilled 1300 barrels of gasoline into the tank dyke. The vapour cloud carried by wind to a nearby incinerator was ignited. The resulting explosion destroyed two adjacent tanks and the terminal (Chang and Lin, 2006).
10	26/5/1983	Prodhoe, Bay, Alaska, USA	A low-pressure Natural Gas Liquid (NGL) feed drum ruptured in a crude oil station, resulting in fire damage to one third of the module and exterior of surrounding structure within 100 ft. (Chang and Lin, 2006).
11	11/12/2005	(Buncefield) Hertfordshire, U.K.	Failure of high-level gauges caused the overfilling of the tank at estimated rate of 550m^3/hr, which resulted to overflow into the bund generating large quantities of vapour. About 20 premises were lost in nearby industrial estate, affecting the livelihood of some 500 people (Buncefield Major Incident Investigation Board, 2008; Herbert, 2010).

2.3. Risk Assessment of Tank Farm Operations

Risk assessment is a comprehensive estimation of the probability and the degree of the possible consequences in a hazardous situation in order to select appropriate safety measures (Wang and Trbojevic, 2007). It has various phases such as HAZID, risk evaluation, risk analysis and management/control. Risk assessment of tank farm operations can be carried out using qualitative or quantitative risk analysis approach. Availability of historical tank farm accidents/incidents data and requirement of experts involved in tank farm risk assessment will determine if the process is qualitative or quantitative base.

The first phase of risk assessment is HAZID. A hazard is defined as a physical situation with a potential to cause injury, damage to environment or some combination of these (Wang and Trbojevic, 2007). HAZID is concerned with the use of “brainstorming” techniques by utilising trained and experienced personnel to determine the hazards (Godaliyadde, 2008; Wang, 2000). The team involved in the exercise works with the theme of believability/credibility, which is that there must be potential for an initiating event to be technically feasible (even if highly unlikely) within the expected lifetime of the activity (Nwaoha *et al.*, 2011; Pitblado *et al.*, 2004). The team used brainstorming technique in HAZID exercise and ensures that the process is proactive. HAZID is usually carried out at the component level, then the sub-system level to the system level. The analysis at system level makes use of the information at sub-system level, while the analysis at the sub-system level uses the information produced at the component level. Traditional safety/risk analysis techniques such as the FTA, ETA, PHA, HAZOP, Bowtie, FMEA and FMECA can be used in the HAZID exercise. In this study, hazards of tank farm operations have been identified using brainstorming approach and thorough literature search by four experts. The hazards are:

- Automatic shut-off oil safety valve failure.
- Pipe corrosion protection system failure.
- Automatic tank gauge system failure.
- Leak detection device/system failure.
- Secondary containment monitoring failure.

The second phase of risk assessment is risk evaluations. It is a process of evaluating risks associated with the hazards identified in the first phase of risk assessment. This phase can also be conducted in a similar manner with the first phase of risk assessment. This phase helps to reveal levels of risks of hazards. It facilitates identification of hazards that need more attention. Methods such as the FTA, ETA, BOWTIE, FMEA and FMECA can be employed in risk evaluation of a hazard as a stand alone or in combination with uncertainty treatments methods. History has shown that tank farm safety is very low (Chang and Lin, 2006). There have been numerous accidents in tank farm operations, which imply that high risk hazards associated with the operations have not been properly addressed. In view of this, the FMEA-FRB method is used in risk evaluation of the hazards identified in first phase of risk assessment, as evidenced in Chapter 3.

The third phase of risk assessment is risk analysis. In this phase, attention is focused on the riskiest hazards, so as to reveal their causes. Identification of their causes will facilitate the provision of possible control measures for that hazard under investigation. Techniques such as the FTA, ETA, BOWTIE, FMEA and FMECA can also be employed as a stand alone or in combination with uncertainty treatment methods. In this study, the FFTA method is used in risk analysis of the riskiest hazard of tank farm operations as evidenced in Chapter 4.

The final phase of risk assessment is managing and controlling of the risks of hazards. In this phase, various control measures are usually identified and the best selected among the lot. The MCDM techniques such as AHP, TOPSIS, MAUT and expected utility theory are usually used in this phase. The safety of tank farms failed to be in optimal level, irrespective of various safety features that are recommended and incorporated in the tank farm operations and other related facilities by API, AIChE, ASME, IMO and NFPA (AIChE, 1988; 1993; API, 1988; 1990; ASME, 2004; NFPA, 1992; UL, 1986; 1987; IMO MSC/Circ.1023, 2002). In this phase, the successful use of the AHP-TOPSIS method in combination with the expected utility theory has been revealed in Chapter 5.

Various experts have demonstrated the applicability of quantitative and qualitative risk analysis approaches in onshore storage tank operations (Argyropoulos *et al*,. 2012; Shuai *et al*., 2012; Massimo *et. al.*, 2013; Fabbrocino, *et. al.*, 2005; Crippa, *et al.*, 2009; Necci *et. al.*, 2014; Shi *et. al*., 2014; Wang, *et. al.*, 2013; Kang, *et al*., 2014). In the works of Argyropoulos *et al*. (2012), a systematic HAZID methodology for liquid hydrocarbon fuel storage tanks is carried out by applying a checklist technique on the accident causes and the relevant protection measures, in the framework of the SEVESO Directive series. Their work revealed that the present hazards assessment methodology facilitated the identification of the major contributors to risk, so as to improve safety measures (Argyropoulos *et al.*, 2012). A quantitative risk assessment approach has been applied to a large-scale crude oil tank (Shuai *et al.*, 2012). In their study, Risk-based Inspection (RBI) technology is used to quantitatively assess the risk of crude oil tanks in an oil depot in China. The risk comparison between tank shell and bottom shows that the risk of tank depends on the risk of tank bottom (Shuai *et al.*, 2012). According to Massimo *et. al.* (2013), quantitative risk analysis is used to quantify the damage and to plan safety of exposed workers and people in surrounding area of a gasoline storage plant. The study revealed an effective means for emergency planning, defined the vulnerability of the potential damage area through the characterization of known exposure levels. The individual risk indicators depend on the exposure levels and the hazard scenarios evolution (Massimo *et. al.*, 2013). Their research demonstrated that it is partial to consider only the accidental events with high probability of occurrence in the emergency management purposes and safety design.

Fabbrocino, et. al. (2005) carried out integrating of structural seismic risk into quantitative probabilistic seismic risk analysis using an oil storage plant with a number of atmospheric steel tanks containing flammable substances. In their work, empirical seismic fragility curves and probit functions, properly defined both for building-like and non-building-like industrial components, have been crossed with outcomes of probabilistic seismic hazard analysis for a test site. Once the seismic failure probabilities have been quantified, consequence analysis has been performed for those events which may be triggered by the loss of containment following seismic action (Fabbrocino, *et. al.*, 2005). Crippa, *et al.* (2009) proposed a fire risk assessment methodology to face the fire risk connected with large atmospheric storage tanks. Same workflow could also be extended to the issues connected with other problems related with large atmospheric tanks storing hydrocarbons, such as environmental impact by soil pollution, to create a common frame work of assessment (Crippa, *et al*., 2009).

Necci *et. al.* (2014) investigated on the identification of event sequences and accident scenarios following lightning impact on atmospheric tanks. An overall methodology was outlined to allow the calculation of the expected frequencies of final scenarios following lightning impact on atmospheric storage tanks, taking into account the expected performance of available safety barriers (Necci *et. al.,* 2014). In their study, the methodology was applied to a case study in order to better understand the data that may be obtained and their importance in the framework of quantitative risk assessment and of the risk management of industrial facilities with respect to external hazards due to natural events. Shi *et. al.,* (2014), contributed towards the development of a quantitative approach for assessing the occurrence probability of fire and explosion accidents of steel oil storage tanks. In their work, a fault tree method is employed in identification of potential causes of fire and explosion accidents of steel oil storage tanks. A hybrid application between an expert elicitation based improved AHP and Fuzzy Set Theory (FST) facilitated the estimation of the occurrence possibility of fire and explosion accidents of steel oil storage tanks for an oil depot in China.

In the works of Wang *et. al.* (2013), FTA technique is used in revealing the various potential causes of the crude oil tank fire and explosion and the calculation of the occurrence probability of the crude oil tank fire and explosion using exact probability data of the basic events. FST is incorporated in their study, to address challenges associated with difficulties in obtaining corresponding precise data and information as a result of changing environment or new components. According to Kang, et al. (2014), a new quantitative risk evaluation model for oil storage tank zones based on the theory of two types of hazards such as inherent hazards and controllable hazards are identified, analysed and classified. A combination of FTA, FST, AHP and risk matrix methodology is used in the aforementioned quantitative risk analysis exercise in oil storage tank zones.

2.4. Rules and Regulation Governing Tank Farm Operations and Safety

Tank farms and associated facilities are designed and constructed using best industrial standards to ensure safety. Employing best industrial standards ensures there is drainage facilities, proper equipment/instrument selection, proper layout, interspacing and safety release system etc. Organizations such as API, IMO, AIChE, ASME, and NFPA have contributed immensely in the tank farm operational safety (IMO MSC/Circ.1023, 2002; AIChE, 1988; 1993; API, 1988; 1990; ASME, 2004; NFPA, 1992). In AIChE, (1988), guidelines for storage and handling of high toxic hazard materials is outlined while in AIChE, (1993), the guidelines for engineering design for process safety is explained. Other organization such as API explained guideline for welded steel tanks for oil storage (API, 1988) and further recommended rules for design and construction of large, welded, low-pressure storage tank (API, 1990). ASME (2004) contributed in tank farm safety via provision of codes for boiler and pressure vessel and NFPA (1992) provided standard for the storage and handling of liquefied petroleum gases. Some notable safety measures used in tank farms operation are (GexCon AS., 2008):

- Blanketing with an inert gas (usually nitrogen) to prevent the formation of an explosive atmosphere inside the tank, thereby eliminating the ignition hazard due to electrostatic discharges.
- Antistatic additives that increase the conductivity of the liquid, thereby preventing electrostatic charges from accumulating on the liquid surface.
- Minimising the formation of static electricity during filling of the tank by maintaining low flow velocities during pumping (typically below 3m/s for pure liquids, and below 1m/s when water is present), avoiding splash filling, and including long lengths of tubing after restriction like filters or orifice plates to allow charges to decay.
- Sensible layout of tank farms, such as sufficient spacing between the tanks, separate bunds for each tank to capture liquid spills, placing pumps and other equipment outside the bunds, etc.
- Flame arresters on all vents for tanks containing flammable liquids.
- Hazardous area classification: preventing ignition sources by dictating design requirements for electrical equipment according to relative explosion risks in defined zones.
- Use of floating roof tanks, thereby eliminating the formation of a confined explosive atmosphere.

Other safety features of storage tanks and their environment include:

- Tank roof safety valves.
- Double deck pontoons on the roof.
- Side entry mixers trip on the tank low level.

- Emergency Shutdown (ESD) switch for emergency shutdown of tank.
- Auto tank radar gauging.
- Tank overflows protection.
- Double seal/liquid mounted seal.
- Fire detection system in rim seal area.
- Loading arms with overflow protection system.
- Loading arms/SPM hoses provided with breakaway couplings.
- Fire and gas detection system.
- Fixed foam pourer system.
- Automatic sprinkler system.
- Rim seal fire detection for larger floating roof tanks.
- Placement of portable firefighting equipment at strategic areas.
- Fire water monitors and hydrants.
- Firefighting equipment.
- Pivot master for floating roof drains.
- Tank dyke walls made of concrete.
- Inbuilt protection for over pressurization of lines due to thermal expansion.
- LPG driers facility.

IMO mainly takes care of shipping related activities of the tank farm. IMO as a body that contributes to the standardisation of the legislations and regulations related to marine activities has put proactive measures in place to address any risk associated with loading/unloading of flammable liquid from tank farm to and from ship, evidenced by their adoption of FSA. The IMO defines FSA as a structured and systematic methodology, aimed at enhancing marine safety, including protection of life, health, the marine environment and property, based on risk and cost benefit assessments which lead to decisions (IMO MSC/Circ.1023, 2002). FSA is a process that involves HAZID, risk assessment, risk control option and decision making in a cost effective manner. The adoption of FSA for shipping represents a fundamental cultural change, from a largely reactive approach, to one which is integrated, proactive and soundly based upon the evaluation of risk (Godaliyadde, 2008). FSA is an outstanding tool because it considers hazards that have not yet given rise to accidents in risk management of loading and unloading operations of ships to and from tank farms. Other benefits of FSA are (MSA, 1993):

- A consistent regulatory regime which addresses all aspects of safety in an integrated way.
- Cost effectiveness, whereby safety investment is targeted where it will achieve the greatest benefit.
- Confidence that regulatory requirements are in proportion to the severity of risks.
- A rational basis for addressing new risks posed by ever changing marine technology.

2.5. Risk Assessment Techniques

Experts can employ various safety/risk analysis techniques in carrying out comprehensive risk assessment of tank farm operations. These safety/risk analysis techniques are outline as follows:

- Failure Mode Effect and Criticality Analysis (FMECA).
- Fault Tree Analysis (FTA).
- Event Tree Analysis (ETA).
- Bowtie Analysis.
- Hazard Operability (HAZOP) Studies.
- Preliminary Hazard Analysis (PHA).
- Risk Matrix.

2.5.1. Failure Mode Effect and Criticality Analysis (FMECA).

Failure Mode Effect and Criticality Analysis (FMECA) is one of the safety/risk analysis technique used in the maritime and oil and gas industries and was developed in the 1960s in the United States. The usefulness of the technique was firstly demonstrated by NASA during the development of the Apollo Project (Carmignani, 2009). It can be used in HAZID, risk evaluation and analysis phases. FMECA is an inductive technique and can handle both qualitative and quantitative assessment (Kumamoto and Henley, 1992; MIL-STD-1629A, 1980; Wang and

Ruxton, 1997). It involves compilation of reliability data for individual items. This technique has been widely used in many industries to address safety and risk assessment problems (Pillay, 2001; Kumamoto and Henley, 1992; Villemeur, 1992; Wang and Trbojevic, 2007). It can be carried out from any indenture level required to examine the failure modes of a component (subsystem) and its possible consequences (Nwaoha, 2011). FMECA is capable to address failure modes with severe effects that have sufficiently low occurrence probabilities (Villemeur, 1992). FMECA is made up of two parts such as:

- FMEA. Associated with identification of potential failures of a system and the effects of such failure on that system's performance. FMEA also reveals the potential severities of such effects on the systems. Further descriptions are detailed in Chapter 3.
- Criticality Analysis (CA). Associated with calculation of the risk of each failure of the system through measurements of the severity and probability of a failure event.

In Wang and Trbojevic (2007), the steps of FMECA are outlined as follows:

1. Define the constraints and assumptions of the analysis.
2. Break down the system to its levels such as the sub-system level and the component level.
3. For each item at the level analysed, identify all possible modes of failures and respective causes.
4. For each identified failure mode, identify or provide the following information:
    - All the distinctive operating conditions under which failure may occur.
    - The failure rate of the identified failure mode.
    - The effects (consequences) on the safety and operability of the higher levels (including the level analysed).
    - The possible means by which failure may be identified.
    - Design provisions and/or actions in operation to eliminate or control the possible resulting effects.
    - The severity class of the possible effects where such a class may be defined by one of the linguistic variables (i.e. catastrophic, critical, marginal and negligible). Catastrophic linguistic variable means death, system loss and/or severe environmental damage, while

critical linguistic variable means severe injury, major system damage and/or major environmental damage. Marginal linguistic variable means minor injury, minor system damage and/or minor environmental damage, while negligible linguistic variable means no injury and negligible damage to the system and the environment.

5. Failure consequence probability defining the likelihood that the effects of the identified failure mode will occur given that the failure mode has taken place.
6. Final step is criticality analysis. Criticality analysis allows a qualitative or a quantitative ranking of the criticality of the failure modes of items as a function of the severity classification and occurrence likelihood.

The FMEA method has been used to solve various problems in combination with other algorithms. For example, Yang *et al.* (2008) used a FRB Bayesian reasoning approach and FMEA in assessment of collision risk between a floating, production, storage and offloading system and a shuttle tanker caused by technical failure during tandem offloading operation. An interesting application of FMEA-FRB model in reliability improvement of diesel engine's turbocharger system is carried out in Xu et al (2002). The difficulties of interdependencies among various failure modes with uncertain and imprecise information in failure analysis of diesel engine's turbocharger system are tackled. Pillay and Wang (2003) incorporated FRB-FMEA model and grey theory in risk analysis of a fishing vessel. Such combination of algorithms addressed the draw backs of traditional FMEA and yielded a more accurate ranking of failure modes of fishing vessel systems.

Risk assessment and management of port security is carried out using the FRB model in combination with FMECA and Expanded Failure Mode and Effects Analysis (EFMEA) (Ung *et al.*, 2009). The fired rules in the 625 rules of the FRB model facilitated the risk ranking and management of the port security. Pam et al. (2013) have demonstrated the relevant of an FRB and Infection Mode Effect Analysis (IMEA) model in risk estimations of ballast water. The mechanism of the FMEA in combination with Data Envelopment Analysis (DEA) is applied in risk prioritization of failure modes of fishing vessel systems (Chin *et al.*, 2009a). Other industries have explored the strength of FMEA and FRB methods in addressing various challenging tasks (Braglia *et al.*, 2003a; Braglia *et al.*, 2003b; Chang *et al.*, 2001; Chang *et al.*, 1999; Guimaraes and Lapa, 2007; Sankar and Prabhu, 2001; Sharma *et al.*, 2005; Stamatis, 1995; Xu *et al.*, 2002).

The FMEA-FRB technique is employed in subjective risk evaluation of tank farm operational hazards in Chapter 3. The technique facilitated the development of generic HAZID and risk evaluation framework of tank farm operations.

2.5.2. Fault Tree Analysis (FTA)

FTA is a safety/risk analysis technique that can be used to handle both quantitative and qualitative risk assessment problems. It can be used in HAZID, risk evaluation and analysis phases. FTA is a top down approach that systemically considers the causes or events at levels below the top level (Lavasani, 2010). It is a deductive reasoning approach and can be applied to a system of any size for risk assessment purposes (Ang and Tang, 1984; Godaliyadde, 2008; Wang and Trbojevic, 2007; Nwaoha, 2011). It was developed by H. A. Watson of the Bell Telephone Laboratories between 1961 and 1962 during an Air Force study contract for the Minuteman Launch Control System (Riahi, 2010; Godaliyadde, 2008). The technique represents the failure logic of a system in an inverted tree structure and provides very good documentation of how the failure logic of the system is developed (Andrews and Ridley, 2002; Nwaoha, 2011). In the maritime and oil and gas industries, FTA is constructed with “AND” or “OR” gate to show the causes of failure of an event. AND gate is used to connect the causes of failure of an event if the causes happen simultaneously, while OR gate is employed in FTA constructions if the causes of failure of an event happen directly (i.e. not simultaneously). The logic gates determine the addition or multiplication of probabilities to obtain the values for the top event (Lavasani, 2010).

FTA is used to estimate the probability of an accident (i.e. TE) resulting from sequences and combinations of faults and failure events (i.e. BEs) (Riahi, 2010; Godaliyadde, 2008). It addresses quantitative risk assessment problem, when probabilities associated with BEs are known/available. The pathways through the FT diagram represent all the events which give rise to the TE, are known as cut sets or implicant sets (Riahi, 2010; Wang and Trbojevic, 2007). The Minimal Cut Set (MCS) is defined as the irreducible pathways leading to the occurrence of a top event (Wang and Trbojevic, 2007). TE is the release of a hazard/undesired event of an item (Kumamoto and Henley, 1992; Wang and Trbojevic, 2007). The FTA is widely used technique for HAZID and risk estimation (Kumamoto and Henley, 1992).

A FTA method can be used as standalone or in combination with other algorithm in addressing uncertainty associated with risk assessment of a system. Lavasani et al. (2011a) used fuzzy logic to address uncertainties associated with quantification of FT of offshore pipeline system. It helped the researchers to reduce the ambiguity and imprecision arising from the subjectivity of data. Traditional FTA method needs a sound data base of failure of all BEs for quantifying the probability failure of system, whilst there is not such a database available in offshore pipeline industry; therefore, fuzzy FTA approach is proposed to deal with this issue (Lavasani *et al.*, 2011a). The paper also demonstrated the workability of the model using a case study.

The usefulness of a combination of fuzzy and FTA is also demonstrated in the work of Ping *et al.* (2007). The researchers proved that accurate assessment of system reliability with limited or insufficient statistical data is difficult. Therefore, their paper presented a method which treated the drawbacks of traditional FTA by using the FTA based on possibilistic measures and fuzzy logic. According to Ping *et al*. (2007), the method is designed specifically for situations wherein reliability and safety assessment is imprecise by nature and necessary statistical data is scarce. Based on fundamentals of fuzzy logic, failure possibility is first defined and then fuzzy variables are characterized in the context of possibility theory (Ping *et al*., 2007). An example is used to illustrate the proposed model as evidence.

The relevance of fuzzy FTA is proved in the works of Pan and Wang (2007). In their research, the difficulties in estimation of exact probabilities of occurrence of bridge failure for use in the conventional FTA are subdued through incorporation of fuzzy sets and possibility theory. An example of the collapse of cantilever gantry during construction demonstrates the capability of this technique (Pan and Wang; 2007). Similar approach is used in reliability analysis of auxiliary feedwater system (Guimarees and Ebecken; 1999). The effectiveness of the fuzzy FTA was demonstrated in analysing of safety problem of unexpected robot motion in an aircraft wing drilling system (Lin and Wang; 1997). The results indicated that the proposed approach is very effective in analysing the reliability of a man-machine system (Lin and Wang; 1997). Dong and Yu (2005) analysed failure of oil and gas transmission pipelines using fuzzy FTA model and revealed that the system has fuzzy failure probability of 6.4603×10^{-3}. The FFT model is used to conduct a quantitative assessment of leak detection system of tank farm operations in realm of uncertainties in Chapter 4. The quantitative assessment is successfully applied by adoption of a subjective method, due to lack of failure probabilities of the BEs.

2.5.3. Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is a safety/risk analysis technique and logic diagram employed in the maritime and oil and gas industries to investigate the consequences of an accident or abnormal function of a system. An Event Tree (ET) is a logic diagram applied to analyse the effects of unintended events (Lavasani, 2010). Such a technique first expresses the probability or frequency of an accident linked to the safeguard measures required to be implemented to mitigate or prevent escalation after the occurrence of the event (Lavasani, 2010). This involves the study of the complex relationships among the subsystems of the system given the occurrence of an initiating event (Wang and Trbojevic, 2007). It is usually used in risk evaluation and analysis phases. Initiating event is defined as a postulated occurrence capable of leading to possible consequences (Wang and Trbojevic, 2007). It could be loss of control point, representation of a hazard to be analysed or an unsatisfactory operating event or situation. ETA is developed diagrammatically using inductive bottom-up logic (Halebsky, 1989; Wang and Trbojevic, 2007). In ETA, probabilities are assigned to each branch of an event using historical data or expert judgement in order to estimate the occurrence probability of each possible consequence. Success and failure paths lead to various consequences with different magnitudes (Lavasani, 2010). The likelihood of each consequence can be obtained by multiplying the probability of occurrence of the accident by likelihood of failure or success in each path. ETA can be employed to investigate unknown effects from known causes (Godaliyadde, 2008; Villemeur, 1992).

2.5.4. Bowtie Analysis

The Bowtie analysis was developed at RISO national laboratories, Denmark, in the 1970’s to specifically aid in the reliability and risk analysis of nuclear power plants in Scandinavian countries (Andrews and Ridley, 2002; Andrews and Ridley, 2001; Villemeur, 1992). Bowtie Analysis is formed when an ETA and FTA is combined together to investigate the cause and consequence of a hazard happening in any environment or system. It is a vital tool for risk management of any hazard. It can also be called Cause-Consequence Analysis (CCA). The purpose of the CCA is to identify chains of events that can result in undesirable consequences (Nwaoha, 2011). Bowtie analysis is employed in HAZID, risk evaluation and analysis phases.

Bowtie analysis can be address as a deductive and inductive analysis because it is the combination of ETA and FTA, which are inductive and deductive techniques respectively. Construction of CCA diagrams starts with a choice of a critical event and the "consequence tracing" part of the CCA involves taking the initial event and following the resulting chains of events through the system (Wang and Trbojevic, 2007). The "cause identification" part of the CCA involves drawing the FT and identifying the minimal cut sets leading to the identified critical event (Wang and Trbojevic, 2007). The CCA diagram documents the failure logic of a system (Andrews and Ridley, 2001). Various researchers have employed the CCA tool in risk management exercise because of its ability to identify hazards (FTA) and consequences of the hazards (ETA) (Andrews and Ridley, 2002; Pauperas, 1991; Valaityte *et al.*, 2009; Vyzaite *et al.*, 2006).

2.5.5. Hazard Operability (HAZOP) Study

Hazard Operability (HAZOP) study is a HAZID technique. It can be used to assess the risk of marine and oil and gas systems. The HAZOP technique was developed in the 1970s by loss prevention engineers working for Imperial Chemical Industries at Tees-Side UK (Villemeur, 1992; Smith, 2005). A HAZOP is an inductive technique. It is an extension of FMECA technique, which can be applied by a multidisciplinary team to stimulate systematic thinking for identifying potential hazards and operability problems in systems (Kumamoto and Henley, 1992). It is mainly used to carry out a qualitative analysis in the intermediate stages of a design process to predictable hazards, thus it is an exploratory technique (Godaliyadde, 2008; Mauri, 2000).

It is used in detailed examination of components within a system to determine what would happen if the components were to operate outside their normal design mode conducted by a group of specialists headed by a hazard analyst (Nwaoha, 2011). Each component will have one or more parameters associated with its operation such as “pressure”, “flow”, “temperature”, “composition”, “relief”, “level”, “phase” and “instrumentation” (Nwaoha, 2011). HAZOP involves a full detailed description of the system (up-to-date engineering drawings, line diagrams etc.) and full working knowledge of the operating arrangements (Godaliyadde, 2008). Wang and Trbojevic (2007) and McKelvey (1988), outlined the steps of hazards as follows:

1. Define the scope of the study.
2. Select the correct analysis team.
3. Gather the information necessary to conduct a thorough and detailed study.
4. Review the normal functioning of the process.
5. Subdivide the process into logical, manageable sub-units for efficient study and confirm that the scope of the study has been correctly set.
6. Conduct a systematic review according to the established rules for the procedure being used and ensure that the study is within the special scope.
7. Document the review proceedings.
8. Follow up to ensure that all recommendations from the study are adequately addressed.

2.5.6. Preliminary Hazard Analysis (PHA)

Preliminary Hazard Analysis (PHA) is a HAZID technique. It is a qualitative approach which involves a mixture of inductive and deductive logic (Wang and Trbojevic, 2007). It is performed to identify all the possible hazards that could be created by the system being designed (Nwaoha, 2011). PHA was introduced in the 1966 after the Department of Defence of the United States of America requested safety studies to be performed at all stages of product development (Godaliyadde, 2008). It is the step used to identify the hazards of a system starting from when the system is about to be designed (Nwaoha, 2011). Results of PHA enable system designers to avoid many potential safety problems (Dowlatshahi, 2001).

Brainstorming technique and checklists are used to assist in identifying of hazards (Godaliyadde, 2008). The obtained results are always presented in a tabular form. The procedures and steps of a PHA method are detailed below (Czerny *et al.*, 2005; Nwaoha, 2011):

- Perform brainstorming or review existing potential hazard lists to identify hazards associated with the system.
- Provide a description of the hazards and mishap scenarios associated with them.
- Identify causes of the hazards.
- Determine the risk of the hazards and the mishap scenarios.
- Determine if system hazard avoidance requirements need to be added to the system specification to eliminate or mitigate the risks.

2.5.7. Risk Matrix

Risk matrix is safety/risk analysis technique that can be used in qualitative risk assessment. This method facilitates HAZID and risk prioritization of large systems, since the system failure rate values are not needed (Nwaoha, 2011). It can be used in risk evaluation phase of any system. This safety/risk analysis method is mainly adopted in pre-comprehensive risk assessment exercise of a system. It possesses a mechanism that can be used to screen high risk hazards that requires further investigation using other risk/safety analysis techniques. The success of this method depends heavily on the multi-disciplinary team experience of the system under investigation (Nwaoha, 2011).

This helps experts to focus on those high risk hazards for facilitation of the risk assessment exercise of any system. Tabular format is adopted in risk estimation associated with the hazards (Halebsky, 1989; Eleye-Datubo, 2006; IMO, 2007; Military Standard, 1993; Tummala and Leung, 1995). The table of a risk matrix technique is made of probability of failure and consequence of that failure and estimated risk value that can be used to evaluate any hazard of a system. The risk value is product of values of probability of failure and consequence of that failure.

2.6. Uncertainty in Risk Assessment

Uncertainty is defined as lack of knowledge of the true value of a quantity or relationships among quantities (USEPA 2011). The types of uncertainties associated with risk analysis are scenario, model and input or parameter uncertainties (Cullen and Frey 1999). These uncertainties are described as follows (Cullen and Frey 1999):

- Scenario uncertainty. It is associated with errors and omission, which result from incorrect or incomplete specification of the risk scenario to be evaluated.
- Model uncertainty. It arises when the risk model relies on missing or improperly formulated processes, structures or equations. It is referred to limitations in the mathematical models or techniques that are developed to represent the system of interest.
- Input or parameter uncertainty. It is associated with errors in characterizing the empirical values used as inputs to the model. It arises from random or systematic errors involved in measuring a specific phenomenon (e.g. statistical sampling errors associated with small sample sizes, if the data are based on samples selected with a random, representative sampling design) and the absence of an empirical basis for characterizing an input.

In maritime context, inherent uncertainty can be caused by imperfect understanding of the domain, incomplete knowledge of the state of the domain at the time where a given task is to be performed, randomness in the mechanisms governing the behaviour of the domain, or a combination of these (Eleye-Datubo, 2006). Notable accidents have occurred in tank farm operations as evidenced in Table 2.1. The evaluation of safety/risk level of the tank farm operations posed a challenge, given the high level of uncertainties in the historical failure data associated with tank farm systems and subsystems. Various uncertainty treatment techniques are outlined as:

- Fuzzy Set Theory.
- Evidential Reasoning.
- Bayesian Network.

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2.6.1. Fuzzy Set Theory (FST)

Lofti A. Zadeh, introduced FST in 1965 (Zadeh, 1965). The algorithm is developed for uncertainty treatment and it has been successfully applied in various fields (Riahi, 2010; Durga Rao *et al*., 2007; Gao *et al*., 2008; Hatiboglu *et al*., 2010; Markowski and Mannan, 2009; Pillay and Wang, 2003a, 2003b, 2003c; Moreno and Pascual, 2009; Prato, 2007; Soman and Misra, 1993; Soh and Yang, 1996; Sun and Collins, 2007; Yang and Soh, 2000; Sii *et al*., 2001; Soman et al., 1993; Liu *et al.*, 2005; Wang, 1997; Wang, 2000; Wang et al., 2001; Wang *et al.*, 1995; Wang *et al.*, 2009; Zadeh, 1987 and Yang *et. al*., 2005). Fuzzy logic is the term used for ad-hoc applications of rules based on a simplified FST (Eleye-Datubo, 2006). Fuzzy logic is an extension of classical Boolean logic from crisp sets to fuzzy sets and is the first new method of dealing with uncertainty since the development of probability (Godaliyadde, 2008). Fuzzy logic is based on possibility theory. The theory is a mathematical formalization which enables representation of degrees of membership of members in sets (Eleye-Datubo, 2006). Fuzzy logic is based on the principle that every crisp value belongs to all relevant fuzzy sets to various extents, called the degrees of membership (Yang, 2006). Its applications in system safety and reliability analysis could prove to be useful since such an analysis often requires the use of subjective judgments and uncertain data (Lavasani, 2010).

Fuzzy logic is a versatile tool that is tolerant of imprecise, ambiguous and vague data/information, and one for which its reasoning builds understanding into a process (Nwaoha, 2011; Eleye-Datubo, 2006). It uses the concept of linguistic variables, and provides a framework for dealing with such variables in a systematic way (Nwaoha, 2011). The use of linguistic variables provides flexible modelling of imprecise data and information; and the fuzzy variables are used to facilitate gradual transition between states (Lavasani, 2010). This enables fuzzy logic to address uncertainty problems. A linguistic variable differs from a numerical variable in that its value is not numbers but words and sentences in natural or artificial language (Pillay and Wang, 2003c).

Fuzzy logic employs human analysis and linguistic variables to represent risks and model uncertainty inherent in natural language (Zadeh, 1965; Pam, 2010). It is therefore complimentary to traditional safety analysis methodologies and can be an effective tool in dealing with ill-defined and imprecise information, especially linguistic information (Duckstein, 1994; Pam, 2010). Their successful applications have been proven in many applications (Riahi, 2010; Eleye-Datubo, 2006; Godaliyadde *et al*., 2009; Pillay, 2001; Pillay and Wang, 2002; Pillay and Wang, 2003; Wang *et al.*, 1995; Wang *et al*., 1996; Wang, 1997; Wang, 2000; Sii *et al*., 2001; Ung *et al.*, 2006; Yang *et al*., 2005). Fuzzy logic has many techniques such as discrete and continuous fuzzy sets, and FRB that can be used to address uncertainty problems and their successful applications depend on the experience of the experts and problem formulation. Most fuzzy logic applications use linguistic variables in estimation of failure probabilities of a system. Adoption of fuzzy logic in risk assessment is because of its unique properties such as (Godaliyadde, 2008; Eleye-Datubo, 2006; Nwaoha, 2011):

- Risk or safety assessment may involve the use of linguistic terms. Fuzzy logic is a non-probabilistic method and it can deal with linguistic terms using membership functions. Therefore, fuzzy logic may be used in risk or safety assessment.
- It is a highly recognised uncertainty treatment method which can be used in situations where a high level of uncertainty is involved.
- Fuzzy sets can give good results for modelling qualitative information based on a linguistic approach.
- It is conceptually easy to understand with “natural” mathematics.
- It is tolerant to vague or imprecise data. Its use of FST is particularly adapted to the representation and manipulation of imprecision and uncertainty of the linguistic labels that define the criteria of the classes.
- It presents a flexible way of dealing with different forms of uncertainty. For example, there is a lot of freedom in choosing the membership functions of fuzzy sets.
- It is more intuitive than differential equations and enables analysts and decision-makers to capture knowledge of how the system behaves in everyday linguistic terms (i.e. based on natural language).
- Though making use of heuristics, the framework still offers a convenient way to express and make the most of the experience of experts’ common sense knowledge.

- It has the ability to model any complex or highly non-linear function to any arbitrary degree of accuracy.
- It is based on rules (i.e. rule base logic) that can be specified with a natural language. Basically, the laws are naturally broken down into individual IF-THEN statements that lend themselves to parallel processing.

FRB method uses IF-THEN statement and expert knowledge in formation of rules meant for addressing any risk related uncertainty problems. A fuzzy *IF-THEN* rule is an *IF-THEN* statement in which some words are characterised by continuous membership functions (Pillay and Wang, 2003). More knowledge about the FRB method can be found in Chapter 3. A fuzzy set is characterized by a membership function with membership values ranging between 0 and 1 (Pillay and Wang, 2003). Notable fuzzy membership functions employed in uncertainty treatment of various problems are triangular, trapezoidal, sigmoid curve, generalized bell curve and gaussian curve membership functions (Godaliyadde, 2008; Nwaoha, 2011). Triangular and trapezoidal membership functions are commonly used in uncertainty treatment of risk assessment of a system because they are computationally effective (Zaili, 2006; Nwaoha, 2011; Godaliyadde, 2008; Sii *et al*., 2001; Ung *et al*., 2006). In Chapter 3, the FRB method is used in combination with FMEA for HAZID and risk evaluation systems/failures that posed to threaten effective tank farm operations. Furthermore, fuzzy logic in combination with FTA is used in failure and risk analysis of a leak detection system of tank farm in Chapter 4.

2.6.2. Evidential Reasoning (ER)

The ER algorithm is developed in the 1990s to deal with Multi-Criteria Decision Making (MCDM) challenges under uncertainty using the decision theory and the Dempster-Shafer (D-S) theory of evidence (Yang, 2001; Yang and Singh; 1994). The D-S theory is a theory of evidence that can aggregate different evidences together using their Degree of Beliefs (DoBs). It is well suited for handling incomplete assessment of uncertainty that is either quantitative or qualitative in nature (Godaliyadde, 2008). The ER is unique from other techniques because it uses a belief structure to represent an assessment as a distribution. Its mechanism can be used to assess and combine various levels of a system or condition to reveal the highest level based on evaluation grades associated with the DoBs. The ER has been proved to be a useful tool in many decision making applications, including risk assessment problems (Godaliyadde et al., 2009; Liu et al., 2005; Sönmez et al., 2001; Tang et al., 2004; Wang et al., 1995; Wang et al., 1996; Wang, 1997; Wang, 2000; Wang and Yang, 2001; Yang, 2001; Yang et al., 2005; Yang and Singh, 1994; Yang and Xu, 2002; Xu and Yang, 2005; Xu et al., 2006). The properties of ER are (Sönmez et al., 2001, Yang and Xu, 2002):

- It is difficult to deal with both quantitative and qualitative criteria under uncertainty but ER provides an alternative way of handling such information systematically and consistently.
- The uncertainty and risk surrounding a problem can be represented through the concept of DoB.
- Both complete and incomplete information can be aggregated and modelled by using a belief structure.
- The ER algorithm is integrated into a software package called Intelligent Decision System (IDS) (Xu and Yang, 2005). It is a graphically designed decision support tool. The IDS allows decision makers to build their own models and input their own data.
- The IDS software enables users to provide results of evaluation both in tabular and graphical forms.

2.6.3. Bayesian Networks (BNs).

Bayesian networks (BNs) was developed in the 70s at Stanford University (McCabe *et al*., 1998). The first application of the BN was carried out by Munin (Andreassen et al., 1989). It has been used extensively to model real world problems as evidenced in the works of Oliver and Smith (1990), Ottonello et al. (1992), Burnell and Horvits (1995), Szolovits and Pauker, (1993) and Russell and Norvig, (1995). It has also been used to address maritime risk and reliability assessment under uncertainty by Eleye-Datubo (2006), Riahi *et al*. (2012), Yang *et al*. (2008) and Yang (2006). BNs is also called "Bayesian Belief Networks (BBNs)", "Belief Networks", "Causal Probabilistic Networks", "Causal Nets", "Graphical Probability Networks", and "Probabilistic Cause-Effect" (Riahi, 2010). It is an artificial intelligence technique that aims to provide a decision-support framework for problems involving uncertainty, complexity and probabilistic reasoning (Riahi, 2010; Neapolitan, 1990). BN is a graphical representation of a probability distribution over a set of variables and it consists of two parts such as the directed network structure in the form of a directed acyclic graph (DAG) and a set of the joint probability distributions, one for each node, conditional on each value combination of the parents (Riahi, 2010).

