ADVANCED SAFETY METHODOLOGY FOR RISK MANAGEMENT OF PETROLEUM REFINERY OPERATIONS

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Abstract

Petroleum refineries are important facilities for refining petroleum products that provide the primary source of energy for domestic and industrial consumption globally. Petroleum refinery operations provide significant contribution to global economic growth. Petroleum refineries are complex, multifaceted systems that perform multiple phase operations characterized by a high level of risk. Evidence based major accidents that have occurred within the last three decades in the petroleum refineries, around the world, indicates losses estimated in billions of US dollars. Many of these accidents are catastrophes, which have led to the disruption of petroleum refinery operations. These accidents have resulted in production loss, asset damage, environmental damage, fatalities and injuries. However, the foremost issue analysed in literatures in relation to major accidents in petroleum refineries, is the lack of robust risk assessment and resourceful risk management approaches to identify and assess major accident risks, in order to prevent or mitigate them from escalating to an accident. Thus, it is exceptionally critical to readdress the issue of petroleum refinery risk management with the development of a more dependable, adaptable and holistic risk modelling framework for major accident risks investigation.

In this thesis, a proactive framework for advanced risk management to analyse and mitigate the disruption risks of petroleum refinery operations is presented. In this research, various risk elements and their attributes that can interact to cause the disruption of PRPU operations were identified and analysed, in order to determine their criticality levels. This thesis shows that the convergent effect of the interactions between the risk elements and their attributes can lead to the disruption of petroleum refinery operations. In the scheme

of the study, Fuzzy Linguistic Preference Relation (FLPR), Fuzzy Evidential Reasoning (FER) and Fuzzy Bayesian Network (FBN) methodologies were proposed and implemented to evaluate the criticality of the risk elements and their attributes and to analyse the risk level of PRPU operations. Also, AHP-fuzzy VIKOR methodology was utilised for decision modelling to determine the optimal strategy for the risk management of the most significant risk elements' attributes that can interact to cause the disruption of PRPU operations. The methodologies proposed and implemented in this research can be utilised in the petroleum refining industry, to analyse complex risk scenarios where there is incomplete information concerning risk events or where the probability of risk events is uncertain. The result of the analysis conducted in this research to determine the risk level of petroleum refinery operations can be utilised by risk assessors and decision makers as a threshold value for decision making in order to mitigate the disruption risk of PRPU operations. The decision strategies formulated in this thesis based on robust literature review and expert contributions, contributes to knowledge in terms of the risk management of petroleum refinery operations. The result of the evaluation and ranking of the risk elements and their attributes can provide salient risk information to duty holders and decision makers to improve their perceptions, in order to prioritise resources for risk management of the most critical attributes of the risk elements.

Overall, the methodologies applied in this thesis, can be tailored to be utilised as a quantitative risk assessment tool, by risk managers and decision analysts in the petroleum refining industry for enhancement risk assessment processes where available information can sometimes be vague or incomplete for risk analysis.

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Abbreviations

AIChE	American Institute of Chemical Engineers
AHP	Analytical Hierarchy Process
AIM	Asset Integrity Management
ALARP	As Low As Reasonably Practicable
ANSI	American National Standard Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ARIA	Analysis, Research and Information on Accident
BN	Bayesian Network
BP	British Petroleum
CA	Criticality Analysis
CCA	Cause-Consequence Analysis
CC	Consensus Coefficient Degree
CDU	Crude Distillation unit Fluid Catalytic Cracking unit
CI	Consistency Index
COA	Centre of Area
COMAH	Control of Major Accident Hazards
CR	Consistency Ratio

CSB	Chemical Safety and Hazard Investigation Board
CPT	Conditional Probability Table
DA	Average Degree of Agreement
DEA	Data Envelop Analysis
EIA	U.S Energy Information Administration
ELECTRE	Elimination Et Choix Traduisant la Realité
ET	Event Tree
ETA	Event Tree Analysis
ER	Evidential Reasoning
FBN	Fuzzy Bayesian Networks
FCC	Fluid Catalytic Cracking
FER	Fuzzy Evidential Reasoning
FLPR	Fuzzy Linguistic Preference Relation
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FPS	Fuzzy Possibility Score
FST	Fuzzy Set Theory
FT	Fault Trees
FTA	Fault Tree Analysis

GRA	Grey Relation Analysis
HAZID	Hazard Identification
HAZOP	Hazard Operability Study
HSE	Health and Safety Executive
HTHA	High Temperature Hydrogen Attack
IOWs	Integrity Operating Windows
JPD	Joint probability distribution
JST	Japan Science and Technology Agency
LOPA	Layers of Protection Analysis
LPG	Liquid petroleum gas
MCDM	Multi-criteria Decision Making
MOC	Management of Change
MOM	Mean of Maximum
NFPA	National Fire Protection Association
OGP	International Association of Oil and Gas Producers
OIM	Operations Integrity Management
OL	Other Literatures
OSHA	Occupational Safety and Health Administration
PD	Propane De-Asphalting

PDA Personal Digital Assistant

PHA Preliminary Hazard Analysis

PROMETHEE Preference Ranking Organization Method for Enrichment of Evaluations

PRPU Petroleum Refinery Process Unit

PSM Process Safety Management

RAGAGEP Recognized and Generally Accepted Good Engineering Practices

RBI Reliability and Risk Based Inspection

RDA Relative Degree of Agreement

RI Random Index

RP Recommended Practice

SA Sensitivity Analysis

SGP Saturated Gas Plant

SCADA Supervisory Control and Data Acquisition

TEs Top Events

TFN Triangle Fuzzy Number

TOPSIS Technique for Order Preference by Similarity to the Ideal Solution

VDU Vacuum Distillation unit

Chapter 1 - Introduction

Summary

This chapter introduces the background of the research, the research motivations and problems. The research aims and objectives are outlined and the challenges of the research are highlighted. A brief description of the research methodology and the structure of the thesis is presented.

1.1 Background

The growth in the world of petroleum processing operations has resulted in the increase in the construction of new refineries with sophisticated conversion facilities. Most of the new of generation petroleum refineries possess high nelson complexity indices, which indicates their extensive conversion capabilities in terms of refining and improving the quality of petroleum product for global consumption. Some of the most popular refining processes which include hydro cracking, catalytic cracking and coking are the highly demanding processes in the petroleum refineries for maximizing the production of petroleum products. Because of the high demand for petroleum product yield from the aforementioned processes, there is complexity in technology used in handling the processes. This complexity in technology also increases the complexity of petroleum refinery operations. Thompson (2013), indicates that it is possible that a refinery can suffer from a major accident based on one in ten chances during their operational life because of technology and process complexity. Based on such observation, petroleum refineries are undeniably high risk assets because of the complexity associated with their operations. Therefore, it is almost impossible to operate petroleum refineries in a zero risk condition on a daily basis. Numerous petroleum refinery accidents have been reviewed, reported and published by various accident investigation bodies such as United State Chemical Safety Board (CSB), UK HSE and Marsh, a global insurance broking and risk management company. Based on these credible sources, the history of past accidents can be studied in order to observe what event has triggered the accidents and their consequences in order to learn from such accidents.

In recent times, major accidents in petroleum refineries have been added into the historical database of accidents of investigation bodies such as CSB, HSE and Marsh are highlighted as follows:

2016 - Jamnagar India 2 fatalities

2014 - Bolshoy Uluy Krasnoyarsk Russia, 5 fatalities

2012 - Amuay Venezuela, 48 fatalities

2010 - Tesoro Anacortes United State, 7 fatalities

2005 - Texas City United State, 15 fatalities

2000 - Mina Al-Ahmadi Kuwait, 5 fatalities

When a disastrous accident occurs in a petroleum refining domain, the accident investigation report is recorded and safety recommendations are made by concerned regulators and investigators. Soon after the accident, most of the petroleum refinery operators' reflections, based on the safety recommendations, soon faded. This sometimes occurs when corporate management fails to commit tangible resources and expertise to their risk management program (Wood *et al.,* 2013). The observations from various literature sources on the accounts of petroleum refinery accidents indicates that sometimes lapses or failure in effective application of safety indicators by the companies in their risk management process gradually builds up events, which eventually escalated into an accident. According to Pasman, Knegtering and Roger (2013), continuity in alertness toward the functioning of safety management system is tantamount to observing and improving safety performance indicators. Another observation is a serious under-report of accidents, which has resulted in an upsurge in the weakness of safety indicators. In such situation, safety indicators cannot be effectively utilized to assess the possibility of unplanned events and active failures that can interact and escalate to disruption of petroleum refinery operations (*i.e.* spillage, dangerous leaks, fire and explosion). Due to the aforementioned problems, safety/risk research is left with a gap to question the robustness and the resourcefulness of the risk analysis and risk management approaches adopted by most petroleum refining corporations, to prevent or mitigate major accident risks. Furthermore, investigative questions such as: "How effective are the corporations' policies on major accident risks?", "What is the method employed to identify and evaluate major accident risks?", "What type of criteria do corporations use in determining the risk tolerability level in their risk management picture?", "How is the residual risks or uncertainties associated with operations handled and with what approach?", "In what way do corporations prevent conflicts between production and safety?", "What level of resources and competencies do corporations commit to manage the safety of their operations?", requires fundamental responses.

Another serious concern in terms of risk analysis and risk management of petroleum refining operations is the challenges of the complexity and vulnerability of the technology and processes involved. Some of the findings from petroleum refinery accident reports indicate that operators are sometimes not well equipped with the comprehensive knowledge about the consequence of failure of a complex technology and processes. This sometimes leads operators to push safety boundaries beyond the limit. Korvers and Sonnemans (2008), explain that latent conditions and active failures are failures which happen when safety boundaries are pushed beyond control and the reoccurring of failures could happen again escalate into disruption. Hence, addressing the safety of petroleum refinery operations through safety/risk research can only be effectively accomplished, if a proactive safety/risk management approach is developed in a systematic way to provide feedback at all levels of operations.

1.2 Research motivation and problems

There is a high risk of disruption of petroleum refinery operations because of the increase in diversity of petroleum products, which has led to increase in technological complexity and capacity of petroleum refinery assets. In the petroleum refining industries, stakeholders and decision makers concentrate more investment in expanding and improving the availability of petroleum refinery assets to increase production throughput in order to take advantage of the increase in demand of petroleum product in the global market. The stakeholders and decision makers pay more attention to recouping investment and making profit in the global oil market, because of the high level of uncertainty in product prices and the forces of demand and supply in the global economy. This fluctuation in the global oil market availability for refined products, induces pressure on stakeholders in petroleum refining industry to expand their operations with increasingly complex and risky technologies. This has led to the question on how these complex and risky technologies, which have been employed to increase the production of diverse refined product will not jeopardise the safety of a petroleum refinery operations. However, this question remains explicitly unanswered because disastrous accidents still happen, irrespective of the safety goal and safety policy that have been implemented by most of the stakeholders in the petroleum refining sector. The BP refinery accident that occurred in 2005, which resulted in 15 fatalities, 170 injuries and an approximate loss of over US$1.5 billion due to asset damage, environmental damage, compensations and fines by regulators, provides a typical example of safety decadence in the petroleum refining industry. According to various reports concerning the accident, multiple safety system deficiencies were identified at all phases of operation in the refinery. This shows that decision makers in the BP petroleum refinery pay more attention to production and revenue, while less attention is focused on the risk management of their operations. Based on the lesson learnt from the BP accident, various recommendations were provided to improve the safety level in the petroleum refining domain. A decade after the BP accident, other disastrous accidents have occurred, which claimed over 103 lives and losses of over US$3.5 billion (Marsh, 2015). In most of the accidents investigation, poor risk management of petroleum refinery operation from organizational, technical and operational point of view have been identified as problems, which has largely contributed to the disruption of petroleum refinery operations. Moreover, various approaches for safety assessment and risk management of multifaceted systems have been proposed for a wide-range of practical industrial applications, particularly in the petroleum refining industry and the petrochemical industry. Unfortunately, most of the risk management approaches have limitations in terms of their application for modelling a complex risk scenario and to support decision making on major accident risks in petroleum refineries. Various research has been carried out on safety/risk management of process facilities. Most of the novel research focused on maintenance management, reliability, availability and integrity of process equipment in petrochemical plants and refineries. However, this research is focused on the element of risks and uncertainty that are associated with petroleum refinery operations from organizational, technical and operational viewpoint. This research seeks to propose an advanced safety methodology for risk management of petroleum refinery operations. In the process, a generic framework that incorporates proactive safety methodologies will be developed to analyse possible risk scenarios that can lead to major disruption of petroleum refinery operations. The convergence of potential accident risks will be modelled to analyse the risk level that can disrupt petroleum refinery operations. In addition, the framework will facilitate the treatment of uncertainties associated with the decision making process to enhance the safety improvement of petroleum refinery operations.

1.3 Research aim and objectives

The principal aim of this research is to propose a proactive risk management framework that incorporates advanced risk modelling and decision modelling methodologies for improvement of risk management of petroleum refinery operations. The framework will provide a comprehensive approach to identify and analyse the most significant disruption risks of petroleum refinery operations. The framework will also incorporate a robust approach to enhance the decision making process, to establish a reliable risk reduction or mitigation strategy for risk management of petroleum refinery operations. In order to determine the best approach to enhance the proactive risk management of petroleum refinery operations, the following objectives have been set out:

- To conduct a comprehensive literature review of the underlying sources of risk elements and the uncertainties associated with the risk management of petroleum refinery operations.

- A novel framework shall be developed for advanced risk management of petroleum refinery operations.
- To apply robust risk assessment approaches for risk prioritization, to evaluate the risk levels and the prospect of disruption based on the identified risks of petroleum refinery operations, using uncertainty treatment approaches such as Fuzzy Linguistic Preference Relation (FLPR) technique, Evidential Reasoning (ER) technique, Bayesian Network (BN) technique and Fuzzy Set Theory (FST).
- To develop a novel decision support approach for the selection of a proactive risk management strategy, for safety improvement of petroleum refinery operations based on an integrated AHP-Fuzzy VIKOR method.
- To carry out one or more case studies or test case analysis for the justification of the proposed framework.

These objectives are addressed in Chapters 2, 4, 5, 6 and 7 respectively. A detailed literature review of this research is presented in Chapter 2, to provide the basis for the development of other Chapters. In Chapter 4, the FLPR method is applied for risk evaluation and ranking. In Chapter 5 and 6, fuzzy ER approach and fuzzy BN approach are utilized to illustrate the risk level and to evaluate the prospect of disruption of petroleum refinery operations using case study, while Chapter 7 presents the AHP-Fuzzy VIKOR approach for decision support to determine a robust safety strategy to improve the safety of petroleum refinery operations.

1.4 Research challenges

Numerous challenges were faced and overcome in the process of risk identification, risk evaluation and ranking, risk analysis and decision support for risk mitigation/control of the petroleum refinery operation risks. Efficient risk modelling methodologies and decision support techniques for the treatment of systems and knowledge uncertainties are utilized in various phases of the research to deal with the these challenges. The important challenges encountered in conducting the research and how they were tackled are described as follows:

- The first challenge is the formulation of the generic framework upon which the analysis at every stage of this research depend on.
- Risk investigation: it is quite obvious from a critical literature review of risk/safety analysis studies in the process industry, that there have been no broad investigations focusing on risk elements and their attributes as forerunner risks that can lead to disruption of petroleum refinery operations. Identifying the risk elements and their associated attributes for disruption of petroleum refinery operations is a difficult task, as the process is based on a proactive approach. The earlier challenge of the risk identification was subdued through literature review on petroleum refinery operations, analysis of previous accidents in the petroleum refining industry, as well as consultation and a mind mapping session with experts with knowledge and experience of petroleum refinery operations. These experts' opinions contributed to the substantiation of the risk elements and their associated attributes.
- In this research, the selection of the most suitable methods for analysis is a challenge, because most of the methods which are critically reviewed and assessed have a lesser competitive edge over each other. However, the justification for the selection of each of the method is based on their capability to solve complex

system problems under high uncertainties and their suitability in terms of combining with other methods.