A BN is usually made up of a set of nodes and directed edges. Each node is used to represent a probability distribution. The probability distribution may be "continuous" or "discrete" type. Nodes also represent random variables, while edges/arcs represent probabilistic correlation between the variables. A variable, which is dependent on other variables, is called a "child node". Directly preceding variables are termed "parents". Nodes that have no parents, are termed "root nodes", while the ones without children are named "leaf nodes". Edges/arcs are used to show conditional probabilistic dependence so that the probability of a dependent variable being in a particular state is given for each combination of the states of the preceding variables. The dependence structure is thus represented by a set of conditional probability distributions (Riahi, 2010).

According to Wang and Trbojevic (2007), a generic BN model solution should therefore be defined to describe the functions, features, characteristics and attributes which are common or relevant to the problem under concern. Building the model should consist of the following (Wang and Trbojevic, 2007):

- Create nodes.
    1. Generate list of relevant issues (facts, variables, decisions, payoffs, costs).
    2. Identify key nodes and their possible states.
    3. Insert these nodes into the network pane and label them.
- Add and label the states for each node. Use short descriptive names for the states.
- Identify relationships between nodes; draw links.
- Review the developed scenario model.
    1. Check the logical implications of the links drawn. Be sure that all utility nodes have a decision node as an ancestor.
    2. Look for ways to introduce conditional independence into the network.

    3. Avoid combinatorial explosions (ie the problem of too many parents with too many states).
    4. Revise network structure accordingly.
- Approximate probability and utility values to be entered into the node tables.
- Compile and revise as needed.

2.7. Decision Making Techniques

Decision making is an important phase in risk management of maritime operations. Once a risk that posed to be a threat to operations of maritime systems and subsystems is identified, decision making on best solution that can reduce the risk as low as reasonable practicable, need to be taken. This can be facilitated using MCDM techniques or optimization techniques. They can address single objective or multi objective decision making risk reduction challenges. The relevance of various MCDM techniques in risk-based decision making problems have been demonstrated in various applications (Arslan, 2009; Arunraj and Maiti, 2010; Chan and Kumar, 2007; Chang *et al.*, 2008; Guy *et al.*, 2006; Lim *et al.*, 2003; Lim *et al.*, 2004; Riahi, 2010; Pillay and Wang, 2003; Saaty, 1980; Saaty, 1990; Saaty, 2004; Saaty and Vargas, 2001; Yuen *et al.*, 2012; Song *et al.*, 2004; Lavasani *et al.*, 2011b; Jee and Kan, 2000; Deng *et al*. 2000; Tsaur *et al.*, 2002). Such powerful engineering tools have been fully utilised in this research (See Chapter 5). The mechanisms of the MCDM techniques are used to address decision making challenges in risk management of tank farm operations. Descriptions of various MCDM techniques as a stand-alone and in combination with other MCDM, uncertainty treatment and traditional risk/safety analysis techniques are detailed in Sub-sections 2.5.2, 2.6.1, 2.6.2 and 2.6.3. The notable MCDM techniques are:

- Evidential Reasoning (ER).
- Analytical Hierarchy Process (AHP)
- Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS).
- Expected Utility Theory.

- Multi-Attribute Utility Theory (MAUT)

2.7.1. Analytical Hierarchy Process (AHP)

Saaty (1980) introduced AHP as a multi-criteria decision making tool. Since then, AHP has been proven to be a viable tool for tackling multi-criteria decision making problems, evidenced from the research carried out in various fields by many researchers (Riahi, 2010; Arslan, 2009; Yuen *et al.*, 2012; Song *et al.*, 2004; Lavasani *et al.*, 2011; Chang *et al.*, 2008; Guy *et al.*, 2006; Lim *et al.*, 2003; Lim *et al.*, 2004; Chan and Kumar, 2007; Chang, 1996; Chen and Hwang, 1992; Cheng, 1994; Cheng *et al.*, 1999; Kuo *et al.*, 2002; Kwong and Bai, 2003; Lee, 1996; Leung and Cao, 2000). The AHP decomposes a decision problem into a hierarchy of associated elements (Yuen *et al.*, 2012).

In port operations, Yuen *et al.* (2012) used AHP methodology to explore the relative importance of factors that determine container port competitiveness from the users' perspective. In their research, three groups of port users such as shipping liners, forwarders and shippers are considered. The importance of the various factors is determined via the AHP techniques and the results they obtained were used to evaluate ports in Mainland China, Hong Kong and other Asian cities. Other port problems have been addressed using AHP model as evidenced in Song *et al.* (2004); Lirn *et al.* (2003, 2004); Guy *et al.* (2006); and Chang *et al*. (2008). AHP model has also been employed as one of the decision support tool for spread mooring system selection. In the works of Mentes and Helvacioglu (2012), the AHP method is used to analyse the structure of the mooring system selection problem and determine the weights of the attributes. Risk and safety related problems have been addressed using AHP model. For example, Lavasani et al. (2011b) used AHP model in estimation of weights required for grouping non-commensurate risk sources in analysing fuzzy risk assessment of oil and gas offshore wells. Arsan (2009) used the AHP model for prioritizing precautions that will guide the clarification of the risk assessment option needed for proactive approach, in order to prevent marine casualties. The AHP model revealed appropriate management tool that can increase the level of safety for chemical tankers during cargo operations at a terminal.

The successful applications of the AHP in multi-criteria decision making problems lie on its mechanism and experts involves in the study. The AHP can be described using step by step approach. The AHP steps are:

1. Identification and definition of a multi-criteria decision making problem (i.e. overall goal).
2. Identification of criteria and decision alternatives that made up the multi-criteria decision making problem and the relationship between each criterion and decision alternatives.
3. Diagrammatical representation of all the overall goal, criteria and decision alternatives in one structure, showing their relationship with one another in a hierarchical structural form. The hierarchy structure must be arranged in a way that each criterion of a level in the hierarchy would be related to the decision alternatives/elements at the adjacent levels and there is no hypothesized relationship between the elements of different groups at the same level (Cheng and Li, 2001).
4. Pairwise comparison of all the criteria and decision alternatives with respect to their levels in the developed hierarchical structure using a defined numerical rating and expert judgement. The pairwise comparison exercise of each set of criteria or decision alternatives level is presented in a matrix form and each of the paired criteria or decision alternatives in the matrices is compared. This is used to facilitate each criterion and decision alternatives weight estimation exercise.
5. Estimation of weights of the criteria or decision alternatives. The weights can be estimated by addition of all the values in each of the column of the pairwise comparison matrix, followed by dividing each criterion or decision alternative values in the matrix by total added values in the column. Finally, calculate the mean of the values of a criterion or decision alternatives in each row.
6. Conduction of consistency ratio for each level of criteria and decision alternatives in the hierarchical structure. The weights estimate of criteria and decision alternatives are acceptable if the consistency ratio associated with them is less than 0.1, otherwise the exercise need to be reviewed.

The usefulness of the AHP model is extended in Chapter 5. The mechanism of the model is used to demonstrate how to select best safety improvement measure for leak detection system of tank farm operations.

2.7.2. Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)

TOPSIS method was introduced for the past three decades by Hwang and Yoon (1981) as a powerful multi-criteria decision making tool. Its crisp version was introduced by Chen and Hwang in 1992 (Chen and Hwang, 1992). In the works of Yoon and Hwang (1981), TOPSIS was developed using the principle that a selected option should have the shortest distance from the positive ideal reference point (PIRP) and the farthest distance from the negative ideal reference point (NIRP). TOPSIS method uses weighted normalised decision matrix to identify the positive ideal solution (PIS) and negative ideal solution (NIS). In the weighted normalised decision matrix, the criteria/attributes are usually monotonic. The cost criteria are defined as the most desirable candidate scoring at the lowest and benefit criteria are described as if more desirable the candidate, the higher its score verses this criterion (Wang and Chang, 2007). This facilitates identification of the PIS and NIS. NIS is a combination of all the best attribute values attainable and NIS is a combination of all the worse attribute values attainable (Yoon and Hwang, 1995).

TOPSIS has been proved to be one of the best methods in addressing rank reversal issue (Pam, 2010; Bottani and Anthony, 2006). It has also been proved to be insensitive to the number of alternatives (Pam, 2010). According to Rahman (2012), the advantages of the TOPSIS method are:

- Ability to identify the best alternative quickly.
- Simple and rationally comprehensive concept.
- Good computational efficiency.
- Ability to measure the relative performance of each alternative in a simple mathematical form.
- Large flexibility in the definition of the choice set.
- A sound logic that represents the rationale of human choice.

- A simple computational process that can be easily programmed into a spreadsheet.

Usefulness of the TOPSIS technique has been recorded in works of Wang and Chang (2007). The researchers used the model to evaluate and select initial training aircraft. The method was also employed by Bottani and Rizzi (2006) in solving outsourcing of third party logistics service providers problems. Jee and Kan (2000) utilised TOPSIS method in materials selection, while Deng *et al*. (2000) used it to address evaluation of competitive companies. It has also been evidenced in Tsaur *et al*., (2002) that TOPSIS method can be used in the assessment of service quality in the airline industry. Other relevance of TOPSIS method have been revealed in works of Wu (2007), Aghajani *et al.* (2008), Mahmoodzadeh *et al.* (2007), Mohammad *et al.* (2010), Balli and Korukoglu (2009), Olson (2004) and Wang et al. (2005). Wu (2007) used the TOPSIS model to address supply chain management problem, while loading haulage equipment selection challenges is subdued using the aforementioned TOPSIS method by Aghajani *et al.* (2008). Mahmoodzadeh *et al.* (2007), Mohammad *et al.* (2010) and Balli and Korukoglu, (2009) have used TOPSIS method in addressing project selection, foreign direct investment and computer systems problems.

Applications of combination of AHP and TOPSIS methods have been demonstrated in various applications (Rahman, 2012; Pam, 2010; Lavasani, 2010). An AHP-TOPSIS model has been utilised in the work of Rahman (2012). The researcher used the model in selection of the most efficient steaming speed of containerships. The strength of AHP-TOPSIS model is also demonstrated in subjective evaluation of ballast water decision alternatives by Pam (2010). The weights of criteria associated with ballast water such as safety, cost, practicability, environmental acceptability and biological effectiveness are revealed using the AHP technique, while TOPSIS method is used to select the best ballast water alternatives such as surface filtration, hydrocyclones, chlorination, biocides, ultra-violet irradiation (UVI) and filtration + UVI. The usefulness of combination of the AHP and TOPSIS techniques is also extended to the works of Lavasani (2010). In the research, the best Risk Control Option (RCO) for oil and gas offshore wells with respect to cost and benefit is selected using the AHP-TOPSIS model.

2.7.3. Expected Utility Theory

Yang (2001) developed expected utility theory with the aim of adopting an utility approach in obtaining a single crisp number for each option. This facilitates the ranking of the options. Expected utility theory uses the evaluation grades and associated decree of beliefs (DoBs) to estimate the crisp numbers of assessed systems or operations. It suits well in ranking of risk-based hazards as evidenced in Chapter 3. The success of the algorithm have been recorded in the works of Riahi (2010), Riahi *et al*. (2012), Yang (2010), Godaliyadde (2008), Yang (2006), Zhou *et al*. (2010), Yang and Xu (2002). The characteristics of the expected utility theory are described as follows:

- In situations where H_{n+1} is preferred to H_n, $u(H_{n+1})$ must be greater than $u(H_n)$.
- The utility value, $u(H_n)$ of evaluation grade, H_n, is estimated using experts preference.
- The utility value, $u(H_n)$ of evaluation grade, H_n, is assumed to be equidistantly distributed in normalised utility space, in situation where no preference information is available.
- Its mechanism can be used to estimate crisp number for situation where safety/risk assessment of a system is either complete or incomplete.
- The least preferred evaluation grade, H_n with the lowest utility is denoted as $u(H_1)$.
- The most preferred evaluation grade with the highest utility is denoted as $u(H_N)$.
- It is developed for only characterising an assessment and not for aggregation of criteria.

2.7.4. Multi-Attribute Utility Theory (MAUT)

MAUT was first developed by Edwards (1954, 1961), Fishburn (1968), Feridman and Savage (1952) and Keeney and Raiffa (1976) as a MCDM method used for estimation of the utilities of multiple objectives. The mechanism is used to take decisions on different problems after analysis of the utilities that are given a set of well-defined objectives. According to Keeney (1974), MAUT is essentially an extension of Multi-Attribute Value Theory (MAVT). In the works of Loken (2007), MAUT is described as a more rigorous approach for incorporation of risk preferences and uncertainty into multi criteria decision support methods. It is used to assists in providing solution of problems, where a plethora of factors are involved and their assessment is essential to the final outcome (Yang, 2006). The seven steps of MAUT framework are outlined as follows (Edwards and Newman, 1982):

- Identify objectives and functions.
- Identify stakeholders.
- Identify attributes and construct value trees.
- Assess relative importance of attributes.
- Ascertain location measures.
- Aggregate weights and utilities.
- Perform Sensitivity Analysis.

The strength of MAUT has been used to address risk related problems (Amanda and Herath, 2005; Limon et al., 2003; Wang *et al.*, 1996). Other usefulness of the MAUT has been demonstrated in various publications (Zhang *et al.*, 2003; Min, 1994; Talluri and Narasimhan, 2003; Platts *et al.*, 2002; Khan *et al.*, 2004; Linares, 2002; Von, 1982; McDaniels, 1995; Erkut and Verter, 1998). MAUT is superior to other MCDM techniques because of its robustness in problem formulation, preferences and probabilities. In other words, it has mechanism that can analyse and formulate problems with imprecision. Problem formulation is associated with the set of available alternatives, which are not fixed but can be extended (Korhonen, *et al.*, 1986; Yang, 2006).). Preference can be expressed in an imprecise and intransitive way, which gives the scope for more in depth analysis of the plausible scenarios under study (Fishburn, 1991; Yang, 2006).). Probabilities provide decision makers with the ability to conduct robust analysis and facilitate the creation of a set of alternatives which will determine the future course of actions depending on the assumptions made and prevailing conditions at the time the actions need to be taken (Keeney and Raiffa, 1993; Yang, 2006). Other MCDM techniques such as case-based reasoning, data envelopment analysis, simple multi-attribute rating technique, goal programming, ELECTRE, PROMETHEE and simple additive weighting can be found in the works of Velasquez and Hester (2013).

2.8. Conclusions

In this chapter, detailed critical review has been carried out, focusing on the tank farm accidents, rules and regulations governing tank farm operations and safety, HAZID and risk assessment of tank farm operations, various safety/risk assessment techniques, and uncertainty treatment and decision making techniques. The number of tank farm accidents experienced so far in the world, provided need for the research and the most catastrophic ones are described in details using tabular form. International organizations such as API, AIChE, ASME, IMO and NFPA that have contributed in ensuring tank farm operational safety in one way or the other are also identified and their roles are explained.

The traditional safety/risk analysis techniques that can be employed in tank farm operational risk assessment are discussed. These include FMECA, FTA, ETA, Bowtie Analysis, HAZOP, PHA and Risk Matrix. Their relevance in risk assessment are described and supported with relevance literature. Brainstorming, FMEA and FTA techniques are engaged in the HAZID and risk management of tank farm operations in this research. Their qualitative and quantitative assessment potentials are fully utilized in this research. An advanced computing technique such as fuzzy logic for uncertainty treatment and a multi-criteria decision making technique such as AHP and TOPSIS are outlined. Their usefulness on the subject under investigation is discussed.

The scientific assessment methods adopted in this research can be used to facilitate HAZID and risk/safety management of very large and complex tank farm operations under uncertainty. Experts involved in tank farm operational risk assessment have been provided with versatile proactive tools demonstrated in this innovative research, evidenced from the three novel chapters. They are outlined as enabling FMEA-FRB methodology in analysing tank farm operational hazards (Chapter 3), incorporation of FFT model to failure analysis of leak detection system of tank farm operations (Chapter 4), and optimal safety improvement of tank farm operations via AHP-TOPSIS methodology (Chapter 5).

Chapter 3 - Enabling Failure Mode Effect Analysis - Fuzzy Rule Based (FMEA-FRB) Methodology in Risk Evaluation and Prioritization of Tank Farm Operational Hazards

Summary

Maritime industry has in recent years, as a result of increased trade volumes in crude oil globally, witnessed a higher need and utilization of tank farms, especially in ports/terminals. Tank farms are industrial installations used for the storage of crude oil, petroleum products and other hazardous materials for transportation to users or processing. The tank farms are prone to accidents because of the sensitive and complex nature of their operations. Failure of tank farm operational systems such as leak detection device/system, pipe corrosion protection system, automatic tank gauge system, automatic shut-down oil safety valve and secondary containment monitoring system, can result in losses amounting to huge sums of money, human lives or down time in operations. Therefore, it is necessary to perform a risk/safety assessment and analysis on these vital industrial facilities. In this regard, a subjective technique such as FMEA-FRB methodology will be used for the development of generic HAZID and risk evaluation framework based on the safety principles of the IMO.

3.1. Introduction

The ports handle transport related operations, including the discharge and transfer of liquid cargo, such as oils, gasoline, petrochemicals, from vessels to tank farms (marine-based storage systems). The tank farms are usually located in ports in order to enhance logistics and facilitate the processing of liquid bulk and liquefied gases (Ronza *et al.*, 2007). A safety management system is a necessity in tank farm operations in view of the hazardous nature of the substances and to prevent accidents that can lead to fatalities, injuries, loss of lives and so on. The IMO recognized the urgency of safety situation in marine activities, including the discharge operations of liquid cargo and proactively adopted the FSA with the aim of attaining improved maritime safety performance. The application of FSA has achieved noticeable acceptability as a method for enhancing decision making in the industry (Wang, 2001). The ranking of origin of accidents in ports/terminals put the movement of containers and equipment as number one, while placing accidents in tank farms and other locations where hazardous materials are stored in second position (Darbra *et al.*, 2004). It is noteworthy, that lack of failure rates data in most cases, has made the risk assessment of tank farm operations very difficult.

In this chapter, a comparatively effective and reliable risk assessment technique such as FMEA in combination with FRB model will be used to address the problem of uncertainty in risk estimation of tank farm operations. The FMEA can provide a systematic method of examining all the ways in which failure of tank farm operations can occur. Therefore, its failure analysis is conducted using the components of FMEA such as severity, occurrence and detection. The FRB will be incorporated in the components of FMEA to subdue uncertainty challenges of failure rates data of the causes of tank farm operational failure. In view of this, 125 rules will be developed and used in the risk evaluations of the causes/failure modes of tank farm operational failures. The crisp number of the experts judgement on the tank farm operational failures will be obtained using Weighted Mean of Maximum (WMoM) defuzzification method for effective ranking of their Priority for Attention of Hazard (PAH) (i.e. Risk Priority Number (RPN)).

3.2. Background Analysis

The review of storage tanks accidents showed that, fire and explosion account for 85% of the accidents (Chang *et al.*, 2006). The December 11th, 2005 Buncefield Oil Storage Depots disaster is a worrisome accident that attracts a review of tank farm operation (Buncefield Incident, 2005). Another accident is the storage tank explosion and fire in Glenpool, Oklahoma (Pipeline Accident Report, 2003). These accidents would have been prevented if a predictive model such as the FMEA-FRB is used in uncertainty treatment of risk assessment of tank farm operations.

The FMEA and FRB have been used as a standalone or in combination with each other in solving various maritime challenges (Chin *et al.*, 2009a; Chin *et al.*, 2009b; Pam *et al.*, 2013; Pillay and Wang, 2003; Ung *et al.*, 2009; Yang *et al.*, 2008; Xu *et al.*, 2002). The literature review of applications of FMEA in combination with other methods/algorithms has been carried out in Chapter 2. In this research, the strength of FMEA-FRB model such as effective risk ranking of failure modes/hazards is extended in tank farm operational failure modes/hazards. Four experts involved in this study, described risk parameters (i.e. Occurrence Likelihood of Hazard (OLH), Consequence Severity of Hazard **(**CSH) and Detectability of Hazard (DH)) of FMEA with five linguistic terms and developed 125 IF-THEN rules for effective prediction of the risk rank of tank farm operational hazards/failure modes.

3.3. Hazards of Tank Farm Operations

Aboveground Storage tanks (AST) and Underground Storage Tanks (UST) are tank farms commonly in use today. In ports, tank farms are provided with adequate storage capacity for port efficiency (Merk et al., 2012). To achieve the objectives of efficient tank farm operations, the safety management must be taken as a vital function. In the maritime industry, HAZID is carried out using risk and safety analysis techniques (Wang and Trbojevic, 2007). Though, it depends on the subject under investigation and experience of the experts involved in the process. The tank farm hazards can come in the form of failures that may arise from some of the important operational elements in the system. These could be failures in systems such as leak detection device, pipe corrosion protection system, automatic tank gauge system, automatic shut-off oil safety valve and secondary containment monitoring. These systems are vital in the determination of the efficiency and safety of tank farm operations. It has been recognized that major source of accidents in tank farm operations are fire and explosion, which are caused by leakages and failures in the aforementioned systems. Such accidents can be catastrophic to the port personnel, environment and maritime systems. In fact, leakages represent an increasing danger to the maritime environment because of toxic nature of the petroleum hydrocarbons that could leak from the tanks.

In this research, a brain storming technique and thorough literature search is used to identify the tank farm operational failure modes/hazards as evidenced in Section 2.3 of Chapter 2. According to Section 2.3 of Chapter 2, the identified major hazards/failure modes of tank farm operations are automatic shut-off oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure and secondary containment monitoring failure. The experts used in the brainstorming exercise, have equal experiences of tank farm operations. They are described as follows:

1. Expert #1: He is a marine engineer and works at Nigerian Ports Authority. He has more than 10 years experience in ports and tank farm operations.
2. Expert #2: A senior operations manager at the MRS Oil & Gas Tank Farm, Lagos Nigeria with more than 10 years experience on the job.
3. Expert #3: A principal manager at the Nigerian Ports Authority with more than 10 years experience in ports, marine and commercial operations.
4. Expert #4: A technical assistant to the Managing Director, Nigerian Ports Authority with more than 10 years experience in ports and marine operations.

3.4. Failure Mode Effect Analysis (FMEA)

FMEA is a risk, safety and reliability analysis tool used for identifying and evaluating failure modes of a system. The technique originated as a formal step-by-step procedure for the systematic evaluation of the severity of potential failure modes in the 1960s (Yang et al., 2008). In the work of Stamatis (1995), FMEA is described as an engineering technique for defining, identifying and eliminating known or potential failures, problems and errors in a system, design, process or service. FMEA has been successfully applied in the maritime risk assessment (Yang *et al.*, 2008; Chin *et al.*, 2009a, Chin *et al.*, 2009b, Pillay and Wang, 2003, Pam *et al.*, 2013; Ung *et al.*, 2009) and other industries (Guimaraes and Lapa, 2007; Stamatis, 1995). Failure mode is a specific manner in which the item under investigation could malfunction (BS, 1986; Wang and Trbojevic, 2007). The riskiness of a failure mode of a system can be predicted through the RPN. A failure mode of a system associated with high RPN is riskier than the failure mode with low

RPN. Therefore, priority for attention on a failure mode with high RPN should be higher than others in order to ensure effective allocation of available safety improvement resources. RPN can be defined as product of failure consequence probability, failure consequence severity and failure consequence detectability of the failure mode of a system (Pam *et al.*, 2013; Ung *et al.*, 2009). Mathematically, RPN can be expressed as follows:

$$\text{RPN} = \text{OLH} \times \text{CSH} \times \text{DH} \tag{3.1}$$

where, OLH = Occurrence Likelihood of a Hazard
CSH = Consequence Severity of a Hazard
DH = Detection of a Hazard

A comprehensive traditional FMEA application on risk assessment of maritime system operations follows the procedures below (Pillay and Wang, 2003):

- Develop a good understanding of what the system is supposed to do when it is operating properly.
- Divide the system into sub-systems and/or assemblies in order to 'localise' the search for components.
- Use blue prints, schematics and flow charts to identify components and relations among components.
- Develop a complete component list for each assembly.
- Identify operational and environmental stresses that can affect the system. Consider how these stresses might affect the performance of individual components.
- Determine failure modes of each component and the effects of failure modes on assemblies, sub-systems, and the entire system.
- Categorise the hazard level (severity) of each failure mode (several qualitative systems have been developed for this purpose).
- Estimate the probability. In the absence of solid quantitative statistical information, this can also be done using qualitative estimates.

- Calculate the RPN: the RPN is given as the multiplication of the index representing the probability, severity and detectability.
- Determine if action needs to be taken depending on the RPN.
- Develop recommendations to enhance the system performance.
- Summarise the analysis in tabular form.

The level of uncertainties associated failure rate data of tank farm operations keeping on increasing due to complexity of the modern engineering systems. To overcome this challenge, FRB methodology will be incorporated in FMEA methodology in the next section of this research for effective address of the subject under investigation.

3.5. Failure Mode Effect Analysis - Fuzzy Rule Based (FMEA-FRB)

Incorporating FRB model in safety/risk assessment of tank farm operations using the FMEA tool can treat uncertainties associated with tank farm operational failure rates data; and address the drawbacks of the traditional FMEA as illustrated in Figure 3.1. The flow of information in Figure 3.1 starts from the definition of tank farm operations, followed by identification of hazards associated with the operations. The next step is to review if all the tank farm operational hazards have been identified. Once all the hazards have been identified, their risk parameters such as OLH, CSH and DH will be defined. The next step is to check if all the risk parameters have been identified. If the risk parameters are acceptable, the triangular membership functions of OLH, CSH and DH described as antecedent part and the triangular membership function of PAH (i.e. equivalent to RPN) described as consequent part are developed in fuzzy rule based environment. In view of this, the antecedents (OLH, CSH and DH) and the consequent (PAH) are used to develop the 125 IF-THEN rules of the FRB. A review is carried out on the developed 125 IF-THEN rules of the FRB to ensure all the rules have been identified before estimation of the fuzzy scale values of OLH, CSH and DH of each hazard. If the experts are more than one, combine their expert judgement to reveal fuzzy scale of the OLH, CSH and DH of the hazards. Use the revealed fuzzy scales of OLH, CSH and DH of hazards to identify the relevant rules of the developed 125 IF-THEN rules. Fire these relevant rules for risk estimation of the tank farm operational hazards. The next step is estimation of fuzzy conclusion of the fired IF-THEN rules for each hazard of the tank farm operations using their belief degree and max-min method, followed by calculation of their expected utility values. The final step is to rank the the tank farm operational hazards using their expected utility values.

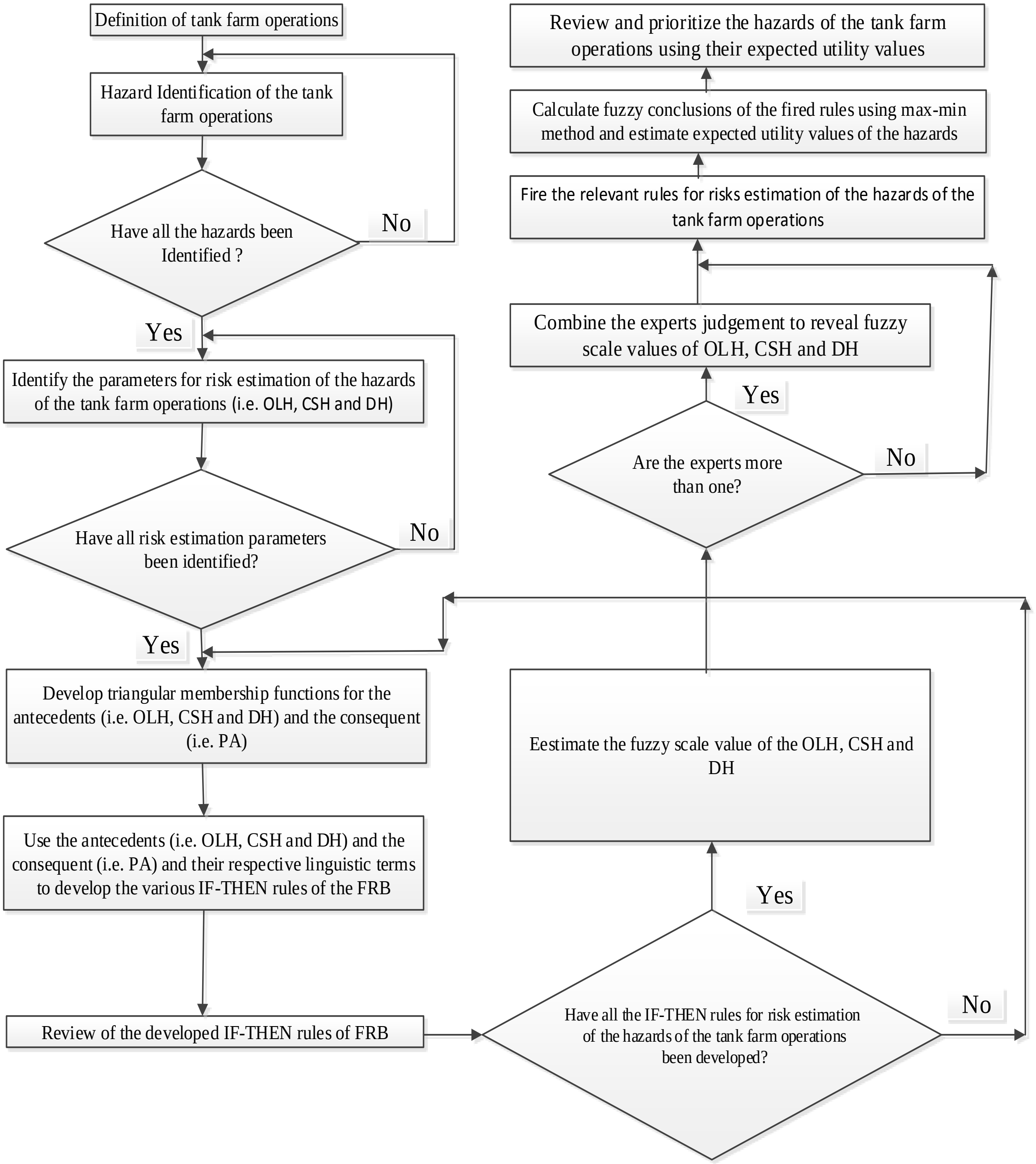

Figure 3.1: Incorporation of FMEA-FRB Methodology in Hazard Analysis of Tank Farm Operations

The drawbacks of the traditional FMEA can mislead experts and stakeholders involved in the subject under investigation if not address. The shortcoming of traditional FMEA can be described as follows (Pam *et al.*, 2013; Ung *et al.*, 2009; Pillay and Wang, 2003; Ben-Daya and Raouf, 1996; Gilchrist, 1993):

- The same RPN value can be assigned to failure modes/hazards, produced by various set of OLH, CSH and DH but their risk implications differ. Such information can mislead decision makers.
- The ranking of the RPN overlooks the relative importance among OLH, CSH and DH. They are assumed to have the same importance. In most practical cases, the RPN assigned to a failure mode/hazard is arguable and not acceptable.
- Assignment of a score to the possible failure occurrence rate and detection rate does follow any precise algebraic rule.
- There is no rationale in obtaining the RPN value of a failure mode/hazard as a product of OLH, CSH and DH.

FST was first proposed by Zadeh in 1965, and its objective is to help in making decisions characterized by imprecise information (Ung *et al.*, 2009). It provides a systematic way of interpreting linguistic variables in a natural decision-making procedure (Zadeh, 1965). FST was developed by Zadeh to provide an approximate and yet effective means of describing the behaviour of situations which are too complex to allow mathematical analysis (Pam *et al.*, 2013). It employs human analysis and linguistic variables to represent risks and model uncertainty inherent in natural language (Zadeh, 1965; Pam *et al.*, 2013). The fuzzy logic is a logic developed from the FST, which uses a range from 0 to 1 to express the degree of truth of a sentence (Nwaoha, 2011). Fuzzy logic systems are knowledge/rule based systems constructed from human knowledge in form of Fuzzy IF-THEN rules (Wang, 1997). According to Nwaoha (2011), Zadeh (Zadeh, 1965), Mamdani (1974), Takagi and Sugeno (Sugeno and Kang, 1988; Sugeno and Yasukawa 1993), and Kosko (Kosko, 1994; Kosko, 1997), the fuzzy logic algorithm have been strengthened via development of a FRB technique. The IF-THEN rules of FRB can be fuzzified using membership functions (Mamdani, 1974; Sugeno and Kang, 1988; Sugeno and Yasukawa 1993; Kosko, 1994; Kosko, 1997, Jones *et al.*, 2009; Pam *et al.*, 2013; Nwaoha, 2011;

Yang *et al.*, 2008; Ung *et al.*, 2009; Eleye-Datubo, 2006; Pillay and Wang, 2003; Sii *et al.*, 2001). Fuzzy sets are represented by membership functions on the universe of (X) and in different shapes (Pam *et al.*, 2013)**.** The notable fuzzy membership functions employed in addressing maritime risk are trapezoid and triangular types (Pam *et al.*, 2013; Nwaoha, 2011; Yang *et al.*, 2008; Ung *et al.*, 2009; Eleye-Datubo, 2006; Pillay and Wang, 2003; Sii *et al.*, 2001).

In this research, a triangular membership function is used. A membership function is a curve that defines how each point in the input space is mapped to a membership value (often indicated on the vertical axis) starting at 0 (no membership) and continuing to 1 (full membership) (Pam *et al.*, 2013), as illustrated in Figure 3.2. The horizontal axis of Figure 3.2 shows the scale values at which the curve is develop. Each curve (triangle) in Figure 3.2 is used to define a linguistic term (i.e. "Excellent", "Very Good", "Good", "Average", "Poor"). The fuzzy membership function values of a scale value depend on the shapes of the triangles. It can be determined by drawing a straight line from the chosen scale value (i.e. 3.44) to the apex of Figure 3.2. The drawn straight line normally cuts across the triangles used in defining the linguistic terms as shown in Figure 3.2. The point of interception between the drawn straight line and the triangles in Figure 3.2 is used to locate the fuzzy membership function values representing the scale value (i.e. 3.44). Therefore, the fuzzy membership function values are (0.75, "Very Good"; 0.25, "Good") as illustrated in Figure 3.2.

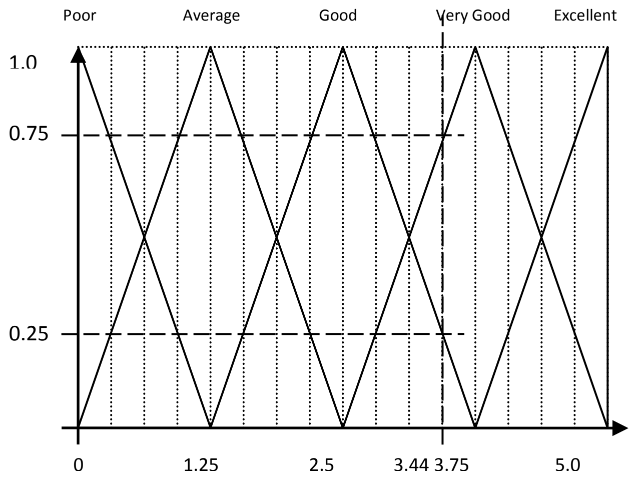

Figure 3.2: A Typical Diagram of Fuzzy Membership Function

3.5.1. IF-THEN Rules Development

IF-THEN statement is used in rule development of the FRB model. The IF-THEN statement has consequent and antecedent parts (Nwaoha, 2011; Pillay and Wang, 2003; Yen and Langari, 1999). The values of the antecedent part determine the values of the consequent part. The IF part is called antecedent while the THEN part is called consequent (Nwaoha, 2011). The IF-THEN statement can be described as "IF<antecedent>THEN<consequent>" (Nwaoha, 2011; Pillay and Wang, 2003; Yen and Langari, 1999). If antecedent part is associated with more than one linguistic term, a logic connector such as AND, OR and NOT can be used to connect them (Nwaoha, 2011; Pillay and Wang, 2003; Yen and Langari, 1999). In this study, there is more than one linguistic term used to describe the antecedent part as illustrated in Figures 3.3 - 3.5 and Tables 3.1 - 3.3 respectively. The consequent part is also described with more than one linguistic term as shown in Table 3.4. The meanings of the linguistic terms of the risk parameters used in this research are explained in Tables 3.1 - 3.4.

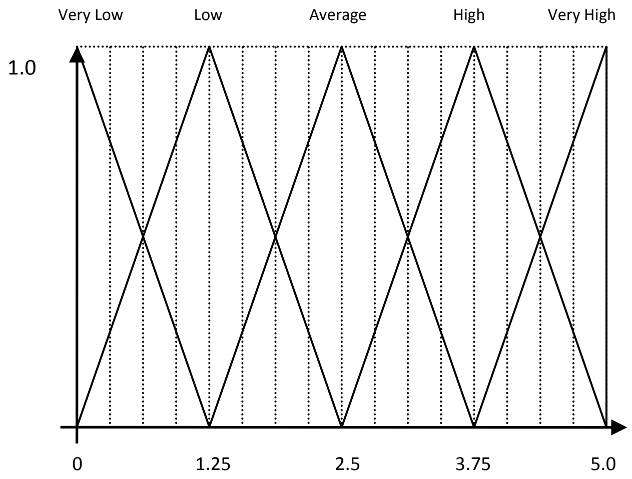

Figure 3.3: A Membership Function for Linguistic Terms of OLH

AND logic connector is used to connect/link the linguistic terms of the antecedents (i.e. the risk parameters (OLH, CSH and DH) of tank farm operations) because of their nature. There are five linguistic terms used to describe the OLH, CSH and DH as shown in Tables 3.1 - 3.3. A RPN can be described as a PAH in the IF-THEN rules used in this research because a PAH value indicates the riskiness of a failure mode/hazard over another failure mode/hazard. Higher PAH value indicates higher risk of a failure mode/hazard and vice versa. The number of linguistic terms used to describe each of the antecedents (i.e. OLH, CSH and DH) determines the number of the IF-THEN rules that is developed. The numbers of IF-THEN rules in this research are the multiplication of the number of linguistic terms used to describe OLH, CSH and DH. Since five linguistic terms are used to describe OLH, CSH and DH, 125 IF-THEN rules (i.e. $5 \times 5 \times 5$) are developed (see Appendix 3A for details).

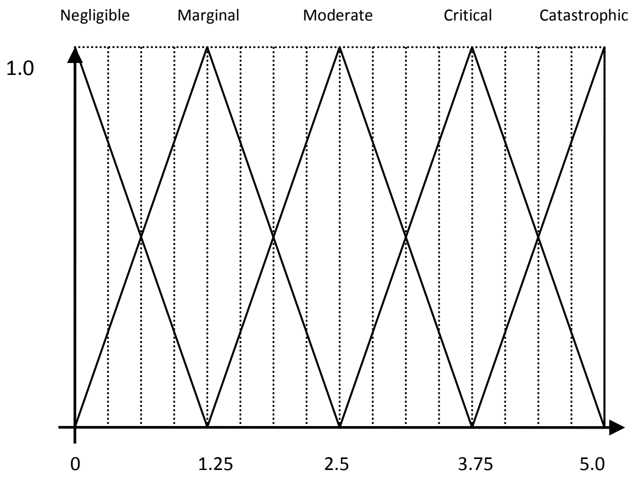

Figure 3.4: A Membership Function for Linguistic Terms of CSH

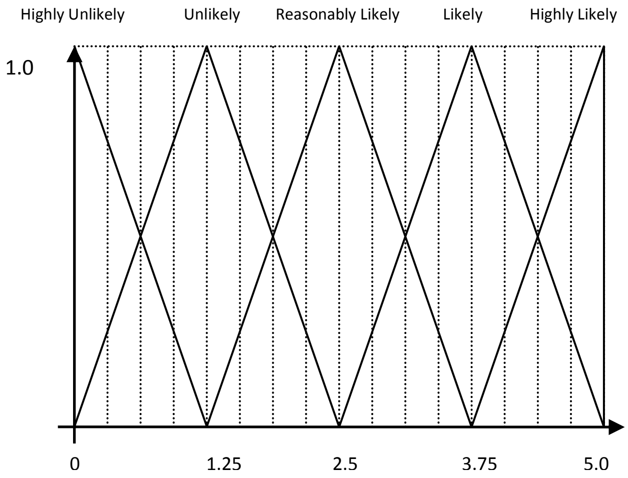

Figure 3.5: A Membership Function for Linguistic Terms of DH

Table 3.1: Ratings/Categories of OLH

Category/Rating	Linguistic Term	Meaning of the Linguistic Term
1	Very Low	The hazard of tank farm operations is unlikely to occur in lifetime of the system
2	Low	The hazard of tank farm operations might occur few times in lifetime of the system.
3	Average	The hazard of tank farm operations is likely to occur more than once or occasional in lifetime of the system.
4	High	The hazard of tank farm operations is likely to occur from time to time in lifetime of the systems.
5	Very High	It is certain; there will be frequent occurrence of the hazard of tank farm operations.

Table 3.2: Ratings/Categories of CSH

Category/Rating	Linguistic Terms	Meanings of the Linguistic Terms
1	Negligible	The occurrence of the hazard may have no or minor impact or effect on the tank farm operations.
2	Marginal	The occurrence of the hazard would have minor impact or effect on the tank farm operations.
3	Moderate	The occurrence of the hazard would have multiple impact or effect on the tank farm operations.
4	Critical	The occurrence of the hazard would have major impact or effect on the tank farm operations.
5	Catastrophic	The occurrence of the hazard would lead to total loss of tank farm operations.

Table 3.3: Ratings/Categories of DH

Category/Rating	Linguistic Terms	Meanings of the Linguistic Terms
1	Highly Unlikely	The chance of detecting the hazard of the tank farm operations is very low. In most cases, the hazard can be detected when the productivity of the tank farm operations has collapsed or system loss.
2	Unlikely	The chance of detecting the hazard of tank farm operations is low. In most cases, the hazard can be detected when the productivity of tank farm operations is found to be in low level.
3	Reasonably Likely	The chance of detecting the hazard of tank farm operations may be possible. In most cases, the hazard can be detected when there are major effects/impacts on the productivity of the tank farm operations.
4	Likely	It is possible to detect the hazard of tank farm operations in time. In most cases, the hazard can be detected when the productivity of the tank farm operations is found not to be in optimal level.
5	Highly Likely	The hazard can be detected when the productivity of the tank farm operation is still in optimal level. In most cases, the hazard can be detected by visual inspection.

Table 3.4: Categories and Meanings of Linguistic Terms of PAH

Linguistic Term	Meanings of the Linguistic Term
Very Low	The hazard of tank farm operations needs no or little attention.
Low	The hazard of tank farm operations needs minor attention.
Moderate	The hazard of tank farm operations needs average or more attention.
High	The hazard of tank farm operations needs high attention.
Very High	The hazard of tank farm operations needs major or very high attention.

3.5.2. Estimation of Fuzzy Conclusion

The fuzzy conclusion of an expert in maritime risk assessment can be estimated using max-min method (Pam *et al.*, 2013; Nwaoha, 2011; Yang, 2008; Ung *et al.*, 2009; Eleye-Datubo, 2006; Pillay and Wang, 2003; Sii *et al.*, 2001; Yen and Langari, 1999). The approach is utilized in estimation of the fuzzy membership function value of the consequent part of the 125 IF-THEN rules used in tank farm operational risk assessment. The max-min method is applied by selecting the minimum fuzzy membership function value of the antecedent part (i.e. OLH, CSH and DH) of relevant IF-THEN rules as the fuzzy membership function value of the consequent part (i.e. PAH). Then, selection of the maximum fuzzy membership function value of the same linguistic term in the relevant IF-THEN rules follows. Finally, the resultant fuzzy membership function values of the consequent part (i.e. PAH) are associated with their respective linguistic terms and identified as fuzzy conclusion of risk estimation of tank farm operational hazard/failure by an expert. In a situation where experts are more than one, and they have equal experience as in the case of this study, their risk assessment judgement of tank farm operational hazards/failure modes can be combined using the formula as follows:

$$A_{ki} = \sum_{j=1}^{n} w_{ij} a_{ijk} \quad (i = 1,2.........n) \tag{3.2}$$

where, A_{ki} = Is the aggregated weighted ratings of a risk parameter *k* for failure mode/hazard *i* produced after n experts' judgement that have equal tank farm operational experience are combined. It is called the fuzzy scale value.

a_{ijk} = Rating of a failure mode/hazard *i* by *j*th expert judgement and $j \in n$.

w_{ij} = Weight of *j*th expert involved in rating of a failure mode/hazard *i* and $j \in n$.

3.5.3. Expected Utility Approach

Ranking of hazards/failure modes of tank farm operations can be carried out using their crisp numbers in order to clarify their risk implications. The expected utility approach developed by Yang (2001) can be used to reveal the crisp values of the fuzzy conclusions of the hazards/failure modes of tank farm operations. In this research, detailed description of this method is necessary to facilitate its application in tank farm operations. Suppose H_n is the evaluation grade and $u(H_n)$ is the utility value of evaluation grade, H_n. According to Yang (2001), $u(H_n)$ and $u(H_{n+1}) > u(H_n)$ if H_{n+1} is preferred to H_n. $u(H_n)$ is estimated using experts preference. In situations where no preference information is available and $u(H_n)$ is assumed to be equidistantly distributed in normalised utility space, $u(H_n)$ can be equal to $n-1/N-1$ ($n=1,..........N$). According to Riahi *et al*. (2012), $u(H_n)$($n=1,..........N$) that are equidistantly distributed in a normalised utility space can be calculated using the formula below.

$$u(H_n) = \frac{V_n - V_{\min}}{V_{\max} - V_{\min}} \tag{3.3}$$

Where V_n stands for ranking value of the evaluation grade, H_n been considered. $V_{\max}$ is described as the ranking value of the most preferred evaluation grade/linguistic term H_N. $V_{\min}$ is described as the ranking value of the least preferred evaluation grade/linguistic term, H_1. In situation where safety/risk assessment of a system is complete, $\beta_H = 0$. β_H stands for incomplete assessment. This can be mathematically represented as $\beta_H = 1 - \sum_{n=1}^{N} \beta_n$. Where β_n is the belief degree assigned to each evaluation grade, H_n. When $\beta_H = 0$, the expected utility value of safety/risk level of a system can be calculated as follows:

$$u(S(E)) = \sum_{n=1}^{N} \beta_n(E) u(H_n) \tag{3.4}$$

In situations, where $\beta_H \neq 0$, belief interval $[\beta_n, (\beta_n + \beta_H)]$ is formed. This provides the likelihood that $S(E)$ is assessed to evaluation grade, H_n. Therefore, the average utility value can be used to calculate the expected utility value of safety/risk level of a system. Average utility value is an average of minimum and maximum utility values. The minimum, maximum and average utility are denoted as $u_{\min}(S(E))$, $u_{\max}(S(E))$ and $u_{average}(S(E))$. The mathematical descriptions are (Yang (2001)):

$$u_{\min}(S(E)) = \sum_{n=2}^{N} \beta_n(E) u(H_n) + (\beta_1(E) + \beta_H(E)) u(H_1) \tag{3.5}$$

$$u_{\max}(S(E)) = \sum_{n=1}^{N-1} \beta_n(E) u(H_n) + (\beta_N(E) + \beta_H(E)) u(H_N) \tag{3.6}$$

$$u_{average}(S(E)) = \frac{u_{\max}(E) + u_{\min}(E)}{2} \tag{3.7}$$

The least preferred evaluation grade/linguistic term with the lowest utility is denoted as $u(H_1)$. The most preferred evaluation grade with the highest utility is denoted as $u(H_N)$. Expected utility theory is developed for only characterising an assessment and not for aggregation of criteria. Additionally, each $u(S(E))$ or $u_{average}(S(E))$ is used to reveal the risk rank of a failure mode/hazard of tank farm operations.

3.6. Illustration of Application of Failure Mode Effect Analysis-Fuzzy Rule Based (FMEA-FRB) Methodology in Risk Analysis of Tank Farm Operations.

Safe operations of tank farm lies on the efficiency of various systems such as automatic shut-off oil safety valve, pipe corrosion protection system, automatic tank gauge system, leak detection device and secondary containment monitoring system. Assessments and prioritization of risks associated with these systems will contribute in improving the safety of tank farm operations via allocation of available resources for safety management of the systems.

3.6.1. Hazard Identification (HAZID) of Tank Farm Operations

Experts #1, #2, #3 and #4 involved in this study used the brainstorming method to identify hazards/failure modes of tank farm operations in marine environment as automatic shut-down oil safety valve failure, leak detection device/system failure, automatic tank gauge system failure, pipe corrosion protection system failure and secondary containment monitoring system failure. These hazards can affect the optimal operations of the tank farm operations if attention is not given to them. The implications of the occurrence of these hazards (i.e. failures of these systems) can be catastrophic to the environment and personnel at the port and onboard marine vessel. Therefore, their PAH ranks need to be identified in marine environment under uncertainties.

3.6.1.1. PAH Rank Estimation of Automatic Shut-down Oil Safety Valve Failure by Experts under Uncertainty.

The PAH rank estimation of automatic shut-down oil safety valve failure in risk/safety assessment of tank farm operations need to be identified in this research. To address this problem, PAH rank estimation of leak detection/system failure by Experts #1, #2, #3 and #4 can be described as follows:

3.6.1.1.1. Experts Judgement in Fuzzy Environment

The fuzzy scale values for OLH, CSH and DH can be estimated using Tables 3.1, 3.2 and 3.3 respectively and Equation 3.2. In view of this, Experts #1, #2, #3 and #4 with equal experience of the subject under investigation used Table 3.1 to rate/estimate occurrence likelihood of automatic shut-down oil safety valve failure as high. Numerical value for high is 4 in Table 3.1. Therefore, the fuzzy scale value for OLH denoted as A_{11} is calculated using Equation 3.2 as follows:

$$A_{11} = w_{11}a_{111} + w_{12}a_{121} + w_{13}a_{131} + w_{14}a_{141}$$

$$A_{11} = 0.25 \times 4 + 0.25 \times 4 + 0.25 \times 4 + 0.25 \times 4$$

$$= 4.0$$

In a similar way, the fuzzy scale value for CSH denoted as A_{12} can be estimated. To achieve this, Experts #1, #2, #3 and #4 rated consequence severity of automatic shut-down oil safety valve failure as marginal, marginal, moderate and marginal respectively. Their equivalent numerical values are 2, 2, 3 and 4 respectively as shown in Table 3.2. In view of this, A_{12} can be calculated as follows:

$$A_{12} = w_{11}a_{112} + w_{12}a_{122} + w_{13}a_{132} + w_{14}a_{142}$$

$$A_{12} = 0.25 \times 2 + 0.25 \times 2 + 0.25 \times 3 + 0.25 \times 2$$

$$= 2.25$$

Similar approach is adopted in finding A_{13}. In this case, the Experts #1, #2, #3 and #4 rated the detectability of automatic shut-down oil safety valve failure as reasonably likely with numerical value of 3. Therefore, A_{13} is found as follows:

$$A_{13} = w_{11}a_{113} + w_{12}a_{123} + w_{13}a_{133} + w_{14}a_{143}$$

$$A_{13} = 0.25 \times 3 + 0.25 \times 3 + 0.25 \times 3 + 0.25 \times 3$$

$$= 3.0$$

Therefore, 4.0, 2.25 and 3.0, which are the fuzzy scale values of OLH, CSH and DH respectively, can be used to estimate their respective fuzzy membership function values as shown in Figures 3.6, 3.7 and 3.8. In view of this, the fuzzy membership function values of OLH, CSH and DH are identified as (0.75, "high"; 0.25, "very high"), (0.8, "moderate"; 0.2, "marginal") and (0.6, "reasonably likely"; 0.4, "likely") respectively in their corresponding Figures 3.6, 3.7 and 3.8. To find the fuzzy conclusions of all Experts' judgements, relevant rules in the 125 rules of PAH of tank farm operations need to be fired. In this study, 8 rules are relevant and can be identified as follows:

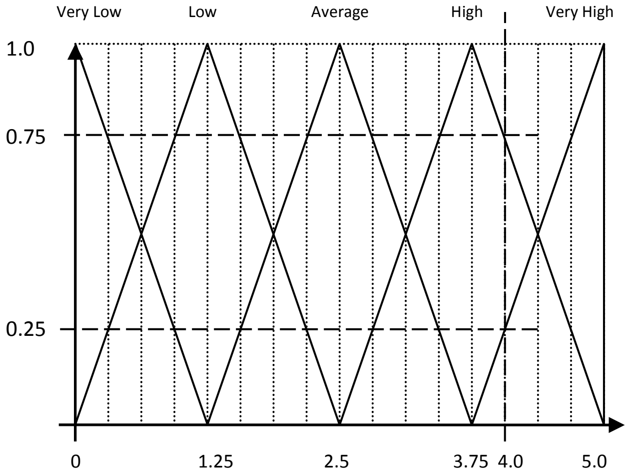

Figure 3.6: A Membership Function for OLH of Automatic Shut-down Oil Safety Valve Failure

Rule #18: IF OLH is high, CS is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #23: IF OLH is very high, CS is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #94: IF OLH is high, CS is marginal AND DH is likely, THEN PAH is high.

Rule #99: IF OLH is very high, CS is marginal AND DH is likely, THEN PAH is high.

Rule #118: IF OLH is high, CS is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #119: IF OLH is high, CS is moderate AND DH is likely, THEN PAH is high.

Rule #123: IF OLH is very high, CS is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #124: IF OLH is very high, CS is moderate AND DH is likely, THEN PAH is high.

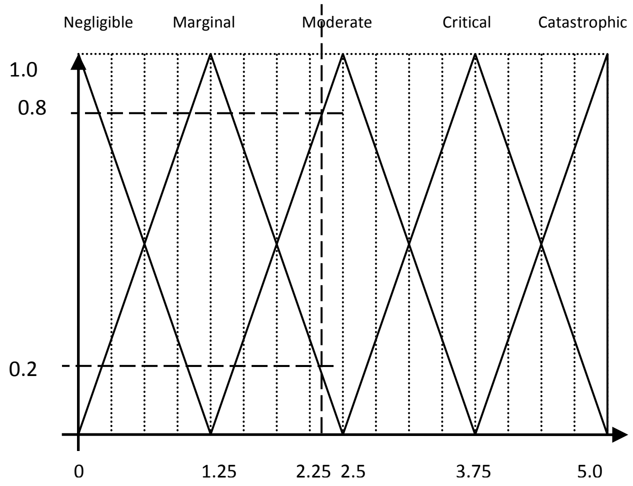

Figure 3.7: A Membership Function for CSH of Automatic Shut-down Oil Safety Valve Failure

The 8 rules are fired by incorporating the fuzzy membership functions values of the linguistic terms associated with OLH, CSH and DH in them, using the information found in Figures 3.6, 3.7 and 3.8 respectively. The fuzzy membership functions values of the linguistic terms associated with PAH in the fired 8 rules can be calculated using the min-max method. Therefore, the fired 8 rules in fuzzy environment can be described as follows:

Rule #18: IF OLH is (0.75, “high”), CSH is (0.8, “moderate”) AND DH is (0.6, “reasonably likely”), THEN PAH is (0.6, “moderate”).

Rule #23: IF OLH is (0.25, “very high”), CSH is (0.8, “moderate”) AND DH is (0.6, “reasonably likely”), THEN PAH is (0.25, “moderate”).

Rule #94: IF OLH is (0.75, “high”), CSH is (0.2, “marginal”) AND DH is (0.4, “likely”), THEN PAH is (0.2, “high”).

Rule #99: IF OLH is (0.25, "very high"), CSH is (0.2, "marginal") AND DH is (0.4, "likely"), THEN PAH is (0.2, "high").

Rule #118: IF OLH is (0.75, "high), CSH is (0.2, "marginal") AND DH is (0.6, "reasonably likely"), THEN PAH is (0.2, "moderate").

Rule #119: IF OLH is (0.75, "high"), CSH is (0.8, "moderate") AND DH is (0.4, "likely"), THEN PAH is (0.4, "high").

Rule #123: IF OLH is (0.25, "very high"), CSH is (0.2, "marginal") AND DH is (0.6, "reasonably likely"), THEN PAH is (0.2, "moderate").

Rule #124: IF OLH is (0.25, "very high"), CSH is (0.8, "moderate") AND DH is (0.4, "likely"), THEN PAH is (0.25, "high").

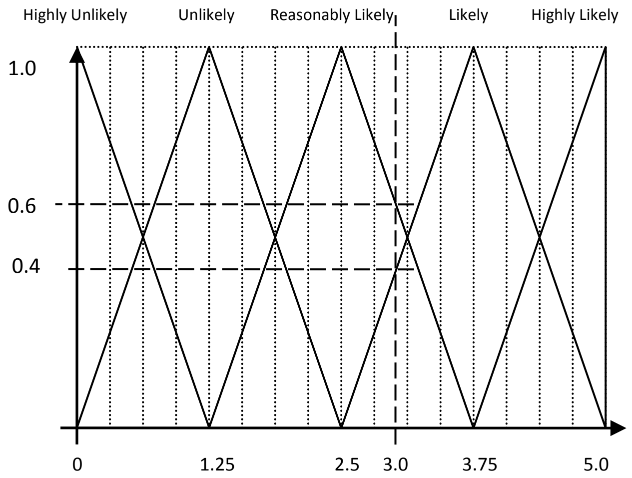

Figure 3.8: A Membership Function for DH of Automatic Shut-down Oil Safety Valve Failure

In Rule #18, PAH is (0.6, "moderate") because 0.6 is the minimum of 0.75, 0.8 and 0.6 (i.e. min (0.75, 08, 0.6)). Where 0.75, 0.8 and 0.6 are fuzzy membership function values of OLH, CS and DH respectively. OLH, CS and DH are associated with linguistic terms such as "high", "moderate" and "reasonably likely" respectively. The fired Rule #23, Rule #94, Rule #99, Rule #118, Rule #119, Rule #123, and Rule #124 are explained in the same way.

Since the minimum fuzzy membership functions values of linguistics terms associated with OLH, CS and DH on each of the 8 fired rules have been found as shown above (i.e. belief degrees/fuzzy values of PAH), then the maximum values of each of the categories of linguistics terms associated with PAH can be calculated as:

For “moderate” linguistic term of PAH;

max (0.6, 0.25, 0.2, 0.2) = 0.6. 0.6 is now the belief degree/fuzzy value associated with “moderate” linguistic term of PAH, described as fuzzy conclusions of Experts #1 - #4.

For “high” linguistic term of PAH;

max (0.2, 0.2, 0.4, 0.25) = 0.4. 0.4 is now the belief degree/fuzzy value associated “high” linguistic term of PAH, described as fuzzy conclusions of all Experts judgements.

Therefore, the PAH estimated belief degrees/fuzzy values of automatic shut-down oil safety valve failure can be described as {(0, “very low”), (0, “low”), (0.6, “moderate”), (0.4, “high”), (0, “very high”)}. This result can be used to estimate the PAH rank of automatic shut-down oil safety valve failure in risk/safety assessment of tank farm operations.

3.6.1.1.2. Expected Utility Value for PAH of Automatic Shut-down Oil Safety Valve Failure

It has been revealed that the PAH belief degrees/fuzzy values of automatic shut-down oil safety valve failure is described as {(0, “very low”), (0, “low”), (0.6, “moderate”), (0.4, “high”), (0, “very high”)}. This shows that the assessment of the automatic shut-down oil safety valve failure is complete. That is, $\beta_H = 0$. In view of this, the expected utility value of automatic shut-down oil safety valve failure can be revealed using combination of Equations 3.3 and 3.4 as follows:

$$u(S(E)) = \sum_{n=1}^{N} \beta_n(E)\left(\frac{V_n - V_{\min}}{V_{\max} - V_{\min}}\right)$$

Where V_1, V_2, V_3, V_4 and V_5 ranked as 1, 2, 3, 4 and 5 respectively are for evaluation grades, very low, low, moderate, high and very high. Therefore, $V_{\max} = 5$ and $V_{\min} = 1$. The fuzzy conclusions of {(0, "very low"), (0, "low"), (0.6, "moderate"), (0.4, "high"), (0, "very high")} means that 0, 0, 0.6, 0.4 and 0 associated with the evaluation grades stand for β_1, β_2, β_3, β_4 and β_5 respectively. Therefore, $u(S(E))$ of automatic shut-down oil safety valve failure can be found as expressed below.

$$u(S(E)) = 0\times\left(\frac{1-1}{5-1}\right) + 0\times\left(\frac{2-1}{5-1}\right) + 0.6\times\left(\frac{3-1}{5-1}\right) + 0.4\times\left(\frac{4-1}{5-1}\right) + 0\times\left(\frac{5-1}{5-1}\right)$$

$$= 0.3 + 0.3$$

$$= 0.6$$

Therefore, PAH rank (i.e. crisp value) of automatic shut-down oil safety valve failure in tank farm operations is 0.6.

3.6.1.2. PAH Rank Estimation of Pipe Corrosion Protection System Failure by Experts under Uncertainty

Pipe corrosion protection system failure is one of the failure modes (hazards) of tank farm operations. The risk rank need to be estimated in fuzzy environment using the judgement of Experts #1 - #4. In this study, the fuzzy conclusions of PAH of pipe corrosion protection system failure are described as (0.15, "very low") and (0.85, "low") using procedures and methods adopted in Sub-sub-section 3.6.1.1.1 (See Appendix 3B). This means that the PAH estimated belief degrees/fuzzy values of pipe corrosion protection system failure is described as {(0.15, "very low"), (0.85, "low"), (0, "moderate"), (0, "high"), (0, "very high")}. Adopting similar methods used in Sub-sub-section 3.6.1.1.2, the PAH rank (i.e. crisp value) of pipe corrosion protection system failure of 0.2125 is revealed in Appendix 3B.

3.6.1.3. PAH Rank Estimation of Automatic Tank Gauge System Failure by Experts under Uncertainty

Automatic tank gauge system failure has contributed more or less significantly in hindering optimal operations of tank farm and its riskiness has not been determined under uncertainty**.** In this research, the riskiness of automatic tank gauge system failure in fuzzy environment has been revealed in Appendix 3C. In Appendix 3C, the fuzzy conclusions of PAH of automatic tank gauge system failure are (0.4, “low”) and (0.6, “moderate”) using the procedures and methods in Sub-sub-section 3.6.1.1.1. Therefore, the PAH belief degrees/fuzzy values of automatic tank gauge system failure is described as {(0, “very low”), (0.4, “low”), (0.6, “moderate”), (0, “high”), (0, “very high”)}. PAH rank (i.e. crisp value) is found as 0.4 using the procedures and methods in Sub-sub-section 3.6.1.1.2.

3.6.1.4. PAH Rank Estimation of Leak Detection Device/System by Experts under Uncertainty

Investigation of the safety level of tank farm operations showed that leak detection device/system failure is one of the causes of tank farm operational failures. Predictions of the levels of risk parameters such as OLH, CSH and DH of leak detection device/system failure in uncertain marine environment are difficult. To address this problem, experts have carried out detailed estimations of the data associated with the aforementioned risk parameters using FRB model in Appendix 3D. It has been revealed in Appendix 3D that the fuzzy conclusions of PAH of the leak detection device/system failure are (0.45, “moderate”) and (0.55, “high”) using the procedures and methods in Sub-sub-section 3.6.1.1.1. Therefore, the PAH belief degrees/fuzzy values of leak detection device/system failure can be described as {(0, “very low”), (0, “low”), (0.45, “moderate”), (0.55, “high”), (0, “very high”)}. It has also been revealed in Appendix 3D that the PAH rank (i.e. crisp value) of leak detection device/system failure is 0.6375 using the procedures and methods in Sub-sub-section 3.6.1.1.2.

3.6.1.5. PAH Rank Estimation of Secondary Containment Monitoring System Failure by Experts under Uncertainty

Failure of secondary containment monitoring system can affect the operations of tank farm more or less than other hazards. The PAH rank of secondary containment monitoring system failure need to be identified in order to ascertain how it reduces the efficiency and safety level of tank farm operations more than other tank farm hazards. In view of this, the fuzzy conclusions are found as (0.6, “moderate”) and (0.4, “high”) in Appendix 3E using the procedures and methods in Sub-sub-section 3.6.1.1.1. Therefore, the fuzzy conclusions can be described in details as {(0, “very low”), (0, “low”), (0.55, “moderate”), (0.45, “high”), (0, “very high”)} to facilitate estimation of PAH rank of secondary containment monitoring system failure. The expected utility theory used in Sub-sub-section 3.6.1.1.2, is employed in estimation of the PAH rank (i.e. crisp value) of secondary containment monitoring system failure as evidenced in Appendix 3E. A crisp value of 0.6125 is produced.

3.6.2. Ranking of Hazards of the Tank Farm Operations

Ranking of hazards of tank farm operations will be based on estimated expected utility values (i.e. crisp values) of PAH associated with them. The hazards that need more attention than others can be identified via the ranks of the crisp values of PAH associated with them in Table 3.5. Any failure mode/hazard with highest crisp value, is ranked 1 and need more attention than other ones because is the riskiest failure mode/hazard. Such decision can be taken using Table 3.5. Table 3.5 can be described as follows:

- Risk level of automatic shut-down oil safety valve failure is estimated using triangular fuzzy membership function, which resulted to Experts #1, #2, #3 and #4 fuzzy conclusion of {(0, “very low”), (0, “low”), (0.6, “moderate”), (0.4, “high”), (0, “very high”)}, PAH crisp value of 0.6 and rank of 3.
- Risk level of pipe corrosion protection system failure is estimated using triangular fuzzy membership function, which resulted to Experts #1, #2, #3 and #4 fuzzy conclusion of

{(0.15, “very low”), (0.85, “low”), (0, “moderate”), (0, “high”), (0, “very high”)}, PAH crisp value of 0.2125 and rank of 5.

- Risk level of automatic tank gauge system failure is estimated using triangular fuzzy membership function, which resulted to Experts #1, #2, #3 and #4 fuzzy conclusion of {(0, “very low”), (0.4, “low”), (0.6, “moderate”), (0, “high”), (0, “very high”)}, PAH crisp value of 0.4 and rank of 4.
- Risk level of leak detection device/system is estimated using triangular fuzzy membership function, which resulted to Experts #1, #2, #3 and #4 fuzzy conclusion of {(0, “very low”), (0, “low”), (0.45, “moderate”), (0.55, “high”), (0, “very high”)}, PAH crisp value of 0.6375 and rank of 1.
- Risk level of secondary containment monitoring system failure is estimated using triangular fuzzy membership function, which resulted to Experts #1, #2, #3 and #4 fuzzy conclusion of {(0, “very low”), (0, “low”), (0.55, “moderate”), (0.45, “high”), (0, “very high”)}, PAH crisp value of 0.6125 and rank of 2.

Table 3.5: Risk-Based Ranks of Hazards of the Tank Farm Operations

Hazard of Tank Farm Operations	Fuzzy Membership Type/Form	Experts #1, #2, #3 and #4 Fuzzy Conclusion	Expected Utility Value of PAH (i.e. Crisp Value)	Rank of PAH
Automatic shut-down oil safety valve failure	Triangular	{(0, “very low”), (0, “low”), (0.6, “moderate”), (0.4, “high”), (0, “very high”)}	0.6000	3
Pipe corrosion protection system failure	Triangular	{(0.15, “very low”), (0.85, “low”), (0, “moderate”), (0, “high”), (0, “very high”)}	0.2125	5
Automatic tank gauge system failure	Triangular	{(0, “very low”), (0.4, “low”), (0.6, “moderate”), (0, “high”), (0, “very high”)}	0.4000	4
Leak detection device/system failure	Triangular	{(0, “very low”), (0, “low”), (0.45, “moderate”), (0.55, “high”), (0, “very high”)}	0.6375	1
Secondary containment monitoring system failure	Triangular	{(0, “very low”), (0, “low”), (0.55, “moderate”), (0.45, “high”), (0, “very high”)}	0.6125	2

It has been revealed in Table 3.5, that leak detection device/system failure is the failure mode/hazard that is riskier than others with expected utility value (i.e. PAH crisp value) and rank of 0.6375 and 1 respectively. Therefore, leak detection device/system failure needs more attention than other failure modes/hazards.

3.6.3. Results Verification

The model of a risk and safety problem needs to be verified via sensitivity analysis, in order to ascertain the relevance of the model. In this research, the model is verified and acceptable if the two axioms described below are satisfied.

- Axiom 1. Increment of "very low" belief degree by 0.1 and decrement of highest belief degree by 0.1 of safety/risk level expression of a hazard, should result in decrease of the expected utility value.
- Axiom 2. Increment of "very high" belief degree by 0.1 and decrement of 0.1 from highest belief degree of safety/risk level expression of a hazard, should result in increase of the expected utility value.

In Table 3.5, the safety/risk level of automatic shut-down oil safety valve failure is described as {(0, "very low"), (0, "low"), (0.6, "moderate"), (0.4, "high"), (0, "very high")} with expected utility value of 0.6. Increment of the belief degree of "very low" by 0.1 and decrement of highest belief degree by 0.1 of safety/risk level of automatic shut-down oil safety valve failure produced a new safety/risk level of {(0.1, "very low"), (0, "low"), (0.5, "moderate"), (0.4, "high"), (0, "very high")} for automatic shut-down oil safety valve failure. Substitution of the belief degree values (i.e. 0.1, 0, 0.5, 0.4, 0) of automatic shut-down oil safety valve failure in Equation 3.4, produced expected utility value of 0.55. This is in harmony with Axiom 1, therefore Axiom 1 is satisfied.

In a similar way, the safety/risk levels of pipe corrosion protection system, automatic tank gauge system, leak detection device and secondary containment monitoring system are modified/developed and described as {(0.25, "very low"), (0.75, "low"), (0, "moderate"), (0, "high"), (0, "very high")}, {(0.1, "very low"), (0.4, "low"), (0.5, "moderate"), (0, "high"), (0, "very high")}, {(0.1, "very low"), (0, "low"), (0.45, "moderate"), (0.45, "high"), (0, "very high")}, and {(0.1, "very low"), (0, "low"), (0.45, "moderate"), (0.45, "high"), (0, "very high")} respectively. Substitution of their belief degrees values in Equation 3.4, produced their respective expected utility values. These expected utility values are 0.1875, 0.35, 0.5625 and 0.5725 for pipe corrosion protection system, automatic tank gauge system, leak detection device and secondary containment monitoring system respectively. It has been revealed that expected utility values of 0.2125, 0.4, 0.6375 and 0.6125 for pipe corrosion protection system, automatic tank gauge system, leak detection device and secondary containment monitoring system have decreased to 0.1875, 0.35, 0.5625 and 0.5725 respectively. This is in line with Axiom 1, therefore Axiom 1 has been satisfied.

Increment of "very high" belief degree by 0.1 and decrement of 0.1 on highest belief degree of safety/risk level expression of automatic shut-off oil safety valve found in Table 3.5, produced {(0, "very low"), (0, "low"), (0.5, "moderate"), (0.4, "high"), (0.1, "very high")}. Therefore, substituting (0, 0, 0.5, 0.4, 0.1) in Equation 3.4, resulted to expected utility value of 0.65 for automatic shut-off oil safety valve. Similar approach is applied on the safety/risk levels of pipe corrosion protection system, automatic tank gauge system, leak detection device and secondary containment monitoring system described in Table 3.5. Therefore, their safety/risk levels can now be described as {(0.15, "very low"), (0.75, "low"), (0, "moderate"), (0, "high"), (0.1, "very high")}, {(0, "very low"), (0.4, "low"), (0.5, "moderate"), (0, "high"), (0.1, "very high")}, {(0, "very low"), (0, "low"), (0.45, "moderate"), (0.45, "high"), (0.1, "very high")} and {(0, "very low"), (0, "low"), (0.45, "moderate"), (0.45, "high"), (0.1, "very high")} respectively. Their respective expected utility values of 0.65, 0.2875, 0.45, 0.6625 and 0.6725 are produced using Equation 3.4. It has been shown that the expected utility values of automatic shut-off oil safety valve, pipe corrosion protection system, automatic tank gauge system, leak detection device and secondary containment monitoring system increased from 0.6, 0.2125, 0.4, 0.6375 and 0.6125 respectively, to 0.65, 0.2875, 0.45, 0.6625 and 0.6725. This is in line with Axiom 2, therefore Axiom 2 has been satisfied.

3.7. Conclusions

This research has demonstrated that the FMEA-FRB model can effectively prioritise risks of failure modes/hazards of tank farm operations under uncertainties. Relevant rules in the developed 125 FRB IF-THEN rules are fired and used to facilitate uncertainty treatments of the risk parameters (i.e. OLH, CSH and DH) of tank farm operational failure modes/hazards in the FMEA structure. The tank farm operational hazards/failure modes are automatic shut-down oil safety valve failure, leak detection device/system failure, automatic tank gauge system failure, pipe corrosion protection system failure and secondary containment monitoring system failure. The fuzzy conclusions of the PAH of tank farm operational failure modes are estimated via max-min method. The fuzzy conclusions of the experts for each hazard are converted to crisp number using expected utility theory. In the FMEA-FRB model, the crisp value of the PAH of a failure mode/hazard of tank farm operations is described as the RPN. Therefore, experts concluded that the leak detection device/system failure is the riskiest failure mode/hazard of the tank farm operations, evidenced by the crisp value of the PAH in Table 3.5. Leak detection device/system failure is associated with a crisp value of PAH, 0.6125 and rank of 1, whereas the crisp values of PAH of automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, and secondary containment monitoring system failure are 0.6000, 0.6375, 0.4000 and 0.2125 respectively. In view of this, further investigation on the causes of leak detection system failure will be carried out in the next chapter under uncertainties.

Chapter 4 - Incorporation of Fuzzy Fault Tree (FFT) Model to Failure Analysis of Leak Detection System of Tank Farm Operations

Summary

In this research, the implication of the growth and operations of tank farms in the storage of petroleum products in port environment is examined. There is no doubt that tank farms play an important role in the logistics of petroleum products and have gained strategic importance in recent years. The tank farms in ports, oil refineries and petrochemical plants usually contain hazardous material and damage to them, can result in a catastrophic consequence. Such damage could be caused by failures in a system such as leak detection device. Therefore, it is necessary to analyze these failures in the realm of uncertainty in order to identify and quantify their causes. In view of this, a FFT model is employed for the failure analysis of tank farm operations.

4.1. Introduction

Failure of tank farms can result to catastrophic consequences. In Chapter 3, the failure of leak detection system was identified as the one with the highest risk, when a FMEA-FRB methodology was used in the risk estimation exercise of the tank farm operations. In this study, an analysis of the causes of leak detection system of tank farm operations under uncertainty is undertaken. The failure analysis exercise will be successful via the use of FTA model in combination with fuzzy logic. The FTA model will be used to illustrate the causes of the leak detection system failure, while fuzzy logic will address uncertainties due to lack of failure rate data.

Use of fuzzy FT model in failure analysis of leak detection system produces comprehensive causes of the system, so as to select appropriate SCDs in future work. It is useful to tank farm users in identifying hazards and protecting against them. FT is mainly use to demonstrate the failure logic of a system, thereby facilitating the evaluation of failure probabilities of the system as evidenced in various applications (Dong and Yu, 2005; Huang *et al*., 2004; Guimarees and Ebecken, 1999; Lin and Wang, 1997; Sawer and Rao, 1994; Liang and Wang, 1993; Suresh *et al*., 1996; Cheng and Mon, 1993; Cai *et al*., 1991; Singer, 1990). To develop a FT, one needs to know the failure rate data of the basic events (BEs). In situations where there are lack of failure rate data, experts involved in the failure analysis of a system, need to employ fuzzy logic methods to address the uncertainty. The feasibility of such combination will be demonstrated in this chapter.

4.2. Background Analysis

The rapid growth in demand for petroleum product has led to expansion and building of tank farms in port environment. The increasing size and complexity of tank farms has made it difficult to carry out comprehensive failure analysis of tank farm operations. To overcome such challenge, a combination of FTA and fuzzy logic has been adopted because of the break through of the methodology in various fields. The aforementioned methods have been proved to be useful in the works of Lavasani *et al.* (2011a); Ping *et al*. (2007); Pan and Wang (2007); Shu *et al.* (2006); Dong and Yu (2005); Huang *et al*. (2004); Guimarees and Ebecken (1999); Lin and Wang (1997); Sawer and Rao (1994); Liang and Wang (1993). The importance of these methods have also been demonstrated in Suresh *et al*. (1996); Cheng and Mon (1993); Cai *et al*. (1991); Singer (1990); Onisawa (1988); Misra and Weber (1990); Furuta and Shiraishi (1984); Tanaka *et al*. (1983) and Celik *et al.* (2010). The literature reviews of the FFT tool in Chapter 2 have proved that the tool can solve uncertainty problems. Therefore, the model will be adopted in risk/failure analysis of leak detection system of tank farm operations. Firstly, an FTA of leak detection system of tank farm operations will be developed in order to identify the causes/failure modes and their failure logics. Expert judgement will be used to incorporate the fuzzy model on the FTA to facilitate the identification of fuzzy possibility and probability of each BE.

4.3. Leak Detection System of Tank Farm Operations

A leak detection system is one of the systems that make up tank farm operations. Monitoring the tank farm for leaks is required by stalk holders and regulatory bodies. Failure of such system to detect any leak during tank farm operations could lead to catastrophic consequences. Therefore, understanding its mode of operations contributes in providing optimal safety for the tank farm operations. The leak detection system mainly alerts the tank farm operator whenever a leak is experienced via shutting off the flow of petroleum products through the piping system, so that appropriate action can be applied immediately. Failure to perform such function means the system is functioning abnormally. Leak detection system is usually installed in the product line or in/near the pump head (State Water Resources Control Board, 2000).

4.4. Fault Tree Analysis (FTA) Methodology

The FTA technique involves the decomposition of a system into a logic diagram or FT in which certain primary events lead to a specified Top Event (TE) that signifies the total failure of the system **(**Sawer and Rao, 1994**)**. The FTs can be used to find the Minimal Cut Sets (MCSs) which, when coupled with the failure rates of the primary events, lead to an estimation of the reliability of the system **(**Sawer and Rao, 1994**)**. In this study, two type of gate is used in quantification of FTA. The gates are “AND” and “OR”.