- Risks prioritization: after the risk identification process, prioritizing the risk elements involves the challenges of implementing the propositions behind the FLPR method, which was utilized to define the significance of the attributes associated with the risk elements of petroleum refinery operations based on their relative weights.
- In order to estimate the disruption risk level of a petroleum refinery operation, there is a need to overcome the uncertainties of data availability and incompleteness in knowledge in the assessment process. The Evidential Reasoning (ER) and Fuzzy Set Theory (FST) techniques are the uncertainty treatment approaches which were used in the methodology to determine the disruption risk level of petroleum refinery operations. Qualitative data acquired from experts were transformed into quantitative data to evaluate the disruption risk level of petroleum refinery operations. The Intelligent Decision Software (IDS) was utilized in the assessment process.
- Determining the prospect of disruption of a petroleum refinery operation is a major challenge, because it involves defining the relative weight of the variables in the BN model. The transformation approach adopted from Hsu and Chen 1996 is incorporated into the FBN methodology to determine the relative weights or prior probabilities of the variables in the BN model. Another challenge is the development of the Conditional Dependence Table (CPT) between variables in the BN model. In order to avoid a biased CPT, a symmetric model was utilized in

a systematic fashion to establish the CPT of each dependent variable in the BN model.

- Development of a fuzzy membership function for risk measurement parameters for risk modelling of petroleum refinery is a challenge, which was addressed based on experts' opinion.

1.5 Scope of the thesis

In this research both qualitative and quantitative investigation methods are employed. The framework for this research is a generic risk management framework which constitutes three important phases. The first phase is risk elements identification, the second phase is a risk assessment process and the third phase is the risk mitigation and control. Based on the three phases of the framework, the research questions are met with logical conclusions. The challenges in the delivery of each phase of the framework involve the design of the methodologies for modelling, data acquisition and analysis. In view of these challenges, expert appraisal and various uncertainty treatment techniques are employed to deal with uncertainties connected to data shortage and any inexactness in knowledge about the risks associated with a petroleum refinery operation. The methodologies employed in the framework for optimal risk management of petroleum refinery operations are FLPR, Fuzzy ER, Fuzzy BN and AHP-Fuzzy VIKOR methodologies. However, the data collection process for this research was conducted via questionnaire appraisal from selected experts that specialize in petroleum refining operations from major petroleum refining countries. The experts that are considered were specialist refinery engineers, refinery health & safety managers, senior refinery managers, an academic, with a wealth of experience in petroleum refining industry, and consultants. The data acquisition process is via e-mail questionnaire and e-mail of a website link where responders can easily complete the survey within the shortest time. Before the experts are invited for the survey, the questionnaire was pilot tested and the response from the pilot study is utilized to reword the questionnaire. This will allow experts to provide a meaningful and timely response. The scope of this research involves developing of novel methodologies to reveal the risk level and the prospect of disruption of a petroleum refinery operation, and to propose an optimal strategy to enhance safety improvement of petroleum refinery operations. This study is required to help decision makers to cope with uncertainties associated with making risk informed decisions for optimum operations in a petroleum refinery domain.

1. 6 Research achievement

The key achievement of this research is the development of an advanced risk management framework to enhance decision making of stakeholders in the petroleum refining industry to identify, assess and mitigate risk elements and their attributes, which can interact to trigger the disruption of petroleum refinery operations. The risk management framework is a decision support platform to minimize the high level of uncertainty associated with complex decision making for the risk management of petroleum refinery operations. The proposed risk management framework provides a platform for improvement of risk based investigation for petroleum refinery operations.

1.7 Structure of the PhD Thesis

The thesis comprises of eight chapters. Chapter 1 consists of a brief introduction relating to the background and motivation of the research, research aim and objectives, relevant research questions, the scope of the research. Chapter 2 involves the critical review of petroleum refinery accidents and the lessons learnt, overview of guidelines and regulations for safety in petroleum refining industry, examining the current trend of petroleum refinery operations, current issues relating uncertainty and decision making in terms of risk management of petroleum refinery operations, risk assessment approaches and applications in the petroleum refining industry and overview of advance risk management methods for the petroleum refinery operations. In Chapter 3, the research methodology and the conceptual research framework are discussed. Chapter 4 presents the methodology for the risk identification and risk ranking of salient risk elements and attributes that can cause disruption of petroleum refinery operations. Fuzzy Linguistic Preference Relations (FLPR) methodology is applied to the risk identification and risk ranking process. In Chapter 5, a comprehensive analysis to determine the disruption risk level of a complex petroleum refinery operations is carried out. In this Chapter a Fuzzy Evidential Reasoning (FER) methodology is applied as the risk modelling approach to estimate the disruption risk level of petroleum refinery operations. In Chapter 6, the prospect of disruption of a petroleum refinery operation under a dynamic conditions is analysed based on the application of a fuzzy BN modelling methodology. In Chapter 7, the necessary risk management strategies to reduce or mitigate risk element attributes that can cause the disruption of petroleum refinery operations are analysed. An integrated approach based on AHP- fuzzy VIKOR multicriteria decision analysis methodology was utilized to determine the most appropriate risk management strategy among the proposed risk management alternatives. Chapter 8 discusses the main conclusion of the research. This chapter discusses the results obtained in each of the technical chapters of this research and the strength and the limitation of the risk modelling and decision methodologies applied in each technical Chapter. The research results, research novelty, research contribution to knowledge and recommendation for further studies is presented in Chapter 8.

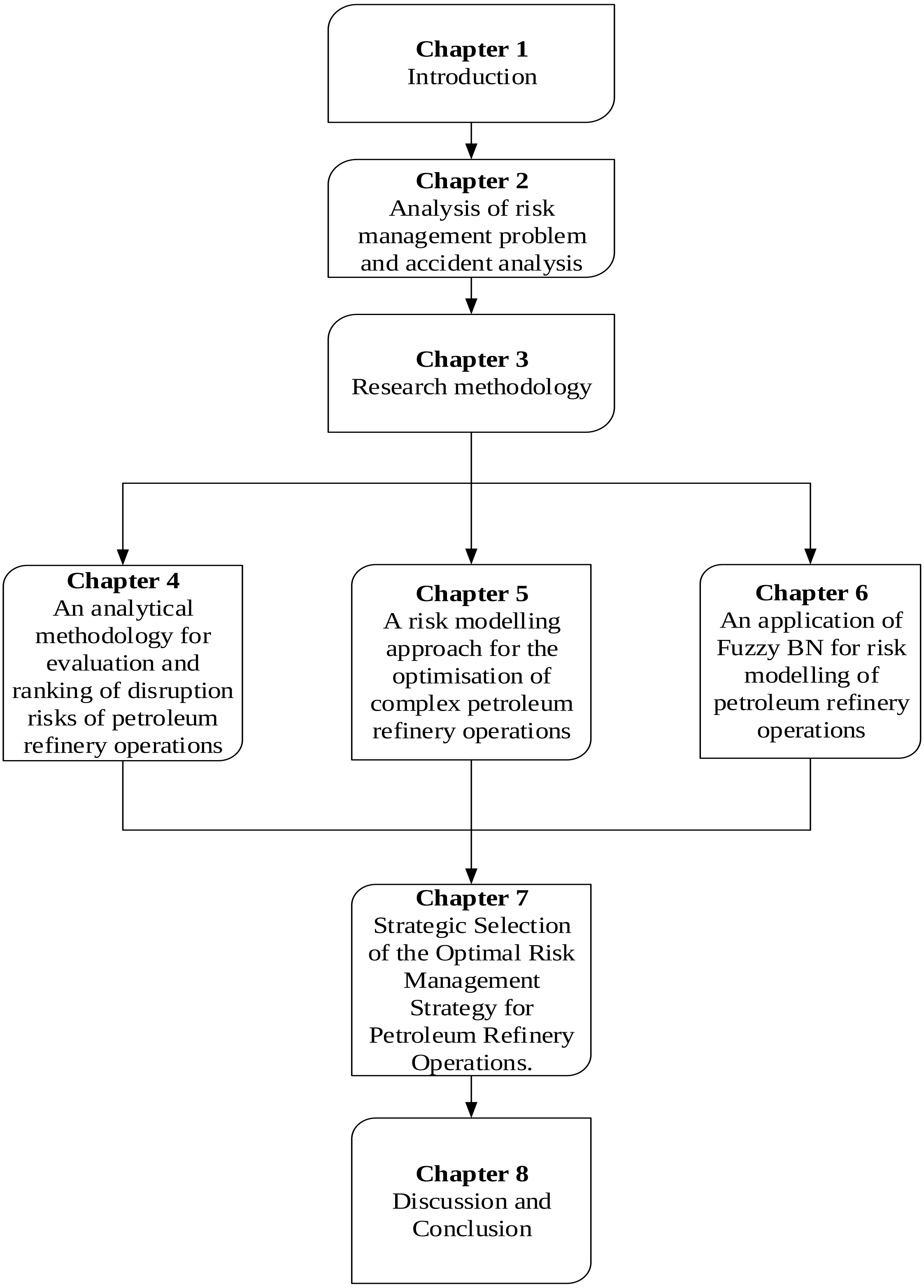

Figure 1.1: Structure of the thesis

Chapter 2 - Literature Review

Summary

This chapter presents the current issues relating to overview of petroleum refinery processes, operation and configuration, guidelines and regulations for safety in the petroleum refining industry, the current trend of risk management of petroleum refinery operations, and the reviews of recent major petroleum refinery accidents. In addition, various safety/risk modelling techniques and their applications were discussed, decision modelling techniques for uncertainty treatments, which are utilized in this research, are also described.

2.1 Introduction

Petroleum refinery operations have widely increased over the last two decades based on the fact that global demand for energy will on average, increase by 2% per year until 2020 (BP, 2014). Over 790 refineries in 116 countries are in operation producing petroleum, gas and petrochemical products to meet the ever increasing need of energy around the world in the industrial production sector, power generation sector, transportation sector, commercial sectors and marine sector.

Petroleum refineries produce over 80 million barrels of product per day to run daily global demand for energy consumption (MARSH & McLENNAN, 2014: John Rudill, 2005). This shows that petroleum refineries are important facilities in the world in general to accelerate economic growth in various sectors of industrial operations. Petroleum refineries are complex integrated systems which are capital intensive and a constant flow production infrastructure. Due to the complexity of this infrastructure, it is essential to consider precise, engineered operation procedures to assure the safety of petroleum refinery operations and to protect people working within this infrastructure. However, the pressure of daily demand and commitment to target in operations of most refineries around the globe has led to a strong push of safety boundaries, which has led to numbers of occurrences of major accidents. Therefore, the regular occurrence of mishaps in the petroleum refineries has increased the risk of disruption to petroleum refinery operations. Despite the lessons learnt from historical cases of accident in petroleum refineries, risk management lapses still persist, because after a few years, the lessons learnt from previous accidents are forgotten.

One of the challenges in the risk management of petroleum refinery operations is that petroleum refinery operators predominantly focus their attention on safety performance indicators for the conception of the current safety level of operations in order to enhance organizational means of controlling risk.

According to Reiman and Pietikainen (2012), the safety level in an organization is determined based on the view of top management in terms of their interpretation of safety indicators in line with the goal that the organisation sets. This kind of approach is not sufficient enough to address latent conditions that can contribute to the underlying safety deficiencies in the risk management of petroleum refinery operations. Evidence based on review of major accidents of petroleum refinery operations has provided a clear insight on latency issues, which are risk elements that can build up to cause serious disruption of petroleum refinery operations, as a result of their interrelations and coincidences.

Risk elements are risks inherent in operations which can be based on uncertain knowledge, oversight and lack of perception in risk management practice. Risk elements can be organizational, technical, operational or external latent conditions. In order to circumvent events that can cause disruption in a petroleum refinery, the dynamics of the risks associated with petroleum refinery operations need to be investigated. Such investigation can facilitate the provision of mitigation measures for unanticipated risks that can threaten proper operations of a petroleum refinery process unit.

Based on the rate of major accidents in the petroleum refining industry and the devastating consequences of the accidents (*i.e.* fatalities, severe injuries and asset damages), it is evident that risks associated with petroleum refinery operations need to be systematically addressed in order to efficiently reduce their threats. This indicates that there is a need for the improvement of risk management process by taking into account, the treatment of risks of petroleum refinery operations in a broader perspective, considering objective knowledge, subjective judgements, treatment of data uncertainties and way of dealing with decision intangibles under fuzzy situations.

Developing a novel risk management from such a broader perspective will enhance optimum safety improvement of petroleum refinery operations. Consequently, a dynamic risk/hazard identification, risk assessment and a decision framework for risk mitigation and control techniques are adopted in this thesis to synthesize a proactive risk management approach with a comprehensive assessment of the risk level and decision management of petroleum refinery operations.

2.2 Overview of Petroleum Refinery Processes, Operation and Configuration

Petroleum refinery processes and operations are multifaceted, advanced and highly incorporated for processing and transforming crude oil into various products. The end product from petroleum refineries provides fuel for transportation; power generation and heating, and provision of resources for the chemical process industry.

Petroleum and gas refinery processes and operations are an important link in the petroleum industry supply chain with the primary objective of refining crude oil to take full advantage of its economic value after converting crude oil into finished products.

Primarily, the refinery process for separation of crude oil incorporates both physical and chemical reactive processes to yield various valuable finished products which include; fuel oil, Liquefied Petroleum Gas (LPG), diesel fuel, kerosene, gasoline, jet fuel, lubricants, bunker oil, asphalt, and petrochemical feedstock.

2.2.1 Petroleum refining operations

Petroleum refining processes and operations can be divided into five steps (OSHA, 1999):

Fractionation is the process of separating crude oil into sets of hydrocarbon compounds of different boiling point ranges called "fractions" in an atmospheric and vacuum distillation unit.

Conversion Processes is a process of decomposition of heavy hydrocarbon molecules of crude oil into light products by thermal and catalytic cracking which includes: an alkylation and polymerization process, isomerization process and catalytic reforming process.

Treatment Processes is a process of transforming and upgrading hydrocarbon stream into finished products through chemical process to remove contaminant hetero-atoms compounds such as sulphur, nitrogen, metal and other undesired compounds from crude oil fractions. The treatment process in refinery process streams comprises of chemical or physical separation processes including desalting, drying, hydro-desulfurizing, solvent refining, sweetening, solvent extraction, and solvent dewaxing. In addition, treatment processes also protect catalysts in many refining processes from deactivation as a result of prolonged contact with hetero-atoms.

Blending is a process which involves a physical combination of various liquid hydrocarbons to produce a finished product with precise performance properties. Additives such as octane enhancers, anti-oxidants, anti-knock agents, rust inhibitors and detergent are added during or after blending to provide specific properties which are lacking in hydrocarbons.

Utility Operations: these include: light-ends recovery, sour-water stripping, solid waste, process-water and wastewater treatment, cooling, storage and handling and product movement, hydrogen production, acid and tail-gas treatment and sulphur recovery.

2.2.2 Petroleum refinery processing units

Petroleum refineries processing units are large, continuous-flow production facilities that transform crude oils into refined products. Hence, to comprehend the details of petroleum refining processes it is important to consider a refinery physical configuration and operating features. A refinery configuration defines the set of process units, the capacity of the various units, their significant technical features, and the flow configurations that link these units (John Rudill, 2005). Refinery process units are integrated as necessary to meet product targets based on their capacity and configuration.

The entire refinery consists of a number of processing units which include (OSHA, 1999; John Rudill, 2005):

Crude Oil Distillation Unit (CDU): To separate crude oil into valuable distillates such as naphtha, kerosene, diesel, and other heavy components for further processes.

Vacuum Distillation unit (VDU): For distillation to recuperate valuable gas oils from crude oil residue from CDU via vacuum distillation.

Hydrotreater unit: Desulphurize sulphur contaminant from unsaturated aromatics and olefins hydrocarbons of crude oil to yield a clean product for advance processing or finished product.

Catalytic Reforming unit: This unit produces high-octane reformate from desulfurized hydrocarbon molecules for gasoline blending and also produce other petrochemical raw materials.

Alkylation unit: This unit produces alkylate, a high-octane constituent of the end-product gasoline or petrol from butylene and isobutene.

Isomerization unit: Transforms normal hydrocarbon molecules of low octane number into higher-octane branched molecules for blending to finished product such as gasoline or petrol. Normal butane is converted to branched isobutane in isomerization unit.

Fluid Catalytic Cracking (FCC) unit: FCC converts low gas oil from crude oil distillation to upgraded valuable light product such as naphtha, diesel and slurry oil.

Hydrocracker unit: Provides catalytic cracking and hydrogenation of heavy aromatic hydrocarbon fractions from the crude oil distillation unit and the vacuum distillation units to produce light hydrocarbon products.

Visbreaker unit: Convert heavy residual oils from the vacuum distillation unit into light product with lower viscosity by thermal cracking process.

Delayed coking and Fluid Coker units: This unit converts low value residual oils into lighter product such as cooker gas oil, diesel and naphtha by severe thermal cracking.

2.2.3 Classifying a petroleum refinery by configuration and complexity

Petroleum and gas refineries yield various refined products ranging from the very light product like LPG, to heavy product, such as residual fuel oil. Production at refineries is not only based on market demand for various refined crude oil products, it further depends on factors such as the constituent value of crude oil and capabilities of crude oil processing facilities. These factors can limit capacity of production in a refinery. The classification of petroleum refineries based on their category, processes, product yield and complexity is presented in Table 2.1. The operation of a petroleum refinery can change based on the response to recurrent variations in crude oil and product markets, measured by the performance characteristics of the petroleum refinery, and the properties of the crude oils they process. Refineries can be categorized based on their complexity into four classes using the following criteria (Meyer, 2004):

- Refinery configuration and operating characteristics.
- Product quality specifications (e.g. low sulphur content).
- Market requirements for refined products.
- Capital investment intensity.
- Capability to convert heavy crude fraction into lighter high yield products.
- Environmental, Safety, Economy and other refinery design constraints.

Table 2.1: Classification of petroleum refineries

Refinery Category	Processes	Product Yield (Gasoline & Diesel/Jet) Vol.%	Complexity	Comment
Topping	Crude distillation	58	Low	• No capability to alter the natural yield pattern of crude oil. • No facilities to control sulphur levels in crude fraction. • Crude constituents determine Product yields and quality. • Produce low octane gasoline in some cases
Hydro skimming	Crude distillation Reforming Hydrotreating	61	Moderate	• No capability to alter natural yield pattern of crude oil • Control sulphur level in products by hydro-treating. • Improvement of product yield and quality. • Reforming of gasoline.
Conversion	Crude distillation FCC and Hydrocracking Reforming Alkylation and other upgrading Hydro-treating	76	High	• Produce ultra-low sulphur product • Considerable capability to increase yield and quality upgrading.

Table 2.1- Continues

Deep conversion	Crude distillation Coking FCC and Hydrocracking Reforming Alkylation and other upgrading Hydrotreating	89	Very High	• Capability to produce ultra-low sulphur fuel Products. • Capability to produce high-value refined products • Suitable to Fracture least value residual oil into a lighter stream for gasoline blending.

2.2.4 Petroleum Refinery products

Refined products produced in petroleum and gas refining may be classified into four categories: Light distillates, middle distillates, heavy distillates and others (OSHA, 1999). See Table 2.2 for details.

Table 2.2: Refined product (OSHA, 1999)

Class	**Refined product**
Light distillates	Liquid petroleum gas (LPG) ,Gasoline (or petrol) Kerosene and Jet fuel.
Middle distillates	Automotive and rail diesel fuels and other residential heating fuel and light fuel oils.
Heavy distillates	Heavy fuel oils bunker fuel oil and residual fuel oils.
Others	Petroleum naphtha Petrochemical feed-stocks, asphalt, tar petroleum coke, lubricating oils, waxes and greases, Transformer and cable oils, sulphur, special solvent and Carbon black.

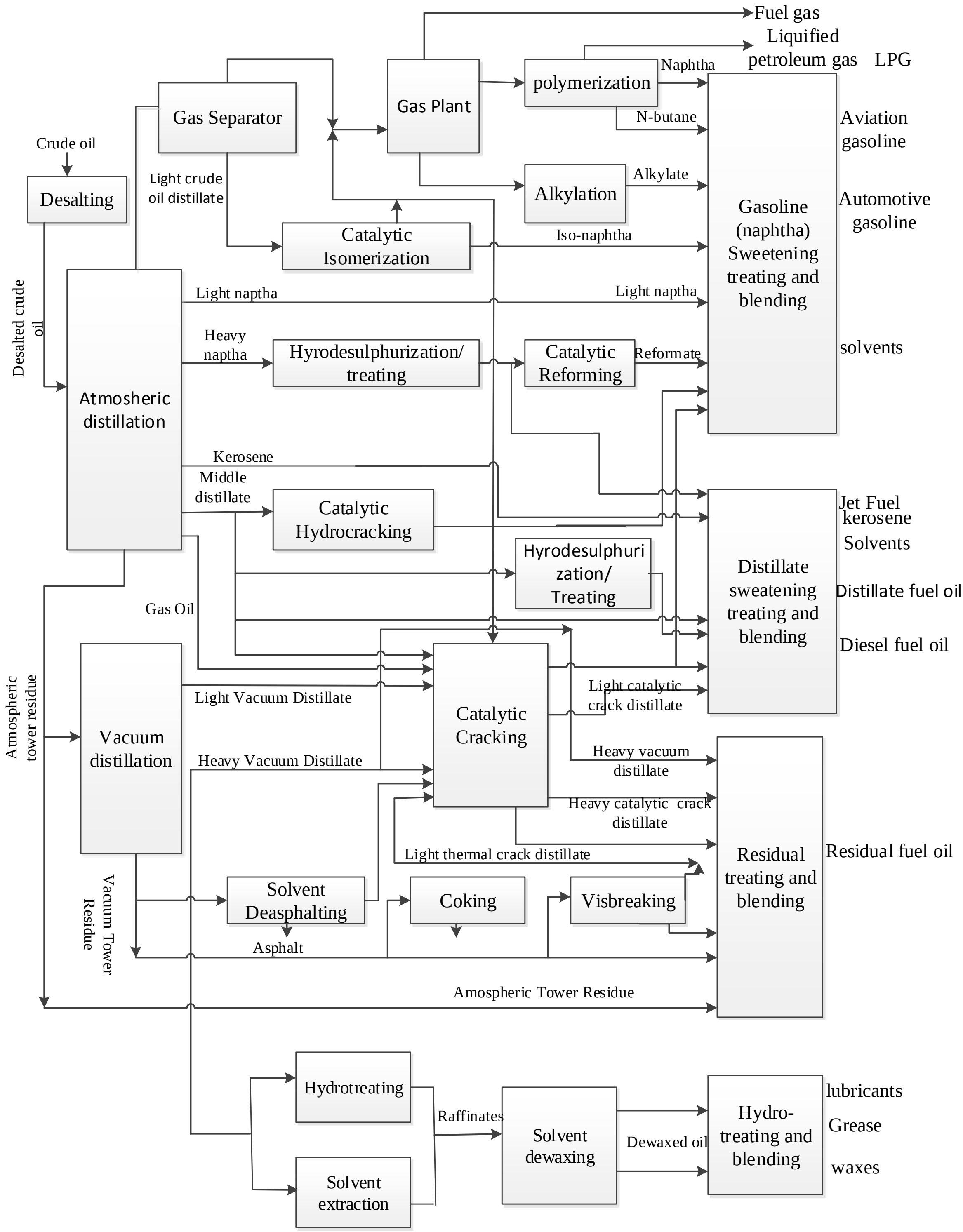

Figure 2. 1: Schematic diagram of a complex petroleum refinery (Source: OSHA refinery process chart, 1999)

2.3 Overview of guidelines and regulations for safety in petroleum refining industry

In the petroleum refining industry, considerable effort has been made over the past decades to provide a proactive safety management system, in order to prevent accidents from happening and/or to mitigate accident escalation. Intermittently, lessons have been learnt from major accidents in the petroleum refining industry, recommendations have been provided based on knowledge and lessons learnt from investigation of the past catastrophic accidents by organizations such as the US Chemical Safety and Hazard Investigation Board (US CSB), the UK Health and Safety Executive (UK HSE), the U.S Occupational Safety and Health Administration, EU commission, America Petroleum Institute (API), Centre for Chemical Process Safety (CCPS) and other independent investigation panels that express more opinion on the need to strengthen risk controls in order to prevent the release of hazards that can lead to major accidents. However, significant effort has been made by the aforementioned organizations to develop and publish a comprehensive guidance and regulations for refiners in the petroleum industry, in order to manage process units risk and prevent unintentional loss of hazardous materials (OGP, 2011). Various regulations and guidelines in relation to environmental health and safety, to prevent foreseeable future accidents in the petroleum refining industry, are presented as follows:

- In the UK, the HSE is the organisation that is responsible for the enforcement of major accident prevention regulations called Control of Major Accident Hazards (COMAH). The COMAH Regulations aims to prevent major accidents involving dangerous substances and reduce the consequences of any accident to people and the environment.

- The EU commission developed regulations that deal with the prevention of major accidents, which is called the Seveso III directive (Directive 2012/18/EU). The main aim of the Seveso III directive is to prevent major accidents involving dangerous substances and reducing the consequences of such accidents to human health and the environment.
- In 2010, API published a recommended practice for process safety performance indicators for the refining and petrochemical industries API RP 745. This recommended practice standard aims to identify process safety performance indicators suitable for dynamic performance and improvement in process plants. Process safety performance indicators are the key elements to maintain an effective and robust risk control system in order to eliminate major incidents. According to OGP report (2011), process safety performance indicators therefore generate a range of relevant data which can be analysed to improve preventive actions such as management systems revisions, procedural changes, training opportunities or facility engineering improvement that aims to minimise or eliminate the potential for major incidents. API RP 750 prescribe recommendation for conducting management of change review for changes in technology. The recommendation indicates that refiners review hazards that may be introduced as a result of projects or changes in operating conditions that increase throughput or accommodate different feedstocks.

API RP 571 is prescribed for damage mechanism affecting fixed equipment in refinery; API RP 574 prescribes inspection practices for piping system component and API RP 752 prescribes the management of hazards associated with the locations of process plant building. In addition, API RP 780 prescribes a universal approach for assessment of security vulnerabilities at petroleum and petrochemical facilities.

- United States Occupational Safety and Health Administration (OSHA) also prescribe Process Safety Management (PSM) regulations for petroleum and petrochemical refining industry.

Regardless of the regulations and guidelines, some of the stakeholders in petroleum refining industry have failed to follow the guidelines and regulations in their risk assessment and their decision management process. The evidence of inadequacy and non-compliance or wilful violations have been identified in various accident reports and the OSHA fact sheet which is made available to the public domain (see Section 2.7.1 for more details). This shows that enforcement of guidelines and regulations is important in practice to effectively combat major hazard or reduce its impact on loss of human life, property and environment damage.

2.4 Examining current trend of petroleum refinery operations: Risk management perspective

In the petroleum refining industry, recent disastrous accidents have been challenging the practicality and resourcefulness of risk management measures, which are designed to improve safety of operation and/or to reduce likelihood of operational failures. Due to the complexity and sizes of most refineries, it is nearly impossible for operators to eliminate all the risks associated with the operations of such facilities. In such circumstances, it is obvious that every refinery is required to have a reliable and consistent risk management process that can be implemented to deal with events and other latent condition that can create a potential pathway to accidents. Various reports on major accidents in the petroleum refining industry emphasized the failure in risk management, leading to systematic causes of accidents (CSB, 2015; CSB 2012; CSB, 2007; CSB, 2001; HSE, 2001). Based on the summary from various cases of accidents, the following risk management failures are identified:

- Inadequate attention or awareness of management to significance of a hazard that can trigger an accident.
- Failure in hazard/risk identification and risk assessment of major hazard resulting in poor assessment of hazards and associated risks.
- Failure to conduct adequate risk analysis prior to management of change process (*i.e.* Failure of operator to conduct risk assessment prior to any change event or lack of recognition for need to carry out risk assessment before any change).
- Failure to conduct adequate risk analysis for planning inspections (*i.e.* lack of appropriate risk assessment to identify latent degradation threat to process equipment and control systems in refinery process units).
- Other issues relating to uncertainty of risk management information in terms of its application in risk assessment and decision making process.
- Lack of interest or negligence in acquisition of new knowledge and technology to tackle emerging risks from high degree of complexity of refinery process operations.
- Application of risk analysis method with limited ability to provide valuable safety information to support complex decision making.
- Lack of dynamic update on vital changes in safety parameters or technical conditions which are utilised on a continuous basis for risk management of operations.

- Tacit knowledge and experience gain by operators from operating a refinery process unit is not explicitly utilized in risk management process, rather, such knowledge and experience is overshadowed by company procedures and governing documentation for handling major accident risks (Andersen and Mostue, 2012).

2.5 Risk management of petroleum refinery operations: Uncertainty perspective

According to Markowski *et al.,* (2010), as the complexity of a system increases, the capability to provide precise and yet vital information about the system's behaviour diminishes until a range is reached beyond which precision and significance have mutually exclusive characteristics. Hence, the complexity of a system is proportional to its level of uncertainty (Deng *et al.,* 2011).The growing complexity of modern plants has brought about an increase in the intensity of safety regulations for critical examination of the safety procedures (Zio and Aven, 2013). In the petroleum refining industry, operating multifaceted assets has resulted in more complexity and an increase in the level of uncertainty in risk modelling of refinery operations. Uncertainties associated with risk modelling can also result in uncertainties in the decision making process. Decision making involves high risk and uncertainties in terms of risk management of petroleum refinery operations because of the difficulty in predicting the consequence of such decisions. In practice, it is important to consider uncertainty treatment as an important component of a risk management process, especially in the risk analysis to determine the nature and level of risk and consequences of a decision.

Most risk assessment procedures for decision support are affected by diverse uncertainties, such as incompleteness of the list of elements of risk, uncertainty with underlying root causes of events for the estimation of occurrence probability, and the assessment of the consequences of events. In terms of the treatment of uncertainties in the risk assessments of extreme events under investigation, the standpoint is what kind of risk analysis approach will be suitable for the purpose of risk assessments while considering the aspect of uncertainties. Furthermore, the decision making which follows the risk assessment is concerned with comprehensive information about the tolerability of risk level, in order to establish active measures for protections. In risk assessment, uncertainties associated with the input parameters of a risk analysis model should be clearly treated.