The failure logics and basic events of a FTA determine how the FTA can be quantified. An FTA without repeated events can be quantified using Equations 4.1 and 4.2. Equation 4.1 can be used in quantification of an FTA that is made of “AND” gates only and has no repeated events; while Equation 4.2 can be used to calculate an FTA that is made of “OR” gates only and has no repeated events.

$$F\,\mathrm{Pr}TE = \prod_{i=1}^{n} F\,\mathrm{Pr}BE_i \qquad (4.\ 1)$$

where $F\,\mathrm{Pr}TE$ = Failure probability (FPr) of TE.

$F\Pr BE_i$ = Failure probability (FPr) of *ith* basic event (BE_i).

n = Number of BEs that made up the AND gate.

$$F\Pr TE = 1\text{-}\prod_{i=1}^{n}\left(1 - F\Pr BE_i\right) \tag{4.2}$$

where $F\Pr TE$ = Failure probability (FPr) of TE.

$F\Pr BE_i$ = Failure probability (FPr) of *ith* basic event (BE_i).

n = Number of BEs that made up the OR gate.

In situations where there are repeated events in a FT, a new quantification formula needs to be introduced. In view of this, a FT can be described as a tree made up of MCSs; and MCSs are made of BEs. A TE of the FT can only occur when all or any of the BE occurs. It implies that TE can be described as follows (Andrew and Moss, 2002):

$$\text{TE} = MCS_1 + MCS_2 + \ldots\ldots\ldots\ldots + MCS_n = \bigcup_{i=1}^{n} MC_i \tag{4.3}$$

Therefore, the formula for quantification of $F\Pr TE$ of the FT with repeated events can be described as follows (Celik *et al*., 2010; Lavasani *et al*., 2011; Andrew and Moss, 2002):

$$\begin{aligned} F\Pr TE &= F\Pr\left(MCS_1 \cup MCS_2 \cup \ldots\ldots\ldots \cup MCS_N\right) \\ &= F\Pr\left(MCS_1\right) + F\Pr\left(MCS_2\right) + \ldots. F\Pr\left(MCS_N\right) - \begin{pmatrix} F\Pr\left(MCS_1 \cap MCS_2\right) + \\ F\Pr\left(MCS_1 \cap MCS_3\right) + \left(MCS_i \cap MCS_j\right)\ldots. \end{pmatrix}\ldots \\ &+ (-1)^{N-1} F\Pr\left(MCS_1 \cap MCS_2 \cap \ldots \cap MCS_N\right) \end{aligned} \tag{4.4}$$

4.5. Fuzzy-Fault Tree Analysis (FFTA) Methodology

FFTA methodology is a combination of fuzzy logic and FTA techniques in order to address uncertainties due to lack of failure rate data. In this research, the methodology will be made feasible in failure analysis of leak detection system of tank farm operations as evidenced in Figure 4.1. To facilitate the FFTA application, the procedures are detailed below.

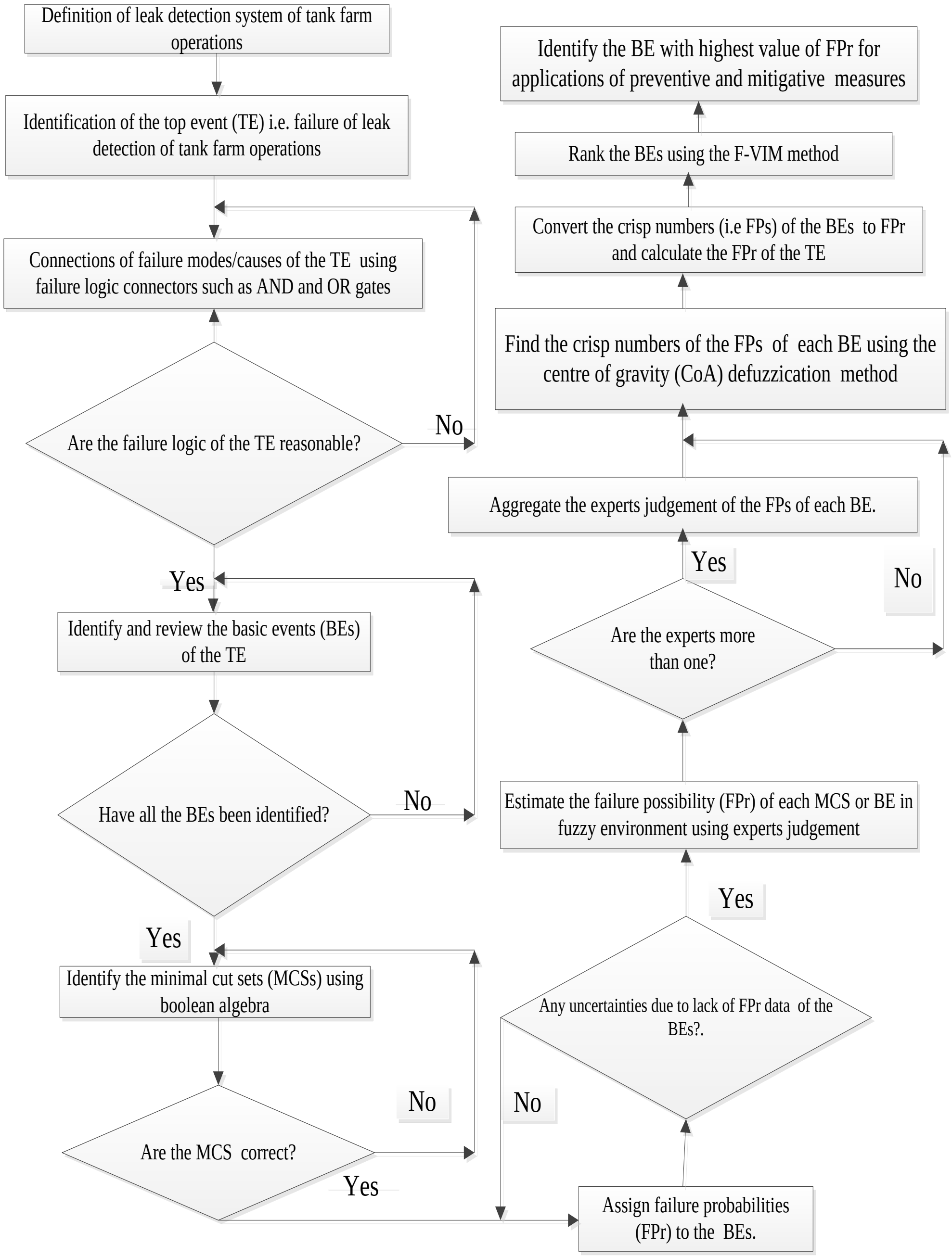

Figure 4.1: A Methodology for Application of Fuzzy Fault Tree Analysis (FFTA) to Leak Detection System of Tank Farm Operations

1. Identification of the BEs.
2. Estimation of the fuzzy numbers in triangular or trapezoid form for each BE.
3. Aggregate experts' opinion.
4. Defuzzify the fuzzy triangular/trapezoid description of each BE using CoA defuzzification method in order to obtain their respective FPs.
5. Convert the FPs of the BE (i.e. $FPsBE$) to FPr (i.e. $F\Pr BE$).
6. Determine the failure probability of the TE.
7. Rank the BEs in order of importance/riskiness.

The flow of information in Figure 4.1 starts from definition of leak detection system of tank farm operations, followed by identification of top event, denoted as TE (i.e. failure of leak detection system) and development failure logic of the causes of TE with gates. The next step is to check if the failure logics are reasonable and identification of BEs of the TE. Once all the BEs have been identified, the MCSs can be estimated using boolean algebra and reviewed to ensure correctness. Then, assign FPr to the BEs or MCSs if available. The next step is to treat uncertainties associated with the BEs or MCSs by assigning FPs values to them using expert judgement. Then, check if the experts are more than one and aggregate judgement of each BEs. The next step is to find the crisp number of each FPs of the BEs using the CoA method, followed by conversion of the FPs of the BEs and calculation of the FPr of the TE. The final step is to rank the BEs using their FPr values, so as to identify the BEs with highest FPr value for proposing of effective preventive or mitigative measures.

4.5.1. Identification of Basic Events (BEs) of the Fault Tree Analysis (FTA) and Estimation of Their Fuzzy Numbers

BEs need to be identified before estimation of their fuzzy numbers. BEs can be found and identified in a constructed FTA of a system or hazard. Figure 4.2 and Table 4.1 will be used in estimations of fuzzy numbers of the BEs of the FTA of leak detection system of tank farm operations. The linguistic terms and associated membership function found in Figure 4.2 and Table 4.1 will be used to facilitate such estimation exercise.

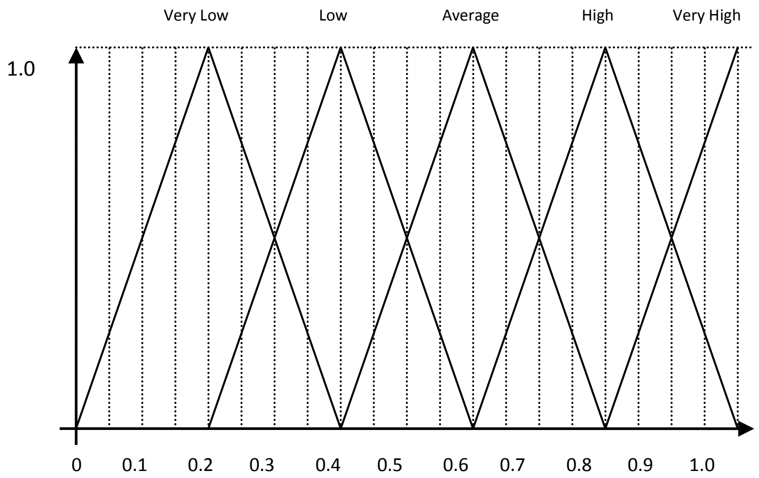

Figure 4.2: A Representation of Linguistic Terms in Triangular Fuzzy Membership Function Form

4.5.2. Aggregation of Experts' Opinion

Various experts are involved in the failure analysis of leak detection system of tank farm operations so as to ensure comprehensive analysis of tank farm operational failures. In view of this, there individual opinion needs to be aggregated using available method in the literature (Hsu and Chen, 1994; Clement and Winkler, 1999). In this research, the one of Clement and Winkler (1999) is adopted because of its computational effectiveness; and represented as follows:

$$FPsBE_i = \sum_{k=1}^{n} w_{ki} a_{kji} \tag{4.5}$$

where $FPsBE_i$ = Failure possibility (FPs) of *ith* basic event (BE_i).

i = Number of BE.

w_{ki} = The value of *kth* expert's weight for *ith* basic event (BE_i).

k = Number of expert.

i = Number of BE.

a_{kji} = Fuzzy triangular membership scale value j of a linguistic term described by expert k for basic event i (BE_i).

j = Number of scale values of a fuzzy triangular membership.

Table 4.1: Description of Linguistic Terms of Failure Probability (FPr) in Fuzzy Scale

Linguistic Term of Failure Probability	Definition of Linguistic Term in Triangular Fuzzy Scale	Definition of the Linguistic Terms of BE of the TE (i.e. Failure of Leak Detection System of Tank Farm)
Very Low	(0, 0.2, 0.4)	The BE of the TE is unlikely to occur in lifetime of the system
Low	(0.2, 0.4, 0.6)	The BE of the TE might occur few times in lifetime of the system.
Average	(0.4, 0.6, 0.8)	The BE of the TE is likely to occur more than once or occasional in lifetime of the system.
High	(0.6, 0.8, 1.0)	The BE of the TE is likely to occur from time to time in lifetime of the systems.
Very High	(0.8, 1.0, 1.0)	It is certain that the BE of the TE will occur frequently.

4.5.3. Defuzzification

The centre of area (CoA) defuzzification method was developed by Sugeno in 1985 (Sugeno, 1999). This method can be expressed as:

$$X^* = \frac{\int \mu_i(x)xdx}{\int \mu_i(x)dx} \tag{4.6}$$

where X^* = Defuzzified output.

$\mu_i(x)$ = Aggregated membership function.

x = Output variable.

A triangular fuzzy number $\tilde{A} = (a_1, a_2, a_3)$ can be defuzzified as follows:

$$\mu(x) = \begin{cases} 0 & x \leq a \\ (x - a_1)/(a_2 - a_1) & a_1 \leq x \leq a_2 \\ (a_3 - x)/(a_3 - a_2) & a_2 \leq x \leq a_3 \\ 0 & x \geq a_3 \end{cases} \tag{4.7}$$

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x - a_1}{a_2 - a_1} xdx + \int_{a_3}^{a_2} xdx + \int_{a_4}^{a_3} \frac{a_4 - x}{a_4 - a_3} xdx}{\int_{a_1}^{a_2} \frac{x - a_1}{a_2 - a_1} dx + \int_{a_2}^{a_3} dx + \int_{a_3}^{a_4} \frac{a_4 - x}{a_4 - a_3} dx} \tag{4.8}$$

$$= \frac{1}{3}(a_1 + a_2 + a_3) \tag{4.9}$$

A trapezoidal fuzzy number $\tilde{A} = (a_1, a_2, a_3, a_4)$, can be defuzzified as follows:

$$\mu(x) = \begin{cases} 0 & x \leq a_1 \\ (x - a_1)/(a_2 - a_1) & a_1 \leq x \leq a_2 \\ 1 & a_2 \leq x \leq a_3 \\ (a_4 - x)/(a_4 - a_3) & a_3 \leq x \leq a_4 \\ 0 & x \geq a_4 \end{cases} \tag{4.10}$$

$$X^{*}=\frac{\int_{a_1}^{a_2}\frac{x-a_1}{a_2-a_1}x\,dx+\int_{a_2}^{a_3}x\,dx+\int_{a_3}^{a_4}\frac{a_4-x}{a_4-a_3}x\,dx}{\int_{a_1}^{a_2}\frac{x-a_1}{a_2-a_1}dx+\int_{a_2}^{a_3}dx+\int_{a_3}^{a_4}\frac{a_4-x}{a_4-a_3}dx} \tag{4.11}$$

$$=\frac{1}{3}\frac{(a_4+a_3)^2-a_4a_3-(a_1+a_2)^2+a_1a_2}{a_4+a_3-a_1-a_2} \tag{4.12}$$

4.5.4. Conversion of Fuzzy Possibility (FPs) to Failure Probability (FPr)

In this research, the conversion method adopted in the works of Onisawa (1988); Lin and Wang (1997); Nishiwaki and Onisawa (1998) are used in the conversion of *FPs* to *FPr*. The conversion formula is described as follows:

$$F\,\mathrm{Pr}\,BE=\begin{cases}\frac{1}{10^{K}},\ FPsBE\neq 0\\[2ex] 0,\ FPsBE=0\end{cases} \tag{4.13}$$

where $K=\left[\frac{1-FPsBE}{FPsBE}\right]^{1/3}\times 2.301$

where FPr stands for failure probability and FPs stands for failure possibility respectively.

The values of FPr of the MCSs/BEs can be used in ranking of the MCSs or BEs leading to the occurrence of the TE. Ranking is used to reveal which MCSs/BEs is more important than the other.

4.6. A Test Case of Application of Fuzzy-Fault Tree Analysis (FFTA) Model in Analysing the Risk of Leak Detection System of Tank Farm Operation and its Causes

In Chapter 3 five causes/hazards were identified. These are: 1) automatic shut-down oil safety valve failure, 2) pipe corrosion protection system failure, 3) automatic tank gauge system failure, 4) leak detection device/system failure and 5) secondary containment monitoring system failure hinders optimal operations of the tank farm. The riskiest one among the five hazards was found to be leak detection system failure. Therefore, investigation of the probability of the failure of leak detection system will be carried out in this research so that appropriate control measure can be employed. In this study, four experts with equal weights are utilised in addressing of uncertainties associated with failure rates data of causes of the failure of leak detection system. The experts' experiences have been detailed in previous chapter.

4.6.1. Hazard Analysis of Leak Detection System of Tank Farm Operation

An FTA technique is employed in hazard analysis of leak detection system of tank farm operations. The method has the ability to show all the major causes and failure logics of any system under investigation. The strength of FTA technique has been demonstrated in Figure 4.3. In Figure 4.3, failure of leak detection system of tank farm operations is the TE of the FTA.

The TE occurs when human threats, mechanical failure or control panel failure happens. Human threats occur when human error, human sabotage or human vandalization happens. Mechanical failure occurs when thermal condition, check valve leaks, pressure relief valve leaks, high static head pressure, continuous pump run, material defects and vapour pockets occur. Thermal condition fails when thermal contraction and thermal expansion happen. Control panel failure occurs when fuse unit failure, power supply unit failure and switch failure occur.

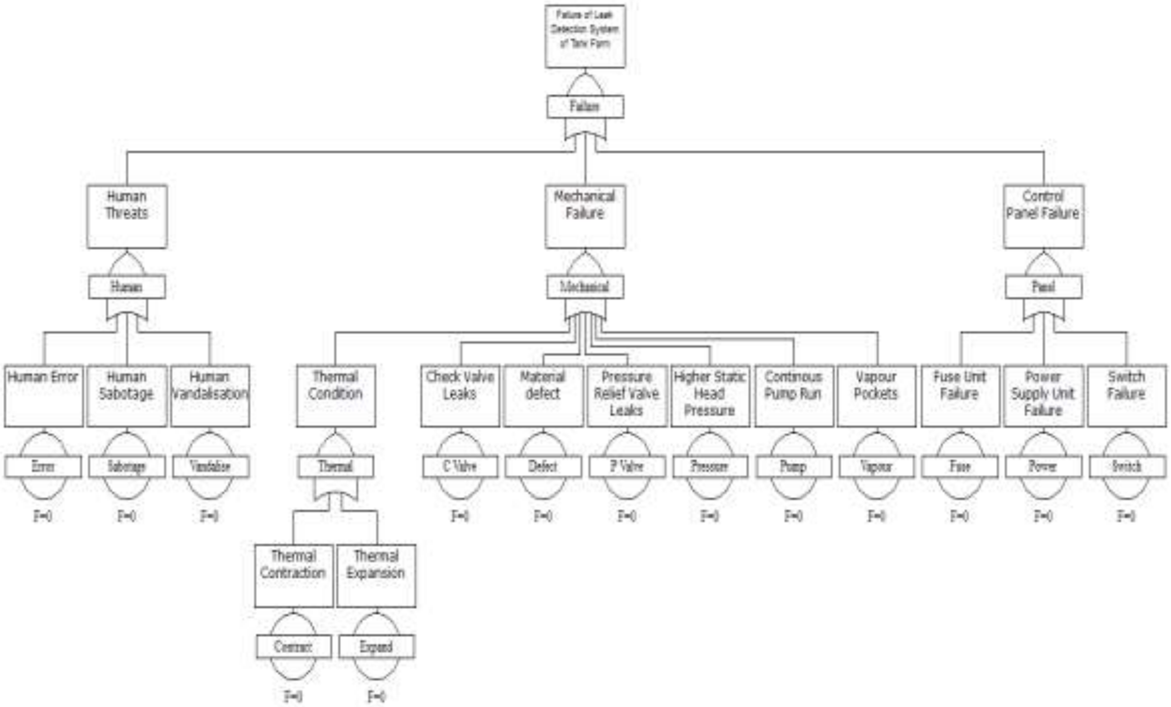

Figure 4.3: Fault Tree Analysis (FTA) Diagram of Failure of Leak Detection System of Tank Farm

4.6.1.1. Experts' Estimation of the Failure Possibility (FPs) of Each Basic Event (BE) of the Tank Farm Leak Detection System Operations in Fuzzy Environment

The FPs of a BE can be estimated using Figure 4.2 and Table 4.1. The four experts involved in this study estimated the FPs of each BE that made up the TE (i.e. leaks detection system failure) in Table 4.2. In Table 4.2: a) listing of the BEs of the TE are outlined in Column 1; b) in Column 2, the experts' judgement of the FPs of each BE are shown using linguistic terms; c) in Column 3, Table 4.1 is used to convert experts' judgement to a triangular fuzzy number.

Table 4.2: Experts' Judgement of Failure Possibility (FPs) of Each Basic Event (BE) of the Top Event (TE) (i.e. Failure of Leak Detection System of Tank Farm)

Basic Events (BEs) of the Top Event (TE) (i.e. Failure of Leak Detection System of Tank Farm)	Experts' Judgement of the Failure Possibility (I each Basic Event (BE) using Linguistic Terms Triangular Fuzzy Scale				Experts' Judgement of the Failure Possibility (FPs) of each Basic Event (BE) using Triangular Fuzzy Scales Values			
	Expert #1	Expert #2	Expert #3	Expert #4	Expert #1 (i.e. (a_{11}, a_{12}, a_{13}))	Expert #2 (i.e. (a_{21}, a_{22}, a_{23}))	Expert #3 (i.e. (a_{31}, a_{32}, a_{33}))	Expert #4 (i.e. (a_{41}, a_{42}, a_{43}))
Human Error	Very Low	Low	Very Low	Low	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)
Human Sabotage	Low	Low	Low	Very Low	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)
Human Vandalization	Average	Low	Low	Average	(0.4, 0.6, 0.8)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.4, 0.6, 0.8)
Thermal Contraction	High	High	Very High	Very High	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)
Thermal Expansion	Very High	Very High	High	High	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)
Check Valve Leaks	Average	High	Average	High	(0.4, 0.6, 0.8)	(0.6, 0.8, 1.0)	(0.4, 0.6, 0.8)	(0.6, 0.8, 1.0)
Pressure Relief Valve Leaks	Low	Low	Low	Low	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)
High Static Head Pressure	Very High	High	High	High	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)
Continuous Pump Run	Average	Average	Average	Average	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)
Material Defects	Low	Very Low	Low	Low	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)
Vapour Pockets	High	High	Average	Average	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)
Fuse Unit Failure	Very Low	Very Low	Very Low	Very Low	(0, 0.2, 0.4)	(0, 0.2, 0.4)	(0, 0.2, 0.4)	(0, 0.2, 0.4)
Power Supply Unit Failure	Very Low	Low	Very Low	Low	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)
Switch Failure	Low	Low	Low	Low	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)

4.6.1.2. Experts' Opinion Aggregation on the Failure Possibility (FPs) of Each Basic Event (BE) of the Leak Detection System of Tank Farm in Fuzzy Environment

In aggregation exercise of experts' judgement of the *FPs* of each *BE* (i.e. *FPsBE*), Equation 4,5 described as $FPsBE_i = \sum_{k=1}^{n} w_k a_{kj}$ is used as follows:

1. Human Error

$$FPsBE_1 = \sum_{k=1}^{4} w_{ki} a_{kji}$$

$$FPsBE_1 = w_{11}(a_{111}, a_{121}, a_{131}) \oplus w_{21}(a_{211}, a_{221}, a_{231}) \oplus w_{31}(a_{311}, a_{321}, a_{331}) \oplus w_{41}(a_{411}, a_{421}, a_{431})$$

$= 0.25(0, 0.2, 0.4) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0, 0.2, 0.4) \oplus 0.25(0.2, 0.4, 0.6)$

$= (0\times0.25,\ 0.2\times0.25,\ 0.4\times0.25) \oplus (0.2\times0.25,\ 0.4\times0.25,\ 0.6\times0.25) \oplus (0\times0.25,\ 0.2\times0.25,\ 0.4\times0.25) \oplus (0.2\times0.25,\ 0.4\times0.25,\ 0.6\times0.25)$

$= (0, 0.05, 0.1) \oplus (0.05, 0.1, 0.15) \oplus (0, 0.05, 0.1) \oplus (0.05, 0.1, 0.15)$

$= (0 \oplus 0.05 \oplus 0 \oplus 0.05,\ 0.05 \oplus 0.1 \oplus 0.05 \oplus 0.1,\ 0.1 \oplus 0.15 \oplus 0.1 \oplus 0.15)$

$= (0.1, 0.3, 0.5)$

Therefore, FPs of Human Error ($FPsBE_1$) is described as (0.1, 0.3, 0.5).

The values of $FPsBE_2$, $FPsBE_3$, $FPsBE_4$, $FPsBE_5$, $FPsBE_6$, $FPsBE_7$, $FPsBE_8$, $FPsBE_9$, $FPsBE_{10}$, $FPsBE_{11}$, $FPsBE_{12}$, $FPsBE_{13}$, and $FPsBE_{14}$ are found in a similar way, described and outlined in Appendix 4A and Table 4.3 as (0.15, 0.35, 0.55), (0.35, 0.55, 0.75), (0.7, 0.9, 1), (0.7, 0.9, 1), (0.5, 0.7, 0.9), (0.2, 0.4, 0.6), (0.65, 0.85, 1), (0.4, 0.6, 0.8), (0.15, 0.35, 0.55), (0.5, 0.7, 0.9), (0, 0.2, 0.4), (0.1, 0.3, 0.5) and (0.2, 0.4, 0.6) respectively. The $FPsBE_2$, $FPsBE_3$, $FPsBE_4$, $FPsBE_5$, $FPsBE_6$, $FPsBE_7$, $FPsBE_8$, $FPsBE_9$, $FPsBE_{10}$, $FPsBE_{11}$, $FPsBE_{12}$, $FPsBE_{13}$, and $FPsBE_{14}$ are known as failure probabilities of Human Sabotage, Human Vandalization, Thermal Contraction, Thermal Expansion, Check Valve Leaks, Pressure Relief

Valve Leaks, High Static Head Pressure, Continuous Pump Run, Material Defects, Vapour Pockets, Fuse Unit Failure, Power Supply Unit Failure and Switch Failure.

Table 4.3: Aggregation of Experts' Judgement on the Failure Possibilities (FPs) of Basic Events (BEs) of Leak Detection System of Tank Farm Operations in Fuzzy Environment

Basic Events (BEs) of the Top Event (TE) (i.e. Failure of Leak Detection System of Tank Farm)	Weight of Experts				Experts' Judgement of the Failure Possibility (FPs) of each Basic Event (BE) using Triangular Fuzzy Scales Values				Aggregation of Experts' Judgement on the Failure Possibility (FPs) of each Basic Event (BE) (i.e. $FPsBE_i$)
	Weight of Expert #1 (i.e. w_1)	Weight of Expert #2 (i.e. w_2)	Weight of Expert #3 (i.e. w_3)	Weight of Expert #4 (i.e. w_4)	Expert #1 (i.e. (a_{11}, a_{12}, a_{13}))	Expert #2 (i.e. (a_{21}, a_{22}, a_{23}))	Expert #3 (i.e. (a_{31}, a_{32}, a_{33}))	Expert #4 (i.e. (a_{41}, a_{42}, a_{43}))	
Human Error	0.25	0.25	0.25	0.25	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0.1, 0.3, 0.5)
Human Sabotage	0.25	0.25	0.25	0.25	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.15, 0.35, 0.55)
Human Vandalization	0.25	0.25	0.25	0.25	(0.4, 0.6, 0.8)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.4, 0.6, 0.8)	(0.35, 0.55, 0.75)
Thermal Contraction	0.25	0.25	0.25	0.25	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.7, 0.9, 1)
Thermal Expansion	0.25	0.25	0.25	0.25	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.7, 0.9, 1)
Check Valve Leaks	0.25	0.25	0.25	0.25	(0.4, 0.6, 0.8)	(0.6, 0.8, 1.0)	(0.4, 0.6, 0.8)	(0.6, 0.8, 1.0)	(0.5, 0.7, 0.9)
Pressure Relief Valve Leaks	0.25	0.25	0.25	0.25	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)
High Static Head Pressure	0.25	0.25	0.25	0.25	(0.8, 1.0, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.65, 0.85, 1)
Continuous Pump Run	0.25	0.25	0.25	0.25	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)
Material Defects	0.25	0.25	0.25	0.25	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.15, 0.35, 0.55)
Vapour Pockets	0.25	0.25	0.25	0.25	(0.6, 0.8, 1.0)	(0.6, 0.8, 1.0)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)
Fuse Unit Failure	0.25	0.25	0.25	0.25	(0, 0.2, 0.4)	(0, 0.2, 0.4)	(0, 0.2, 0.4)	(0, 0.2, 0.4)	(0, 0.2, 0.4)
Power Supply Unit Failure	0.25	0.25	0.25	0.25	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0, 0.2, 0.4)	(0.2, 0.4, 0.6)	(0.1, 0.3, 0.5)

Switch Failure	0.25	0.25	0.25	0.25	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)	(0.2, 0.4, 0.6)

In Table 4.3, BEs are outlined in Column 1, while the weights of the experts are listed in Column 2. In the Column 3 of Table 4.3, the experts' judgement of the FPs of each BE using triangular fuzzy scales values are outlined while the aggregation of experts' judgement on the FPs of each BE using triangular fuzzy scales values are listed in Column 4 of Table 4.3.

4.6.1.3. Defuzzification of the Aggregated Experts' Opinion on the Failure Possibility (FPs) of Each Basic Event (BE) of Leak Detection System of Tank Farm

In this research, CoA method is used to defuzzify each $FPsBE$ value described in Table 4.3. The CoA defuzzification method is applied to each BE of the TE as follows:

Considering Human Error.

In Equation 4.9, the formula for CoA defuzzification method is described as follows:

$X = \frac{1}{3}(a_1 + a_2 + a_3)$ for fuzzy triangular membership function.

Since X is the defuzzified output, $FPsBE_1$ can be described as X. a_1, a_2 and a_3 are described as the fuzzy triangular scale values. a_1, a_2 and a_3 are represented as 0.1, 0.3 and 0.5 respectively; and can be addressed as a_{11}, a_{21} and a_{31} of $FPsBE_1$. 0.1, 0.3 and 0.5 are the aggregated experts' opinion on the FPs of each BE using triangular fuzzy scale values, listed in Column 4 of Table 4.3. The defuzzified $FPsBE_1$ can be calculated as follows:

$$FPsBE_1 = \frac{1}{3}(0.1 + 0.3 + 0.5)$$

$$= 0.3$$

$FPsBE_1$ can also be described as $FPsError$. In a similar way, values of $FPsBE_2$, $FPsBE_3$, $FPsBE_4$, $FPsBE_5$, $FPsBE_6$, $FPsBE_7$, $FPsBE_8$, $FPsBE_9$, $FPsBE_{10}$, $FPsBE_{11}$, $FPsBE_{12}$,

$FPsBE_{13}$, and $FPsBE_{14}$ are found as 0.35, 0.55, 0.867, 0.867, 0.7, 0.4, 0.833, 0.6, 0.35, 0.7, 0.2, 0.3 and 0.2 respectively (See Appendix 4B for details). $FPsBE_2$, $FPsBE_3$, $FPsBE_4$, $FPsBE_5$, $FPsBE_6$, $FPsBE_7$, $FPsBE_8$, $FPsBE_9$, $FPsBE_{10}$, $FPsBE_{11}$, $FPsBE_{12}$, $FPsBE_{13}$, and $FPsBE_{14}$ stand for failure possibilities of Human Sabotage, Human Vandalization, Thermal Contraction, Thermal Expansion, Check Valve Leaks, Pressure Relief Valve Leaks, High Static Head Pressure, Continuous Pump Run, Material Defects, Vapour Pockets, Fuse Unit Failure, Power Supply Unit Failure and Switch Failure. They can also be addressed as $FPsSabotage$, $FPsVandalise$, $FPsContract$, $FPsExpand$, $FPsCValve$, $FPsPValve$, $FPs\Pr essure$, $FPsPump$, $FPsDefect$, $FPsVapour$, $FPsFuse$, $FPsPower$ and $FPsSwitch$ respectively.

4.6.1.4. Conversion of the Failure Possibility (FPs) of Each Basic Event (BE) of the Top Event (TE) to Failure Probability (FPs)

In this research, the $FPsBE$ will be converted to $F\Pr BE$ so as to facilitate the estimation of FPr of the TE and ranking of the BEs. Equation 4.13 described $FPsBE$ as follows:

$$F\Pr BE = \begin{cases} \dfrac{1}{10^K}, FPsBE \neq 0 \\ \\ 0, FPsBE = 0 \end{cases}$$

where $K = \left[\dfrac{1 - FPsBE}{FPsBE}\right]^{1/3} \times 2.301$

In view of this, $F\Pr BE$ can be calculated as follows, with respect to Human error:

Since $FPsBE_1 \neq 0$, $F\Pr BE_1 = \dfrac{1}{10^K}$ will be used in the conversion of $FPsBE_1$ to $F\Pr BE_1$ as expressed below.

$$F\Pr BE_1 = \frac{1}{10^{\left[\frac{1-FPsBE_1}{FPsBE_1}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.3}{0.3}\right]^{1/3}\times 2.301}} = 0.001$$

Using the same method, the values of $F\Pr BE_2$, $F\Pr BE_3$, $F\Pr BE_4$, $F\Pr BE_5$, $F\Pr BE_6$, $F\Pr BE_7$, $F\Pr BE_8$, $F\Pr BE_9$, $F\Pr BE_{10}$, $F\Pr BE_{11}$, $F\Pr BE_{12}$, $F\Pr BE_{13}$, and $F\Pr BE_{14}$ are found to be 0.0015, 0.007, 0.059, 0.059, 0.018, 0.002, 0.045, 0.01, 0.0015, 0.018, 0.0002, 0.001 and 0.002 respectively (See Appendix 4C for details). The $F\Pr BE_2$, $F\Pr BE_3$, $F\Pr BE_4$, $F\Pr BE_5$, $F\Pr BE_6$, $F\Pr BE_7$, $F\Pr BE_8$, $F\Pr BE_9$, $F\Pr BE_{10}$, $F\Pr BE_{11}$, $F\Pr BE_{12}$, $F\Pr BE_{13}$, and $F\Pr BE_{14}$ are described as failure probabilities of Human Sabotage, Human Vandalization, Thermal Contraction, Thermal Expansion, Check Valve Leaks, Pressure Relief Valve Leaks, High Static Head Pressure, Continuous Pump Run, Material Defects, Vapour Pockets, Fuse Unit Failure, Power Supply Unit Failure and Switch Failure. They are also denoted as $F\Pr Error$, $F\Pr Sabotage$, $F\Pr Vandalise$, $F\Pr Contract$, $F\Pr Expand$, $F\Pr CValve$, $F\Pr PValve$, $F\Pr Pressure$, $F\Pr Pump$, $F\Pr Defect$, $F\Pr Vapour$, $F\Pr Fuse$, $F\Pr Power$ and $F\Pr Switch$ respectively.

4.6.2. Calculation of Failure Probability (FPr) of Top Event (TE) of Tank Farm Operations

In this study, the FPr of each BE has been identified in Section 4.12, while the FPr of TE remains unknown. To identify the value of FPr of the TE (i.e. failure of leak detection system of tank farm), Equation 4.2 and bottom-top approach (i.e. starting from the base (BEs) of the FT to the top) will be used, since the TE is made up of OR gates and unrepeated events. In view of this, $F\Pr TE$ can be calculated as follows:

$$F\Pr TE = 1\text{-}\prod_{i=1}^{n}\left(1 - F\Pr BE_i\right)$$

$$F\Pr TE = \left[1 - (1 - F\Pr Human)(1 - F\Pr Mechanical)(1 - F\Pr Panel)\right] \qquad (4.14)$$

$$F\Pr Human = \left[1-(1-F\Pr Error)(1-F\Pr Sabotage)(1-F\Pr Vandalise)\right] \tag{4.15}$$

$$F\Pr Mechanical = \begin{bmatrix} 1-(1-F\Pr Thermal)(1-F\Pr CValve)(1-F\Pr PValve) \\ (1-F\Pr Pressure)(1-F\Pr Pump)(1-F\Pr Defect)(1-F\Pr Vapour) \end{bmatrix} \tag{4.16}$$

$$F\Pr Panel = \left[1-(1-F\Pr Fuse)(1-F\Pr Power)(1-F\Pr Switch)\right] \tag{4.17}$$

The value of $F\Pr Thermal$ is unknown. From Figure 4.3, $F\Pr Thermal$ can be revealed as follows:

$$F\Pr Thermal = \left[1-(1-F\Pr Contract)(1-F\Pr Expand)\right] \tag{4.18}$$

$F\Pr Error$, $F\Pr Sabotage$, $F\Pr Vandalise$, $F\Pr Contract$, $F\Pr Expand$, $F\Pr CValve$, $F\Pr PValve$, $F\Pr Pressure$, $F\Pr Pump$, $F\Pr Defect$, $F\Pr Vapour$, $F\Pr Fuse$, $F\Pr Power$ and $F\Pr Switch$ are denoted as $F\Pr BE_1$, $F\Pr BE_2$, $F\Pr BE_3$, $F\Pr BE_4$, $F\Pr BE_5$, $F\Pr BE_6$, $F\Pr BE_7$, $F\Pr BE_8$, $F\Pr BE_9$, $F\Pr BE_{10}$, $F\Pr BE_{11}$, $F\Pr BE_{12}$, $F\Pr BE_{13}$ and $F\Pr BE_{14}$ respectively. Their FPr values described as 0.001, 0.0015, 0.007, 0.059, 0.059, 0.018, 0.002, 0.045, 0.01, 0.0015, 0.018, 0.0002, 0.001 and 0.002 respectively; can be substituted in Equations 4.16, 4.17, 4.18 and 4.19 in order to calculate $F\Pr TE$ as expressed below.

$$\begin{aligned} F\Pr Human &= \left[1-(1-0.001)(1-0.0015)(1-0.007)\right] \\ &= \left[1-(0.999)(0.9985)(0.993)\right] \\ &= 0.009 \end{aligned}$$

$$\begin{aligned} F\Pr Thermal &= \left[1-(1-0.059)(1-0.059)\right] \\ &= \left[1-(0.941)(0.941)\right] \\ &= 0.115 \end{aligned}$$

$$F\,\mathrm{Pr}\,Mechanical = \left[\begin{array}{l} 1-(1-0.115)(1-0.018)(1-0.002)(1-0.045)(1-0.01)(1-0.0015) \\ (1-0.018) \end{array}\right]$$

$$= \left[\begin{array}{l} 1-(0.885)(0.982)(0.998)(0.955)(0.99)(0.9985) \\ (0.982) \end{array}\right]$$

$$= 0.196$$

$$F\,\mathrm{Pr}\,Panel = [1-(1-0.0002)(1-0.001)(1-0.002)]$$

$$= [1-(0.9998)(0.999)(0.998)]$$

$$= 0.003$$

Therefore, $F\,\mathrm{Pr}\,TE = [1-(1-F\,\mathrm{Pr}\,Human)(1-F\,\mathrm{Pr}\,Mechanical)(1-F\,\mathrm{Pr}\,Panel)]$

$$= [1-(1-0.009)(1-0.196)(1-0.003)]$$

$$= [1-(0.991)(0.804)(0.997)]$$

$$= 0.205$$

Since the FPr of each BE has been revealed, the ranking of the BEs in order of importance can be described as follows:

$$0.059 > 0.045 > 0.018 > 0.01 > 0.007 > 0.002 > 0.0015 > 0.001 > 0.0002$$

It means that any BE associated with the value of 0.059 is more important that others and should be given more attention via application of preventive and mitigative measures. Thermal contraction (i.e. BE_4) and thermal expansion (i.e. BE_5) are associated with 0.059 as their FPr values, while BE_1 and BE_{13}; BE_2 and BE_{10}; BE_6 and BE_{11}; and BE_7 and BE_{14}; have the same FPr values described as 0.001, 0.0015, 0.018 and 0.002 respectively.

4.6.3. Verification of the Model

A sensitivity analysis is conducted to partially verify the usefulness and robustness of the model used in this research. The $F\Pr TE$ will be logical if the three axioms below are satisfied.

- Axiom 1. Elimination of any event should result in a reduction of TE failure probability (i.e. $F\Pr TE$).
- Axiom 2. Elimination of an event with higher failure probability should result in a reduction of TE failure probability (i.e. $F\Pr TE$) more than the one with lower probability.
- Axiom 3. Elimination of the entire events should result in TE failure probability (i.e. $F\Pr TE$) equal to zero.

Table 4.4 is produced after elimination of intermediate events. The intermediate events (i.e. Human Threat, Mechanical Failure and Control Panel Failure) are eliminated by changing their failure probabilities from their initial value to zero. Elimination of $F\Pr Human$, $F\Pr Mechanical$ and $F\Pr Panel$ values resulted in a reduction of $F\Pr TE$ values by 3.41%, 94.14% and 0.98% respectively as evidenced in Table 4.4. This is in line with Axiom 1, therefore Axiom 1 is satisfied. In Table 4.4, change of the $F\Pr Human$ and $F\Pr Panel$ values to zero, resulted in a reduction of $F\Pr TE$ values by 0.0341 (i.e. 3.41%) and 0.0098 (0.98%) respectively, while change of $F\Pr Mechanical$ value (i.e. 0.196) to zero, yields a $F\Pr TE$ value of 0.012 (i.e. 94.14% reduction from initial value). Elimination of $F\Pr Mechanical$ value reduced the $F\Pr TE$ value than others and the $F\Pr Mechanical$ value is the highest in Table 4.4. This is in line with Axiom 2. Therefore, Axiom 2 is satisfied. Elimination of $F\Pr Mechanical$, $F\Pr Human$ and $F\Pr Panel$ values at the same time, will result to 100% elimination of $F\Pr TE$ value. This is in harmony with Axiom 3. Therefore the logic of Axiom 3 has been satisfied and used to verify the model.

Table 4.4: Model Verification by Elimination of Intermediate Events

Intermediate Events	Failure Probability of Events	Main Top Event (TE) Failure Probability ($F\Pr TE$)	New Top Event (TE) Failure Probability after an Event Elimination	Rate/Amount of Reduction of Main Top Event (TE) Failure Probability ($F\Pr TE$)	Percentage Reduction of Main Top Event (TE) Failure Probability ($F\Pr TE$)
Human Threats	$F\Pr Human$ = 0.009	0.205	0.198	0.0341	3.41%
Mechanical Failure	$F\Pr Mechanical$ =0.196	0.205	0.012	0.9415	94.14%
Control Panel Failure	$F\Pr Panel$ = 0.003	0.205	0.203	0.0098	0.98%

4.7. Conclusions

After a careful failure analysis of leak detection system of tank farm operations, various causes of the failure such as Human Error, Human Sabotage, Human Vandalization, Thermal Contraction, Thermal Expansion, Check Valve Leaks, Pressure Relief Valve Leaks, High Static Head Pressure, Continuous Pump Run, Material Defect, Vapour Pockets, Fuse Unit Failure, Power Supply Unit Failure and Switch Failure have been revealed via FTA methodology.

The failure contribution of each cause is identified using fuzzy logic because of uncertainties associate with their failure rate data. Demonstration of how the failures occurred, are carried out using the logic gates. Four experts with equal experience of the tank farm operations used expert judgement in fuzzy environment to identify the FPs of each BE. This facilitated the conversion process of the FPs to their respective FPr *a*nd it is revealed that $F\Pr TE$ is 0.205.

The importance of a BE over another has been identified using their FPr values. Their FPr values facilitated the prioritisations of the BEs for efficient adoption of an improvement measure. In this research, it has been revealed that the most important BEs of the TE (i.e. failure of leak detection system of tank farm operations) are Thermal Contraction (i.e. BE_4) and Thermal Expansion (i.e.

BE_5) because they are associated with FPr highest values of 0.059 and 0.059 respectively. Therefore, available resources on safety improvement measure should be focused on the causes/BEs such as Thermal Contraction (i.e. BE_4) and Thermal Expansion (i.e. BE_5). The feasibility of such study will be demonstrated in the next chapter using AHP-TOPSIS model.

Chapter 5 - Optimal Safety Improvement of Tank Farm Operations using an Analytic Hierarchy Process-Technique for Order Preference by Similarity to the Ideal Solution(AHP-TOPSIS) Model

Summary

The analysis of various alternatives that can be adopted to ensure optimal tank farm operations, can be seen as a multi-criteria decision process. In view of this, this research aims to provide a logical approach in identification of important SCD using the AHP-TOPSIS model. The alternatives and criteria levels are the two levels of the AHP-TOPSIS hierarchical structure for optimal operations of tank farm. The alternatives are comprised of SCD #1, SCD#2 and SCD #3, while the criteria is made up of labour cost, equipment cost, company organisational strategy, company structure and technology management. The AHP model and experts' judgement are used to estimate the weights of the criteria, while the TOPSIS technique provided the needed ranks of the SCDs for optimal operations of the tank farm.

5.1. Introduction

Occurrence of tank farm accidents may lead to millions-dollar property loss and production interruption and the consequences could be lawsuits against the company, company's stock devaluation, or company bankruptcy (Chang and Lin, 2006). These accidents demonstrate not only the large-scale of destruction in the surroundings, together with the implication of potential environmental issues, but also the necessity to prevent similar accidents (Argyropoulos *et al.*, 2012; Pitblado, 2010)

In view of this, this research aims at investigation and identification of safety improve measures and associated criteria on tank farm operations in order of importance using AHP-TOPSIS methodology. To achieve this aim, the safety of the tank farm operations is discussed in Section

5.3, after a thorough background analysis of AHP and TOPSIS applications in Sections 5.2 and 5.3 respectively. Safety improvement of leak detection system of tank farm operations is discussed in Section 5.4 and AHP and TOPSIS methodologies are analysed in Section 5.5 and Section 5.6 respectively, so as to facilitate ranking of the SCDs in Section 5.7. The ranks of the SCDs are finally used to make decision on the best SCD in Section 5.8. An illustrative case study is carried out to demonstrate the workability of the proposed methodology in Section 5.9 and conclusion is drawn that the model is logical in Section 5.10.

5.2. Background Analysis

Difficulties encountered in solving complex multi-criteria decision making problems can be subdued by using powerful engineering tools and mathematical model (Satty, 1980; 1990, 2004, Saaty and Vargas, 2001; Yang and Singh 1994; Yang, 2001; Yang and Xu, 2002; Chan and Kumar, 2007; Olcer and Odabasi, 2005). An AHP method is one of the techniques that can make a difference in such problems. The importance of an AHP methodology has been proved in many applications (Satty, 1980; Chan and Kumar, 2007; Yuen *et al.*, 2012; Pam, 2010; Song *et al.*, 2004; Lirn *et al.*, 2003; Lirn *et al.*, 2004; Guy *et al.*, 2006; and Chang *et al.*, 2008). It can be used alone or in combination with other method such as TOPSIS technique as evidenced in Chapter 2. Successful application of the TOPSIS method in various applications have been demonstrated in Pam (2010), Wu (2007), Lavasani et al. (2011), Mahmoodzadeh et al. (2007), Mohammad et al., (2010) and Balli and Korukoglu (2009). Literature reviews of applications of the AHP and TOPSIS methods have been carried out in Chapter 2, including the combination of both. Since the purpose of this research is to rank all the SCDs in order of preferences, the AHP-TOPSIS model will be adopted in addressing such challenges for optimal tank farm operations.

5.3. Safety of Tank Farm Operations

In previous chapters, the safety of tank farm operations are found not to be in an acceptable level, due to various safety levels of the systems such as automatic shut-down oil safety valve, pipe corrosion protection system, automatic tank gauge system, leak detection device/system and secondary containment monitoring system, that make up tank farm operations. To address this abnormal operating condition of the tank farm, a model that can optimize the system performance is shown in Figure 5.1.

Flow of information in Figure 5.1 starts from description of safety level of leak detection system of tank farm operations. The next step is to check if the system safety operations are satisfactory. If the system safety is satisfactory, there will be no need for further investigation as shown in Figure 5.1, otherwise investigation continues by identification of SCDs and associated criteria for optimal system operations. Once all the SCDs and associated criteria have been identified, a review is conducted and how reasonable all criteria are, is checked. The next step is to investigate the weights of the SCDs and associated criteria via AHP methodology and a review of such weights values so as to confirm the values have been properly estimated. In situation where the weights values are not properly estimated, weight values' investigation is reconducted before application of TOPSIS method. The mechanism of TOPSIS method is used to reveal the ranks of the SCDs. Finally, the best SCD, which is the one with highest rank of 1, can be used to improve the safety of leak detection system of tank farm operations.

5.4. Safety Improvement of Leak Detection System of the Tank Farm

In Chapter 3, risk assessment of various causes of tank farm operational failures is investigated so as to identify high risk ones, which will be evaluated and controlled. The leak detection system failure has been identified as the riskiest cause of tank farm operational failure and need to be controlled. The leak detection system is one of the systems that can ensure optimal tank farm operations, and failure of such system can be catastrophic. To prevent the failure of leak detection system and ensure optimal operation of the tank farm, safety improvement measures need to be identified and implemented. According to Lois *et al* (2004) and PVA (1997), casual chain can be used by experts to facilitate identification of safety improvement measures via development of appropriate measures at a selected control point in sequence of cause, incident, accident and consequence. According to MSA (1993), any safety improvement measure must possess attributes such as:

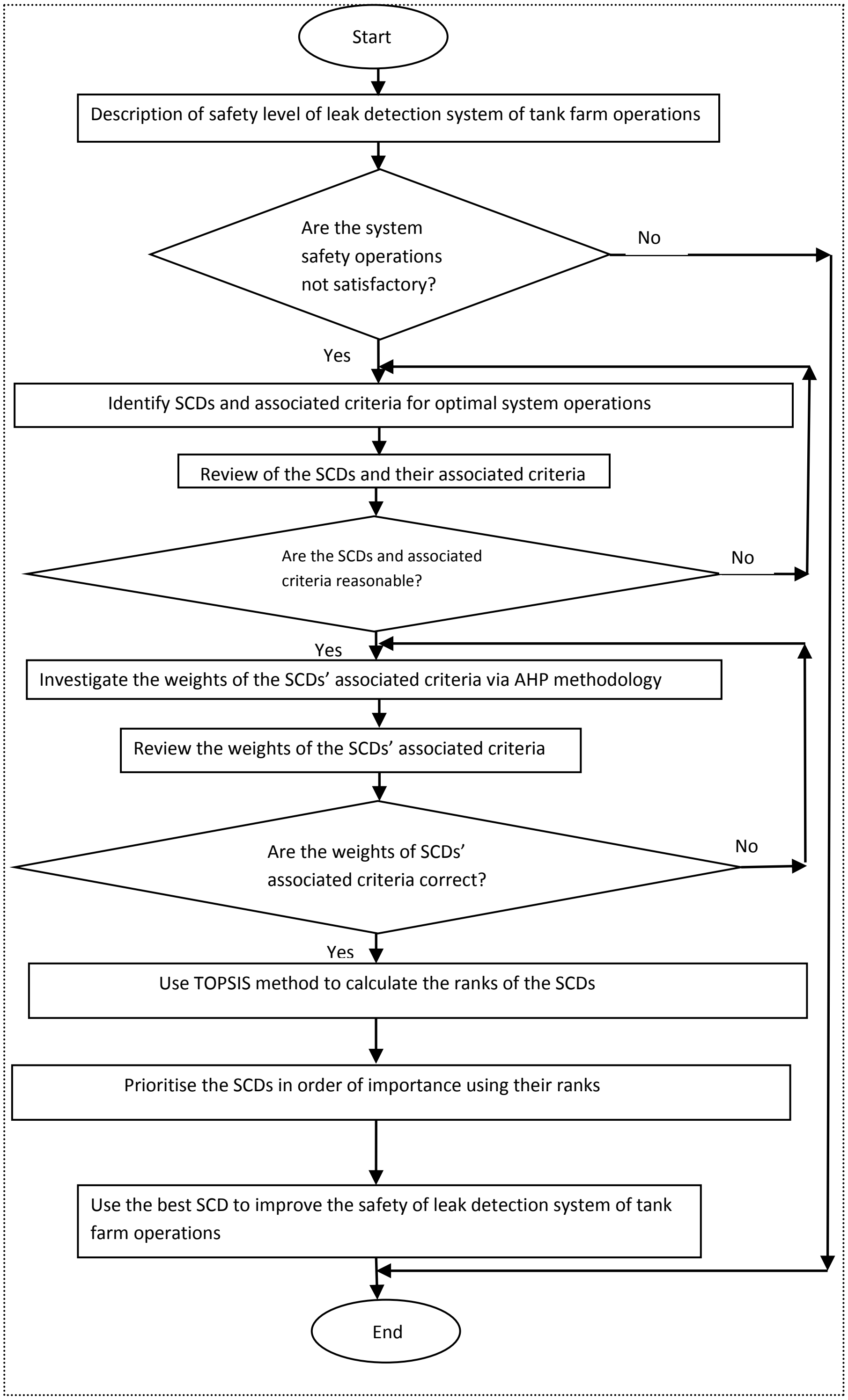

Figure 5.1: A Flow Chart of Safety Improvement of Leak Detection System of Tank Farm Operations using the AHP-TOPSIS Methodology.

- Those relating to the fundamental type of risk reduction (preventative or mitigating).
- Those relating to the type of action required and therefore to the costs of the action (engineering or procedural).
- Those relating to the confidence that can be placed in the measure (active or passive, single or redundant).

5.5. Analytical Hierarchical Process (AHP) Methodology

AHP technique was developed by Saaty (1977). The technique is one of the mathematical methods for analysing complex decision problems with multiple criteria, and it can deal with qualitative attributes as well as quantitative (Arslan, 2009). AHP is a methodical approach that implies structuring criteria of multiple options into a system hierarchy, including relative values of all criteria, comparing alternatives for each particular criterion and defining average importance of alternatives (Lavasani et al., 2011). Criteria associated with any system can be quantitatively weighted and rated using AHP. The assessment grades of the criteria can be described using Table 5.1 and 5.2. An AHP methodology is applied on multi-criteria problems via pairwise comparison and experts' judgement, facilitated with Tables 5.1 and 5.2. The pairwise comparison is mainly conducted by arranging n criteria in row and column of n×n matrix. The judgments of each expert in AHP applications can be aggregated using Equation 5.1. The AHP methodology can be mathematically described by assuming that quantified judgement on the pairs of criteria A_i and A_j; is represented by an n×n single value comparison matrix *A* (Pillay & Wang, 2003). Then Equations 5.2-5.6 can be used and described below.

$$\text{Average Numerical Value Rating} = \frac{\sum_{i=1}^{n} a_i}{n} \qquad (5.1)$$

where a_i is each value estimated by experts for the same criterion and n is the total number of experts involved in the exercise.

Table 5.1: Scale for Assessment Grades of the Criteria for the Important Pair-wise Comparison

Assessment Grade	Description of Assessment Grade	Numerical Value Rating
Equally important	Two criteria contribute equally to the objective	1
Between moderately more and equally important	There is a compromise between two criteria being considered within the grades.	2
Moderately more important	Experience and judgment slightly favour a criterion over another	3
Between moderately more and strongly more important	There is a compromise between two criteria being considered within the grades.	4
Strongly more important	Experience and judgment strongly favour a criterion over another	5
Between strongly more and very strong important	There is a compromise between two criteria being considered within the grades.	6
Very strongly important	A criterion is strongly favoured over another and its importance is demonstrated in practice	7
Between very strong and extreme important	There is a compromise between two criteria being considered within the grades.	8
Extreme important	The evidence favouring a criterion over another is of the highest order of affirmation	9

$$\mathrm{A} = \left(a_{ij}\right) = .\begin{bmatrix} 1 & a_{12} & \ldots & a_{1n} \\ a/a_{12} & 1 & \ldots & a_{2n} \\ . & . & \ldots & . \\ 1/a_{1n} & 1/a_{2n} & \ldots & 1 \end{bmatrix} \tag{5.2}$$

where each a_{ij} is the relative importance of the criteria A_i and A_j; and $i,\ j$ =.1, 2, 3,….n. The weighting vector of a specific element k in the pair wise comparison matrix is described as w_k. The weighting vector indicates the priority of each element in the pairwise comparison matrix in terms of its overall contribution to the decision making process (Pam, 2010). In view of this, w_k can be mathematically represented as follows:

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) \qquad (k = 1,2,3..........n) \qquad (5.3)$$

Where a_{ij} represents the entry of row *i* and column *j* in a comparison matrix of order n. For better and easy understanding of the method, Equation 5.3 can be grammatically described as follows (Pam, 2013):

Table 5.2: Scale for Assessment Grades of the Criteria for the Unimportant Pair-wise Comparison

Assessment Grade	Description of Assessment Grade	Numerical Value Rating
Equally important	Two criteria contribute equally to the objective	1
Between moderately more and equally unimportant	There is a compromise between two criteria being considered within the grades.	1/2
Moderately more unimportant	Experience and judgment slightly favour a criterion over another	1/3
Between moderately more and strongly more unimportant	There is a compromise between two criteria being considered within the grades.	1/4
Strongly more unimportant	Experience and judgment strongly favour a criterion over another	1/5
Between strongly more and very strong unimportant	There is a compromise between two criteria being considered within the grades.	1/6
Very strongly unimportant	A criterion is strongly favoured over another and its unimportance is demonstrated in practice	1/7
Between very strong and extreme unimportant	There is a compromise between two criteria being considered within the grades.	1/8
Extreme unimportant	The evidence favouring a criterion over another is of the highest order of affirmation	1/9

- Summation of the values in each column of the pairwise comparison matrix.
- Division of each element of the matrix by its column.
- Establishment of the average of the elements in each row.

The values of weights (i.e. w_k) obtained in the pair-wise comparison exercise and expert judgement, need to be verified using Consistency Ratio (CR). The prime determinant of the CR value is Consistency Index (CI) and Random Index (RI) values. According to Satty (1980), whenever a CR value of 0.10 or less is obtained, it means that the pairwise comparison exercises and experts' judgement are reasonable and can be acceptable results. But, any pairwise comparison exercises and expert judgements, where CR value is greater than 0.10, w_k is subject to review or outright results rejection. In view of this, CI can be mathematically described as follows:

$$\text{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{5.4}$$

Where n stands for the number of items being compared and $\lambda_{\max}$ stands for the maximum Eigen value of an $n \times n$ comparison matrix. To identify $\lambda_{\max}$ value in any pairwise comparison exercise, $\lambda_{\max}$ can be mathematically described as follows:

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{kj}}{w_k}}{n} \tag{5.5}$$

Since the values of CI and $\lambda_{\max}$ can be identified using Equations 5.4 and 5.5, CR value can be known using its mathematical definition as follows.

$$\text{CR} = \frac{CI}{RI} \tag{5.6}$$

Where RI, is the random index, which the value depends on the n (i.e. the number of items being compared in pairwise comparison exercise. RI value can be chosen from Table 5.3.

Table 5.3: Average RI values (Satty, 1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

5.6. Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) Methodology

Hwang and Yoon (1981) developed TOPSIS method as a technique that can be utilized in addressing a multi-criteria decision making problem. The technique was developed based on the concept that the chosen alternative should have the shortest distance from the PIRP and the farthest distance from the NIRP (Hwang & Yoon, 1981). Its mechanism can be used to assign the relative importance of attributes on any multi-criteria decision making problem using precise numbers. Therefore, TOPSIS can be used to rank finite number of feasible alternatives according to the features of each attribute/criterion for every alternative and to the decision maker’s choice (Mentes and Helvacioglu, 2012). This method is applied in situations, where selection criteria developed for addressing any problem is monotonic. Criteria are monotonic if two or more criterion that makes up the criteria can be classified as either benefits or costs. A criterion can be classified as a benefit if the more desirable the alternative, the higher its score versus this criterion (Pam, 2010). On the contrary, cost criteria see the most desirable alternative scoring at the lowest (Pam, 2010). 1. TOPSIS method is employed in various applications because its logic is rational and understandable; computation processes are straightforward; the concept permits the pursuit of best alternatives for each criterion depicted in a simple mathematical form; it allows the straight linguistic definition of weights and ratings under each criterion, without the need of cumbersome pairwise comparisons and the risk of inconsistencies (Deng et al, 2000; Olson, 2004; Pam, 2010; Bottani and Rizzi, 2006). The process of TOPSIS method starts from development of a decision matrix, shown in Equation 5.7, with given *m* alternatives/options, *n* criteria/attributes and *k* decision analysts (Wang and Chang, 2007; Bottani and Rizzi, 2006).

$$R_K = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ \vdots \\ A_m \end{array} & \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \end{array} \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \qquad (5.7)$$

In Equation 5.7, A_1, $A_2, \ldots\ldots A_m$ stands for the alternatives/options, while C_1, $C_2, \ldots C_n$ stands for criteria/attributes, and r_{ij} represents crisp number that shows the rating of the alternative/option A_i with respect to criterion C_j. In situations, where decision makers/experts are more than one and rated r_{ij}. The average of their ratings is taken as r_{ij} value. The decision matrix in Equation 5.7, can be normalised using X_{ij}. X_{ij} is mathematically defined in Equation 5.8. Equation 5.8 is used to transform various attribute/criteria dimensions into non-dimensional attributes/criteria, so as to facilitate choosing of any alternatives/option with respect to all the criteria.

$$X_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots\ldots n \qquad (5.8)$$

The normalised decision matrix, need to be weighted using Equation 5.9, in order to facilitate determination of D_i^+ (i.e. the distance separation measure for the PIS) and the D_i^- (i.e. the distance separation measure for the NIS).

$$V_{ij} = w_j \times X_{ij}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots\ldots n \qquad (5.9)$$

According to Yoon and Hwang (1995) and Raham (2012), w_j stands for weight of *jth* attribute/criterion, while V_{ij} is the crisp number that represents the rating of the alternative/option A_i with respect to criterion C_j in a weighted normalised decision matrix.

The PIS and NIS denoted as V^{+} and V^{-} respectively, are mathematically defined in Equations 5.10 and 5.11, so as to facilitate the calculation of the D_i^{+} and D_i^{-}.

$$V^{+}=\{V_1^{+},V_2^{+},V_3^{+}............V_n^{+}\}=\{(\max{}_j V_{ij}\mid j\in J)\},\{(\min{}_j V_{ij}\mid j\in J^{'})\} \qquad (5.10)$$

$$V^{-}=\{V_1^{-},V_2^{-},V_3^{-}............V_n^{-}\}=\{(\min{}_j V_{ij}\mid j\in J)\},\{(\max{}_j V_{ij}\mid j\in J^{'})\} \qquad (5.11)$$

In the works of (Mahmoodzadeh et al., 2007) J and $J^{'}$ are associated with benefit and cost criteria respectively. Therefore, in this research, J and $J^{'}$ are associated with benefit and cost criteria respectively. D_i^{+} and D_i^{-} are developed, so as to measure all the alternatives/options with their PIS and NIS. D_i^{+} and D_i^{-} are mathematically described in Equations 5.12 and 5.13 respectively.

$$D_i^{+}=\sqrt{\sum\nolimits_{j=1}^{n}\left(V_{ij}-V_j^{+}\right)^2}\ ,\ i=1,2,\ldots.,m \qquad (5.12)$$

$$D_i^{-}=\sqrt{\sum\nolimits_{j=1}^{n}\left(V_{ij}-V_j^{-}\right)^2}\ ,\ i=1,2,\ldots.,m \qquad (5.13)$$

Ranking of the various alternatives/options, A_1, A_2,…… A_m, can only be carried out using the relative closeness to ideal solution, denoted as RC_i^{+}. Therefore, D_i^{+} and D_i^{-} are used to described RC_i^{+} mathematically as follows:

$$RC_i^{+}=\frac{D_i^{-}}{D_i^{+}+D_i^{-}}\ ,\quad i=1,2,\ldots\ldots\ldots,\mathrm{m} \qquad (5.14)$$

$0\leq RC_i^{+}\leq 1$ and the best alternative/option is the one with value of RC_i^{+} closest to 1.

5.7. Ranking of Safety Control Designs (SCDs)

Ranking of the SCDs is used to facilitate decision making process on which alternative that can improve system operations in Sub-Section 4.3. The SCDs are ranked according to the values of their RC^{+} revealed from application of AHP-TOPSIS model on a tank farm operations. A SCD associated with highest RC^{+} value is assigned rank of 1. The SCD with second highest RC^{+} value is assigned rank of 2. Other rankings of alternatives follow same procedure.

5.8. Decision Making on Best Safety Control Design (SCD)

Information provided from conduction of AHP-TOPSIS methodology and ranking exercise on tank farm operations is used for decision making on the best SCD that can be used to improve the safety level of that system. The SCDs are ranked using their respective RC^{+} values. Experts use the ranks of the SCDs to take decision on the most effective one. The most effective alternative will be recommended by the experts involved in the study, for improvement of the safety level of the system.

5.9. A Test Case of Using Analytical Hierarchical Process-Technique for Order Preference by Similarity to the Ideal Solution (AHP-TOPSIS) Methodology in Safety Improvement of Tank Farm Operations

In this section, the workability of the aforementioned AHP-TOPSIS methodology on the subject under investigation is illustrated. Synthesis of AHP, TOPSIS and experts judgement is adopted for optimal operations of tank farm via improvement of safety of the leak detection system. Various safety improvement alternatives will be identified and adopted in this exercise. The evaluation criteria will be developed by the four experts, whose levels of experiences have been detailed in Chapter 3.

5.9.1. Safety Assessment of Leak Detection for Optimal Tank Farm Operations

Various factors/causes that affect the optimal operations of tank farm have been discussed in Chapter 3. These are automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure and secondary containment monitoring system failure. It has been revealed that the leak detection system has the highest risk level in Chapter 3, evidenced by further analysis of the system in Chapter 4. Uncertainties associated with the operations of leak detection system have also been addressed in a fuzzy environment in the same chapters, so as to reveal the exact safety level. Due to the present level of safety of leak detection system, safety measures need to be identified and adopted, with the view of obtaining optimal tank farm operations.

5.9.2. Establishment of Safety Control Designs (SCDs) for Optimal Tank Farm Operations

In this research, SCDs for optimal tank farm operations are established via AHP-TOPSIS methodology. An AHP-TOPSIS hierarchical structure for safety improvement of leak detection system of tank farm operations is developed in Figure 5.2. Figure 5.2 revealed two levels, as evidenced in Table 5.4. The information flow in Figure 5.2 started from safety improvement of leak detection system of tank farm operations, which is referred to the selection of best SCD for optimal operations of the leak detection system. The first level of alternatives/options in Figure 5.2 is made up of various SCDs such as SCD #1 (i.e. weekly maintenance), SCD #2 (i.e. weekly visual inspections) and SCD #3 (i.e. use of experts in system operations) that can be used to optimised the safety operations of leak detection system; followed by the second level of criteria, which are labour cost, equipment cost, company organisational strategy, company’s structure and technology management.

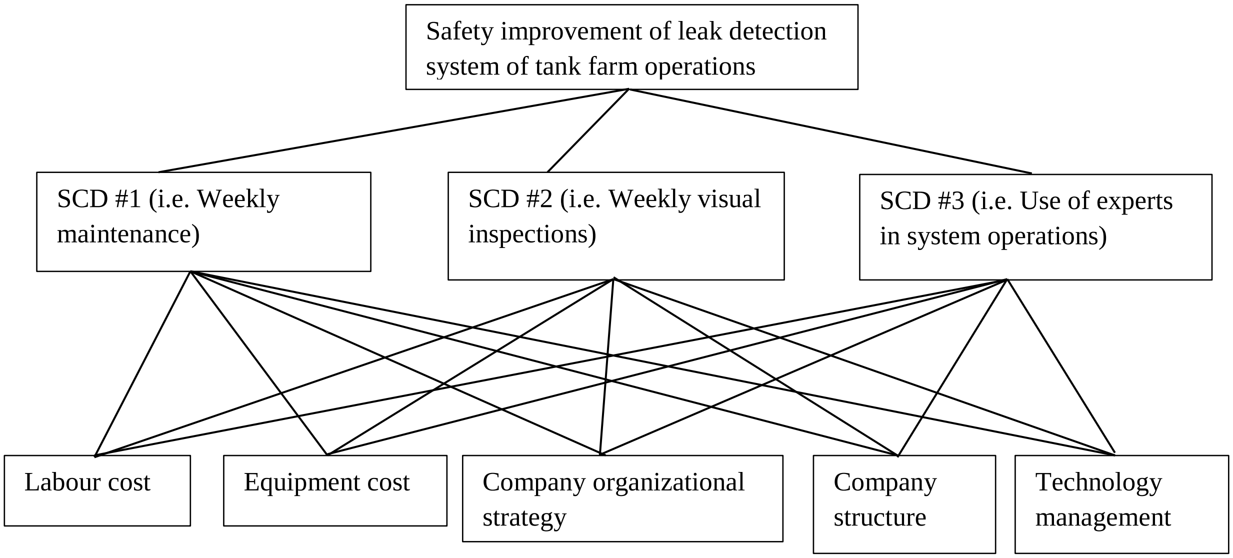

Figure 5.2: An AHP-TOPSIS Hierarchical Structure for Safety Improvement of Leak Detection System of Tank Farm Operations

5.9.3. Identification of Weights of Criteria for Optimal Tank Farm Operations using the Analytical Hierarchical Process (AHP) Methodology

In this section, an AHP method is used to identify the weights of the criteria/attributes in order to facilitate the estimation of the ranks of the SCDs via the TOPSIS method. The aforementioned criteria described in Table 5.4 are labour cost, equipment cost, company organisational strategy, company structure and technology management. Their weights are described as w_1, w_2, w_3, w_4 and w_5 respectively.

5.9.3.1. Expert #1 Opinion on Criteria for Optimal Tank Farm Operations via Analytical Hierarchical Process (AHP) Methodology

Table 5.5 is used to carry out the pairwise comparisons of the evaluation criteria of Figure 5.2. Table 5.5 is used by Expert #1 to demonstrate as follows:

Table 5.4: Definition of the Alternatives and Criteria

Name of Levels	Definition of Levels	Explanation of Levels
Level 1	SCD #1	Weekly maintenance of the tank farm operations
	SCD #2	Weekly visual inspections of tank farm operations
	SCD #3	Use of experts in system operations
Level 2	Labour cost	Cost of labour in using/carrying out any of the SCDs
	Equipment cost	Cost of equipment used or hired for carrying out any of the SCDs
	Company organisational strategy	Entails anticipation and making of contingency plans for obstacles that may arise in the future. It also involves assigning of roles to different teams in the company and laying out timelines of progress that shows different milestones.
	Company structure	It means decentralization of company structure in order to provide a better way to make quick decisions especially regarding safety or emergency situation.
	Technology management	It means improvement of speed and quality of service provided by the company via optimisation of resource allocation.

- In Row 2 of Table 5.5, labour cost and labour cost are compared, and the Expert #1 revealed that both are “Equally Important” with numerical value of 1.
- In Row 3 of Table 5.5, labour cost and equipment cost are compared, and the Expert #1 revealed that equipment cost is “Between Moderately more and Equally Important” than Labour cost with numerical value of 2.
- In Row 4 of Table 5.5, labour cost and company organisational strategy are compared, and the Expert #1 revealed that labour cost is “Between Moderately more and Equally Important” than company organisational strategy with numerical value of 2.
- In Row 5 of Table 5.5, labour cost and company structure are compared, and the Expert #1 revealed that labour cost are “Moderately more Important” than company structure with numerical value of 3.
- In Row 6 of Table 5.5, labour cost and technology management are compared, and the Expert #1 revealed that labour cost is “Between Moderately more and Equally Important” than technology management with numerical value of 2.
- In Row 7 of Table 5.5, equipment cost and equipment cost are compared, and the Expert #1 revealed that both are “Equally Important” with numerical value of 1.
- In Row 8 of Table 5.5, equipment cost and company organisational strategy are compared, and the Expert #1 revealed that equipment cost is “Between moderately more and strongly more Important” than company organisational strategy with numerical value of 4.
- In Row 9 of Table 5.5, equipment cost and company structure are compared, and the Expert #1 revealed that equipment is “Moderately more Important” than company structure with numerical value of 3.
- In Row 10 of Table 5.5, equipment cost and technology management are compared, and the Expert #1 revealed that equipment cost is “Moderately more Important” than equipment cost with numerical value of 3.
- In Row 11 of Table 5.5, company organisational strategy on the use of SCD #1 and company organisational strategy on the use of SCD #1 are compared, and the Expert #1 revealed that both are “Equally Important” with numerical value of 1.
- In Row 12 of Table 5.5, company organisational strategy and company structure are compared, and the Expert #1 revealed that company organisational strategy is “Moderately more Important” than company structure with numerical value of 3.

- In Row 13 of Table 5.5, company organisational strategy and technology management are compared, and the Expert #1 revealed that company organisational strategy is “Moderately more Important” than technology management with numerical value of 3.
- In Row 14 of Table 5.5, company structure on the use of SCD #1 and company structure are compared, and the Expert #1 revealed that both are “Equally Important” with numerical value of 1.
- In Row 15 of Table 5.5, company structure and technology management are compared, and the Expert #1 revealed that company structure is “Moderately more Important” than technology management with numerical value of 3.
- In Row 16 of Table 5.5, technology management and technology management are compared, and the Expert #1 revealed that both are “Equally Important” with numerical value of 1.

Four experts judgement are used in the numerical value ratings of pairwise comparison of the level 2 criteria of the Table 5.4 associated with SCDs. The experts’ judgement of the Experts #2, #3 and #4 are described in Appendix 5A. Equation 5.1 is used to aggregate the numerical value ratings by the four experts as shown in Table 5.6, so as to facilitate the estimation of the weights of the level 2 criteria of the Table 5.4 associated with the SCDs. The numerical value ratings in Table 5.6 and Equation 5.2 is use to develop a 5 x 5 pair-wise comparison matrix as evidenced in Table 5.7.

5.9.3.2. Estimation of Weights of the Criteria for Optimal Tank Farm Operations

Table 5.7 and Equation 5.3 is used to calculate the weights (i.e. w_1, w_2, w_3, w_4 and w_5) of labour cost, equipment cost, company organisational strategy, company structure and technology management respectively as follows:

Table 5.5: Illustration of Conduction of Pairwise Comparison of the Criteria by Expert #1

Pairwise Comparison		Which Criterion is Important than the other?	Details of level of Important	Numerical Value
Labour cost	Labour cost	None	Equally Important	1
Labour cost	Equipment cost	Equipment cost	Between Moderately more and Equally Important	2
Labour cost	Company organisational strategy	Labour cost	Between Moderately more and Equally Important	2
Labour cost	Company structure	Labour cost	Moderately more Important	3
Labour cost	Technology management	Labour cost	Between Moderately more and Equally Important	2
Equipment cost	Equipment cost	None	Equally Important	1
Equipment cost	Company organisational strategy	Equipment cost	Between moderately more and strongly more Important	4
Equipment cost	Company structure	Equipment cost	Moderately more Important	3
Equipment cost	Technology management	Equipment cost	Moderately more Important	3
Company organisational strategy	Company organisational strategy	None	Equally Important	1
Company organisational strategy	Company structure	Company organisational strategy	Moderately more Important	3
Company organisational strategy	Technology management	Company organisational strategy	Moderately more Important	3
Company structure	Company structure	None	Equally Important	1
Company structure	Technology management	Company structure	Moderately more Important	3
Technology management	Technology management	None	Equally Important	1

Table 5.6: Aggregation of Numerical Value Rating of Pairwise Comparison of the Criteria

Pairwise Comparison		Numerical Value Rating by Expert #1	Numerical Value Rating by Expert #2 (See Appendix 5A for details)	Numerical Value Rating by Expert #3 (See Appendix 5A for details)	Numerical Value Rating by Expert #4 (See Appendix 5A for details)	Aggregated Numerical Value Ratings using Equation 5.1
Labour cost	Labour cost	1	1	1	1	1
Labour cost	Equipment cost	2	2	3	2	2.25
Labour cost	Company organisational strategy	2	3	2	2	2.25
Labour cost	Company structure	3	3	4	3	3.25
Labour cost	Technology management	2	3	2	2	2.25
Equipment cost	Equipment cost	1	1	1	1	1
Equipment cost	Company organisational strategy	4	3	4	4	3.75
Equipment cost	Company structure	3	3	3	4	3.25
Equipment cost	Technology management	3	4	3	3	3.25
Company organisational strategy	Company organisational strategy	1	1	1	1	1
Company organisational strategy	Company structure	3	3	3	4	3.25
Company organisational strategy	Technology management	3	4	3	3	3.25
Company structure	Company structure	1	1	1	1	1
Company structure	Technology management	3	2	3	3	2.75
Technology management	Technology management	1	1	1	1	1

Table 5.7: Pairwise Comparison of the Criteria by Experts #1 - #4

Criterion	Labour cost	Equipment cost	Company organisational strategy	Company structure	Technology management
Labour cost	1	1/2.25 (i.e. 0.444)	2.25	3.25	2.25
Equipment cost	2.25	1	3.75	3.25	3.25
Company organisational strategy	1/2.25 (i.e. 0.444)	1/3.75 (i.e. 0.267)	1	3.25	3.25
Company structure	1/3.25 (i.e. 0.308)	1/3.25 (i.e. 0.308)	1/3.25 (i.e. 0.308)	1	2.75
Technology management	1/2.25 (i.e. 0.444	1/3.25 (i.e. 0.308)	1/3.25 (i.e. 0.308)	1/2.75 (i.e. 0.364)	1
SUM	4.446	2.327	7.616	11.11	12.5

$$w_1 = \frac{1}{5}\left(\frac{1}{4.446} + \frac{0.444}{2.327} + \frac{2.25}{7.616} + \frac{3.25}{11.11} + \frac{2.25}{12.5}\right)$$

= 0.237

$$w_2 = \frac{1}{5}\left(\frac{2.25}{4.446} + \frac{1}{2.327} + \frac{3.75}{7.616} + \frac{3.25}{11.11} + \frac{3.25}{12.5}\right)$$

= 0.396

$$w_3 = \frac{1}{5}\left(\frac{0.444}{4.446} + \frac{0.267}{2.327} + \frac{1}{7.616} + \frac{3.25}{11.11} + \frac{3.25}{12.5}\right)$$

= 0.18

$$w_4 = \frac{1}{5}\left(\frac{0.308}{4.446} + \frac{0.308}{2.327} + \frac{0.308}{7.616} + \frac{1}{11.11} + \frac{2.75}{12.5}\right)$$

= 0.11

$$w_5 = \frac{1}{5}\left(\frac{0.444}{4.446} + \frac{0.308}{2.327} + \frac{0.308}{7.616} + \frac{0.364}{11.11} + \frac{1}{12.5}\right)$$

= 0.077

The values of w_1, w_2, w_3, w_4 and w_5 are 0.237, 0.396, 0.18, 0.11 and 0.077 respectively.