The manner in which risk assessment are utilised in a risk management process depends on what type of model is provided as a representation of reality, based on a number of hypotheses and parameters. Because of inherent unevenness and the incompleteness of knowledge on risk assessment parameters a gap exists for uncertainty which can impede the description of a model behaviour in terms of predicting the risk level in a system or any failure event. Such uncertainty exists where a team of experts does not have enough information to describe explicitly the parameters of interest, have their attention focused only on those parameters and salient pieces of data/available information that are considered very vital, neglecting the others. Risk analysts may provide different interpretations of the same piece of information and data, depending on their risk perception, risk tolerance, experience and competence in the field of analysis. Fortunately, uncertainty stemming from lack of knowledge about unknown quantities (including events) can be expressed as subjective probability based on the knowledge of an assessor about a system problem. However, risk modelling of complex system operation requires approaches that integrate human knowledge and experience and decision makers' judgements, in a situation where historical data are sparingly available or available information is ambiguous and imprecise (Deng *et al.*, 2011). Such approaches that can handle uncertainty associated with the use of vague and approximate data are important in the risk assessment process.

In recent times, various risk assessment approaches have been adopted to handle process system risk modelling for prevention of hazardous events or accidents. Methods of risk assessment such as Hazard and Operability Assessment (HAZOP), Fault Tree Analysis (FTA), Failure Mode Effect and Criticality Analysis (FMECA), Layer of Protection Analysis (LOPA) among others, are proving techniques which have been used to systematically analyse refinery infrastructure to identify probable unsafe conditions and to prevent such conditions leading to a serious accident. Even though these safety techniques have been widely applied to tackle potential hazardous conditions for so many years, each of the techniques is not sufficient as a standalone approach to execute a proactive risk analysis for a complex system operations. Consequently, the uncertainties in the risk assessment such as information shortages, imprecision in system problem definition, oversights in hazard analysis and errors in modelling, which may lead to important overlooks in risk assessment of refinery process unit operations still exist. Such uncertainties in risk assessment can be collectively handled based on techniques such as probabilistic and Evidential Reasoning, Bayesian reasoning, fuzzy logic and other evolutionary algorithms.

2.6 Risk management of petroleum refinery operations: Decision perspective

High risks and uncertainties are associated with decision making on complex system operations and the case of petroleum refinery operations is not an exception. Based on recent accident reports, poor decision making has been mentioned as a contributory cause of the accidents. During the operation of a petroleum refinery process unit, operators sometimes make decisions more or less incessantly without considering the effect of the decisions on the risks that can result in disastrous accident. For instance, the knowledge of recent accidents such as BP refinery accident in 2005, and Chevron Richmond refinery in 2012, implies that decisions can have considerable effect on the risk management of petroleum refinery operations. Numerous reasons can accumulate to poor a decision that might result in a major accident. The decision made at a point in time based on the knowledge or availability of information may seem to a decision maker as the best choice at the time. Sometimes the assumption behind poor decision making can be due to lack of sufficient information about risk. Even when correct risk information is provided to support decision making, a team of decision makers or operators can misinterpret or overlook information in their decisions (*e.g.* Chevron refinery accident, see Section 2.7.1.1 for more details).

Lessons from the devastating incident indicates that risk communication is vital to the outcome of decision process in a complex system environment. Other issues relating to poor decision making in the petroleum refining industry include poor implementation of safety management systems, prioritising the decision between safety, production and revenue, inconsistent incident investigation and reporting, carefree attitude of operators to safety and ignorance or low perception about the implication of risk. Based on all the aforementioned issues, it is lack of the acquisition of quality risk information for robust decision making has resulted in a fuzzy situation whereby the validity of a decision alternative is not exhaustively established. In a risk management process for a complex system like a petroleum refinery, the key to sustainable decision lies in the understanding of the risk level associated with the petroleum refinery operations, in order for a decision maker or team of experts to prioritise risk reduction measures.

2.7 Overview of major petroleum refinery accidents and the lesson learnt

Due to the complexity of petroleum refinery operations, unanticipated accidents can occur based on interactions among the refineries subsystem failures as a result of inherent design error, operational procedure or process and other safety-related problems. However, past accidents that claimed numerous fatalities, severe injuries and asset damage happens due to hazardous events which are out of control. These hazardous events take place because of the accumulation of failures relating to technical risks, organizational risks, operational risks, poor knowledge of making risk informed decisions and other external events.

Real-world understanding of the causes of accidents in the petroleum refining industry are obtained based on the information from a variety of sources. Information is obtained from institutions such as the UK HSE, Chemical Safety and Hazard Investigation Board (CSB) in America, Japan science and technology agency and other journals that review petroleum, chemical and petrochemical industry accidents. The accident reports and journals provide comprehensive knowledge on various accidents, their root causes, lesson learnt and the proposed recommendations which can prevent the recurrence of such accidents. Also, available information from the aforementioned sources provide effective understanding of the common features of past accidents and the sequence of the events that result in the accidents. The lesson learnt from the petroleum refinery accidents provides a clear view of observable recurrent issues that have contributed to petroleum refinery accidents.

2.7.1 Review of recent major petroleum refineries accidents

Major accidents that have happened in recent times are analysed in the following sections.

2.7.1.1 Chevron Richmond Refinery Accident 6th August, 2012

A catastrophic pipe failure occurred in crude unit 4 of Chevron Richmond refinery in California, U.S.A. A 52-inch long carbon steel piping component of the crude unit 4 line ruptured and released flammable hydrocarbon, which partly turned into a large vapour cloud that engulfed 19 Chevron employees and ignited. Most of the employees narrowly escaped serious injury. Continuous burning of the ignited flammable from the process hydrocarbon resulted in the release of toxic particulates and vapours, which traveled across Richmond, California. Nearly 15,000 people living and working in the surrounding area were affected due to the release. The initiating events and circumstances surrounding the accident include (CSB, 2015):

- Sulfidation corrosion led to pipe rupture in the crude unit of the refinery. The corrosion was caused by sulphur compound which is present in the crude oil. This compound attacks the steel pipes under high temperature of about 450 to 800 degrees (°F) causing extreme thinning of pipe wall near the ruptured location.
- Inadequate inspection to monitor and control sulfidation corrosion.
- Chevron's technical team failed to conduct a concrete review of corrosion and damage mechanisms present in the crude unit.
- Chevron's technical team failed to implement effective inherent safety that identify sulfidation corrosion as a major hazard.

- Prior to the incident, Chevron management failed to implement internal recommendations from technical staff to inspection and upgrade high temperature carbon steel piping vulnerable to sulfidation corrosion to 9-Chrome.
- The Chevron's Richmond refinery crude unit process hazard analysis failed to identify sulfidation corrosion as a latent cause of a leak or rupture in piping.
- Chevron's Management of Change (MOC) process fail to cover important scope from employee recommendations, as a result, 52-inch component failed to remain in service.
- Ineffective safety management system.

2.7.1.2 Tesoro Anacortes Refinery Accident, 2nd April 2010

The Tesoro Anacortes petroleum refinery accident happened during start-up activities to restore operation of the A/B/C bank of a heat exchangers back into service, following cleaning to remove build-up contaminant that cause fouling, which affects normal process condition of the heat exchangers. The accident was a result of disastrous ruptures of the heat exchanger in the catalytic reformer / naphtha hydro-treated unit of the refinery. The heat exchanger ruptured due to High Temperature Hydrogen Attack (HTHA) ejecting highly flammable hydrogen and naphtha at temperature of 500 degrees Fahrenheit (ºF) which ignited, causing an explosion and fierce fire that burned for between three to four hours. The fire fatally burned seven of the Tesoro employees who were working very close to the heat exchanger during the start-up activity. The injured seven Tesoro employees include a shift supervisor and six operators. Tesoro Anacortes Refinery NHT unit contained two banks, of three heat exchangers (A/B/C and D/E/F) for preheat process fluid entering a reactor, where contaminants were treated for consequent removal.

According to the chemical safety and hazard investigation board report, it was the heat exchanger E in the midst of the operating bank of heat exchangers D/E/F that ruptured. Initiating events and circumstances surrounding the accident include (CSB, 2012):

- Increased mechanical stress from the start-up of the A/B/C heat exchangers led to a temporary increase in temperature which caused the material strength of the critically weakened heat exchanger to be exceeded, thereby rupturing the heat exchanger E at its most vulnerable point.
- Problem of extensive history of recurrent leaks and intermittent fires when restoring the heat exchangers back to normal operation was not addressed.
- Inherent extensive practices of hazardous non-routine operation before start-up contributed to the accident.
- Cumbersome start-up procedure that failed to specify definite roles for each of the operators and supervisors led to inappropriate operation of the naphtha hydro-treated unit heat exchangers during start up.
- Failure to maintain process control, affected the level of temperature of operation in the heat exchanger E.
- The E heat exchanger was in a state of severe mechanical degradation due to extensive cracking damage from the high temperature hydrogen attack (HTHA) from the process fluid flowing through the heat exchanger.
- Lack of process safety culture led to a failure to control HTHA hazards, which resulted in the fire disaster that claimed seven lives.
- Failure to control heat exchanger start-up hazards.
- There is lack of administrative controls to reduce the number of employees exposed to the start-up hazards at the naphtha hydro-treated unit.

- Lack of sufficient process instrumentation to monitor and measure the process conditions of the E heat exchangers.
- Failure in process hazard analyses to identify hazards during start-up contributed to ineffective control of HTHA hazards.
- Process Hazard Analyses (PHA) failed to prevent or reduce the consequences.
- Based on chemical safety and hazard investigation board report, the management of change at the Tesoro Anacortes refinery failed to review operation procedures and work practice.

2.7.1.3 Valero Mckee Refinery Accident 16th of February 2007

The McKee refinery accident happened on the 16th of February 2007 near the town of Sunray in Texas. Based on the chemical safety and hazard investigation board report, liquid propane was released from a control station very close to the extraction tower in the Propane De-Asphalting (PDA) unit of the refinery. The propane formed a vapour cloud which found a source of ignition as it travelled towards the boiler house and caused a fire which seriously injured four of the refinery workers. The fire caused damage to the unit piping and equipment and major pipe rack. The fire also spread to the other units in the refinery including the storage area for LPG. The refinery was shut down for almost two months and the operation capacity of the refinery was reduced for nearly one year. The initiating events and circumstances surrounding the accident include (CSB, 2008):

- The accident was due to harsh weather causing freeze-related fracture of high-pressure piping at an elbow in a propane mix control station, where water settling from the propane stream was leaked from a 10” NPS20 (250 DN) inlet block valve and accumulated in the low point, formed by the control station which was out of service for nearly 15 years.

- The McKee Refinery had no prescribed measures in place to identify, review, and freeze-protect dead-legs or intermittently used piping and equipment, such as the propane mix control station.
- The McKee Refinery failed to utilise the emergency isolation valve procedure when assessing risks in the PDA unit to ensure that large quantities of flammable materials in the unit could be swiftly isolated in an emergency.
- PDA unit process hazard analysis (PHA) failed to identify hazards that contributed to the refinery incident.
- The Mckee refinery failed to conduct a Management of Change (MOC) review when the control station was removed from active service. Consequently, the freeze-related hazards of the dead-leg formed by the control station were not identified or corrected.

2.7.1.4 BP Texas City Refinery Accident 23th March, 2005

According to the Chemical Safety and Hazard Investigation Board report (CSB, 2007), the BP Texas City facility is the third-largest oil refinery in the United States. Amoco owned the refinery but BP amalgamated with Amoco in 1999 and BP afterward took over the operation of the refinery. The BP Texas city refinery accident happens on March 23, 2005. The accident resulted in explosions and fires that killed 15 people and injured 180, and the financial losses were in excess of US $1.5 billion. The incident happened during the start-up of an isomerization (ISOM) unit when a raffinate splitter tower was overfilled causing pressure relief devices to open, which resulted in the release of flammable liquid geyser from a blowdown stack that was not equipped with a flare. The release of the flammables that find ignition source from near office trailers located close to the blowdown drum led to an explosion and fire. All recorded fatalities occurred in the office trailer. Properties as far away as three-quarters of a mile from the refinery were damaged. This accident is one of the worst industrial disasters in recent U.S. history. Initiating events and circumstances surrounding the accident include (CSB, 2007):

- Operation personnel failed to follow the ISOM start-up procedure, which led to overfilling of the raffinate splitter tower with flammable liquid hydrocarbon.
- Critical alarms and control instrumentation created false indications that failed to alert the operators of the high level of flammable liquid with high pressure in the tower.
- Occupied trailers on the site are stationed very close the process unit where start-up operation began.
- Inadequate supervision, poor staffing and lack of technically trained personnel during the start-up.
- Poor communication of critical information regarding the start-up during the shift turnover among operators and supervisors.
- Serious work fatigue for ISOM operators working 12-hour shifts consecutively over 29 days.
- Inadequate operator training program.
- Obsolete and ineffective procedures which failed to handle recurring operational problems.
- Lack of effective key safety system.
- BP Texas city management failed to implement effective safety review policy before start-up.
- BP management was responsible for redundancies in process safety performance and lack of effective oversight of accident reporting in the Texas City refinery.

- BP's lack of mechanical integrity program resulted in the failure of process equipment at Texas City.
- BP's poor management practice and poor safety monitoring and auditing also contributed.

2.7.1.5 Delaware City Refinery Accident 5th Nov., 2005

Delaware city refinery is located in United States beside Delaware River. The refinery site staffed almost 600 employees. The main activity in the facility involves converting crude oil into light hydrocarbons such as gasoline, diesel, kerosene and both domestic and industrial heating oil. The refinery also produces other product such as gasoline naphtha and road bitumen. On 5 November 2005, two employees from a subcontracting firm were conducting maintenance work in the hydro-cracking unit's reactor of the refinery when one of the subcontractor's employees attempted to retrieve a roll of adhesive tape from the reactor with iron wire suddenly fell into the reactor and fainted. The other employee was also asphyxiated while attempting to rescue his colleague. Both employees died of suffocation due to the presence of inert gas (nitrogen) in the reactor. The nitrogen was fed into the reactor to reduce the level of the oxygen content circulating in the pipes and machine to enable reloading the reactor catalyst. The incident led to death of the two subcontractor's employees because of loss of oxygen concentration in air following its replacement by an inert gas in the reactor. Investigation made by Delaware city refinery rescue team indicates that the percentage of oxygen in the reactor was less than 1% at the time of the accident. The initiating events and circumstances surrounding the accident includes (CSB, 2006):

- A state of breathlessness due to low level of oxygen in the reactor causes breathing difficulties and quick physical exhaustion which led to collapse of personnel in the reactor.
- Inappropriate decision by subcontractor's employees to remove the protection around the reactor without any specific approval from safety personnel onsite.
- Failure of subcontractor's employees to stick closely to procedures for installation.
- Inadequate warning signs indicating danger of "risk of asphyxiation by nitrogen" around the reactor.
- No proper safety barriers to prevent subcontractor employees on site from getting close to the reactor entry opening.
- Work permit form fails to mention the presence of nitrogen inside the reactor.
- Lack of induction and training for personnel carrying out the maintenance operation close to the hydro-cracker unit onsite relative to the latent hazards of environments with depleted oxygen levels.

2.7.1.6 Humber Refinery Accident 16th April 2001

The Humber Refinery is situated on the south bank of the Humber Estuary, almost 0.5km from the village of South Killing Holme and 1.5km away from the town of Immingham. The refinery produces a range of products comprising petroleum coke, propane/butane (LPG), gasoline (petrol), diesel and aviation fuel. According to a HSE report, on the 16th of April 2001, a disastrous failure of six inch diameter pipe P4363 in the Saturated Gas Plant (SGP) unit of the Humber Refinery caused a major explosion and fire. The incident happened when flammable gas which contains almost 90% mixture of ethane/propane/butane was released from the ruptured six inch pipe of an overhead line in the SGP unit that transport flammable gas under high pressure. The explosion and fire occurred after 20 seconds when a huge gas cloud was ignited. The widespread explosion and fire resulted in overheating that led to the failures of other pressurized pipework which further contribute quantities of fuel, which later caused fireballs 15 minutes after the first explosion. The location of the fire was between the De-ethaniser and Stabiliser columns, in the surrounding area of the surge/feed drum. The overhead stream in the ruptured P4363 contained the enormously flammable mixture of ethane/ propane /butane. The explosion caused widespread damage to property and other investments within a 1.5 km radius of the refinery location. Due to the level of damage caused by the accident, the Humber Refinery was shut down for several weeks before start-up operations. Initiating events and circumstances surrounding the accident include (HSE, 2001):

- The main cause of the explosion originated from erosion/corrosion of the 6" diameter pipe, known as P4363, an overhead line from the de-ethaniser (W413) to the heat exchanger (X452) in the SGP.
- The failure of P4363 line happened at the elbow in close vicinity to a water injection point that was installed on the line but was not part of the original design.
- Humber refinery Management of Change (MOC) procedure fails to re-evaluate the effect of corrosion and erosion potential which the water injection could have on the pipework (P4363 overhead line).
- Failure of Humber refinery technical management team to implement plant designers recommended procedure to control site modifications which can lead to loss of containment.
- The location of the water injection point on P4363 was a key contributing factor to the later failure of the pipe due to the continual flow of water from a jet into a pipe with a potentially corrosive environment such that the influence of the

erosion on the whole of the pipe resulted in thinning of the pipe wall at the elbow which later ruptured.

- Humber refinery safety management system failed to include the inspection of any part of line P4363 for wall integrity.
- Ineffective corrosion monitoring, inspection and management caused the ruptured of P4363 pipe elbow. Investigations further revealed that the failed pipe elbow had not been inspected for 20 years.

2.7.1.7 Tosco Avon Refinery Accident 23th February 1999

At Martinez, California, U.S.A (on February 23, 1999) fire broke out in the crude unit of Avon oil refinery owned by Tosco Corporation. The accident occurred during maintenance repair of naphtha piping when workers were attempting to replace piping connected to a 150-foot-tall fractionator tower while the process unit was in operation. Naphtha was released from the open end of a piping that had been cut which contains almost 90 gallons of naphtha while the line was being drained. The naphtha was ignited as it was released to the hot fractionator and flames suddenly engulfed five workers, killing four and one sustained serious injury. Before the accident a pinhole leak was detected in the crude unit inside the elbow of a naphtha piping on February 10, 1999. The emergency response personnel reacted to situation by closing four valves as a measure to isolate the leaking pipe while the crude unit remains in operation. After careful inspection of the naphtha line, a decision was made to replace a large segment of the naphtha line due to detection of extensive corrosion defect which caused the thinning of the naphtha pipe. As the maintenance personnel proceeded to replace the leaking pipe segment, the open end cut of the pipe section suddenly release naphtha which find ignition source around the hot fractionator and a fire broke out. Initiating events and circumstances surrounding the accident include (CSB, 2001):

- Maintenance personnel conducting the removal of the naphtha piping within confined space while process unit was in operation failed to consider significant hazards involved in the pipe removal work of 6-inch pipe containing naphtha, a highly flammable liquid.
- Procedures and safe work authorization did not identify ignition sources as a latent hazard.
- Plausible leakage of isolation valve led to unsuccessful attempts to drain the naphtha line containing flammable naphtha.
- Avon refinery permit for the hazardous nonroutine work classified naphtha pipe repair work as a low risk maintenance work.
- The procedures for the maintenance repair of the naphtha line did not stipulate other course of action if a safety precondition for the maintenance fails.
- Avon refinery management failed to provide effective maintenance planning procedures that re-evaluated the hazards associated with the replacement of naphtha piping and also failed to formulate a plan to control the known hazards.
- Lack of proper supervision of the maintenance activities by operations supervisor and refinery safety personnel during the piping removal work contributed to the cause of accident.
- Tosco's corporation safety management failed to conduct documented audits of the refinery's line breaking, lockout/tagout, or blinding procedures and practices.
- Tosco management failed to perform a management of change (MOC) review to examine probable hazards related to process changes, to prevent extreme

corrosion in the naphtha piping and operational problem of plugging in the crude unit.

2.7.1.8 Equilon Anacortes Refinery Coking Plant Accident, 25th November 1998

On the 23rd November 1998 a terrible storm hit western Washington in U.S; the aftermath of the storm caused extensive damage and also interrupted the power supply to the Equilon Anacortes refinery in Puget Sound for about two hours. This incident delayed process operation in the delayed coking unit which had to be re- started. Anacortes refinery delay coking unit have two large stainless steel coke drums, Drums A and B, each with sufficient capacity for daily coke production. At the time when power supply to the refinery was interrupted, the process conditions in the operational coke Drum A was around 450 to 500 degrees centigrade and 20 to 30 bar pressure of the refinery. Due to the power interruption, the charge line at the bottom of the vessel, through which the coke would normally flow out of the drum at the end of the process, was blocked with coke that had formed because operators were not able to put steam or water into the drum to cool the coke. When electricity was restored on 24th of November, the Anacortes refinery operators decided to leave the Drum A in the coking plant to cool until the next day to clear the congested charge line. On 25th of November, Equilon refinery management and operators reviewed the drum temperature sensors and resolved that the drum contents had cooled enough and a decision was made by the management to issue permit to work for specialist contractor called Western Plant Services to open up the drum. Six workers putting on safety kits performed the work after the permit was issued, the top lid of the drum was removed and the bolts holding the bottom head in place were removed and a hydraulic lift began to lower the head from the bottom of the coking drum. While the four workers standing directly under the bottom head of drum were expecting to find a solid mass of crude oil residue, hot heavy oil broke through the layer of cooled coke and poured from the drum on the four workers. The hot heavy oil was ignited by surrounding air causing flame and explosion which burned and killed the six workers. Two of the six workers killed were Equilon employees and the other four are contractor employees. The accident cost Equilon US $45 million. The investigation conducted by Washington State Department of Labor and Industries, criticised Equilon management for making a false decision based on assumption by allowing the coking drum to be opened without considering a thorough review of the precondition of the content in the coking drum. The initiating events and circumstances surrounding the accident include (Thompson, 2013):

- The workers had no idea of the hazard associated with the task to clear the clogged charge line.
- Operators and managers of Equilon refinery failed to establish the fact about the temperature of coke in the coke drum.
- Operators and managers of Equilon refinery failed to consult specialist for offsite assistance before making the decision to issue work permit to clear the clogged line after 37 hours based on assumption that the coke drum is sufficiently cool.
- The managers and operators failed to consider the fact that the situation was considerably different from the normal plant operating procedures, but fail to identify and review the hazard of a dangerously hot oil and coke.

2.7.1.9 Milford Haven refinery Accident 24th of July 1994

On 24th of July 1994, severe electrical storms cause disruption of operation in Milford Haven refinery located in Pembroke, UK. The event affected the major process units in the refinery such as the Crude Distillation Unit (CDU), Fluid Catalytic Cracking Unit

(FCCU), Alkylation unit and Butamer unit. The CDU was shut down due to the fire which was caused by ignition of escaped vapour from pressure safety valves by a lightning storm. After 5 hours of shutdown, an explosion occurred in the FCCU due to process anomalies whereby flammable hydrocarbon was being continuously pumped into process vessel which had a valve malfunction and it outlet closed. When the vessel was full, the liquid hydrocarbon was escaping through the pressure relief system to the flare line of the FCCU to the flare knock out drum. A pulsing leak occurred in the flare drum discharge elbow where the outlet pipe ruptured, causing the release of mixture of a total of 20 tonnes of liquid hydrocarbon and vapour, which was ignited by a heater around the process area. The hydrocarbon mixture exploded and caused a major fire about 110m from the flare drum. The refinery emergency response team was able to contain and prevent the escalation of the fire which was eventually extinguished on 26th of July 1994. No fatality was recorded. The accident resulted in damage costing US $78 million. The initiating events and circumstances surrounding the accident include (HSE, 1997):

- Control system failure during plant upset.
- Inadequate maintenance of plant and instrumentation.
- Plant modification and change procedures.
- Poor emergency operation procedure.

Based on the information gathered from the review of the recent major petroleum refinery accidents and the list of the 122 reported accident cases (see Appendix D for details), it is observed that the disruption of petroleum refinery operations emanated from a common source of the technical risk element, organizational risk element, operation risk elements and external risks. The most significance sources are issues related to process equipment failure, instrument failure, piping system failure, utility system failure, inappropriate management procedure, inappropriate decision making, inadequate staffing, poor safety monitoring and auditing, lack of safety training and drills inadequate or inappropriate organised procedures, natural hazards (*i.e.* hurricane, tsunami, earthquake, lighting *etc*.) sabotage, terrorist attacks, deviations from operational procedure, operator incompetency, inadequate communications and inadequate maintenance procedure. The safety management system, which includes organized procedures and training, is of special importance in order to promote an appropriate safety culture inside the establishment. Based on the review, some of the identified risk elements are either underestimated by operators and other decision maker's in petroleum refineries or the consequences of the interrelationship among of the risk elements are unknown to those operators and top management in a petroleum refinery.

2.7.2 Accident Analysis

In this section, the analysis of the frequency of major accidents in the petroleum refineries in the United State of America from 1982 – 2016 is presented. The data utilized for the analysis was obtained from the U.S energy information administration database (EIA, 2017). The incident frequency of 44 major accidents that has occurred in the United State of America from 1982 - 2016 was developed using the time series graph. The time series plot is depicted in Figure 2.2. Based on the time series plot, the trend of incident frequency is observed. The following deductions are obtained from the time series plot:

- The incident frequency from 1982 – 1985 indicates a marginal increase from 0.0039 to 0.0045. This is because the number of petroleum refinery installations gradually decreases from 301 to 223 while the number of incidents per year is 1.
- In 1986 and 1987 incident frequency is zero, this is because no accident was recorded in those years. From 1988 to 1989, there has been a significant increase

in incident frequency from 0.0094 to 0.0147, an increase of 56.26%. This is due to the increase in the number of accidents per year and the reduction in the numbers of installations. From 1992 – 1995 the incident frequency fall between 0.0048 and 0.0052.

- Looking at the time series incident frequency in the years 1997-1999, there is a significant increase from 0.0048 to 0.0183. In 2001, the incident frequency rises significantly to 0.0258 and later fall to zero in 2002 and 2003.
- From 2004 to 2007, the incident frequency rise to 0.0134 and gradually reduce to 0.0064 in 2010. There is no record of a major accident in 2011, therefore, the incident frequency for that year is zero.
- In 2012 the incident frequency is at the highest value of 0.0486. This incident frequency value is very high compared to the incident frequency of 0.0258 in 2001. In terms of comparing the two incident frequencies, the incident frequency for 2012 is significantly higher by 88.37%. This difference is based on the fact that a significant number of accidents is recorded in 2012 and the number of operable installation has reduced from 301 in 1982 to 144 in 2012.
- Based on the graph, incident frequency is high from 1988-1989, 1991, 1997-1999, 2001 and 2012.
- Based on the graph, the trend line shows that from 1982-1990, the cumulative frequency of accident gradually increase from 0. 0018 to 0.043. Also, the trend line indicates that the cumulative frequency of accident from 1991 to 2008 increase marginally from 0.0052 to 0.0062. From 2009 - 2015, the highest cumulative frequency is 0.073.

Based on these deductions, it is observed that the reduction in the number of installations per year from 1982 to 2016 has contributed to the significant increase in the incident frequency per year. According to EPA preliminary data summary for the petroleum refining category 1996 report, from 1976 to 1990, approximately 25 percent of the petroleum refineries in the U.S was closed and production was reduce by six percent. The reason provided was that the closed installations were the small refineries which are not profitable, and their capacity was replaced by increasing production at the larger existing refineries. Furthermore, Marsh report 2015, indicates that there is a significant fall in the price of crude oil from 1980 to 1986, late 1990s and 2008. Based on this information, it can be justified that the low price of crude oil has a significant impact in terms of petroleum refineries stakeholders cost saving initiative, which might have led to the closing down of smaller refineries and other aging refineries in the U.S.

In conclusion, this analysis has provided an overview of the frequency of accidents in the US petroleum refining industry. The trend line of the incident frequency has provided comprehensive information that indicated that the cumulative frequency of accidents in US is 0.0073 at the peak from 1982-2016.

This accident analysis is limited to US petroleum refinery installations as there is limited availability of data to conduct a complete analysis for all major incidents and operating refineries across the globe.

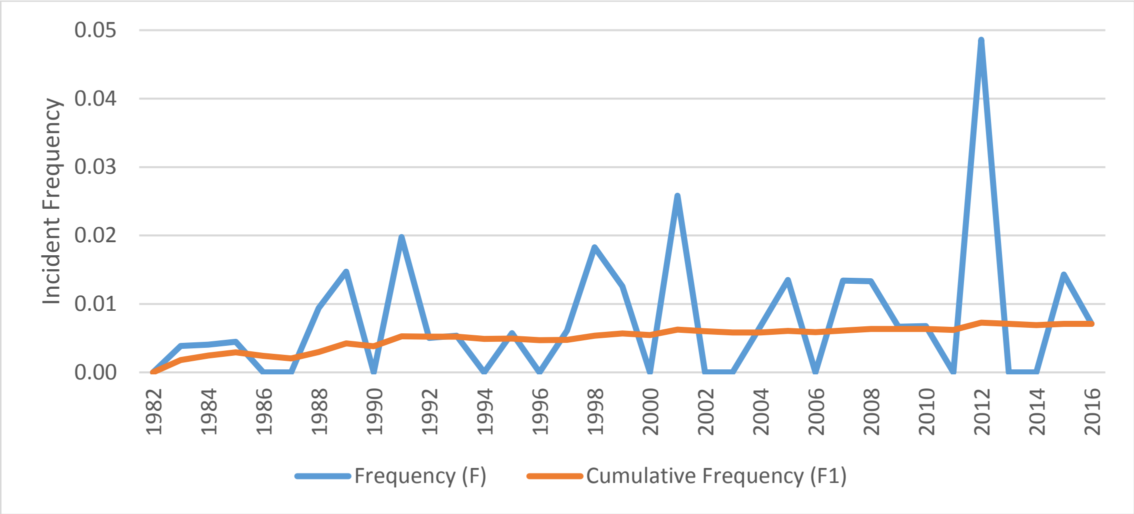

Figure 2.2: Time series graph for incident Frequency in US from 1982- 2016

Table 2.3: Incident frequency for petroleum refinery installations in the U.S from 1982-2016

Year	No. of Installations (n)	No. of Incidents (z)	Frequency (F)	Cumulative installations (n1)	Incidents (z1)	Cumulative Frequency (F1)
1982	301	0	0.0000	301	0	0.0000
1983	258	1	0.0039	559	1	0.0018
1984	247	1	0.0040	806	2	0.0025
1985	223	1	0.0045	1029	3	0.0029
1986	216	0	0.0000	1245	3	0.0024
1987	219	0	0.0000	1464	3	0.0020
1988	213	2	0.0094	1677	5	0.0030
1989	204	3	0.0147	1881	8	0.0043
1990	205	0	0.0000	2086	8	0.0038
1991	202	4	0.0198	2288	12	0.0052
1992	199	1	0.0050	2487	13	0.0052
1993	187	1	0.0053	2674	14	0.0052
1994	179	0	0.0000	2853	14	0.0049
1995	175	1	0.0057	3028	15	0.0050
1996	175	0	0.0000	3203	15	0.0047
1997	164	1	0.0061	3367	16	0.0048
1998	164	3	0.0183	3531	19	0.0054
1999	159	2	0.0126	3690	21	0.0057
2000	158	0	0.0000	3848	21	0.0055
2001	155	4	0.0258	4003	25	0.0062
2002	153	0	0.0000	4156	25	0.0060
2003	149	0	0.0000	4305	25	0.0058