5.9.3.3. Investigation of the Consistency of the Pairwise Comparison of Criteria

The consistency of pairwise comparison criteria associated with SCDs can be investigation via multiplication of w_1, w_2, w_3, w_4 and w_5 of labour cost, equipment cost, company organisational strategy, company structure and technology management respectively with each numerical values ratings in columns of Table 5.7 as described below.

$$0.237\begin{bmatrix}1\\2.25\\0.444\\0.308\\0.444\end{bmatrix} + 0.396\begin{bmatrix}0.444\\1\\0.267\\0.308\\0.308\end{bmatrix} + 0.18\begin{bmatrix}2.25\\3.75\\1\\0.308\\0.308\end{bmatrix} + 0.11\begin{bmatrix}3.25\\3.25\\3.25\\1\\0.364\end{bmatrix} + 0.077\begin{bmatrix}2.25\\3.25\\3.25\\2.75\\1\end{bmatrix} = \begin{bmatrix}0.237\\0.533\\0.105\\0.073\\0.105\end{bmatrix} +$$

$$\begin{bmatrix}0.176\\0.396\\0.106\\0.122\\0.122\end{bmatrix} + \begin{bmatrix}0.405\\0.675\\0.18\\0.055\\0.055\end{bmatrix} + \begin{bmatrix}0.358\\0.358\\0.358\\0.11\\0.040\end{bmatrix} + \begin{bmatrix}0.173\\0.250\\0.250\\0.212\\0.077\end{bmatrix} = \begin{bmatrix}1.349\\2.212\\0.999\\0.572\\0.399\end{bmatrix}$$

CI is defined in Equation 5.4 as follows:

$$\text{CI} = \frac{\lambda_{\max} - n}{n-1}$$

The number of criteria in Table 5.4 and Figure 5.2 associated with SCDs is 5. Therefore, n is 5. $\lambda_{\max}$ can be calculated using Equation 5.5 as follows:

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{kj}}{w_k}}{n}$$

$$= \frac{\frac{1.349}{0.237} + \frac{2.212}{0.396} + \frac{0.999}{0.18} + \frac{0.572}{0.11} + \frac{0.399}{0.077}}{5}$$

$$= \frac{5.692 + 5.586 + 5.55 + 5.2 + 5.182}{5}$$

= 5.442

Therefore CI can be calculated as follows:

$$\text{CI} = \frac{5.442 - 5}{5 - 1}$$

= 0.1105

The CR value will be calculated using Equation 5.6 and Table 5.3. Since the number of criteria is 5, RI value of 1.12 will be chosen from Table 5.3 for estimation of the CR value as follows.

$$\text{CR} = \frac{CI}{RI} = \frac{0.1105}{1.12} = 0.099$$

5.9.4. Application of Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) Method in Identification of Best Safety Control Design (SCD) for Optimal Tank Farm Operations

In this section, the mechanism of TOPSIS method is used to facilitate the ranking of the SCD #1, SCD #2 and SCD #3. In this study, the criteria associated with SCD #1, SCD #2 and SCD #3 are monotonic, as evidenced in Figure 5.2 and Table 5.4. Therefore, they need to be classified as benefit or cost criteria for successful application of the TOPSIS method.

5.9.4.1. Development of Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) Decision Matrix

Using Equation 5.7, a decision matrix can be developed. Criteria classified as benefits are company organisational strategy, company structure and technology management, while the criteria classified as costs are labour cost and equipment cost. The SCD #1, SCD #2 and SCD #3 will be rated with respect to labour cost, equipment cost, company organisational strategy, company structure and technology management. Experts #1 - #4 will use Table 5.8 to rate the SCD #1, SCD #2 and SCD #3 with respect to the criteria classified as benefits. The criteria classified as cost will be rated using cost data provided by the experts. Therefore, the decision matrix is illustrated in Table 5.9.

Table 5.8: Rating Scale for Criteria Classified as Benefit

Low				Average			High			
0	1	2	3	4	5	6	7	8	9	10

Table 5.9: TOPSIS Decision Matrix

	Labour cost ($)	Equipment cost ($)	Company organisational strategy	Company structure	Technology management
SCD #1	1900	875	7.5	8.25	8.5
SCD #2	1925	963	5.25	3.5	7.25
SCD #3	2400	2025	7.25	7.0	8.25

$1900 for SCD #1 with respect to labour cost in Table 5.9, is the average of $2000, $1700, $2100 and $1800 estimated by Experts #1, #2, #3 and #4 respectively. That is ($2000 + $1700 + $2100 + $1800)/4 = $1900. In a similar way, other cost estimate for SCDs with respect to cost criteria in Table 5.9 is found. In addition, the rated value of 7.5 for SCD #1 with respect to benefit criteria, company organisational strategy in Table 5.9 is estimated by Experts #1, #2, #3 and #4. The experts used the rating scale for benefit criteria in Table 5.8. 7.5 is the average value of 7, 8, 7 and 8 rated by Experts #1, #2, #3 and #4 respectively. That is (7 + 8 + 7 + 8)/4 = 7.5. Similarly, other SCDs in Table 5.9 are rated with respect to benefit criteria. Therefore, 1900, 875, 7.5, 8.25, 8.5, 1925, 963, 5.25, 3.5, 7.25, 2400, 2025, 7.25, 7 and 8.25 found in Table 5.9 are values of r_{11}, r_{12}, r_{13}, r_{14}, r_{15}, r_{21}, r_{22}, r_{23}, r_{24}, r_{25}, r_{31}, r_{32}, r_{33}, r_{34} and r_{35} respectively.

5.9.4.2. Construction of Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) Normalised Decision Matrix

Table 5.9 is normalised using Equation 5.8. Therefore, the normalised decision matrix is found in Table 5.10. For instance, 0.5254 for SCD #1 with respect to labour cost in Table 5.10 is found by dividing 1900 with 3616.023. 3616.023 is $\sqrt{\sum_{i=1}^{m} r_{ij}^{2}}$ ($i = 1, 2, .., m$; $j = 1, 2, \ldots..$n) and 1900 is r_{11}.

Table 5.10: TOPSIS Normalised Decision Matrix

	Labour cost	Equipment cost	Company organisational strategy	Company structure	Technology management
SCD #1	0.5254	0.3635	0.6422	0.7255	0.6120
SCD #2	0.5324	0.4001	0.4496	0.3078	0.5220
SCD #3	0.6637	0.8413	0.6208	0.6156	0.5940

In a similar way, other values in Table 5.10 are found. The values are 0.5254, 0.3635, 0.6422, 0.7255, 0.6120, 0.5324, 0.4001, 0.4496, 0.3078, 0.5220, 0.6637, 0.8413, 0.6208, 0.6156 and 0.5940. They are described as X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{21}, X_{22}, X_{23}, X_{24}, X_{25}, X_{31}, X_{32}, X_{33}, X_{34} and X_{35} respectively.

5.9.4.3. Construction of Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) Weighted Normalised Decision Matrix

The normalised decision matrix needs to be converted to weighted normalised decision matrix using Equation 5.9. Since weight is one of the variable in Equation 5.9. Therefore, the values of w_1, w_2, w_3, w_4 and w_5 of labour cost, equipment cost, company organisational strategy, company structure and technology management need to be revealed, so as to facilitate development of weighted normalised decision matrix. w_1, w_2, w_3, w_4 and w_5 have been revealed in Sub-sub-section 5.9.3.2 using the AHP technique. They are 0.237, 0.396, 0.18, 0.11 and 0.077 respectively. Application of Equation 5.9 in this study, resulted to formation of weighted normalised decision matrix in Table 5.11.

Table 5.11: TOPSIS Weighted Normalised Decision Matrix

	Labour cost	Equipment cost	Company organisational strategy	Company structure	Technology management
SCD #1	0.1245	0.1439	0.1156	0.0798	0.0471
SCD #2	0.1262	0.1584	0.0809	0.0339	0.0402
SCD #3	0.1573	0.3332	0.1117	0.0677	0.0457

In Table 5.11, 0.1245 for SCD #1 with respect to labour cost is found as a result of multiplication of w_1 (i.e. 0.237) with X_{11} (i.e. 0.5254). In a similar way, other values of V_{ij} are revealed as shown in Table 5.11. Values such as 0.1245, 0.1439, 0.1156, 0.0798, 0.0471, 0.1262, 0.1584, 0.0809, 0.0339, 0.0402, 0.1573, 0.3332, 0.1117, 0.0677 and 0.0457 are for V_{11}, V_{12}, V_{13}, V_{14}, V_{15}, V_{21}, V_{22}, V_{23}, V_{24}, V_{25}, V_{31}, V_{32}, V_{33}, V_{34} and V_{35} respectively.

5.9.4.4. Determination of Positive Ideal Solution, PIS, V^{+}

Values of V_{11}, V_{12}, V_{13}, V_{14}, V_{15}, V_{21}, V_{22}, V_{23}, V_{24}, V_{25}, V_{31}, V_{32}, V_{33}, V_{34} and V_{35} and Equations 5.10 and 5.11 will be used to identify V^{+} and V^{-} respectively, so as to calculate D_i^{+} and D_i^{-}. Therefore, $V^{+} = \{V_1^{+}, V_2^{+}, V_3^{+}, V_4^{+}, V_5^{+}\}$ = {0.1245, 0.1439, 0.1156, 0.0798, 0.0471}. These five values of V^{+} are selected from columns of labour cost, equipment cost, company organisational strategy, company structure and technology management in Table 5.11. These values are as results of selection of minimum and maximum values in columns of criteria classified as costs (i.e. labour cost and equipment cost) and benefits (i.e. company organisational strategy, company structure and technology management) respectively, in Table 5.11. This is in line with Equation 5.10.

5.9.4.5. Determination of Negative Ideal Solution, NIS, V^{-}

Application of Equation 5.11, yielded $V^{-} = \{V_1^{-}, V_2^{-}, V_3^{-}, V_4^{-}, V_5^{-}\}$ = {0.1573, 0.3332, 0.0809, 0.0339, 0.0402}. The values of V^{-} are selected from columns of labour cost, equipment cost, company organisational strategy, company structure and technology management in Table 5.11 in line with the principle of Equation 5.11. The principle states that maximum value should be selected from each column of a criterion in a weighted normalised decision matrix classified as cost and minimum value chosen from the ones classified as benefits.

5.9.4.6. Determination of the Distance Separation Measure for the PIS, D^{+}

Since the values of V^{+} and V^{-} have been revealed, D^{+} and D^{-} can now be calculated using Equations 5.12 and 5.13 respectively. D_i^{+} for SCD #1, SCD #2 and SCD #3 can be calculated using the information in Table 5.11 and provided values of V^{+}. In Table 5.11, the row for SCD #1 is associated with V_{11}, V_{12}, V_{13}, V_{14} and V_{15}. Their corresponding values are 0.1245, 0.1439, 0.1156, 0.0798 and 0.0471. V_{11} and V_{12} are weighted normalised value for SCD #1 with respect to criteria classified as cost, such as labour cost and equipment cost respectively. Therefore, in the calculation of D_1^+, 0.1245 and 0.1439, which are values of V_1^+ and V_2^+ are for criteria classified as cost (i.e. labour cost and equipment cost). While 0.1156, 0.0798 and 0.0471 which are values of V_3^+, V_4^+ and V_5^+ are criteria classified as benefit (i.e. company organisational strategy, company structure and technology management).

In view of the above explanation, D_1^+ for SCD #1 can be calculated as follows:

$$D_1^+ = \sqrt{\sum_{j=1}^{5}\left(V_{1j} - V_j^+\right)^2} = \sqrt{\left(V_{11} - V_1^+\right)^2 + \left(V_{12} - V_2^+\right)^2 + \left(V_{13} - V_3^+\right)^2 + \left(V_{14} - V_4^+\right)^2 + \left(V_{15} - V_5^+\right)^2}$$

$$= \sqrt{(0.1245 - 0.1245)^2 + (0.1439 - 0.1439)^2 + (0.1156 - 0.1156)^2 + (0.0798 - 0.0798)^2 + (0.0471 - 0.0471)^2}$$

$$= 0$$

In a similar way, D_2^+ and D_3^+ for SCD #2 and SCD #3 respectively, are calculated as follows:

$$D_2^+ = \sqrt{\sum_{j=1}^{5}\left(V_{2j} - V_j^+\right)^2} = \sqrt{\left(V_{21} - V_1^+\right)^2 + \left(V_{22} - V_2^+\right)^2 + \left(V_{23} - V_3^+\right)^2 + \left(V_{24} - V_4^+\right)^2 + \left(V_{25} - V_5^+\right)^2}$$

$$= \sqrt{(0.1262 - 0.1245)^2 + (0.1584 - 0.1439)^2 + (0.0809 - 0.1156)^2 + (0.0339 - 0.0798)^2 + (0.0402 - 0.0471)^2}$$

$$= 0.0592$$

$$D_3^+ = \sqrt{\sum_{j=1}^{5}\left(V_{3j} - V_j^+\right)^2} = \sqrt{\left(V_{31} - V_1^+\right)^2 + \left(V_{32} - V_2^+\right)^2 + \left(V_{33} - V_3^+\right)^2 + \left(V_{34} - V_4^+\right)^2 + \left(V_{35} - V_5^+\right)^2}$$

$$= \sqrt{(0.1573 - 0.1245)^2 + (0.3332 - 0.1439)^2 + (0.1117 - 0.1156)^2 + (0.0677 - 0.0798)^2 + (0.0457 - 0.0471)^2}$$

$$= 0.1924$$

5.9.4.7. Determination of the Distance Separation Measure for the NIS, D^-

D_i^- for SCD #1, SCD #1 and SCD #1 can be calculated using their respective V_{ij} values and $V^- = \{V_1^-, V_2^-, V_3^-, V_4^-, V_5^-\}$. Since the values of V_1^-, V_2^-, V_3^-, V_4^- and V_5^- has been revealed as 0.1573, 0.3332, 0.0809, 0.0339 and 0.0402 respectively, Equation 5.13 can be implemented for each SCD.

To facilitate calculation of the D_1^- for SCD #1, the values of V_{11}, V_{12}, V_{13}, V_{14} and V_{15} described as 0.1245, 0.1439, 0.1156, 0.0798 and 0.0471 respectively in the row of SCD #1 in Table 5.11, need to be classified as value for benefit or cost criteria. It has been revealed in Sub-sub-section 5.9.4.1 that V_{11} and V_{12} are for labour cost and equipment cost respectively. V_{13}, V_{14} and V_{15} are for company organisational strategy, company structure and technology management. In view of this, the values of V_{11}, V_{12}, V_{13}, V_{14} and V_{15} and the ones of V_1^-, V_2^-, V_3^-, V_4^- and V_5^- can now be used to calculate D_1^- as follows:

$$D_1^- = \sqrt{\sum_{j=1}^{5}\left(V_{1j} - V_j^-\right)^2} = \sqrt{\left(V_{11} - V_1^-\right)^2 + \left(V_{12} - V_2^-\right)^2 + \left(V_{13} - V_3^-\right)^2 + \left(V_{14} - V_4^-\right)^2 + \left(V_{15} - V_5^-\right)^2}$$

$$= \sqrt{(0.1245 - 0.1573)^2 + (0.1439 - 0.3332)^2 + (0.1156 - 0.0809)^2 + (0.0798 - 0.0339)^2 + (0.0471 - 0.0402)^2}$$

$$= 0.2005$$

Similarly, D_2^- and D_3^- for SCD #2 and SCD #3 respectively, are calculated as expressed below.

$$D_2^- = \sqrt{\sum_{j=1}^{5}\left(V_{2j} - V_j^-\right)^2} = \sqrt{\left(V_{21} - V_1^-\right)^2 + \left(V_{22} - V_2^-\right)^2 + \left(V_{23} - V_3^-\right)^2 + \left(V_{24} - V_4^-\right)^2 + \left(V_{25} - V_5^-\right)^2}$$

$$= \sqrt{(0.1262 - 0.1573)^2 + (0.1584 - 0.3332)^2 + (0.0809 - 0.0809)^2 + (0.0339 - 0.0339)^2 + (0.0402 - 0.0402)^2}$$

$= 0.1778$

$$D_3^- = \sqrt{\sum_{j=1}^{5}\left(V_{3j} - V_j^-\right)^2} = \sqrt{\left(V_{31} - V_1^-\right)^2 + \left(V_{32} - V_2^-\right)^2 + \left(V_{33} - V_3^-\right)^2 + \left(V_{34} - V_4^-\right)^2 + \left(V_{35} - V_5^-\right)^2}$$

$$= \sqrt{(0.1573 - 0.1573)^2 + (0.3332 - 0.3332)^2 + (0.1117 - 0.0809)^2 + (0.0677 - 0.0339)^2 + (0.0457 - 0.0402)^2}$$

$= 0.0447$

5.9.4.8. Determination of the Relative Closeness to Ideal Solution, RC^+

The ranks of SCDs will be used to facilitate decision making processes in the next section. The RC^+ values of the SCDs will be used to show how important each alternative is through ranking. SCD with high RC^+ value is more important than the one with low RC^+ value. In this study, RC_i^+ values of SCD #1, SCD #2 and SCD #3 are calculated using Equation 5.14, so as to rank them in order of importance. Therefore, their D_i^+ and D_i^- values are used to calculate their various RC_i^+ values as follows:

$$RC_1^+ = \frac{D_1^-}{D_1^+ + D_1^-} = \frac{0.2005}{0 + 0.2005} = 1$$

$$RC_2^+ = \frac{D_2^-}{D_2^+ + D_2^-} = \frac{0.1778}{0.0592 + 0.1778} = 0.7502$$

$$RC_3^+ = \frac{D_3^-}{D_3^+ + D_3^-} = \frac{0.0447}{0.1924 + 0.0447} = 0.1885$$

In view of this, the ranks of the SCDs are detailed in Table 5.12. Table 5.12 is explained as follows:

Table 5.12: D_i^+, D_i^- and RC_i^+ Values and Ranking of SCDs

Alternatives/Options	D_i^+	D_i^-	RC_i^+	Rank
SCD #1	0	0.2005	1	1
SCD #2	0.0592	0.1778	0.7502	2
SCD #3	0.0447	0.1924	0.1885	3

- SCD #1 is associated with 0 for D_1^+, 0.2005 for D_1^-, 1 for RC_1^+ and rank of 1.
- SCD #2 is associated with 0.0592 for D_2^+, 0.1778 for D_2^-, 0.7502 for RC_2^+ and rank of 2.
- SCD #3 is associated with 0.0447 for D_3^+, 0.1924 for D_3^-, 0.1885 for RC_3^+ and rank of 3.

5.9.5. Decision Making on Best Safety Control Design (SCD) for Optimal Tank Farm Operations

Most important design options can be identified using the ranks associated with the three SCDs (i.e. SCD #1, SCD #2 and SCD #3). The SCD #1, SCD #2 and SCD #3 are identified by Experts #1, #2, #3 and #4 for safety improvement of leak detection system in order to achieve optimal tank farm operations. Information provided in Table 5.12 can be employed in decision making on most important SCD. In view of this, SCD #1 is identified as the most important SCD, because it has RC_1^+ value of 1 and rank of 1, while SCD #2 and SCD #3 have RC_2^+ and RC_3^+ values of 0.7502 and 0.1885 and ranks of 2 and 3 respectively. Since $SCD\#2 < SCD\#3 < SCD\#1$, therefore, SCD #1 will be used to ensure optimal operations of tank farm via safety improvement of leak detection system.

5.9.6. Sensitivity Analysis

In this study, sensitivity analysis is will be used to verify the robustness of the model employed. In view of this, the following axioms are outlined as follows:

- Axiom 1. Slight increase of the value of distance separation measure for the PIS, D_i^+ for an alternative/option, should result in decrease of the relative closeness to ideal solution, RC_i^+ for that alternative/option.

- Axiom 2. Slight decrease of the value of distance separation measure for the PIS, D_i^+ for an alternative, should result in increase of the relative closeness to ideal solution, RC_i^+ for that alternative/option.

In Table 5.12, D_1^+ for SCD #1 is 0. When the value is increased by 0.01, it becomes 0.01 (i.e. 0 + 0.01). Substituting 0.01 in Equation 5.14, produced RC_1^+ value of 0.9525. Similarly, the D_2^+ value for SCD #2 shown in Table 5.12 is increased by 0.01. The resultant value (i.e. 0.0692) is used in Equation 5.14 to produce RC_2^+ value of 0.7198. In a similar way, the D_3^+ value for SCD #3 illustrated in Table 5.14 is increased by 0.01 to produce 0.0547. Using the 0.0547 in Equation 5.14, yielded RC_3^+ value of 0.1809. The new RC_1^+, $RC_{2,}^+ \, and \, RC_3^+$ values satisfied Axiom 1.

The values of D_1^+, $D_2^+ \, and \, D_3^+$ illustrated in Table 5.12 are decreased by 0.01 to produce new values of -0.01, 0.0492, and 0.1824 respectively. Substituting each of the values in Equation 5.14, resulted in RC_1^+, $RC_{2,}^+ \, and \, RC_3^+$ values of 1.052, 0.7833 and 0.1968 respectively. This is in harmony with Axiom 2.

5.10. Conclusions

Obtaining of optimal tank farm operations is the desire of users and stake holders in the maritime industry. The consequences of failure of any tank farm operations can be disastrous. This can be subdued by identification of SCDs and multi-criteria decision making tools. In this research, it has been revealed that combined multi-criteria decision making tools such as AHP-TOPSIS model can be employed to identify the best SCD that can be used to improve the safety level of a leak detection of tank farm, so as to achieve optimal tank farm operations. The mechanism of the AHP-TOPSIS model is used by four experts to investigate the weight values of the criteria such as labour cost, equipment cost, company organisational strategy, company structure and technology management and ranks of the alternatives (i.e. SCD #1, SCD #2 and SCD #3).

The AHP technique and expert judgement is used to reveal the weights of the labour cost, equipment cost, company organisational strategy, company structure and technology management, while TOPSIS method is employed for ranking exercise of the SCD #1, SCD #2 and SCD #3. In doing so, the SCD #1 is identified as the SCD that can be used to improve the leak detection system of tank farm, evidenced by its RC_1^+ value of 1 and rank of 1. The RC_1^+ value of 1 is the highest RC_1^+ value assigned to the SCDs, which makes SCD #1 most important one, because the higher the RC_1^+ value, the more important the SCD. The methodology of this study can be used by oil and gas companies, chemical and nuclear industries and regulatory authorities for decision making processes on various operations of their systems and subsystems.

Chapter 6 – Discussion and Conclusions

Summary

In this chapter, the models and results used in Chapters 3, 4 and 5 are discussed. Verifications of the models are also outlined. The strengths and weaknesses of the models are described and relevant industries that can use the research are discussed. Furthermore, the research conclusions and limitations are explained. Finally, the areas of recommendation for future research are outlined.

6.1. Introduction

There is no doubt that the safety level of tank farm operations need to be improved evidenced from various accidents that has happen in the industry, which is described in Chapter 2 of this research. The number of tank farms needed for storage of petroleum and chemical products is significantly increasing in recent time. There is public concern about their safety. Occurrences of tank farm accidents are likely to be catastrophic. Therefore, prevention of these accidents is a necessity. To accomplish this task, high risk tank farm operational hazards have been investigated using proactive approach in company with traditional risk/safety analysis methods, advanced computational techniques and multi-criteria decision making method as described in Chapters 3, 4 and 5.

The impact of various organizations in tank farm optimal operations via setting of standards, codes and regulations contributed in accidents preventions as described in Chapter 2. For instance, AIChE and API provided guidelines for storage and handling of high toxic hazard materials and guideline for welded steel tanks for oil storage respectively. Additionally, API developed rules for design and construction of large, welded, low-pressure storage tank and NFPA recommended standard for the storage and handling of liquefied petroleum gases.

This study illustrated how the FMEA-FRB methodology is incorporated in risk evaluation of tank farm operational hazards such as leak detection system failure, pipe corrosion protection system failure, automatic tank gauge system failure, automatic shut-down oil safety valve failure and secondary containment monitoring system failure in Chapter 3 and investigation of the causes of the riskiest hazard under uncertainty in fuzzy environment in Chapter 4. Furthermore, identification of designs/measures that can improve tank farm operational safety is facilitated using the AHP-TOPSIS technique in Chapter 5.

6.2. Discussion of the Failure Mode Effect Analysis - Fuzzy Rule Based (FMEA-FRB) Methodology in Risk Analysis of Tank Farm Operations

Estimations of ranks of tank farm operational hazards/failure modes such as automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure, and secondary containment monitoring system failure are facilitated using the FMEA-FRB methodology and four experts' judgement in Chapter 3. The FMEA-FRB methodology is a combination of FMEA and FRB techniques for the purpose of addressing uncertainty due lack of failure rate data of tank farm operational hazards/failure modes. The ranking exercise is a risk based one. Such exercise is conducted with the aid of risk and FMEA parameters such as RPN (i.e. PAH), OLH, CSH and DH, and the FRB. The experts involved in the study are experienced and understand the subject under investigation. They employed brainstorming techniques in the investigation of the risk ranks of the aforementioned hazards in fuzzy environment.

The OLH, CSH, DH and PAH of the FMEA methodology are described using five linguistic terms as shown in Figures 3.3, 3.4, 3.5 and 3.6 respectively, in order to facilitate the implementation of the developed fuzzy 125 IF-THEN rules for detail analysis and investigation of the risk ranks of the tank farm operational hazards/failure modes. The fuzzy 125 IF-THEN rule is developed as a result of associating five linguistic terms to each parameter in the antecedent part of the IF-THEN rule. The OLH, CSH and DH are described as antecedent parameters of the IF-THEN rule, while PAH is known as the consequent part of the IF-THEN rule. OLH is associated with very low, low, average, high and very high linguistic terms as demonstrated in Table 3.1 and Figure 3.3, while CSH is categorised as negligible, marginal, moderate, critical and catastrophic as illustrated in Table 3.2 and Figure 3.4. The last parameter of the antecedent IF-THEN rule part, DH is described using highly unlikely, unlikely, reasonably likely, likely and highly likely linguistic term as evidenced in Table 3.3 and Figure 3.5, whereas the only parameter of the consequent IF-THEN rule part, PAH is described using five linguistic terms such as very low, low, moderate, high and very high as shown in Table 3.4 and Figure 3.6. Fuzzy membership functions of the OLH, CSH, DH and PAH are developed using their respective linguistic terms, which created platforms that can be used for estimation of the degree of belief (i.e. fuzzy values) of tank farm operational hazards/failure modes.

Experts with the domain knowledge as evidenced in this study, employed these fuzzy membership functions of OLH, CSH, DH and PAH as a guide in the estimation exercise of fuzzy values for OLH, CSH, DH and PAH for all the five tank farm operational hazards/failure modes under investigation. The number of fired rules out of 125 fuzzy IF-THEN rules depends purely on if the fuzzy values of linguistic terms associated with OLH, CSH and DH that made up a rule are known. The fuzzy value associated with the linguistic term of the PAH of a rule depends on the ones of OLH, CSH and DH. The minimum fuzzy value among the ones of OLH, CSH and DH is assigned and described as the one of PAH due to adoption of min-max method in the subject under investigation.

In the investigation of risk based ranks of automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure, and secondary containment monitoring system failure, 8 rules are fired and min-max method adopted for facilitation of estimation of fuzzy conclusions for PAH of each tank farm operational hazards. The fuzzy conclusions for PAH of automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure, and secondary containment monitoring system failure are described as {(0, “very low”), (0, “low”), (0.6, “moderate”), (0.4, “high”), (0, “very high”)}, {(0.15, “very low”), (0.85, “low”), (0, “moderate”), (0, “high”), (0, “very high”)}, {(0, “very low”), (0.4, “low”), (0.6, “moderate”), (0, “high”), (0, “very high”)}, {(0, “very low”), (0, “low”), (0.45, “moderate”), (0.55, “high”), (0, “very high”)} and {(0, “very low”), (0, “low”), (0.55, “moderate”), (0.45, “high”), (0, “very high”)} respectively, as evidenced in Table 3.5.

These fuzzy conclusions are converted to crisp values using the expected utility theory method. The crisp values for automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure, and secondary containment monitoring system failure are described as 0.6, 0.2125, 0.4, 0.6375 and 0.6125 respectively as illustrated in Table 3.5. These values are used to rank the automatic shut-down oil safety valve failure, pipe corrosion protection system failure, automatic tank gauge system failure, leak detection device/system failure, and secondary containment monitoring system failure as 3, 5, 4, 1 and 2 respectively as shown in Table 3.5. In this study, the hazards are ranked according to their riskiness. The riskiest hazard is ranked as 1. Thus, the leak detection system failure is the riskiest hazard.

Sensitivity analysis carried out on the model, proved that the model is robust and effectively served its purpose as evidenced in Sub-section 3.6.3. This groundbreaking method can be employed in the HAZID and risk evaluation of various maritime, oil and gas facilities by maritime and oil companies. However, this method posed some challenges such as very difficult to use when the number of fuzzy rules increase and is prone to error during computation, if not carefully handled.

6.3. Discussion of Fuzzy Fault Tree (FFT) Methodology in Failure Analysis of Leak Detection System of Tank Farm Operations

The results verification conducted via sensitivity analysis reveals that the FFT model served its purpose in this research and justified the estimated values of the failure probabilities of all the events. The causes of the leak detection system failure are revealed using a novel model such as FFT method. In this research, traditional risk/safety analysis (i.e. FTA) in combination with fuzzy logic is employed for investigation of the subject under investigation. The failure logics structure of an FTA facilitated the linking of causes of the leak detection system failure of tank farm operations. The characteristics of an FTA such as possession of a TE, BE and intermediate events facilitated the structuring of the leak detection system failure as TE, human error, human sabotage, human vandalization, thermal contraction, thermal expansion, check valve leaks, pressure relief valve leaks, high static head pressure, continuous pump run, material defects, vapour pockets, fuse unit failure, power supply unit failure and switch failure as BEs, while human threats, mechanical failure, control panel failure and thermal condition as intermediate events. The FTA structure of leak detection system failure in Figure 4.3, revealed that the TE can only occur when any of the intermediate events such as human threats, mechanical failure, control panel failure happens.

Estimation of the failure probabilities of these events posed to be a challenge. The challenge is subdued by incorporation of fuzzy logic into an FTA technique, so as to address uncertainties in failure probabilities estimation of all the events that made up the FTA of the leak detection system failure. In estimation of the BEs failure probabilities denoted as $F\Pr BE$, a fuzzy membership function described with very low, low, average, high and very high linguistic terms is used as illustrated in Figure 4.2. The exercise is facilitated using triangular fuzzy scales of (0, 0.2, 0.4), (0.2, 0.4, 0.6), (0.4, 0.6, 0.8), (0.6, 0.8, 1.0) and (0.8, 1.0, 1.0) for very low, low, average, high and very high respectively, as illustrated in Table 4.1. The judgement of four experts involved in the investigation of each BE failure possibility, denoted as $FPsBE$, using the triangular fuzzy scales is aggregated. (0.1, 0.3, 0.5), (0.15, 0.35, 0.55), (0.35, 0.55, 0.75), (0.7, 0.9, 1), (0.7, 0.9, 1), (0.5, 0.7, 0.9), (0.2, 0.4, 0.6), (0.65, 0.85, 1), (0.4, 0.6, 0.8), (0.15, 0.35, 0.55), (0.5, 0.7, 0.9), (0, 0.2, 0.4), (0.1, 0.3, 0.5) and (0.2, 0.4, 0.6) are found as BEs triangular fuzzy scales such as human error, human sabotage, human vandalization, thermal contraction, thermal expansion, check valve leaks, pressure relief valve leaks, high static head pressure, continuous pump run, material defects, vapour pockets, fuse unit failure, power supply unit failure and switch failure respectively.

The defuzzification process is conducted using CoA defuzzification method and the defuzzified values revealed are 0.3, 0.35, 0.55, 0.867, 0.867, 0.7, 0.4, 0.833, 0.6, 0.35, 0.7, 0.2, 0.3 and 0.2. They are described as failure possibilities of BEs such as human error, human sabotage, human vandalization, thermal contraction, thermal expansion, check valve leaks, pressure relief valve leaks, high static head pressure, continuous pump run, material defects, vapour pockets, fuse unit failure, power supply unit failure and switch failure respectively. These failure possibilities values are converted to failure probabilities and found as 0.001, 0.0015, 0.007, 0.059, 0.059, 0.018, 0.002, 0.045, 0.01, 0.0015, 0.018, 0.0002, 0.001 and 0.002 respectively. BEs failure probabilities values and the FTA failure logics is used to estimate the failure probabilities of the TE (i.e. leak detection system failure) and intermediate events.

The failure probability of leak detection system failure is found to be 0.205 and the ones of the intermediate events such as human threats, mechanical failure, control panel failure and thermal condition are revealed as 0.009, 0.196, 0.003 and 0.059 respectively. The TE failure probability is 0.205, and the consequences will be catastrophic, if the correct preventive and mitigative measures are not in place. The higher the failure probability of a BE, the more important of that BE and vice versa. This study revealed that BEs such as thermal expansion and thermal contraction are the most important ones, while the fuse unit failure is the least important one. Various industries can adopt the methodology used in this research for their system failure and risk analysis in realm of uncertainty. The successful application of this method has been proven in this research but there are still some shortcomings. Hazards with the same failure probability may have different risk implications in reality. Therefore, preventive and mitigative measures employed must be able to address and prevent the occurrence of all the BEs and intermediate events.

6.4. Discussion of Analytic Hierarchy Process-Technique for Order Preference by Similarity to the Ideal Solution (AHP-TOPSIS) Methodology in Optimal Safety Improvement of Tank Farm Operations

Various SCDs are identified but selection of most effective one for optimal operations of tank farm is a challenge. This multi-criteria decision making problem is overcome using the AHP-TOPSIS model in this study. The mechanism of the AHP-TOPSIS model is used to facilitate the identification of the best SCD. The SCDs are SCD #1 described as weekly maintenance, SCD #2 detailed as daily visual inspections and SCD #3 known as use of experts in system operations.

The SCDs and their associated criteria are identified and developed in a hierarchical structural form to facilitate selection of most efficient one using the AHP-TOPSIS model. Linguistic terms are identified and defined in Tables 5.1 and 5.2 for pair-wise comparison of various criteria associated with the SCDs using four experts judgement. Scores are assigned to them for effective utilisation of the linguistic terms by four experts in the judgement of the relevance of the criteria in facilitation of the identification of a SCD that can ensure optimal tank farm operations.

The pair-wise comparison is carried out using linguistic terms as a guide at the criteria level of the hierarchical structure developed in Figure 5.2 i.e. each criterion is compared with one another. Criteria in the hierarchical structure are linked to the alternatives (i.e. SCD #1, SCD #2 and SCD #3) as shown in Figure 5.2 and Table 5.4. The criteria are labour cost, equipment cost, company organisational strategy, company structure and technology management as illustrated in Figure 5.2 and Table 5.4. The results of the four experts' judgement in the pair-wise comparison exercise are aggregated and used to estimate the weights of all the criteria. The weights of the labour cost, equipment cost, company organisational strategy, company structure and technology management are found as 0.237, 0.396, 0.18, 0.11 and 0.077 respectively as evidenced in Sub-section 5.9.3.2. A CR is conducted to ascertain if the four experts' judgement used in this research is reasonable and acceptable. A CR value equal or less than 0.1 must be produced for the four experts' judgement to be reasonable in the pair-wise comparison of the criteria. 0.099 CR value is produced in the pair-wise comparison of the criteria associated with SCD #1, SCD #2 and SCD#3 as demonstrated in Sub-section 5.9.3.3. Therefore, the four experts' judgements are reasonable.

These weights of the criteria associated with SCD #1, SCD #2 and SCD#3 revealed, are incorporated in TOPSIS model so as to find out an SCD that can ensure optimal tank farm operations. Rated scale and TOPSIS decision matrix illustrated in Tables 5.8 and 5.9 respectively are used to investigate the most efficient SCD. The criteria associated with the SCDs illustrated in Figure 5.2 and Table 5.4 are classified as cost and benefits, so as to facilitate the revealing of the relative closeness to ideal solution, RC^+ values of the SCDs. RC^+ values are used for ranking of the SCDs. RC^+ values are estimated using the distance separation measure for the

NIS, D^{-} and the distance separation measure for the PIS, D^{+}values illustrated in Table 5.12. D^{-} and D^{+} values are revealed using the information in Table 5.11. RC^{+} values of SCD #1, SCD #2 and SCD#3 are revealed in Table 5.12 as 1, 0.7502 and 0.1885 respectively. In this study, any SCD with highest RC^{+} value is the most efficient one. Therefore, SCD #1 is more desirable than others in addressing optimal operations problem of tank farm and ranked as 1.

This work can serve as a platform for experts in the maritime and oil and gas industries with domain knowledge to make rational decision in multi-criteria problems. Though, this model possesses significant advantages, some weaknesses still exist. If the criteria are in hundreds, the computation of the pair-wise comparison becomes difficult and error is inevitable. Sometimes, the model may estimates the same weight values for two or more control measures. In the real world, these control measures may have different impact on safety improvement level of a system/operation.

6.5. Main Conclusions of the Research

In this research, HAZID, risk evaluation and safety/risk control of tank farm operational hazards were conducted and addressed for the purpose of improving tank farm operations under uncertainty. The investigations and analysis were proactive based. Therefore, the research findings are:

- A brainstorming technique was employed in the HAZID of the tank farm operations, facilitated by the adoption of the FMEA-FRB methodology. The major tank farm operational hazards such as leak detection system failure, pipe corrosion protection system failure, automatic tank gauge system failure, automatic shut-down oil safety valve failure and secondary containment monitoring system failure were revealed and their risks estimated and ranked. The riskiest one was noted and described as leak detection system failure.

- The causes of leak detection system failure were investigated using the FTA method. The failure probabilities of the causes were identified using FFT. The FTA diagram was made up of a TE (leak detection system failure), 14 BEs (i.e. human error, human Sabotage, human vandalization, thermal contraction, thermal expansion, check valve leaks, pressure relief valve leaks, high static head pressure, continuous pump run, material defects, vapour pockets, fuse unit failure, power supply unit failure and switch failure) and 4 intermediate events (human threat, control panel failure, mechanical failure and thermal condition). All their failure probabilities were revealed under uncertainty and used to rank them.
- An AHP-TOPSIS model has been adopted as a decision making tool and was used in combination with experts' judgements to illustrate how the SCD #1, SCD #2 and SCD #3 can be identified and selected for optimal tank farm operations. The SCD #1 is identified as the best SCD that can prevent the occurrence of the leak detection system failure and improve the tank farm operations optimally.

6.6. Research Limitations

This research is focused on HAZID and risk/safety evaluation and control of tank farm operational hazards. The HAZID exercise is limited to the major ones that can hinder the proper operations of tank farms in Chapter 3. Risk evaluation has been conducted on them using the FMEA-FRB method to reveal the high risk ones and their respective ranks. The leak detection system failure is the hazard that needs further investigation because it is the riskiest among all the major hazards considered. This research is not extended to investigation of causes of other hazards that have lesser risk than the one of leak detection system failure.

The causes of leak detection system failure and their failure probabilities were investigated using a powerful tool, described as FFT. The FTA method is limited to identification and addressing of the causes of the leak detection system failure quantitatively and qualitatively. The fuzzy values served only as reasonable alternative to the failure probabilities of the causes (i.e. BE) in Chapter 4.

The experts used in this research are limited to four, due to their recognizable experiences in the subject investigated. The research framework is limited to the use of only AHP-TOPSIS model for multi-criteria decision making on the best SCD in Chapter 5. Other similar methods were not accommodated in this research framework due to the nature and limitation of the investigated subject.

6.7. Recommendations for Future Research

The areas recommended for future research are described as follows:

- Future research on investigation of the causes of other tank farm operational hazards such as pipe corrosion protection system failure, automatic tank gauge system failure, automatic shut-down oil safety valve failure and secondary containment monitoring system failure using the FTA method is necessary. The FFT method should be used in the identification of the failure probabilities of their respective BEs and TEs. Such informations will contribute immensely in strengthening the safety management of the tank farm operations.
- The usefulness of the AHP model cannot be ignored in future research work. Therefore, it should be extended to management of other tank farm operational hazards. The AHP-TOPSIS method can be adopted in decision making on the best control measure that can be used to eliminate hazards such as pipe corrosion protection system failure, automatic tank gauge system failure, automatic shut-down oil safety valve failure and secondary containment monitoring system failure.
- It will be useful if future researchers can employ other multi-criteria decision making technique and involvement of more than four experts' judgements in testing of how sound the developed model is. This may give rise to interesting findings and will boast the confidence of the researchers on this work. It will encourage the researchers to apply this model to other areas of interest.
- This research can accommodate other traditional safety/risk analysis techniques described in Chapter 2. I recommend future researchers to use this work to investigate the usefulness of those techniques.

- The novel models (i.e. FMEA-FRB, FFT and AHP-TOPSIS models) developed in this research, should be extended and applied to safety/risk management of the areas where the tank farms are sited. Other facilities very close to the tank farm operations should also be considered. This will guarantee maximum protection of the tank farm operations.
- Applications of the PRA are hindered by lack of failure rates data. Such method can be employed in comprehensive risk assessment of tank farms operation and their surroundings if industries can make failure rates data available for researchers. This will facilitate effective safety/risk management of the systems in certain environment. Therefore, industries should be encouraged to make data available for various researches.

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Appendices

Appendices of Chapter 3

Appendix 3A: The 125 IF-THEN Fuzzy Rules of PAH of Tank Farm Operations

Rule #1: IF OLH is very low, CSH is negligible AND DH is highly unlikely, THEN PAH is very low.

Rule #2: IF OLH is very low, CSH is marginal AND DH is unlikely, THEN PAH is low.

Rule #3: IF OLH is very low, CSH is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #4: IF OLH is very low, CSH is critical AND DH is likely, THEN PAH is high.

Rule #5: IF OLH is very low, CSH is catastrophic AND DH is highly likely, THEN PAH is very high.

Rule #6: IF OLH is low, CSH is negligible AND DH is highly unlikely, THEN PAH is very low.

Rule #7: IF OLH is low, CSH is marginal AND DH is unlikely, THEN PAH is low.

Rule #8: IF OLH is low, CSH is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #9: IF OLH is low, CSH is critical AND DH is likely, THEN PAH is high.

Rule #10: IF OLH is low, CSH is catastrophic AND DH is highly likely, THEN PAH is very high.

Rule #11: IF OLH is average, CSH is negligible AND DH is highly unlikely, THEN PAH is very low.

Rule #12: IF OLH is average, CSH is marginal AND DH is unlikely, THEN PAH is low.

Rule #13: IF OLH is average, CSH is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #14: IF OLH is average, CSH is critical AND DH is likely, THEN PAH is high.

Rule #15: IF OLH is average, CSH is catastrophic AND DH is highly likely, THEN PAH is very high.

Rule #16: IF OLH is high, CSH is negligible AND DH is highly unlikely, THEN PAH is very low.

Rule #17: IF OLH is high, CSH is marginal AND DH is unlikely, THEN PAH is low.

Rule #18: IF OLH is high, CSH is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #19: IF OLH is high, CSH is critical AND DH is likely, THEN PAH is high.

Rule #20: IF OLH is high, CSH is catastrophic AND DH is highly likely, THEN PAH is very high.

Rule #21: IF OLH is very high, CSH is negligible AND DH is highly unlikely, THEN PAH is very low.

Rule #22: IF OLH is very high, CSH is marginal AND DH is unlikely, THEN PAH is low.

Rule #23: IF OLH is very high, CSH is moderate AND DH is reasonably likely, THEN PAH is moderate.

Rule #24: IF OLH is very high, CSH is critical AND DH is likely, THEN PAH is high.

Rule #25: IF OLH is very high, CSH is catastrophic AND DH is highly likely, THEN PAH is very high.

Rule #26: IF OLH is very low, CSH is marginal AND DH is highly unlikely, THEN PAH is very low.

Rule #27: IF OLH is very low, CSH is moderate AND DH is unlikely, THEN PAH is low.

Rule #28: IF OLH is very low, CSH is critical AND DH is reasonably likely, THEN PAH is moderate.

Rule #29: IF OLH is very low, CSH is catastrophic AND DH is likely, THEN PAH is high.

Rule #30: IF OLH is very low, CSH is negligible AND DH is highly likely, THEN PAH is very high.

Rule #31: IF OLH is low, CSH is marginal AND DH is highly unlikely, THEN PAH is very low.

Rule #32: IF OLH is low, CSH is moderate AND DH is unlikely, THEN PAH is low.

Rule #33: IF OLH is low, CSH is critical AND DH is reasonably likely, THEN PAH is moderate.

Rule #34: IF OLH is low, CSH is catastrophic AND DH is likely, THEN PAH is high.

Rule #35: IF OLH is low, CSH is negligible AND DH is highly likely, THEN PAH is very high.

Rule #36: IF OLH is average, CSH is marginal AND DH is highly unlikely, THEN PAH is very low.

Rule #37: IF OLH is average, CSH is moderate AND DH is unlikely, THEN PAH is low.

Rule #38: IF OLH is average, CSH is critical AND DH is reasonably likely, THEN PAH is moderate.

Rule #39: IF OLH is average, CSH is catastrophic AND DH is likely, THEN PAH is high.

Rule #40: IF OLH is average, CSH is negligible AND DH is highly likely, THEN PAH is very high.

Rule #41: IF OLH is high, CSH is marginal AND DH is highly unlikely, THEN PAH is very low.

Rule #42: IF OLH is high, CSH is moderate AND DH is unlikely, THEN PAH is low.

Rule #43: IF OLH is high, CSH is critical AND DH is reasonably likely, THEN PAH is moderate.

Rule #44: IF OLH is high, CSH is catastrophic AND DH is likely, THEN PAH is high.

Rule #45: IF OLH is high, CSH is negligible AND DH is highly likely, THEN PAH is very high.

Rule #46: IF OLH is very high, CSH is marginal AND DH is highly unlikely, THEN PAH is very low.

Rule #47: IF OLH is very high, CSH is moderate AND DH is unlikely, THEN PAH is low.

Rule #48: IF OLH is very high, CSH is critical AND DH is reasonably likely, THEN PAH is moderate.

Rule #49: IF OLH is very high, CSH is catastrophic AND DH is likely, THEN PAH is high.

Rule #50: IF OLH is very high, CSH is negligible AND DH is highly likely, THEN PAH is very high.

Rule #51: IF OLH is very low, CSH is moderate AND DH is highly unlikely, THEN PAH is very low.

Rule #52: IF OLH is very low, CSH is critical AND DH is unlikely, THEN PAH is low.

Rule #53: IF OLH is very low, CSH is catastrophic AND DH is reasonably likely, THEN PAH is moderate.

Rule #54: IF OLH is very low, CSH is negligible AND DH is likely, THEN PAH is high.

Rule #55: IF OLH is very low, CSH is marginal AND DH is highly likely, THEN PAH is very high.

Rule #56: IF OLH is low, CSH is moderate AND DH is highly unlikely, THEN PAH is very low.

Rule #57: IF OLH is low, CSH is critical AND DH is unlikely, THEN PAH is low.

Rule #58: IF OLH is low, CSH is catastrophic AND DH is reasonably likely, THEN PAH is moderate.

Rule #59: IF OLH is low, CSH is negligible AND DH is likely, THEN PAH is high.

Rule #60: IF OLH is low, CSH is marginal AND DH is highly likely, THEN PAH is very high.

Rule #61: IF OLH is average, CSH is moderate AND DH is highly unlikely, THEN PAH is very low.

Rule #62: IF OLH is average, CSH is critical AND DH is unlikely, THEN PAH is low.

Rule #63: IF OLH is average, CSH is catastrophic AND DH is reasonably likely, THEN PAH is moderate.

Rule #64: IF OLH is average, CSH is negligible AND DH is likely, THEN PAH is high.

Rule #65: IF OLH is average, CSH is marginal AND DH is highly likely, THEN PAH is very high.

Rule #66: IF OLH is high, CSH is moderate AND DH is highly unlikely, THEN PAH is very low.

Rule #67: IF OLH is high, CSH is critical AND DH is unlikely, THEN PAH is low.

Rule #68: IF OLH is high, CSH is catastrophic AND DH is reasonably likely, THEN PAH is moderate.

Rule #69: IF OLH is high, CSH is negligible AND DH is likely, THEN PAH is high.

Rule #70: IF OLH is high, CSH is marginal AND DH is highly likely, THEN PAH is very high.

Rule #71: IF OLH is very high, CSH is moderate AND DH is highly unlikely, THEN PAH is very low.

Rule #72: IF OLH is very high, CSH is critical AND DH is unlikely, THEN PAH is low.

Rule #73: IF OLH is very high, CSH is catastrophic AND DH is reasonably likely, THEN PAH is moderate.

Rule #74: IF OLH is very high, CSH is negligible AND DH is likely, THEN PAH is high.

Rule #75: IF OLH is very high, CSH is marginal AND DH is highly likely, THEN PAH is very high.

Rule #76: IF OLH is very low, CSH is critical AND DH is highly unlikely, THEN PAH is very low.

Rule #77: IF OLH is very low, CSH is catastrophic AND DH is unlikely, THEN PAH is low.

Rule #78: IF OLH is very low, CSH is negligible AND DH is reasonably likely, THEN PAH is moderate.

Rule #79: IF OLH is very low, CSH is marginal AND DH is likely, THEN PAH is high.

Rule #80: IF OLH is very low, CSH is moderate AND DH is highly likely, THEN PAH is very high.

Rule #81: IF OLH is low, CSH is critical AND DH is highly unlikely, THEN PAH is very low.

Rule #82: IF OLH is low, CSH is catastrophic AND DH is unlikely, THEN PAH is low.

Rule #83: IF OLH is low, CSH is negligible AND DH is reasonably likely, THEN PAH is moderate.

Rule #84: IF OLH is low, CSH is marginal AND DH is likely, THEN PAH is high.

Rule #85: IF OLH is low, CSH is moderate AND DH is highly likely, THEN PAH is very high.

Rule #86: IF OLH is average, CSH is critical AND DH is highly unlikely, THEN PAH is very low.

Rule #87: IF OLH is average, CSH is catastrophic AND DH is unlikely, THEN PAH is low.

Rule #88: IF OLH is average, CSH is negligible AND DH is reasonably likely, THEN PAH is moderate.

Rule #89: IF OLH is average, CSH is marginal AND DH is likely, THEN PAH is high.

Rule #90: IF OLH is average, CSH is moderate AND DH is highly likely, THEN PAH is very high.

Rule #91: IF OLH is high, CSH is critical AND DH is highly unlikely, THEN PAH is very low.

Rule #92: IF OLH is high, CSH is catastrophic AND DH is unlikely, THEN PAH is low.

Rule #93: IF OLH is high, CSH is negligible AND DH is reasonably likely, THEN PAH is moderate.

Rule #94: IF OLH is high, CSH is marginal AND DH is likely, THEN PAH is high.

Rule #95: IF OLH is high, CSH is moderate AND DH is highly likely, THEN PAH is very high.

Rule #96: IF OLH is very high, CSH is critical AND DH is highly unlikely, THEN PAH is very low.

Rule #97: IF OLH is very high, CSH is catastrophic AND DH is unlikely, THEN PAH is low.

Rule #98: IF OLH is very high, CSH is negligible AND DH is reasonably likely, THEN PAH is moderate.

Rule #99: IF OLH is very high, CSH is marginal AND DH is likely, THEN PAH is high.

Rule #100: IF OLH is very high, CSH is moderate AND DH is highly likely, THEN PAH is very high.

Rule #101: IF OLH is very low, CSH is catastrophic AND DH is highly unlikely, THEN PAH is very low.

Rule #102: IF OLH is very low, CSH is negligible AND DH is unlikely, THEN PAH is low.

Rule #103: IF OLH is very low, CSH is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #104: IF OLH is very low, CSH is moderate AND DH is likely, THEN PAH is high.

Rule #105: IF OLH is very low, CSH is critical AND DH is highly likely, THEN PAH is very high.

Rule #106: IF OLH is low, CSH is catastrophic AND DH is highly unlikely, THEN PAH is very low.

Rule #107: IF OLH is low, CSH is negligible AND DH is unlikely, THEN PAH is low.

Rule #108: IF OLH is low, CSH is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #109: IF OLH is low, CSH is moderate AND DH is likely, THEN PAH is high.

Rule #110: IF OLH is low, CSH is critical AND DH is highly likely, THEN PAH is very high.

Rule #111: IF OLH is average, CSH is catastrophic AND DH is highly unlikely, THEN PAH is very low.

Rule #112: IF OLH is average, CSH is negligible AND DH is unlikely, THEN PAH is low.

Rule #113: IF OLH is average, CSH is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #114: IF OLH is average, CSH is moderate AND DH is likely, THEN PAH is high.

Rule #115: IF OLH is average, CSH is critical AND DH is highly likely, THEN PAH is very high.

Rule #116: IF OLH is high, CSH is catastrophic AND DH is highly unlikely, THEN PAH is very low.

Rule #117: IF OLH is high, CSH is negligible AND DH is unlikely, THEN PAH is low.

Rule #118: IF OLH is high, CSH is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #119: IF OLH is high, CSH is moderate AND DH is likely, THEN PAH is high.

Rule #120: IF OLH is high, CSH is critical AND DH is highly likely, THEN PAH is very high.

Rule #121: IF OLH is very high, CSH is catastrophic AND DH is highly unlikely, THEN PAH is very low.

Rule #122: IF OLH is very high, CSH is negligible AND DH is unlikely, THEN PAH is low.

Rule #123: IF OLH is very high, CSH is marginal AND DH is reasonably likely, THEN PAH is moderate.

Rule #124: IF OLH is very high, CSH is moderate AND DH is likely, THEN PAH is high.

Rule #125: IF OLH is very high, CSH is critical AND DH is highly likely, THEN PAH is very high.

Appendix 3B: Details of Experts #1, #2, #3, and #4 Judgement for the PAH Rank Estimation of Pipe Corrosion Protection System Failure in Tank Farm Operations under Uncertainty

Experts Judgement in Fuzzy Environment

Tables 3.1 - 3.3 and Equation 3.2 are adopted in estimation of fuzzy scale values for OLH, CSH and DH. Experts #1 - #4 used Table 3.1 to estimate occurrence likelihood of pipe corrosion protection system failure as low, low, low and low respectively. Numerical values for low, low, low and low is 1, 1, 1 and 1 respectively in Table 3.1. Using Equation 3.2, the fuzzy scale value for OLH denoted as A_{21} is expressed as:

$$A_{21} = w_{21}a_{211} + w_{22}a_{221} + w_{23}a_{231} + w_{24}a_{241}$$

$$A_{21} = 0.25 \times 1 + 0.25 \times 1 + 0.25 \times 1 + 0.25 \times 1$$

$$= 1$$

The fuzzy scale value for CSH denoted as A_{22} can be estimated in a similar way. Experts #1 - #4 rated consequence severity of pipe corrosion protection system failure as negligible. The numerical value of negligible is 1 as shown in Table 3.2. Therefore, A_{22} can be calculated as follows:

$$A_{22} = w_{21}a_{212} + w_{12}a_{222} + w_{23}a_{232} + w_{24}a_{242}$$

$$A_{22} = 0.25 \times 1 + 0.25 \times 1 + 0.25 \times 1 + 0.25 \times 1$$

$$= 1$$

The ratings of Experts #1 - #4 on detectability of pipe corrosion protection system failure as highly unlikely with numerical value of 1 is used to calculate the hazard’s fuzzy scale value, A_{23} as follows:

$$A_{23} = w_{21}a_{213} + w_{22}a_{223} + w_{23}a_{233} + w_{24}a_{243}$$

$$A_{23} = 0.25 \times 1 + 0.25 \times 1 + 0.25 \times 1 + 0.25 \times 1$$

$$= 1$$

Therefore, 1, 1 and 1 can be used to estimate the fuzzy membership function values of OLH, CSH and DH respectively as illustrated in Figures B3.1, B3.2 and B3.3. Figures B3.1, B3.2 and B3.3 showed that the fuzzy membership function values of OLH, CSH and DH are as (0.85, “very low”; 0.15, “low”), (0.85, “marginal”; 0.15, “negligible”) and (0.85, “unlikely”; 0.15, “highly unlikely”) respectively. The fuzzy conclusions of experts are revealed by firing 8 relevant rules (i.e. Rules #1, #2, #6, #7, #26, #31, #102 and #107) in the 125 rules of PAH of tank farm operations as follows:

Rule #1: IF OLH is (0.85, “very low”), CSH is (0.15, “negligible”) AND DH is (0.15, “highly unlikely”), THEN PAH is (0.15, “very low”).

Rule #2: IF OLH is (0.85, “very low”), CSH is (0.85, “marginal”) AND DH is (0.85, “unlikely”), THEN PAH is (0.85, “low”).

Rule #6: IF OLH is (0.15, “low”), CSH is (0.15, “negligible”) AND DH is (0.15, “highly unlikely”), THEN PAH is (0.15, “very low”).

Rule #7: IF OLH is (0.15, “low”), CSH is (0.85, “marginal”) AND DH is (0.85, “unlikely”), THEN PAH is (0.15, “low”).

Rule #26: IF OLH is (0.85, “very low”), CSH is (0.85, “marginal”) AND DH is (0.15, “highly unlikely”), THEN PAH is (0.15, “very low”).

Rule #31: IF OLH is (0.15, “low”), CSH is (0.85, “marginal”) AND DH is (0.15, “highly unlikely”), THEN PAH is (0.15, “very low”).

Rule #102: IF OLH is (0.85, “very low”), CSH is (0.15, “negligible”) AND DH is (0.85, “unlikely”), THEN PAH is (0.15, “low”).

Rule #107: IF OLH is (0.15, “low”), CSH is (0.15, “negligible”) AND DH is (0.85, “unlikely”), THEN PAH is (0.15, “low”).

Using the same procedures in Sub-sub-section 3.6.1.1.1, fuzzy conclusions of PAH of pipe corrosion protection system failure are found as (0.15, “very low”) and (0.85, “low”).

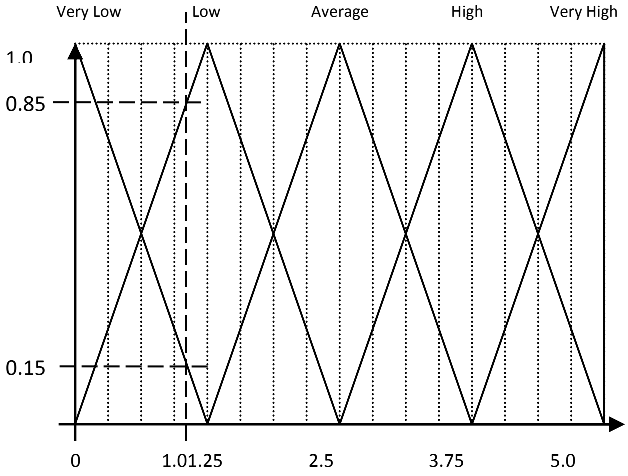

Figure B3.1: A Membership Function for OLH of the Pipe Corrosion Protection System Failure

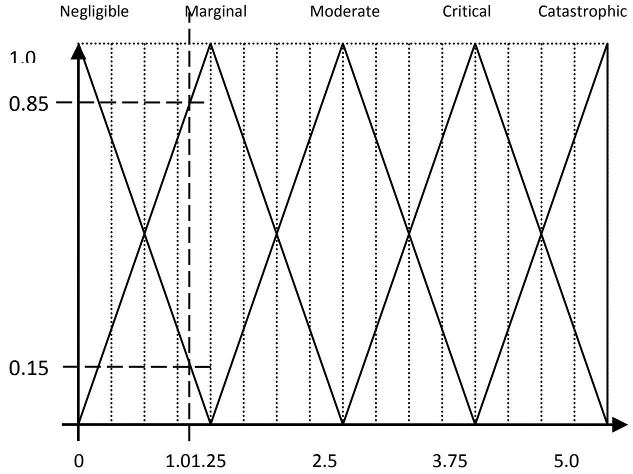

Figure B3.2: A Membership Function for CSH of the Pipe Corrosion Protection System Failure

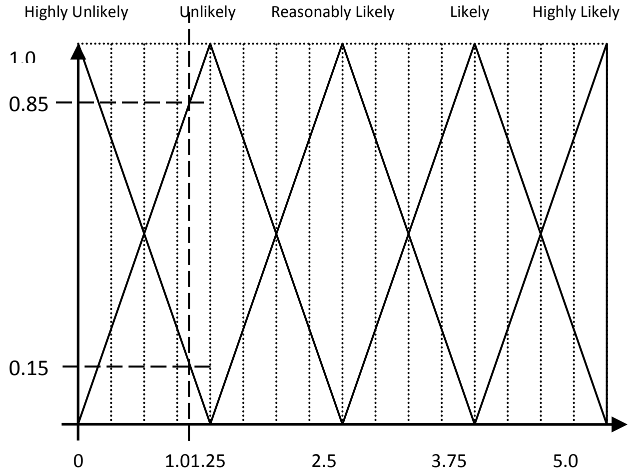

Figure B3.3: A Membership Function for DH of Pipe Corrosion Protection System Failure

Therefore, the PAH belief degrees/fuzzy values of pipe corrosion protection system failure can be described as {(0.15, “very low”), (0.85, “low”), (0, “moderate”), (0, “high”), (0, “very high”)}.

Expected Utility Value for PAH of Pipe Corrosion Protection System Failure

The PAH belief degrees/fuzzy values of pipe corrosion protection system failure is described as {(0.15, “very low”), (0.85, “low”), (0, “moderate”), (0, “high”), (0, “very high”)}. Therefore, 0.15, 0.85, 0, 0 and 0 associated with the evaluation grades stands for β_1, β_2, β_3, β_4 and β_5 respectively. Using procedures and methods adopted in Sub-sub-section 3.6.1.1.2. The expected utility value denoted as $u(S(E))$ of pipe corrosion protection system failure can be revealed as follows:

$$u(S(E)) = 0.15\times\left(\frac{1-1}{5-1}\right)+0.85\times\left(\frac{2-1}{5-1}\right)+0.\left(\frac{3-1}{5-1}\right)+0\times\left(\frac{4-1}{5-1}\right)+0\times\left(\frac{5-1}{5-1}\right)$$

$$= 0.2125$$

Therefore, PAH rank (i.e. crisp value) of pipe corrosion protection system failure in tank farm Operations is 0.2125.

Appendix 3C: Details of Experts #1, #2, #3, and #4 Judgement for the PAH Rank Estimation of Automatic Tank Gauge System Failure in Tank Farm Operations under Uncertainty

Experts Judgement in Fuzzy Environment

The fuzzy scale value for OLH of automatic tank gauge system failure, denoted as A_{31} is 2.25. This is revealed using experts judgement, Equation 3.2 and Table 3.1. The experts #1, #2, #3 and #4 estimated OLH as low, average, low and average respectively. Their respective numerical values in Table 3.1 are incorporated in Equation 3.2 to produce A_{31} as follows:

$$A_{31} = w_{31}a_{311} + w_{32}a_{321} + w_{33}a_{331} + w_{34}a_{341}$$

$$A_{31} = 0.25\times 2 + 0.25\times 3 + 0.25\times 2 + 0.25\times 2$$

$$= 2.25$$

In a similar way, the fuzzy scale value for CSH denoted as A_{32} can be estimated. Experts #1, #2, #3 and #4 rated the CSH of automatic tank gauge system failure using Table 3.2. The ratings of the CSH by Experts #1 - #4 are used to calculate A_{32} as follows:

$$A_{32} = w_{31}a_{312} + w_{32}a_{322} + w_{33}a_{332} + w_{34}a_{342}$$

$$A_{32} = 0.25\times 2 + 0.25\times 2 + 0.25\times 2 + 0.25\times 3$$

$$= 2.25$$

Similar approach is used in finding A_{33}. Experts #1 - #4 used Table 3.3 to rate the DH of automatic tank gauge system failure. The rating values are used in estimation of A_{33} as follows:

$$A_{33} = w_{31}a_{313} + w_{32}a_{323} + w_{33}a_{333} + w_{34}a_{343}$$

$$A_{33} = 0.25\times 2 + 0.25\times 2 + 0.25\times 2 + 0.25\times 2$$

$$= 2.0$$

Therefore, 2.25, 2.25 and 2.0 are respectively used to estimate OLH, CSH and DH fuzzy membership function values as illustrated in Figures B3.4, B3.5 and B3.6. They are described as (0.2, “low”; 0.8, “average”), (0.2, “marginal”; 0.8, “moderate”) and (0.4, “unlikely”; 0.6, “reasonably likely”) for OLH, CSH and DH of automatic tank gauge system failure. This is used to fire 8 rules in the 125 rules of PAH of tank farm operations as follows:

Rule #7: IF OLH is (0.2, “low”), CSH is (0.2, “marginal”) AND DH is (0.4, “unlikely”), THEN PAH is (0.2, “low”).

Rule #8: IF OLH is (0.2, “low”), CSH is (0.8, “moderate”) AND DH is (0.6, “reasonably likely”), THEN PAH is (0.2, “moderate”).

Rule #12: IF OLH is (0.8, “average”), CSH is (0.2, “marginal”) AND DH is (0.4, “unlikely”), THEN PAH is (0.2, “low”).

Rule #13: IF OLH is (0.8, “average”), CSH is (0.8, “moderate”) AND DH is (0.6, “reasonably likely”), THEN PAH is (0.6, “moderate”).

Rule #32: IF OLH is (0.2, “low”), CSH is (0.8, “moderate”) AND DH is (0.4, “unlikely”), THEN PAH is (0.2, “low”).

Rule #37: IF OLH is (0.8, “average”), CSH is (0.8, “moderate”) AND DH is (0.4, “unlikely”), THEN PAH is (0.4, “low”).

Rule #108: IF OLH is (0.2 “low”), CSH is (0.2, “marginal”) AND DH is (0.6, “reasonably likely”), THEN PAH is (0.2, “moderate”).

Rule #113: IF OLH is (0.8, “average”), CSH is (0.2, “marginal”) AND DH is (0.6, “reasonably likely”), THEN PAH is (0.2, “moderate”).

Adopting the same procedures in Sub-section 3.6.1.1.1 and max-min method, Experts estimate the fuzzy conclusions of PAH of automatic tank gauge system failure as (0.4, “low”) and (0.6, “moderate”).

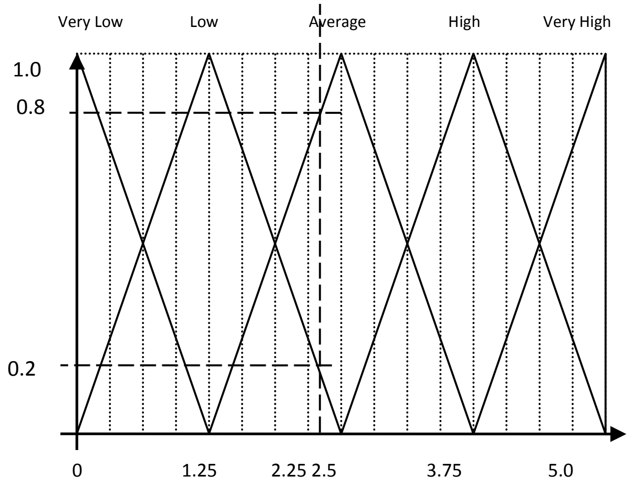

Figure B3.4: A Membership Function for OLH of Automatic Tank Gauge System Failure

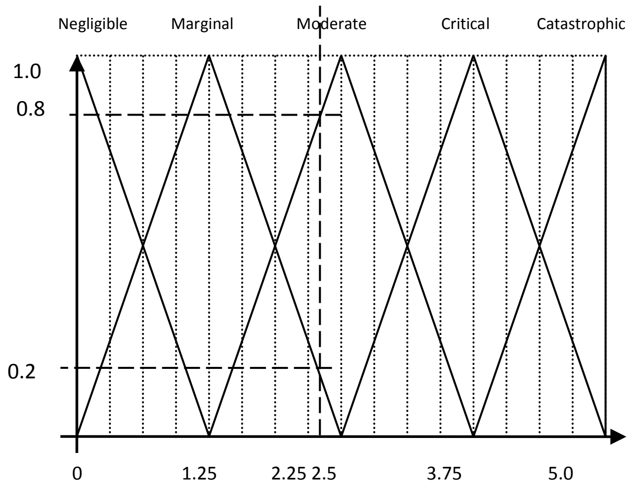

Figure B3.5: A Membership Function for CSH of Automatic Tank Gauge System Failure

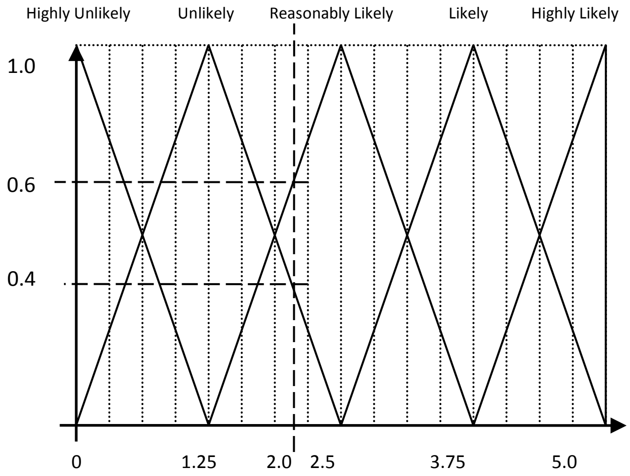

Figure B3.6: A Membership Function for DH of Automatic Tank Gauge System Failure

Expected Utility Value for PAH of Automatic Tank Gauge System Failure

The PAH belief degrees/fuzzy values of automatic tank gauge system failure is described as {(0, “very low”), (0.4, “low”), (0.6, “moderate”), (0, “high”), (0, “very high”)}. It means that 0, 0.4, 0.6, 0 and 0 stands for β_1, β_2, β_3, β_4 and β_5 respectively. Using similar procedures and methods in Sub-sub-section 3.6.1.1.2. The expected utility value denoted as $u(S(E))$ of automatic tank gauge system failure are estimated as follows:

$$u(S(E)) = 0\times\left(\frac{1-1}{5-1}\right)+0.4\times\left(\frac{2-1}{5-1}\right)+0.6\left(\frac{3-1}{5-1}\right)+0\times\left(\frac{4-1}{5-1}\right)+0\times\left(\frac{5-1}{5-1}\right)$$

$$= 0.4$$

Therefore, PAH rank (i.e. crisp value) of automatic tank gauge system failure in tank farm operations is 0.4

Appendix 3D: Details of Expert #1, #2, #3, and #4 Fuzzy Conclusions for the PAH Rank Estimation of Leak Detection Device/System in Tank Farm Operations.

Experts Judgement in Fuzzy Environment

Table 3.1 is used by Experts #1 - #4 to rate the OLH of leak detection device/system failure in order to estimate the fuzzy scale value for the OLH denoted as A_{41}. Equation 3.2 is used to carry out such exercise as follows:

$$A_{41} = w_{41}a_{411} + w_{42}a_{421} + w_{43}a_{431} + w_{44}a_{441}$$

$$A_{41} = 0.25\times1 + 0.25\times1 + 0.25\times1 + 0.25\times1$$

$$= 1.0$$

Similarly, A_{42}, which is the fuzzy scale value for CSH of leak detection device/system failure can be estimated. In view of this, Experts #1, #2, #3 and #4 used Table 3.2 to rate the CSH of leak detection device/system failure. The results of the ratings are used to facilitate the calculation of A_{42}. Therefore, Equation 3.2 is utilised in calculation of A_{42} as follows:

$$A_{42} = w_{41}a_{412} + w_{42}a_{422} + w_{43}a_{432} + w_{44}a_{442}$$

$$A_{42} = 0.25 \times 4 + 0.25 \times 5 + 0.25 \times 5 + 0.25 \times 4$$

$$= 4.5$$

Using similar approach above, the A_{43} described as fuzzy scale value for DH of the leak detection device/system failure can be estimated. The rating values of the DH of the leak detection device/system failure by Experts #1 - #4 are revealed using Table 3.3. Therefore, these values are used to apply Equation 3.2 in order to find A_{43} as follows:

$$A_{43} = w_{41}a_{413} + w_{42}a_{423} + w_{43}a_{433} + w_{44}a_{443}$$

$$A_{42} = 0.25 \times 4 + 0.25 \times 3 + 0.25 \times 3 + 0.25 \times 4$$

$$= 3.5$$

Therefore, 1, 4.5 and 3.5, can be used to estimate the fuzzy membership function values of OLH, CSH and DH of the leak detection device/system failure as shown in Figures B3.7, B3.8 and B3.9. Figures B3.7, B3.8 and B3.9 revealed that the fuzzy membership function values of OLH, CSH and DH of the leak detection device/system failure are (0.85, “low”; 0.15, “very low”), (0.55, “catastrophic”; 0.45, “critical”) and (0.18, “reasonably likely”; 0.82, “likely”) respectively in their corresponding B3.7, B3.8 and B3.9. The experts’ fuzzy conclusion is revealed by firing relevant rules in the 125 rules of PAH of tank farm operations as follows:

Rule #4: IF OLH is (0.15, “very low”), CSH is (0.45, “critical”) AND DH is (0.82, “likely”), THEN PAH is (0.15, “high”).

Rule #9: IF OLH is (0.85, “low”), CSH is (0.45, “critical”) AND DH is (0.82, “likely”), THEN PAH is (0.45, “high”).

Rule #28: IF OLH is (0.15, “very low”), CSH is (0.45, “critical”) AND DH is (0.18, “reasonably likely”), THEN PAH is (0.15, “moderate”).

Rule #29: IF OLH is (0.15, “very low”), CSH is (0.55, “catastrophic”) AND DH is (0.82, “likely”), THEN PAH is (0.15, “high”).

Rule #33: IF OLH is (0.85, “low”), CSH is (0.45, “critical”) AND DH is (0.18, “reasonably likely”), THEN PAH is (0.45, “moderate”).

Rule #34: IF OLH is (0.85, “low”), CSH is (0.55, “catastrophic”) AND DH is (0.82, “likely”), THEN PAH is (0.55, “high”).

Rule #53: IF OLH is (0.15, “very low”), CS is (0.55, “catastrophic”) AND DH is (0.18, “reasonably likely”), THEN PAH is (0.15, “moderate”).

Rule #58: IF OLH is (0.85, “low”), CS is (0.55, “catastrophic”) AND DH is (0.18, “reasonably likely”), THEN PAH is (0.18, “moderate”).

Adopting the same procedures in Sub-section 3.6.1.1.1 and max-min method, Experts estimate the fuzzy conclusions of PAH of the leak detection device/system failure as (0.45, “moderate”) and (0.55, “high”).

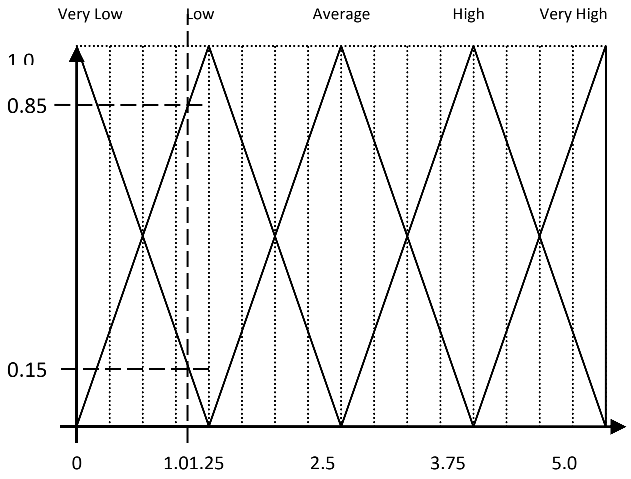

Figure B3.7: A Membership Function for OLH of Leak Detection Device/System Failure

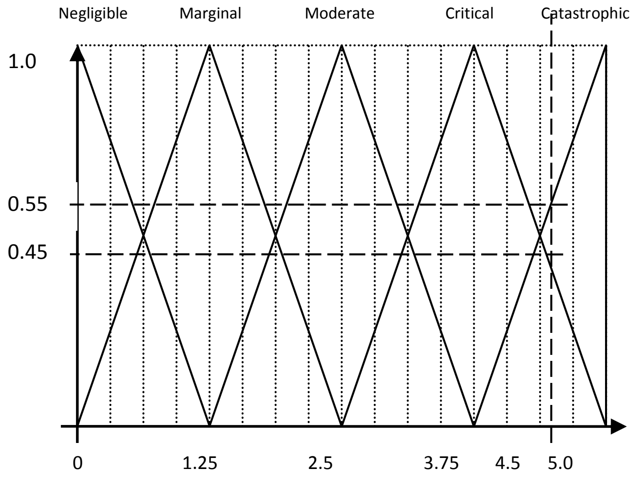

Figure B3.8: A Membership Function for CSH of Leak Detection Device/System Failure

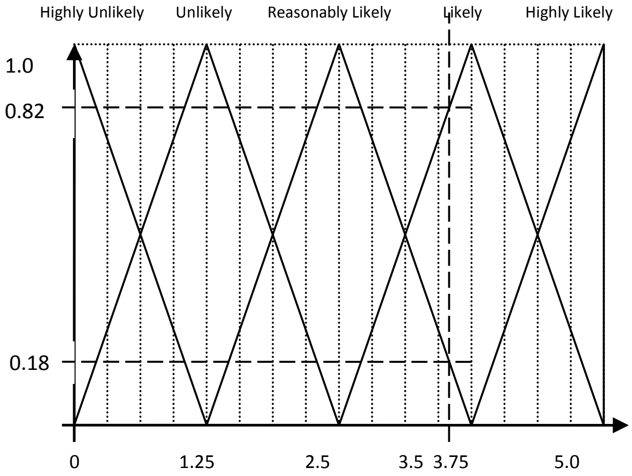

Figure B3.9: A Membership Function for DH of Leak Detection Device/System Failure

Expected Utility Value for PAH of Leak Detection Device/System Failure

The PAH belief degrees/fuzzy values of leak detection device/system failure is described as {(0, “very low”), (0, “low”), (0.45, “moderate”), (0.55, “high”), (0, “very high”)}. It means that 0, 0, 0.45, 0.55 and 0 stands for β_1, β_2, β_3, β_4 and β_5 respectively. In a similar way to Sub-sub-section 3.6.1.1.2, the expected utility value denoted as $u(S(E))$ of leak detection device/system failure are estimated as follows:

$$u(S(E)) = 0\times\left(\frac{1-1}{5-1}\right)+0\times\left(\frac{2-1}{5-1}\right)+0.45\left(\frac{3-1}{5-1}\right)+0.55\times\left(\frac{4-1}{5-1}\right)+0\times\left(\frac{5-1}{5-1}\right)$$

$$= 0.6375$$

Therefore, PAH rank (i.e. crisp value) of leak detection device/system failure farm operations is 0.6375

Appendix 3E: Details of Expert #1, #2, #3, and #4 Fuzzy Conclusions for the PAH Rank Estimation of Secondary Containment Monitoring System Failure in Tank Farm Operations.