Table 2.3 - Continued

2004	149	1	0.0067	4454	26	0.0058
2005	148	2	0.0135	4602	28	0.0061
2006	149	0	0.0000	4751	28	0.0059
2007	149	2	0.0134	4900	30	0.0061
2008	150	2	0.0133	5050	32	0.0063
2009	150	1	0.0067	5200	33	0.0063
2010	148	1	0.0068	5348	34	0.0064
2011	148	0	0.0000	5496	34	0.0062
2012	144	7	0.0486	5640	41	0.0073
2013	143	0	0.0000	5783	41	0.0071
2014	142	0	0.0000	5925	41	0.0069
2015	140	2	0.0143	6065	43	0.0071
2016	141	1	0.0071	6206	44	0.0071

2.8 Risk assessment approach and applications in the petroleum refining industry

Risk assessment is the first step in the risk management process (John, 2013). According to Wang and Trbojevic (2007), risk assessment is a systematic process for comprehensive evaluation of the likelihood and the degree of the possible consequences in a hazardous situation in order to make an appropriate choice of safety measures. In recent times, the risk assessment of a large, complex engineering systems and their operations has been an integral subject of consideration in safety/risk research. Due to critical challenges of acquisition of consistent historical failure data/information and lack of treatment of inherent uncertainties in a comprehensive and flexible manner, the analysis of complex risk scenario of large engineering systems becomes increasingly difficult (Yang and Wang, 2015). For instance, the safety assessment of a petroleum refinery complex operation requires an innovative, high level risk assessment approach that is the best fit in handling, lack of historical failure data, inherent fuzziness of risk parameters and incompleteness of input in a risk model. In order to establish an effective risk assessment of petroleum refinery operations, a qualitative or quantitative safety approach can be adopted. The choice of model depends on the availability of historical data and involvement of experts or other decision makers. The risk assessment of petroleum refinery operation is based on the three phases, which are risk identification, risk analysis and risk evaluations.

Risk identification is the first step of identifying various underlying causes of a failure events with the potential to cause harm to people, damage to the environment and assets. It is the step to identify various elements of risk that can trigger events that can lead to potential system failure (Mabrouki *et al.,* 2014). Risk identification is a systematic approach to understand the how a sequence of potential failure events can cause accidents. Risk analysis is a process of determining the nature and level of risk associated with a system operation. Risk analysis provides a logic and scientific reasoning of a cause and consequence in risk management (Slovic *et al.,* 2004). Basically, most of the risk analysis models rely on a quantitative approach that involves mathematical quantification of risk level in term likelihood and consequences (Deng, *et al.,* 2011). Risk evaluation is a logical approach for weighing the result of risk analysis in order to focus on the most sensitive risk elements or hazards which has significant consequences. Risk evaluation process is important in the study of risk level of risk/hazard associated with a system or its operation in order to identify a set limit for risk level (Mokhtari *et al.,* 2012).

The commonly recognised and applied techniques for risk/hazard identification, risk analysis and risk evaluation methods recommended in various safety/risk assessment literature include:

- Failure Mode Effect and Analysis (FMEA)

- Hazard Operability Study (HAZOP)
- Preliminary Hazard Analysis (PHA)
- Fault Tree Analysis (FTA)
- Event Tree analysis (ETA)
- Bow-tie Analysis

2.8.1 Failure Mode and Effects Analysis (FMEA)

FMEA is a safety analysis method, which is basically developed for reliability and safety assessment of a system, process and operations. FMEA technique is utilise in reliability engineering to identify latent hazards associated with a system component based on studying their failure modes and evaluating their chances of occurrence and their consequences on system behaviour (Mandal and Maiti, 2014). FMEA approach involves the risk computation of different failure modes, which is determined based on risk priority numbers. The Risk Priority Number (RPN) is determined based on three failure mode parameters which are occurrence probability of failure mode (P), severity of the failure mode and the detectability of the failure mode (D). The higher the value of RPN of a failure mode the higher the risk level of the failure mode. The summary of FMEA step is describes as follows:

- Assemble FMEA team.
- System description and identification of the component of the system or subsystem.
- Collation of all possible failure modes.
- Every probable mode of failure for each component function must be investigated.
- Rating the failure rate for each failure mode identified.

- The likely magnitudes of severity for each failure must be identified along with its effects on other system components.
- It is essential to determine and record the preventative approaches that can be implemented to correct the failure, reduce the failure rate or provide appropriate detection.

The main advantage of FMEA is that it provides a systematic methodology to assess failure modes of a system by breaking the process down item by item. However, the FMEA approach has various shortcomings which have been substantiated in risk analysis literatures. The setbacks includes:

- Consumes more resources effort and time
- Difficulty in determining the precise numerical inputs for risk parameter as required in a crisp model (Liu *et al.,* 2011).
- Various combination of risk parameters result in the same RPN values, which can have different risk implication in real life situation (Pillay and Wang 2003).
- The relative importance of risk parameters are not considered in the computation of RPN values (Liu *et al.,* 2011: Yang *et al.,* 2008).

The FMEA technique has been utilised in solving different problems in combination with other safety/risk analysis techniques. Recently, Charnamool and Naenna, (2016) used Fuzzy logic algorithm and FMEA to enhance decision making in an emergency department. Su *et al.,* (2014) proposed the application of FMEA and Taguchi method for improving the reliability of electronic paper display. Mandal and Maiti (2014) proposed a fuzzy FMEA approach for risk analysis in which different weights of risk parameters are considered. Chen, Wu and Qin, (2014) proposed a new methodology for risk assessment of an oxygen enhance combustor using a structural model based on FMEA and Fuzzy Fault Tree.

2.8.2 Hazard and Operability Study (HAZOP)

Hazard and Operability Study is a well-known technique for hazard identification and qualitative risk analysis approach in the process industry. HAZOP has been utilised for several years as a formal approach for review of chemical process design. It is an expedient tool for the identification of all possible risks associated with the operation of a process system or activity (Alaei *et al.,* 2014). The technique thoroughly identifies all the conceivable causes and consequences within the system for each theorized deviation of one of the variables of the process (Bartolozzi *et al.,* 2000). The method provides a systematic approach for careful examination of probable deviation from the design intent for a process system. HAZOP can be conducted at various stages and at different times during the life cycle of the process, from the stage of process development through to the end of operational life of a process system. In the application of HAZOP, a team of experts' brainstorm to a set of engineering and safety guide words used for all parts of a system. The studies by the team of experts is guided by procedure, which is used for systematic identification of hazards which are defined as deviations within these parameters that may have dangerous consequences. The steps in the HAZOP method are as follows:

- Establish the scope of the study.
- Gather a team of specialist with comprehensive knowledge and experience.
- Collate all the relevant information to conduct an in-depth and comprehensive study.

- Review the normal functioning of the process.
- The system under investigation must be divided into appropriate parts or sub-systems, which are analysed one by one.
- The main parameters that is associated with each sub-system need to be identified (i.e. pressure, temperature, volume, viscosity, flow *etc*.).
- Appropriate guidewords are applied to each parameter in each subsystem to enhance the discussion of deviations and likely consequences.
- The potential causes for each relevant deviation are identified.
- Document the review reports.
- Follow up all recommendations from the study in order to ensure the recommendation adequately addressed the targeted situation.

The record of the study should indicate the design intent of a system or subsystem, feasible deviations from the intent, probable consequences of the deviation if it happens and the proactive measures that can be introduced to eliminate or minimise the impact of a hazard related to the deviation in a practicable manner. The benefit of the HAZOP technique lies in the systematic and comprehensive use of guide words and parameters associated with the process to examine the consequence of deviations. It also provide the benefit of aiding the provision of recommendations to minimise or mitigate the consequence of the deviations. The limitations of HAZOP techniques is as follows (Glossop, Loannides and Gould, 2005):

- It consumes resources and much time.

- A lot of details are required to perform the study (i.e. operating conditions, and control instrumentation, additional guide words are required for infrequent hazards).
- Requires specialist team with vast knowledge and experienced.
- Focuses on one-event causes of deviation at a time.

2.8.3 Preliminary Hazard Analysis (PHA)

Preliminary Hazard Analysis (PHA) is a semi-quantitative analysis method based on combination of inductive and deductive reasoning. PHA is a hazard identification technique which is used for the identification of possible hazard and events that can result in accidents, rank the identified hazard according to the severity level and then identified the required control measures and follow up procedure (Rausand, 2005). PHA is a process of identification of all the significant hazards that can happen as a result of a system design (Dantsoho, 2015). In 1966, the United States of America Department of Defence request for safety studies to be performed at all stages of product development led to PHA. The technique is often utilised to follow-up on the hazards that have been identified during hazard analysis. The PHA helps system designers to avoid many potential safety flaws in their design (Dowlatshahi, 2001). The PHA procedure is presented as follows (Rausand, 2005; Czerny *et al.*, 2005):

- Selection of a PHA team.
- Provide a description of the system to be analysed (*i.e*. system boundaries, system description operational and environmental conditions *etc*.).
- Appropriate review and brainstorming on potential hazard lists to determine the significant hazards associated with the system.

- Adequate description of the hazards and failure event scenarios related to them.
- Determine the risk of the hazards and the accident scenarios.
- Define the system hazards prevention requirements to be included in the system design to eliminate or mitigate the risks.

The benefit of PHA is that it can identify hazards or events which can be further analysed using a fault tree technique or event tree technique. The systematic planning of PHA does not require high level expertise. The method provides the benefit of inherent safer design. The limitation of PHA is the lack of comprehensive information for identification of all causes of hazards, therefore, only major hazards can be identified.

2.8.4 Fault Tree Analysis (FTA)

FTA provides a diagrammatic representation of the interrelationship of various failure modes or causes that can lead to undesired event. The representation of system problem in FTA involves the use of algebra to establish the failure state of an event. FTA methodology is a top down deductive approach, which is utilised in developing a system fault logic until it results in an undesired event. FTA is developed based on available knowledge of the system under investigation. FTA methodology is a safety/risk analysis approach employed for both quantitative and qualitative risk assessment problems. It is a risk identification and risk analysis approach which is used to determine risk level or the probability of an undesired event resulting from sequencing of the interrelationship of failure events (*i.e.* basic events and intermediate events) (Riahi, 2010). The pathways in a FTA diagram that can lead to top event is called the Minimum Cut Set (MCS). The top event (TE) is the undesired event. The five main logic gates used in developing a FTA are the AND gate, OR gate priority AND gate, Exclusive OR gate and inhibit gate

(Ericsson, 1999). Recent applications of FTA in combination with other safety and risk assessment are described below:

- Applied for collaborative modelling of ship and port interface operations under uncertainty (John *et al.,* 2015).
- Applied for quantitative risk analysis of leakage in abandoned oil and natural gas wells (Lavasani *et al.,* 2015).
- Applied in risk assessment of an oxygen enhance combustor (Chen, Wu and Qin, 2014).
- Applied for fire and explosion accidents for steel storage tanks (Shi, Shuai and Xu, 2014).
- Applied to spread mooring systems (Mentes and Helvacioglu, 2011).
- Applied as a risk based model for enhancing shipping accident investigation (Celik *et al.,* 2010)

The FTA procedure step is as follows (Glossop, Loannides and Gould, 2005):

- Determine the scope of the analysis.
- Understanding the design, functions, and operations of the process.
- Identification of the target undesired event as the top event.
- Develop the fault tree: This involves a logical sequencing of the undesired event based on top down deductive approach, starting from the top event and down to the basic events.
- Analysis of the fault tree: this involves determining the failure probability of the primary event to quantify the risk of the top event.
- Documentation of the outcome of the FTA with any other associated conclusion.

2.8.5 Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is a safety/risk assessment method employed in the maritime and the oil and gas industry to investigate the consequences of an accident or abnormal function of a system. An Event Tree (ET) provides a logical illustration for analysing the effects of undesired events (Lavasani, 2010). ET approach is essentially used to establish the probability or frequency of an accident associated with the safeguard measures required to be effected to mitigate or prevent the escalation that follow the occurrence of an undesired event (Lavasani, 2010).

Event tree is an inductive approach for investigating all possible responses to the initiating event. It is a technique that is normally used to determine the consequences that can result based on the probable occurrence of a hazardous event. The ETA is used to assess the probability of an accident by analysing and predicting all probable risks. ETA is an innovative technique for the evaluation and quantitative analysis of probable consequences of risks from a critical event. ETA was first utilised in the atomic energy field and it was progressively extended to other domains such as chemical engineering, reliability engineering and maritime and mechanical engineering. In terms of the application of the ETA technique, an initiating event needs to be established as the origin of a system problem, then the initiating event is sequentially propagated in a graphical order until predictable accident results is determined. The initiating event is established based on dichotomous conditions (*i.e.* success/failure, true/false or yes/no) in order to determine the event consequences in diverse branches of the ET (Ferdous *et al.*, 2009). The graphical presentation of an ET comprises of an initiating event, probable subsequent events and final consequences from the sequence of events. The ETA approach is applicable to design, construction, and development of an accident model in risk analysis in order to establish a guide for superposing safety measures that correspond to risk components identified during analysis. The ETA procedure comprises the following steps (Hong *et al.,* 2009):

- Identifying the initiating events.
- Selection of safety function.
- Develop the event tree.
- Define the probability of the initiating events.
- Probability analysis of individual accident path (estimated probability of the success of each safety function).
- Estimation of probability of accident occurrence and criticality (*i.e.* determine the probability of an accident associated with the initiating events).
- Analysed the result of the outcome event.

2.8.6 Bowtie Analysis

The Bowtie analysis is a probabilistic approach based on the integration of cause and consequences of an undesired event (Shahriar *et al.,* 2012). The technique is a logical approach that can be employed to prevent, control and mitigate accidents based on an established relationship between cause and consequence (Ferdous *et al.,* 2013). Bow-tie has been used in various fields of engineering such as reliability, safety and risk for the assessment of complex system operations (*i.e.* maritime transport, marine and offshore systems, nuclear industry, oil and gas and other process industry).

Bowtie Analysis involves the combination of an inductive and a deductive technique based on an FTA and an ETA to study the cause and consequence of a hazardous event in any environment or system. It is an expedient approach to risk management of undesired events. It can also be defined as a Cause-Consequence Analysis (CCA) model (Dantsoho, 2015). There are five basic elements used in developing a Bowtie diagram. The elements are the causes and critical event (*i.e.* the top event in a FT), ET (*i.e.* sequences the possible consequence of the critical event in a binary state, for example success/failure, yes/no and true/false) and the outcome events (*i.e.* the final consequence which is systematically propagated through the critical event) (Ferdous *et al.*, 2013). The basic procedure for developing a Bowtie model is as follows:

- The starting point of a bowtie is from output of FT (top event), which serves as the initiating event in an ET.
- Establish the common link between the FT and the ET based on the critical event.
- Significant causes are identified and establish on the left side of the Bowtie diagram.
- Accident scenario are outcomes are depicted on the right side of the Bowtie.
- The left side of the diagram (*i.e.* the pre-event side) converge towards the critical event and the right side (*i.e.* post event side) diverge until all potential outcomes are determined.

2.9 Overview of risk management methods for the petroleum refinery operations

2.9.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchical Process (AHP) is a technique developed by Thomas Saaty in 1980. It is a well-thought-out approach for organizing and analyzing complex decisions making problems. AHP concept is a mathematical and psychological approach, which has been extensively applied in different field of studies. AHP as being a successful group decision-making method around the world in various decision circumstances, in areas such as project management, business, industry, healthcare, quality and education (Manca and Brambilla, 2011).

Decision makers find AHP as one of the most suitable approach to achieve their decision making goal because it enhances the process of planning and organizing a decision problem in a way it can be understood and analyzed to obtain a tangible solution. All the elements of a decision-making problem can be integrated into a hierarchy in which they can be represented and quantified to achieve the overall decision goal. In the evaluation of the AHP decision making problem, the elements represented in the hierarchy can be measured qualitatively and converted into numerical values that can be processed, compared, and evaluated within the whole problem (Saaty, 2003).

In the application of AHP the decision makers' judgments about the meaning and importance of the information of each element in the hierarchy is computed. The computation is based on making feasible comparison in a direct and consistent way to obtain the numerical weight of the elements. The weights derived is based on the estimate of the relative magnitudes of both tangible and intangible issues by means of pair-wise comparisons of information and experience provided by the decision makers. The principle of AHP allows the consideration of the inconsistency associated with decision maker's perceptions in making judgments, which can be cardinally inconsistent or cardinally consistent when dealing with intangibles, as they cannot be measured as a precise values. Also, dealing with tangibles can provide a situation in which decision maker's judgment matrix may be perfectly consistent but fail to reflect a true values in real life scenario (Tzeng and Huang, 2011; Saaty, 2003). The positive reasons for the introduction of a certain degree of inconsistency is to allow flexibility in decision maker's judgement, because their thoughts, feelings and preferences can change with new evidence or when unable to look within for the judgments that represent a situation.

The fundamental scale provided to decision makers to develop pairwise judgments is presented in Saaty (1990). The qualitative judgments of decision makers are converted into a quantitative score based on the fundamental scale that provides various comparison grade with numerical scores in the interval between 1and 9. This allows decision makers to assign scores for every pairwise comparison of elements to develop a pairwise judgments matrix, whose rows and columns define the interactions among the element of the same level in the hierarchy (Manica and Brambilla, 2011).

The AHP specifically provides an easy way to utilize human perceptions and judgments as elements which can be quantify or compare in a process of priority setting and selection of alternatives in a decision making problem. Furthermore, AHP have been successfully used as a strategic and standard technique for a large-scale multi-criteria decision making that requires the assessment and evaluation of alternatives on the basis of selected criteria and then the aggregation of these evaluations to achieve the relative ranking of the alternatives in regard to a decision making problem. The AHP principle of hierarchical composition involves configuring all problem elements to derive composite priority of alternatives in a multi-criteria decision making process (Saaty, 2003; Al Khalil, 2002). The summary of the steps to execute the AHP technique are decomposed as follows:

Step 1: Identify and select the appropriate criteria and alternatives for MCDM problem and develop a hierarchical structure to depict the interrelationship among them.

Step 2: Develop a set of pairwise comparisons matrix; human perception or experts' judgements are usually presented in a pairwise comparisons matrix. In order to reasonably analyse a MCDM problem on the basis of AHP, pair-wise comparison matrix is used to specify the experts' judgements by inserting the entry a_{ij}($a_{ij} > 0$) declaring how much more important criteria i is than criteria j.

$$A = a_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

Where a_{ij} is the relative importance of criteria a_i and a_j. The pairwise comparisons matrix for the criteria would be a square matrix, *A*, with certain number of criteria n whose relative weights are w_1......w_n. Hence, a_{ij}= 1/a_{ij} (positive reciprocal) in genuine circumstances, and the matrix for criteria weights are measured with regard to the pairwise comparison values as presented in equation

$$a_{ij} = \frac{w_i}{w_j} \tag{2.1}$$

where $w = [w_1 \ w_2 \ \cdots \ w_n]^T$ (2.2)

The T = Transpose matrix for the weight vector, which is defined as:

$$W_k = \begin{bmatrix} W_{1,1} \\ W_{2,1} \\ . \\ . \\ . \\ W_{n,1} \end{bmatrix} \tag{2.3}$$

It is worth mentioning that, in a realistic situation $\frac{w_i}{w_j}$ is usually not known. In addition the weights can be determined based on the following equation:

$$W_k = \frac{1}{n} \sum_{j=1}^{n} \left(\frac{a_{kj}}{\sum_{j=1}^{n} a_{ij}} \right) \ (k = 1, 2, 3, \dots . n) \tag{2.4}$$

Step 3: Evaluate the weighting vectors of criteria; the comparison scale recommended based on Saaty (1990) is used to translate decision makers linguistic judgements into crisp number on the basis of equivalent scores from 1 to 9. The comparison scale is utilized to synthesize the expert's subjective judgment and estimate the relative weight. The pairwise comparison scale is presented in Table 2.4.

Table 2.4: Linguistic Scale for Pairwise Comparison (Saaty, 1990)

Relative importance scale for criteria	Description
1	Equally important
3	Weakly important
5	Strongly important
7	Very strongly important
9	Extremely important
2,4,6,8	Intermediate values between the two adjacent judgments

Step 4: Estimate the relative weight: the principal eigenvector approach is used to calculate the relative weights of the criteria. The criteria weights calculation is the process of averaging over the normalised columns. The eigenvalues estimate based on the priority matrix is required to provide the best fit for criteria in terms of transforming their weights sum to 1. This normalisation can be accomplished based on the division of the relative weights of each criteria by the column sum of the weights obtained.

Step 5: Consistency check of the criteria: it is very important in the AHP to identify the consistency level of subjective perceptions of decision maker's on pair-wise comparisons of criteria. The precision of the comparative weights of criteria based on the pair-wise comparison matrix depends on two indices, which include the consistency index (C.I) and the consistency ratio (C.R). The C.I is define as

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k}^{n} w_k a_{jk}}{w_j}}{n} \tag{2.5}$$

$$C.I = \frac{(\lambda_{max} - n)}{(n-1)} \tag{2.6}$$

where λ_{max} is the maximum eigenvalue and *n* signifies the matrix size. According to Saaty (1980), the expected value of the *C.R.* should not exceed 0.1 to achieve consistency in the result. Moreover, the *C.R.* can be determined as:

$$C.R = \frac{C.I}{R.I} \tag{2.7}$$

where $R.I.$ is defined as a random consistency index is a derivative of a large sample of randomly produced reciprocal matrices based on the scale 1/9, 1/8,…, 1,…,8, 9 (Tzeng and Huang, 2011).The *R.I.* in regard to diverse matrices size is indicated in Table 2.5.

Table 2.5: The R.I for different size matrices (Saaty, 1990)

n	1	2	3	4	5	6	7	8	9	10
$R.I$	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

AHP techniques have been used in a various fields for practical applications. The technique has been applied in the field of economics and conflict resolution, supply chain management, port management, maritime transport and other areas of decision analysis. In recent publications, the application of AHP with other analytic approaches are found in the works of Shi and Xu, (2014); John *et al.,* (2014); Lavasani *et al.,* (2012) Manca and Brambilla, (2011); Kaya and Kahraman, (2011); Kaya and Kahraman, (2010). Most of the authors applied AHP in combination with other analytical approach to solve supplier selection problems, energy planning, risk assessment of complex system, emergency planning and resilience management of port operations.

2.9.2 VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

Opricovic (1998) and Opricovic and Tzeng (2002) provide an approach to deal with Multi-Criteria Decision Making (MCDM) problem with non-commensurate and conflicting criteria. The MCDM method is Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), which means Multicriteria Optimization and Compromise Solution. VIKOR method was utilised as complex multi-criteria process for determination of optimum ranking and sorting of a set of alternatives to obtain a compromise solution in a situation with possibility of conflicting and non-commensurable decision criteria (Serafim Opricovic, 2011; Girubha and Vinodh, 2012). The compromise solution based on VIKOR helps decision maker to reach a final decision. The compromise solution is a feasible solution with a ranking index based on measure of closeness to the ideal solution. The ideal compromise solution is obtained from the compromising ranking based on L_p metric, which is an aggregation function in a compromising programming approach (Tsung-Han Chang, 2014). The form of L_p metric which provide the standard for developing VIKOR method is defined as follows:

$$L_{p,j} = \left\{\sum_{i=1}^{n}\left[w_i\left(f_i^* - f_{ij}\right)/(f_i^* - f_i^-)\right]^p\right\}^{1/p}, \quad 1 \le p \le \infty; j = 1,2, \dots \dots, J.$$

Based on the L_p metric, the ranking measures in the VIKOR method is formulated (*i.e.* $L_{1,j}$ *and* $L_{\infty,j}$ are depicted as $\tilde{S}_i$ and $\tilde{R}_i$). The VIKOR method has been widely used in solving MCDM problems like any other MCDM technique such as AHP, TOPSIS, Grey Relation Analysis (GRA), Data Envelop Analysis (DEA) and others. The VIKOR concept provides a simple computation procedure which incorporate simultaneous consideration that defines the positive and the negative ideal points (Kaya & Kahraman., 2010; Kuo and Liang, 2011). Hence, the VIKOR approach assist decision makers to obtain rationalise results in a MCDM problem which not only provide as much benefits aspired but also provide confidence in decision making (Zhang & Wei, 2013). The main principle of VIKOR approach based on the $L_p$metric in optimizing a compromise solution to a complex system problem, depends on the introduced boundary or separation measures $\tilde{S}_i^{\ *}$, $\tilde{R}_i^{\ *}$ and the aggregating index $\tilde{Q}_i$. These three parameters provide the aggregation function to determine the closeness of an alternative to the ideal solution (Opricovic, 2009; Opricovic and Tzeng, 2004).

An extension of VIKOR is the development of fuzzy VIKOR as a fuzzy multi-criteria decision method to solve discrete fuzzy multi-criteria problem with non-commensurate and conflicting criteria (Opricovic, 2011). Fuzzy VIKOR provide the advantage of dealing with the imprecision in multi-criteria decision making by incorporating fuzzy set theory to define rating of criteria in relation to alternative by aggregating and normalizing the decision makers preference based on operations with fuzzy numbers. The optimal solution based on fuzzy VIKOR, considered decision makers perspective toward cautious risk avoidance in the measure of closeness to the positive ideal compromise solution. Based on fuzzy VIKOR approach linguistic preference can be transform to fuzzy number in order to handle imprecise numerical quantities (Opricovic, 2011).

In the application of the fuzzy VIKOR algorithm to determine a compromise solution for a fuzzy multi-criteria decision problem, decision maker's opinion is expressed as a linguistic judgment in terms of assessment of criteria and alternatives. Assuming a group of decision makers N, their ratings on a set of alternatives with respect to each criterion can be calculated as follow:

$$\tilde{\mathrm{x}}_{\mathrm{ij}} = \frac{1}{\mathrm{N}} \left[\check{\mathrm{x}}_{\mathrm{ij}}^{1} + \check{\mathrm{x}}_{\mathrm{ij}}^{2} + \cdots \check{\mathrm{x}}_{\mathrm{ij}}^{\mathrm{N}} \right] \qquad (2.8)$$

$\tilde{\boldsymbol{x}}_{\boldsymbol{ij}}^{\boldsymbol{N}}$ represents the rating of the Nth expert for ith alternative in regards to jth criterion. A fuzzy decision matrix is developed after the weight w_{ij} of each criterion is determined and the fuzzy rating of each alternative with respect to the criteria is obtained. The fuzzy multi-criteria decision matrix for the decision-making problem can be define as follows:

$$D = \begin{bmatrix} \tilde{\mathbf{x}}_{\mathbf{11}} & \tilde{\mathbf{x}}_{\mathbf{12}} & \cdots & \tilde{\mathbf{x}}_{\mathbf{1k}} \\ \tilde{\mathbf{x}}_{\mathbf{21}} & \cdots & \tilde{\mathbf{x}}_{\mathbf{23}} & \tilde{\mathbf{x}}_{\mathbf{2k}} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{\mathbf{x}}_{\mathbf{m1}} & \tilde{\mathbf{x}}_{\mathbf{m2}} & \cdots & \tilde{\mathbf{x}}_{\mathbf{mk}} \end{bmatrix} \tag{2.9}$$

$$W = [w_1, w_2 \ldots w_k], j = 1, 2, \ldots\ldots k$$

where $\tilde{\boldsymbol{x}}_{\boldsymbol{ij}}$ represents the rating of alternative A_i in regards to criterion (C_j) and w_j depict the weight of the jth criterion. Given $\tilde{\boldsymbol{x}}_{\boldsymbol{ij}} = \left(\tilde{\boldsymbol{x}}_{\boldsymbol{ij1}}, \tilde{\boldsymbol{x}}_{\boldsymbol{ij2}}, \tilde{\boldsymbol{x}}_{\boldsymbol{ij3}}\right)$, the computation of the normalized matrix values is as follows:

$$\bar{U} = \left[\bar{U}_{ij}\right]_{m \times k}$$

$$\tilde{\boldsymbol{x}}_{ij3}^{+} = max_i\ (\tilde{\boldsymbol{x}}_{\boldsymbol{ij3}})\ ,\ C_J\ \in B \tag{2.10}$$

$$\tilde{\boldsymbol{x}}_{ij1}^{-} = max_i\ (\tilde{\boldsymbol{x}}_{\boldsymbol{ij3}})\ ,\ C_J\ \in B \tag{2.11}$$

$$\bar{U}_{ij} = \left(\frac{\tilde{x}_{ij1}}{\tilde{x}_{ij3}^{+}}, \frac{\tilde{x}_{ij2}}{\tilde{x}_{ij3}^{+}}, \frac{\tilde{x}_{ij3}}{\tilde{x}_{ij3}^{+}}\right), C_j\ \in B \tag{2.12}$$

$$\bar{U}_{ij} = \left(\frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij1}}}{\tilde{\boldsymbol{x}}_{ij1}^{-}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij2}}}{\tilde{\boldsymbol{x}}_{ij1}^{-}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij3}}}{\tilde{\boldsymbol{x}}_{ij1}^{-}}\right), C_j\ \in C \tag{2.13}$$

$\bar{U}_{ij}$ is the normalized rating in the decision matrix. In both equations, B and C are define as a set of benefit and cost criteria.