Experts Judgement in Fuzzy Environment

The fuzzy scale values for OLH of secondary containment monitoring system failure denoted as A_{51}, can be estimated using Tables 3.1 and Equation 3.2. The Experts #1, #2, #3 and #4 ratings of the OLH are used to calculate A_{51} as follows:

$$A_{51} = w_{51}a_{511} + w_{52}a_{521} + w_{53}a_{531} + w_{54}a_{541}$$

$$A_{51} = 0.25\times1 + 0.25\times1 + 0.25\times1 + 0.25\times1$$

$$= 1.0$$

In a similar way, the fuzzy scale value for CSH of secondary containment monitoring system failure denoted as A_{52} can be estimated. Experts #1, #2, #3 and #4 used Table 3.2 for ratings of CSH of secondary containment monitoring system failure. Their ratings of CSH of secondary containment monitoring system failure are used to calculate A_{52} as follows:

$$A_{52} = w_{51}a_{512} + w_{52}a_{522} + w_{53}a_{532} + w_{54}a_{542}$$

$$A_{52} = 0.25\times 4 + 0.25\times 4 + 0.25\times 4 + 0.25\times 4$$

$$= 4.0$$

To know the fuzzy scale value of secondary containment monitoring system failure denoted as A_{53}, similar approach used above is adopted. Experts #1, #2, #3 and #4 used Table 3.3 to carry out ratings of DH of secondary containment monitoring system failure. These ratings are used to calculate A_{53} as follows:

$$A_{53} = w_{51}a_{513} + w_{52}a_{523} + w_{53}a_{533} + w_{54}a_{543}$$

$$A_{53} = 0.25\times 3 + 0.25\times 3 + 0.25\times 3 + 0.25\times 1$$

$$= 3.25$$

Therefore, 1.0, 4.0 and 3.25 can be used to estimate the fuzzy membership function values as shown in Figures B3.10, B3.11 and B3.12. As evidenced in Figures B3.10, B3.11 and B3.12, the fuzzy membership function values of OLH, CSH and DH of secondary containment monitoring system failure are described as (0.85, "low"; 0.15, "very low"), (0.75, "critical"; 0.25, "catastrophic") and (0.55, "reasonably likely"; 0.45, "likely") respectively. This is used to estimate the fuzzy conclusions of the Experts. In view of this, relevant rules in the 125 rules of PAH of tank farm operations are fired as follows:

Rule #4: IF OLH is (0.15, "very low"), CSH is (0.75, "critical") AND DH is (0.45, "likely"), THEN PAH is (0.15, "high").

Rule #9: IF OLH is (0.85, "low"), CSH is (0.75, "critical") AND DH (0.45, "likely"), THEN PAH is (0.45, "high").

Rule #28: IF OLH is (0.15, "very low"), CSH is (0.75, "critical") AND DH is (0.55, "reasonably likely"), THEN PAH is (0.15, "moderate").

Rule #29: IF OLH is (0.15, “very low”), CSH is (0.25, “catastrophic”) AND DH is (0.45, “likely”), THEN PAH is (0.15, “high”).

Rule #33: IF OLH is (0.85, “low”), CSH is (0.75, “critical”) AND DH is (0.55, “reasonably likely”), THEN PAH is (0.55, “moderate”).

Rule #34: IF OLH is (0.85, “low”), CSH is (0.25, “catastrophic”) AND DH is (0.45, “likely”), THEN PAH is (0.25, “high”).

Rule #53: IF OLH is (0.15, “very low”), CSH is (0.25, “catastrophic”) AND DH is (0.55, “reasonably likely”), THEN PAH is (0.15, “moderate”).

Rule #58: IF OLH is (0.85, “low”), CSH is (0.25, “catastrophic”) AND DH is (0.55, “reasonably likely”), THEN PAH is (0.25, “moderate”).

Using the same procedures in Sub-sub-section 3.6.1.1.1 and max-min method, Experts estimates the fuzzy conclusions of PAH of secondary containment monitoring system failure as (0.55, “moderate”) and (0.45, “high”).

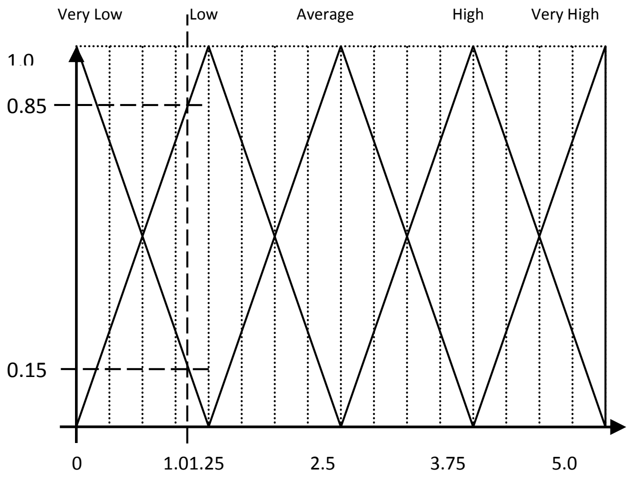

Figure B3.10: A Membership Function for OLH of Secondary Containment Monitoring System Failure

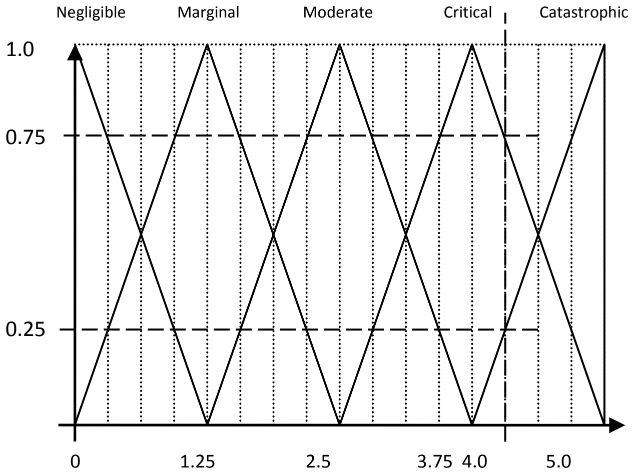

Figure B3.11: A Membership Function for CSH of Secondary Containment Monitoring System Failure

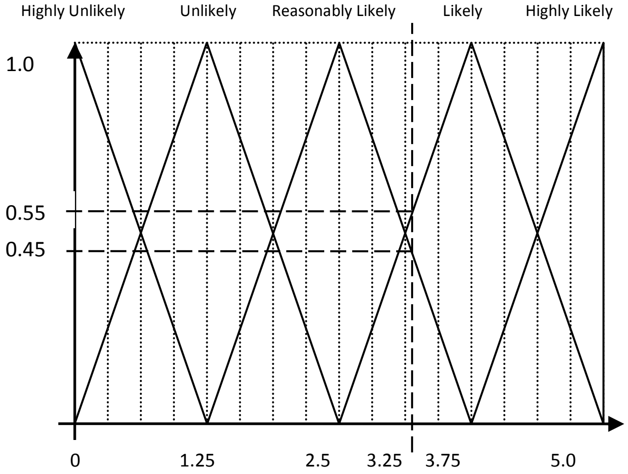

Figure B3.12: A Membership Function for DH of Secondary Containment Monitoring System Failure

Expected Utility Value for PAH of Secondary Containment Monitoring System Failure

The PAH belief degrees/fuzzy values of secondary containment monitoring system failure is described as {(0, "very low"), (0, "low"), (0.55, "moderate"), (0.45, "high"), (0, "very high")}. It means that 0, 0, 0.55, 0.45 and 0 stands for β_1, β_2, β_3, β_4 and β_5 respectively. Using similar procedures in Sub-sub-section 3.6.1.1.2, the expected utility value of secondary containment monitoring system failure denoted as $u(S(E))$ can be calculated as follows:

$$u(S(E)) = 0\times\left(\frac{1-1}{5-1}\right)+0\times\left(\frac{2-1}{5-1}\right)+0.55\left(\frac{3-1}{5-1}\right)+0.45\times\left(\frac{4-1}{5-1}\right)+0\times\left(\frac{5-1}{5-1}\right)$$

$$= 0.6125$$

Therefore, PAH rank (i.e. crisp value) of secondary containment monitoring system failure in tank farm operations is 0.6125.

Appendices of Chapter 4

Appendix 4A: Aggregation of Experts' Judgement on the Failure Possibility (FPs) of Each Basic Event (BE) of the Tank Farm Leak Detection System Operations.

1. Human Sabotage

$$FPsBE_2 = w_{12}(a_{112}, a_{122}, a_{132}) \oplus w_{22}(a_{212}, a_{222}, a_{232}) \oplus w_{32}(a_{312}, a_{322}, a_{332}) \oplus w_{42}(a_{412}, a_{422}, a_{432})$$

$= 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0, 0.2, 0.4)$

$= (0.2\times0.25, 0.4\times0.25, 0.6\times0.25) \oplus (0.2\times0.25, 0.4\times0.25, 0.6\times0.25) \oplus (0.2\times0.25, 0.4 \times0.25, 0.6\times0.25) \oplus (0\times0.25, 0.2\times0.25, 0.4\times0.25)$

$= (0.05, 0.1, 0.15) \oplus (0.05, 0.1, 0.15) \oplus (0.05, 0.1, 0.15) \oplus (0, 0.05, 0.1)$

$= (0.05 \oplus 0.05 \oplus 0.05 \oplus 0, 0.1 \oplus 0.1 \oplus 0.1 \oplus 0.05, 0.15 \oplus 0.15 \oplus 0.15 \oplus 0.1)$

$= (0.15, 0.35, 0.55)$

2. Human Vandalization

$$FPsBE_3 = w_{13}(a_{113}, a_{123}, a_{133}) \oplus w_{23}(a_{213}, a_{223}, a_{233}) \oplus w_{33}(a_{313}, a_{323}, a_{333}) \oplus w_{43}(a_{413}, a_{423}, a_{433})$$

$= 0.25(0.4, 0.6, 0.8) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.4, 0.6, 0.8)$

$= (0.35, 0.55, 0.75)$

3. Thermal Contraction

$$FPsBE_4 = w_{14}\left(a_{114}, a_{124}, a_{134}\right) \oplus w_{24}\left(a_{214}, a_{224}, a_{234}\right) \oplus w_{34}\left(a_{314}, a_{324}, a_{334}\right) \oplus w_{44}\left(a_{414}, a_{424}, a_{434}\right)$$

$$= 0.25(0.6, 0.8, 1.0) \oplus 0.25(0.6, 0.8, 1.0) \oplus 0.25(0.8, 1.0, 1.0) \oplus 0.25(0.8, 1.0, 1.0)$$

$$= (0.7, 0.9, 1.0)$$

4. Thermal Expansion

$$FPsBE_5 = w_{15}\left(a_{115}, a_{125}, a_{135}\right) \oplus w_{25}\left(a_{215}, a_{225}, a_{235}\right) \oplus w_{35}\left(a_{315}, a_{325}, a_{335}\right) \oplus w_{45}\left(a_{415}, a_{425}, a_{435}\right)$$

$$= 0.25(0.8, 1.0, 1.0) \oplus 0.25(0.8, 1.0, 1.0) \oplus 0.25(0.6, 0.8, 1.0) \oplus 0.25(0.6, 0.8, 1.0)$$

$$= (0.7, 0.9, 1.0)$$

5. Check Valve Leaks

$$FPsBE_6 = w_{16}\left(a_{116}, a_{126}, a_{136}\right) \oplus w_{26}\left(a_{216}, a_{226}, a_{236}\right) \oplus w_{36}\left(a_{316}, a_{326}, a_{336}\right) \oplus w_{46}\left(a_{416}, a_{426}, a_{436}\right)$$

$$= 0.25(0.4, 0.6, 0.8) \oplus 0.25(0.6, 0.8, 1.0) \oplus 0.25(0.4, 0.6, 0.8) \oplus 0.25(0.6, 0.8, 1.0)$$

$$= (0.5, 0.7, 0.9)$$

6. Pressure Relief Valve Leaks

$$FPsBE_7 = w_{17}\left(a_{117}, a_{127}, a_{137}\right) \oplus w_{27}\left(a_{217}, a_{227}, a_{237}\right) \oplus w_{37}\left(a_{317}, a_{327}, a_{337}\right) \oplus w_{47}\left(a_{417}, a_{427}, a_{437}\right)$$

$$= 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6)$$

$$= (0.2, 0.4, 0.6)$$

7. High Static Head Pressure

$$FPsBE_8 = w_{18}\left(a_{118}, a_{128}, a_{138}\right) \oplus w_{28}\left(a_{218}, a_{228}, a_{238}\right) \oplus w_{38}\left(a_{318}, a_{328}, a_{338}\right) \oplus w_{48}\left(a_{418}, a_{428}, a_{438}\right)$$

$$= 0.25(0.8, 1.0, 1.0) \oplus 0.25(0.6, 0.8, 1.0) \oplus 0.25(0.6, 0.8, 1.0) \oplus 0.25(0.6, 0.8, 1.0)$$

$$= (0.65, 0.85, 1.0)$$

8. Continuous Pump Run

$$\begin{aligned} FPsBE_9 &= w_{19}(a_{119}, a_{129}, a_{139}) \oplus w_{29}(a_{219}, a_{229}, a_{239}) \oplus w_{39}(a_{319}, a_{329}, a_{339}) \oplus w_{49}(a_{419}, a_{429}, a_{439}) \\ &= 0.25(0.4, 0.6, 0.8) \oplus 0.25(0.4, 0.6, 0.8) \oplus 0.25(0.4, 0.6, 0.8) \oplus 0.25(0.4, 0.6, 0.8) \\ &= (0.4, 0.6, 0.8) \end{aligned}$$

9. Material Defects

$$\begin{aligned} FPsBE_{10} &= w_{110}(a_{1110}, a_{1210}, a_{1310}) \oplus w_{210}(a_{2110}, a_{2210}, a_{2310}) \oplus w_{310}(a_{3110}, a_{3210}, a_{3310}) \oplus w_{410}(a_{4110}, a_{4210}, a_{4310}) \\ &= 0.25(0.2, 0.4, 0.6) \oplus 0.25(0, 0.2, 0.4) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \\ &= (0.15, 0.35, 0.55) \end{aligned}$$

10. Vapour Pockets

$$\begin{aligned} FPsBE_{11} &= w_{111}(a_{1111}, a_{1211}, a_{1311}) \oplus w_{211}(a_{2111}, a_{2211}, a_{2311}) \oplus w_{311}(a_{3111}, a_{3211}, a_{3311}) \oplus w_{411}(a_{4111}, a_{4211}, a_{4311}) \\ &= 0.25(0.2, 0.4, 0.6) \oplus 0.25(0, 0.2, 0.4) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \\ &= (0.5, 0.7, 0.9) \end{aligned}$$

11. Fuse Unit Failure

$$\begin{aligned} FPsBE_{12} &= w_{112}(a_{1112}, a_{1212}, a_{1312}) \oplus w_{212}(a_{2112}, a_{2212}, a_{2312}) \oplus w_{312}(a_{3112}, a_{3212}, a_{3312}) \oplus w_{412}(a_{4112}, a_{4212}, a_{4312}) \\ &= 0.25(0, 0.2, 0.4) \oplus 0.25(0, 0.2, 0.4) \oplus 0.25(0, 0.2, 0.4) \oplus 0.25(0, 0.2, 0.4) \\ &= (0, 0.2, 0.4) \end{aligned}$$

12. Power Supply Unit Failure

$$\begin{aligned} FPsBE_{13} &= w_{113}(a_{1113}, a_{1213}, a_{1313}) \oplus w_{213}(a_{2113}, a_{2213}, a_{2313}) \oplus w_{313}(a_{3113}, a_{3213}, a_{3313}) \oplus w_{413}(a_{4113}, a_{4213}, a_{4313}) \\ &= 0.25(0, 0.2, 0.4) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0, 0.2, 0.4) \oplus 0.25(0.2, 0.4, 0.6) \\ &= (0.1, 0.3, 0.5) \end{aligned}$$

13. Switch Failure

$$\begin{aligned} FPsBE_{14} &= w_{114}(a_{1114}, a_{1214}, a_{1314}) \oplus w_{214}(a_{2114}, a_{2214}, a_{2314}) \oplus w_{314}(a_{3114}, a_{3214}, a_{3314}) \oplus w_{414}(a_{4114}, a_{4214}, a_{4314}) \\ &= 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \oplus 0.25(0.2, 0.4, 0.6) \end{aligned}$$

= (0.2, 0.4, 0.6)

Appendix 4B: Defuzzification of the Aggregated Experts' Opinion on the Failure Possibility (FPs) of Each Basic Event (BE) of Leak Detection System of Tank Farm.

1. Human Sabotage

$$FPsBE_2 = \frac{1}{3}(a_{12} + a_{22} + a_{32})$$

$$= \frac{1}{3}(0.15 + 0.35 + 0.55)$$

$$= 0.35$$

2. Human Vandalization

$$FPsBE_3 = \frac{1}{3}(a_{13} + a_{23} + a_{33})$$

$$= \frac{1}{3}(0.35 + 0.55 + 0.75)$$

$$= 0.55$$

3. Thermal Contraction

$$FPsBE_4 = \frac{1}{3}(a_{14} + a_{24} + a_{34})$$

$$= \frac{1}{3}(0.7 + 0.9 + 1.0)$$

$$= 0.867$$

4. Thermal Expansion

$$FPsBE_5 = \frac{1}{3}(a_{15} + a_{25} + a_{35})$$

$$= \frac{1}{3}(0.7 + 0.9 + 1.0)$$

$$= 0.867$$

5. Check Valve Leaks

$$FPsBE_6 = \frac{1}{3}(a_{16} + a_{26} + a_{36})$$

$$= \frac{1}{3}(0.5 + 0.7 + 0.9)$$

$$= 0.7$$

6. Pressure Relief Valve Leaks

$$FPsBE_7 = \frac{1}{3}(a_{17} + a_{27} + a_{37})$$

$$= \frac{1}{3}(0.2 + 0.4 + 0.6)$$

$$= 0.4$$

7. High Static Head Pressure

$$FPsBE_8 = \frac{1}{3}(a_{18} + a_{28} + a_{38})$$

$$= \frac{1}{3}(0.65 + 0.85 + 1.0)$$

$$= 0.833$$

8. Continuous Pump Run

$$FPsBE_9 = \frac{1}{3}(a_{19} + a_{29} + a_{39})$$

$$= \frac{1}{3}(0.4 + 0.6 + 0.8)$$

$$= 0.6$$

9. Material Defects

$$FPsBE_{10} = \frac{1}{3}\left(a_{110} + a_{210} + a_{310}\right)$$

$$= \frac{1}{3}\left(0.15 + 0.35 + 0.55\right)$$

$$= 0.35$$

10. Vapour Pockets

$$FPsBE_{11} = \frac{1}{3}\left(a_{111} + a_{211} + a_{311}\right)$$

$$= \frac{1}{3}\left(0.5 + 0.7 + 0.9\right)$$

$$= 0.7$$

11. Fuse Unit Failure

$$FPsBE_{12} = \frac{1}{3}\left(a_{112} + a_{212} + a_{312}\right)$$

$$= \frac{1}{3}\left(0 + 0.2 + 0.4\right)$$

$$= 0.2$$

12. Power Supply Unit Failure

$$FPsBE_{13} = \frac{1}{3}\left(a_{113} + a_{213} + a_{313}\right)$$

$$= \frac{1}{3}\left(0.1 + 0.3 + 0.5\right)$$

$$= 0.3$$

13. Switch Failure

$$FPsBE_{14} = \frac{1}{3}\left(a_{114} + a_{214} + a_{314}\right)$$

$$= \frac{1}{3}(0.2 + 0.4 + 0.6)$$

$$= 0.4$$

Appendix 4C: Conversion of the Failure Possibility (FPs) of Each Basic Event (BE) of the Top Event (TE) to Failure Probability (FPr)

1. Human Sabotage

$$F\,\mathrm{Pr}\,BE_2 = \frac{1}{10^{\left[\frac{1-FPsBE_2}{FPsBE_2}\right]^{1/3} \times 2.301}} = \frac{1}{10^{\left[\frac{1-0.35}{0.35}\right]^{1/3} \times 2.301}} = 0.0015$$

2. Human Vandalization

$$F\,\mathrm{Pr}\,BE_3 = \frac{1}{10^{\left[\frac{1-FPsBE_3}{FPsBE_3}\right]^{1/3} \times 2.301}} = \frac{1}{10^{\left[\frac{1-0.55}{0.55}\right]^{1/3} \times 2.301}} = 0.007$$

3. Thermal Contraction

$$F\,\mathrm{Pr}\,BE_4 = \frac{1}{10^{\left[\frac{1-FPsBE_4}{FPsBE_4}\right]^{1/3} \times 2.301}} = \frac{1}{10^{\left[\frac{1-0.867}{0.867}\right]^{1/3} \times 2.301}} = 0.059$$

4. Thermal Expansion

$$F\,\mathrm{Pr}\,BE_5 = \frac{1}{10^{\left[\frac{1-FPsBE_5}{FPsBE_5}\right]^{1/3} \times 2.301}} = \frac{1}{10^{\left[\frac{1-0.867}{0.867}\right]^{1/3} \times 2.301}} = 0.059$$

5. Check Valve Leaks

$$F\,\mathrm{Pr}\,BE_6 = \frac{1}{10^{\left[\frac{1-FPsBE_6}{FPsBE_6}\right]^{1/3} \times 2.301}} = \frac{1}{10^{\left[\frac{1-0.7}{0.7}\right]^{1/3} \times 2.301}} = 0.018$$

6. Pressure Relief Valve Leaks

$$F\Pr BE_7 = \frac{1}{10^{\left[\frac{1-FPsBE_7}{FPsBE_7}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.4}{0.4}\right]^{1/3}\times 2.301}} = 0.002$$

7. High Static Head Pressure

$$F\Pr BE_8 = \frac{1}{10^{\left[\frac{1-FPsBE_8}{FPsBE_8}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.833}{0.833}\right]^{1/3}\times 2.301}} = 0.045$$

8. Continuous Pump Run

$$F\Pr BE_9 = \frac{1}{10^{\left[\frac{1-FPsBE_9}{FPsBE_9}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.6}{0.6}\right]^{1/3}\times 2.301}} = 0.01$$

9. Material Defects

$$F\Pr BE_{10} = \frac{1}{10^{\left[\frac{1-FPsBE_{10}}{FPsBE_{10}}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.35}{0.35}\right]^{1/3}\times 2.301}} = 0.0015$$

10. Vapour Pockets

$$F\Pr BE_{11} = \frac{1}{10^{\left[\frac{1-FPsBE_{11}}{FPsBE_{11}}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.7}{0.7}\right]^{1/3}\times 2.301}} = 0.018$$

11. Fuse Unit Failure

$$F\Pr BE_{12} = \frac{1}{10^{\left[\frac{1-FPsBE_{12}}{FPsBE_{12}}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.2}{0.2}\right]^{1/3}\times 2.301}} = 0.0002$$

12. Power Supply Unit Failure

$$F\Pr BE_{13} = \frac{1}{10^{\left[\frac{1-FPsBE_{13}}{FPsBE_{13}}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.3}{0.3}\right]^{1/3}\times 2.301}} = 0.001$$

13. Switch Failure

$$F\Pr BE_{14} = \frac{1}{10^{\left[\frac{1-FPsBE_{14}}{FPsBE_{14}}\right]^{1/3}\times 2.301}} = \frac{1}{10^{\left[\frac{1-0.4}{0.4}\right]^{1/3}\times 2.301}} = 0.002$$

Appendix 4D: Verification of the Model of Chapter 4 using the Sensitivity Analysis

Elimination of an Intermediate Event, $F\Pr Human$ resulted to reduction of $F\Pr TE$ as follows:

$$\begin{aligned}
F\Pr TE &= \left[1-(1-F\Pr Human)(1-F\Pr Mechanical)(1-F\Pr Panel)\right] \\
&= \left[1-(1-0)(1-0.196)(1-0.003)\right] \\
&= \left[1-(0)(0.804)(0.997)\right] \\
&= 0.198
\end{aligned}$$

The result implies that elimination of $F\Pr Human$ reduced $F\Pr TE$ by 3.41%.

Elimination of an Intermediate Event, $F\Pr Mechanical$ resulted to reduction of $F\Pr TE$ as follows:

$$\begin{aligned}
F\Pr TE &= \left[1-(1-F\Pr Human)(1-F\Pr Mechanical)(1-F\Pr Panel)\right] \\
&= \left[1-(1-0.009)(1-0)(1-0.003)\right] \\
&= \left[1-(0.991)(0.997)\right] \\
&= 0.012
\end{aligned}$$

The result implies that elimination of $F\Pr Mechanical$ reduced $F\Pr TE$ by 94.14%.

Elimination of an Intermediate Event, $F\Pr Panel$ resulted to reduction of $F\Pr TE$ as follows:

$$F\,\mathrm{Pr}\,TE \;=\left[1-\left(1-F\,\mathrm{Pr}\,Human\right)\left(1-F\,\mathrm{Pr}\,Mechanical\right)\left(1-F\,\mathrm{Pr}\,Panel\right)\right]$$

$$=\left[1-\left(1-0.009\right)\left(1-0.196\right)\left(1-0\right)\right]$$

$$=\left[1-\left(0.991\right)\left(0.804\right)\right]$$

$$= 0.203$$

The result implies that elimination of $F\,\mathrm{Pr}\,Panel$ reduced $F\mathrm{Pr}TE$ by 0.98%.

Elimination of all Intermediate Events, $F\,\mathrm{Pr}\,Human$, $F\,\mathrm{Pr}\,Mechanical$ and $F\,\mathrm{Pr}\,Panel$ resulted to reduction of $F\mathrm{Pr}TE$ as follows:

$$F\,\mathrm{Pr}\,TE \;=\left[1-\left(1-F\,\mathrm{Pr}\,Human\right)\left(1-F\,\mathrm{Pr}\,Mechanical\right)\left(1-F\,\mathrm{Pr}\,Panel\right)\right]$$

$$=\left[1-\left(1-0\right)\left(1-0\right)\left(1-0\right)\right]$$

$$=\left[1-\left(1\right)\left(1\right)\left(1\right)\right]$$

$$= 0$$

The result implies that elimination of all Intermediate Events, $F\,\mathrm{Pr}\,Human$, $F\,\mathrm{Pr}\,Mechanical$ and $F\,\mathrm{Pr}\,Panel$ reduced $F\mathrm{Pr}TE$ by 100% .

Appendices of Chapter 5

Appendix 5A

Expert #2 Opinion on Criteria

The pairwise comparisons of the criteria are conducted in Table A5.1. Table A5.1 is used by Expert #2 to demonstrate the following:

- In Row 2 of Table A5.1, labour cost and Labour cost are compared, and the Expert #2 revealed that both are “Equally Important” with numerical value of 1.
- In Row 3 of Table A5.1, labour cost and Equipment cost are compared, and the Expert #2 revealed that Equipment cost is “Between Moderately more and Equally Important” than Labour cost with numerical value of 2.
- In Row 4 of Table A5.1, Labour cost and company organisational strategy are compared, and the Expert #2 revealed that labour cost is “Moderately more Important” than company organisational strategy with numerical value of 3.
- In Row 5 of Table A5.1, labour cost and company structure are compared, and the Expert #2 revealed that labour cost are “Moderately more Important” than company structure with numerical value of 3.
- In Row 6 of Table A5.1, labour cost and technology management are compared, and the Expert #2 revealed that labour cost is “Moderately more Important” than technology management with numerical value of 3.
- In Row 7 of Table A5.1, equipment cost and Equipment cost are compared, and the Expert #2 revealed that both are “Equally Important” with numerical value of 1.
- In Row 8 of Table A5.1, equipment cost and company organisational strategy are compared, and the Expert #2 revealed that Equipment cost is “Moderately more Important” than company organisational strategy with numerical value of 3.
- In Row 9 of Table A5.1, Equipment cost and company structure are compared, and the Expert #2 revealed that Equipment is “Moderately more Important” than company structure with numerical value of 3.
- In Row 10 of Table A5.1, equipment cost and technology management are compared, and the Expert #2 revealed that Equipment cost is “Between moderately more and strongly more important” than equipment cost with numerical value of 4.
- In Row 11 of Table A5.1, company organisational strategy and company organisational strategy are compared, and the Expert #2 revealed that both are “Equally Important” with numerical value of 1.
- In Row 12 of Table A5.1, company organisational strategy and company structure are compared, and the Expert #2 revealed that company organisational strategy is “Moderately more Important” than company structure with numerical value of 3.

- In Row 13 of Table A5.1, company organisational strategy and technology management are compared, and the Expert #2 revealed that company organisational strategy is “Between moderately more and strongly more important” than technology management with numerical value of 4.
- In Row 14 of Table A5.1, company structure and company structure are compared, and the Expert #2 revealed that both are “Equally Important” with numerical value of 1.
- In Row 15 of Table A5.1, company structure and technology management are compared, and the Expert #2 revealed that company structure is “Between moderately more and equally important” than technology management with numerical value of 2.
- In Row 16 of Table A5.1, technology management and technology management are compared, and the Expert #2 revealed that both are “Equally Important” with numerical value of 1.

Expert #3 Opinion on Criteria

The pairwise comparisons of the criteria are conducted in Table A5.2. Table A5.2 is used by Expert #3 to demonstrate the following:

- In Row 2 of Table A5.2, labour cost and Labour cost are compared, and the Expert #3 revealed that both are “Equally Important” with numerical value of 1.
- In Row 3 of Table A5.2, labour cost and Equipment cost are compared, and the Expert #3 revealed that Equipment cost is “Moderately more Important” than Labour cost with numerical value of 3.
- In Row 4 of Table A5.2, labour cost and company organisational strategy are compared, and the Expert #3 revealed that Labour cost is “Between Moderately more and Equally Important” than company organisational strategy with numerical value of 2.
- In Row 5 of Table A5.2, Labour cost and company structure are compared, and the Expert #3 revealed that Labour cost are “Between moderately more and strongly more important” than company structure with numerical value of 4.

- In Row 6 of Table A5.2, labour cost and technology management are compared, and the Expert #3 revealed that Labour cost is “Between Moderately more and Equally Important” than technology management with numerical value of 2.

Table A5.1: Illustration of Conduction of Pairwise Comparison of the Criteria by Expert #2

Pairwise Comparison		Which Criterion is Important than the other?	Details of level of Important	Numerical Value
Labour cost	Labour cost	None	Equally Important	1
Labour cost	Equipment cost	Equipment cost	Between Moderately more and Equally Important	2
Labour cost	Company organisational strategy	Labour cost	Moderately more Important	3
Labour cost	Company structure	Labour cost	Moderately more Important	3
Labour cost	Technology management	Labour cost	Moderately more Important	3
Equipment cost	Equipment cost	None	Equally Important	1
Equipment cost	Company organisational strategy	Equipment cost	Moderately more Important	3
Equipment cost	Company structure	Equipment cost	Moderately more Important	3
Equipment cost	Technology management	Equipment cost		4
Company organisational strategy	Company organisational strategy	None	Equally Important	1
Company organisational strategy	Company structure	Company organisational strategy	Moderately more Important	3
Company organisational strategy	Technology management	Company organisational strategy	Between moderately more and strongly more important	4
Company structure	Company structure	None	Equally Important	1
Company structure	Technology management	Company structure	Between moderately more and equally important	2
Technology management	Technology management	None	Equally Important	1

- In Row 7 of Table A5.2, equipment cost and Equipment cost are compared, and the Expert #3 revealed that both are “Equally Important” with numerical value of 1.

- In Row 8 of Table A5.2, equipment cost and company organisational strategy are compared, and the Expert #3 revealed that Equipment cost is “Between moderately more and strongly more Important” than company organisational strategy with numerical value of 4.
- In Row 9 of Table A5.2, equipment cost and company structure are compared, and the Expert #3 revealed that Equipment cost is “Moderately more Important” than company’s structure with numerical value of 3.
- In Row 10 of Table A5.2, equipment cost and technology management are compared, and the Expert #3 revealed that Equipment cost is “Moderately more Important” than Equipment cost with numerical value of 3.
- In Row 11 of Table A5.2, company organisational strategy and company organisational strategy are compared, and the Expert #3 revealed that both are “Equally Important” with numerical value of 1.
- In Row 12 of Table A5.2, company organisational strategy and company structure are compared, and the Expert #3 revealed that company organisational strategy is “Moderately more Important” than company structure with numerical value of 3.
- In Row 13 of Table A5.2, company organisational strategy and technology management are compared, and the Expert #3 revealed that company organisational strategy is “Moderately more Important” than technology management with numerical value of 3.
- In Row 14 of Table A5.2, company structure and company structure are compared, and the Expert #3 revealed that both are “Equally Important” with numerical value of 1.
- In Row 15 of Table A5.2, company structure and technology management are compared, and the Expert #3 revealed that company structure is “Moderately more Important” than technology management with numerical value of 3.
- In Row 16 of Table A5.2, technology management and technology management are compared, and the Expert #3 revealed that both are “Equally Important” with numerical value of 1.

Table A5.2: Illustration of Conduction of Pairwise Comparison of the Criteria by Expert #3

Pairwise Comparison		Which Criterion is Important than the other?	Details of level of Important	Numerical Value
Labour cost	Labour cost	None	Equally Important	1
Labour cost	Equipment cost	Equipment cost	Moderately more Important	3
Labour cost	Company organisational strategy	Labour cost	Between Moderately more and Equally Important	2
Labour cost	Company structure	Labour cost	Between moderately more and strongly more Important	4
Labour cost	Technology management	Labour cost	Between Moderately more and Equally Important	2
Equipment cost	Equipment cost	None	Equally Important	1
Equipment cost	Company organisational strategy	Equipment cost	Between moderately more and strongly more Important	4
Equipment cost	Company structure	Equipment cost	Moderately more Important	3
Equipment cost	Technology management	Equipment cost	Moderately more Important	3
Company organisational strategy	Company organisational strategy	None	Equally Important	1
Company organisational strategy	Company structure	Company organisational strategy	Moderately more Important	3
Company organisational strategy	Technology management	Company organisational strategy	Moderately more Important	3
Company structure	Company structure	None	Equally Important	1
Company structure	Technology management	Company structure	Moderately more Important	3
Technology management	Technology management	None	Equally Important	1

Expert #4 Opinion on Criteria

The pairwise comparisons of the criteria associated with SCD #1 is conducted in Table A5.3. Table A5.3 is used by Expert #4 to demonstrate the following:

- In Row 2 of Table A5.3, labour cost and Labour cost are compared, and the Expert #4 revealed that both are “Equally Important” with numerical value of 1.
- In Row 3 of Table A5.3, labour cost and Equipment cost are compared, and the Expert #4 revealed that Equipment cost is “Between Moderately more and Equally Important” than Labour cost with numerical value of 2.
- In Row 4 of Table A5.3, labour cost and company organisational strategy are compared, and the Expert #4 revealed that Labour cost is “Between Moderately more and Equally Important” than company organisational strategy with numerical value of 2.
- In Row 5 of Table A5.3, labour cost and company structure are compared, and the Expert #4 revealed that Labour cost are “Moderately more Important” than Effects of company structure with numerical value of 3.
- In Row 6 of Table A5.3, labour cost and technology management are compared, and the Expert #4 revealed that Labour cost is “Between Moderately more and Equally Important” than technology management with numerical value of 2.
- In Row 7 of Table A5.3, equipment cost and Equipment cost are compared, and the Expert #4 revealed that both are “Equally Important” with numerical value of 1.
- In Row 8 of Table A5.3, equipment cost and company organisational strategy are compared, and the Expert #4 revealed that Equipment cost is “Between moderately more and strongly more Important” than company organisational strategy with numerical value of 4.
- In Row 9 of Table A5.3, equipment cost and company structure are compared, and the Expert #4 revealed that Equipment cost is “Between moderately more and strongly more Important” than company structure with numerical value of 4.
- In Row 10 of Table A5.3, equipment cost and technology management are compared, and the Expert #4 revealed that Equipment cost is “Moderately more Important” than Equipment cost with numerical value of 3.
- In Row 11 of Table A5.3, company organisational strategy and company organisational strategy are compared, and the Expert #4 revealed that both are “Equally Important” with numerical value of 1.
- In Row 12 of Table A5.3, company organisational strategy and company structure are compared, and the Expert #4 revealed that company organisational strategy is “Between

moderately more and strongly more Important” than company structure with numerical value of 4.

Table A5.3: Illustration of Conduction of Pairwise Comparison of the Criteria by Expert #4

Pairwise Comparison		Which Criterion is Important than the other?	Details of level of Important	Numerical Value
Labour cost	Labour cost	None	Equally Important	1
Labour cost	Equipment cost	Equipment cost	Between Moderately more and Equally Important	2
Labour cost	Company organisational strategy	Labour cost	Between Moderately more and Equally Important	2
Labour cost	Company structure	Labour cost	Moderately more Important	3
Labour cost	Technology management	Labour cost	Between Moderately more and Equally Important	2
Equipment cost	Equipment cost	None	Equally Important	1
Equipment cost	Company organisational strategy	Equipment cost	Between moderately more and strongly more Important	4
Equipment cost	Company structure	Equipment cost	Between moderately more and strongly more Important	4
Equipment cost	Technology management	Equipment cost	Moderately more Important	3
Company organisational strategy	Company organisational strategy	None	Equally Important	1
Company organisational strategy	Company structure	Company organisational strategy	Between moderately more and strongly more Important	4
Company organisational strategy	Technology management	Company organisational strategy	Moderately more Important	3
Company structure	Company structure	None	Equally Important	1
Company structure	Technology management	Company structure	Moderately more Important	3
Technology management	Technology management	None	Equally Important	1

- In Row 13 of Table A5.3, company organisational strategy and technology management are compared, and the Expert #4 revealed that company organisational strategy is “Moderately more Important” than technology management with numerical value of 3.

- In Row 14 of Table A5.3, company structure and company structure are compared, and the Expert #4 revealed that both are “Equally Important” with numerical value of 1.
- In Row 15 of Table A5.3, company structure and technology management are compared, and the Expert #4 revealed that company structure on the use of SCD #1 is “Moderately more Important” than technology management with numerical value of 3.
- In Row 16 of Table A5.3, technology management and technology management are compared, and the Expert #4 revealed that both are “Equally Important” with numerical value of 1.