The next step involves defining the best $\left(\tilde{f}_j^*\right)$ value and the worst $\left(\tilde{f}_j^-\right)$value of each criteria function.

$$\tilde{f}_j^* = \max \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}, \; j \in B; \; \tilde{f}_j^- = \min \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}, \; j \in B \tag{2.14}$$

Hence, the values $\tilde{w}_j \left(\tilde{f}_j^* - \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}\right)/\left(\tilde{f}_j^* - \tilde{f}_j^-\right)$ is utilized to establish $\tilde{S}_i$ and $\tilde{R}_i$ as follows;

$$\tilde{S}_i = \sum_{j=1}^{k} \tilde{w}_j \left(\tilde{f}_j^* - \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}\right)/\left(\tilde{f}_j^* - \tilde{f}_j^-\right) \tag{2.15}$$

$$\tilde{R}_i = max_j\left[\tilde{w}_j \left(\tilde{f}_j^* - \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}\right)/\left(\tilde{f}_j^* - \tilde{f}_j^-\right)\right] \tag{2.16}$$

where $\tilde{S}_i$ represent the separate measure of A_i from the best value and $\tilde{R}_i$ represent the separation measure of A_i from the worst value . The estimation of the values of the set of parameters $\tilde{S}_i^{\,*}$ $\tilde{S}_i^{\,-}$ $\tilde{R}_i^{\,*}$ $\tilde{R}_i^{\,-}$ $\tilde{Q}_i$ is determine in the next step.

$$\tilde{S}_i^{\,*} = min_i \tilde{S}_i, \;\; \tilde{S}_i^{\,-} = max_i \tilde{S}_i \tag{2.17}$$

$$\tilde{R}_i^{\,*} = min_i \tilde{R}_i, \;\; \tilde{R}_i^{\,-} = max_i \tilde{R}_i \tag{2.18}$$

$$\tilde{Q}_i = \frac{v\left(\tilde{S}_i - \tilde{S}_i^{\,*}\right)}{\tilde{S}_i^{\,-} - \tilde{S}_i^{\,*}} + \frac{(1-v)\left(\tilde{R}_i - \tilde{R}_i^{\,*}\right)}{\tilde{R}_i^{\,-} - \tilde{R}_i^{\,*}} \tag{2.19}$$

where $min_i \tilde{S}_i$ and $min_i \tilde{R}_i$ are depicted as a solution obtained with a maximum group utility and a minimum individual regret of the opponent. v is define as the weight of the strategy of the maximum group utility and $1 - v$ is the weight of the minimum individual regret of an opponent strategy (Kaya and Kahraman, 2010). The values of v is specified as 0.5. Based on this parameters, the index $\tilde{Q}_i$ is estimated in order to determine the best alternative among a set of alternatives, based on the decreasing order of index $\tilde{Q}_i$ (minimum). The defuzzification method employ in the implementation of the VIKOR is the graded mean integrated approach based on the equation below (Yong, 2006):

$$P(\tilde{C}) = C = \frac{c_1 + 4c_2 + c_3}{6} \tag{2.20}$$

where $\tilde{C} = (c_1, c_2, c_3)$ is a fuzzy number.

In the application of the VIKOR ranking algorithm, it is worth mentioning that a compromise solution which is the best ranked alternative based on $\tilde{Q}_i$ (minimum), must satisfy two condition stated as follows:

Condition 1: Acceptable advantage $\tilde{Q}_i(A_2) - \tilde{Q}_i(A_1) \geq (1/j - 1)$. A_2 is the second best alternative according to the $\tilde{Q}_i$ (minimum) order.

Condition 2: Acceptable stability in decision making.

The best ranked alternative can be conclusively regarded as the most stable decision, if only, it is the best ranked alternative by the separate measures $\tilde{S}_i^*$ and/or $\tilde{R}_i^*$.This solution is stable in a decision making process, which could be the strategy of the maximum group utility either "by consensus" (when $v \approx 0.5$), or "by voting by majority rule" (when $v > 0.5$) or by veto ($v < 0.5$). In the decision making process, v is depicted as the weight of the decision making strategy (the majority of criteria or the maximum group utility). However, if one of the conditions is not satisfied, then a compromise solution is proposed as follows:

- The compromise solution will consist of alternatives A_1 and A_2 if only condition 2 is not satisfied.
- If condition 1 is not satisfied, the compromise solution will consist of A_1, A_2,.... A_m whereby A_m is defined by the relation $\tilde{Q}_i(A_M) - \tilde{Q}_i(A_2) < (1/j - 1)$ for maximum M(the rankings of these alternatives are "in closeness").

The VIKOR algorithm has been successfully applied in various fields for a large number of practical applications. Opricovic (2009), applies VIKOR for water resource planning; Kaya and Kahraman (2011) multi-criteria forestry decision making; Shermshadi *et al.*,

(2011) supplier selection; Rezaie *et al.*, (2014), evaluation of the performance of the Iranian cement companies; Liu *et al.*, (2015) failure mode and effects analysis. Other notable applications of VIKOR algorithm in combination with other decision approach include:

- Deriving preference order of open pit mines equipment (Bazzazi *et al.*, 2011).
- Hospital service evaluation in Taiwan (Chang, 2014).
- The evaluation of the service quality of airports under fuzzy environment (Kuo and Liang, 2010).

2.9.3 Fuzzy Set Theory (FST)

FST approach was introduced by Zadeh in 1965. The technique is utilised to deal with a fuzzy situation whereby uncertainty due to imprecision and fuzziness exists. FST is a mathematical approach introduced to deal with information or data that are too complex or ill-defined to be processed in a conventional algorithm (John, 2013). FST is a tool that can be utilised to develop an expedient modelling approach in the field of decision analysis (Mentes and Helvacioglu, 2011). Pillay and Wang (2003) reveal that fuzzy variables can enhance the gradual transition between states and thus possess the normal capacity to express and deal with observation and measurement uncertainties. Such capacity substantiates the fact that FST is a powerful tool for risk analysis under fuzzy situation whereby available information are subjective and data can be uncertain. The fundamental of an FST is based on the degree of membership function assigned to each element in a fuzzy set. Defining a fuzzy set involves vague and ambiguous properties. Therefore, membership value of a given fuzzy set is defined as any real value from 0 to 1. In this way a fuzzy set can deal with any concept of ambiguity. In terms of practical applications, sometimes the exact value of a model parameters is not precisely known. As a result uncertainties and imprecisions loom because of lack of data or incomplete in knowledge. In such situation fuzzy set can be used to overcome a deterministic concept in a decision analysis.

Generally fuzzy sets are represented using triangular fuzzy number, trapezoidal fuzzy number and the gaussian fuzzy number to treat uncertain data. In various applications of FST technique, it was observed that FST deal with linguistic terms by utilising membership functions, best for treating high level uncertainties, adaptable in terms of dealing with imprecise and uncertain linguistic value, very intuitive in terms of enhancing risk analysts and decision-makers to capture the knowledge of a system behaviour.

FST has been used widely in risk/safety analysis of complex systems whereby knowledge of a system performance, failure mode and failure data are uncertain, ambiguous and vague. Among the notable applications of FST in safety/ risk management are:

- Sii *et al*., (2001), present fuzzy-logic-based approach to qualitative safety modelling for marine systems.
- Wang (2000), present a subjective modelling tool applied to formal ship safety assessment.
- Suresh *et al.*, (1996), present a fuzzy approach for uncertainty in FTA.
- Lee (1996), present fuzzy set theory to evaluate the rate of aggregative risk in software development.
- Lavasani *et al.*, (2011), present fuzzy FTA on oil and gas offshore pipelines.
- Liu *et al.*, (2005), present engineering system safety analysis and synthesis using the fuzzy rule-based Evidential Reasoning (ER) approach.

- Mokhtari *et al.,* (2012), present a decision support framework for risk management of seaport and offshore terminals.
- Markowski and Mannan (2009), present Fuzzy Logic for Piping Risk Assessment (pfLOPA).

2.9.4 Fuzzy Linguistic Preference Relations (FLPR)

The FLPR is a method developed from consistent fuzzy preference relations proposed by Herrera-Viedma *et al.,* (2004). It is an alternative method proposed to improve the consistency of fuzzy AHP (Wang and Chen, 2008). The FLPR approach provides a systematic process to solving multi-criteria selection problems through the amalgamation of fuzzy set and hierarchical modelling analysis. The application of FLPR for decision analysis involves developing decision matrices from pairwise comparisons of elements in a decision model. Because of the complexity and uncertainty associated with a decision making problem, with a real life situation, human judgement is clouded by inherent subjectivity which makes it impossible to human to provide a perfect judgement in decision making. Therefore, the application of FLPR allows the use fuzzy linguistic assessments variables to construct fuzzy linguistic preference relation matrices, which provides superior flexibility for solving multi-criteria decision making problems with preference information about alternatives and/or attributes (Wang and Chen, 2011).

The FLPR approach considers the fuzzy opinion of decision makers in a comprehensive manner in order to avoid the rigorous check of consistency of decision maker's judgement. Using a FLPR method allows the decision maker to find it stress-free to assign linguistic variables to express their opinion in a flexible manner (Huang *et al.,* 2011). More importantly, to collect information for FLPR process is more convenient because it is easier to obtain judgement from experts or decision maker using a questionnaire that reduces the number of pairwise comparisons.

In the application of the FLPR method for decision making, a set of criteria, X = $\{x_1 , \dots \dots x_n\}$ can be evaluated based on fuzzy linguistic assessment variables given as $\tilde{P}$ = $(p_{ij}) = (p_{ij}^l,\ p_{ij}^m, p_{ij}^u)$ to develop fuzzy linguistic preference relations matrix. The fuzzy linguistic assessment variables p_{ij}^l and p_{ij}^u indicate the lower and the upper bounds of the fuzzy number $\tilde{P}$ and p_{ij}^m relatively indicates the median value instead of crisp values $\widetilde{P} = (p_{ij})$. In order to develop a preference relation matrix with a complete additive reciprocal consistency, the following propositions are required (Wang and Chen, 2008):

Propositions

$$p_{ij}^l + p_{ij}^u = 1\ \forall i, j \in \{1, \dots \dots .., n\}$$

$$p_{ij}^m + p_{ij}^m = 1\ \forall i, j \in \{1, \dots \dots .., n\}$$

$$p_{ij}^u + p_{ij}^l = 1\ \forall i, j \in \{1, \dots \dots .., n\}$$

$$p_{ij}^l + p_{ij}^l + p_{ij}^u = \frac{3}{2}\ \forall \mathrm{i} < \mathrm{j} < \mathrm{k},$$

$$p_{ij}^m + p_{ij}^m + p_{ij}^m = \frac{3}{2}\ \forall \mathrm{i} < \mathrm{j} < \mathrm{k},$$

$$p_{ij}^u + p_{ij}^u + p_{ij}^l = \frac{3}{2}\ \forall \mathrm{i} < \mathrm{j} < \mathrm{k}, \qquad (2.21)$$

$$p_{i(i+1)}^l + p_{(i+1)(i+2)}^l + \dots \dots + p_{(j-1)j}^l + p_{ji}^u = \frac{(j-i+1)}{2}\quad \forall \mathrm{i} < \mathrm{j},$$

$$p_{i(i+1)}^m + p_{(i+1)(i+2)}^m + \dots \dots + p_{(j-1)j}^m + p_{ji}^m = \frac{(j-i+1)}{2}\quad \forall \mathrm{i} < \mathrm{j},$$

$$p_{i(i+1)}^u + p_{(i+1)(i+2)}^u + \dots \dots + p_{(j-1)j}^u + p_{ji}^l = \frac{(j-i+1)}{2}\quad \forall \mathrm{i} < \mathrm{j},$$

In the case of decision matrix with entries which is in the interval of [-c, 1+c] given $(c > 0)$ rather than interval [0,1], the following transformation function is used to transform the obtained fuzzy numbers to preserve the reciprocity and additive consistency f : [-c, 1+c] → [0,1]

$$f\ (x^l) = \frac{x^l + c}{1+2c}\ ,\ (x^m) = \frac{x^m + c}{1+2c}\ ,\ \ f(x^u) = \frac{x^u + c}{1+2c} \qquad (2.22)$$

where x^l, x^m, x^u are define as the lower, medium and upper bound value of all elements of a fuzzy linguistic preference relation (FLPR) matrix. Also c is the least value of all elements in FLPR matrix, which are not in interval of [0,1]. The FLPR procedure for analysis of a decision problem is presented as follows:

Step 1. Decision makers express their fuzzy opinions on a set of alternatives X = $\{x_1, x_2 \ldots \ldots x_n\}$ in a decision problem with pairwise comparisons of the alternatives using fuzzy linguistic assessment variable and develop an incomplete consistent fuzzy linguistic preference relation matrix $\tilde{P} = (\tilde{p}_{ij})_{n\times n}$ with only n-1 judgments $\{p_{12},\ p_{23,} \ldots .,p_{n-1n}\}$.

Step 2. Develop a complete fuzzy linguistic preference relation matrix $\bar{\tilde{P}} = (\tilde{p}_{ij})_{n\times n}$ by adopting the known elements in $\tilde{P}$ and the reciprocal additive propositions to calculate the unknown elements in $\tilde{P}$.

Step 3 Applying linguistic averaging operator to determine the average $\widetilde{A_i}$ of the ith alternative over all other alternatives in order to obtain the fuzzy weight of all alternatives.

$$\widetilde{A_i} = \frac{\sum_{j=1}^{n}\bar{\tilde{p}}}{n} \qquad (2.23)$$

$\widetilde{A_i}$ is the average of each alternative over other alternatives.

The weight $\widetilde{W}$ of each alternative is estimated as:

$$\widetilde{W} = \widetilde{A}_{\iota} / \sum_{i=1}^{n} \widetilde{A}_{\iota} \tag{2.24}$$

Step 4. Defuzzification process of final fuzzy weight values of alternatives is based on the adoption of defuzzification techniques such as the Centre of Area COA, fuzzy mean and spread method and other methods like Mean of Maximum (MOM), and α cut method. A simple approach using fuzzy mean and spread method by (Lee and Li, 1988) is utilized to obtain the crisp value of triangular fuzzy values. Fuzzy mean and spread method is reliable in terms of defuzzifying and ranking of fuzzy numbers because of its easiness to determine the optimum alternatives. The fuzzy mean and spread method for defuzzification is expressed as:

$$(\widetilde{U}) = x\ (l + m + u)/3 \tag{2.25}$$

Step 5. Determination of the optimum alternative from the highest value of fuzzy mean x $(\widetilde{U})$ values of all alternatives. Using the stated procedure above, a pairwise comparison FLPR matrix can be constructed easily based on $(n-1)$ judgment for n criteria or alternatives.

In the Chapter 4 of this research, FLPR approach is utilised in the risk evaluation and ranking process of the petroleum refinery risk elements and their associated attributes. The important steps and the propositions in the FLPR process is also implemented in Chapter 4. FLPR approach has been applied as a multi criteria decision making approach in Wang and Chen, (2011) for fuzzy multi-criteria selection among transportation companies with linguistic preference relations. Lu *et al.*, (2013) applied FLPR for assessing the importance of risk factors in a software development project. Huang *et al*. (2013) applied FLPR for analysis of the evaluation criteria for security firms based in Taiwan.

2.9.5 Evidential Reasoning (ER)

The ER approach has been utilised in diverse field of studies solve multi-criteria decision making problems. The technique has been applied in engineering construction, management and safety to various decision analysis problem. The ER approach has been applied to a problem with qualitative and quantitative characteristic with uncertainty. The concept of ER is based on Dempster- Shafer theory of evidence and decision theory (Yang, 2001). ER as an uncertain reasoning approach is suited for handling incomplete assessment of a decision maker. In the application of ER algorithm generic evidence which represent assessment are expressed using a belief degrees. The mechanism of the ER algorithm involves transforming the lower level criteria assessment to their relevant upper level criteria and to the top level. The rational assessment based on ER algorithm need to follow some self-evidence rule known as synthesis axioms (Yang and Xu 2002). The synthesis axioms are proposed as follows:

- If a criteria or attribute is not assessed to a particular belief grade, then the general criteria or attribute should not be assessed to the same belief grade either.
- If all criteria or attributes are accurately assessed to a particular belief grade then the general criteria or attribute should also be exactly assessed to the same grade.
- If all criteria or attributes are completely assessed to a subset of a belief grades, then the general criteria or attribute must also be completely assessed to the same subset.
- If an assessment is incomplete, then a general assessment attained by aggregating the incomplete and complete assessments should also be incomplete with the degree of incompleteness correctly given.

Based on Sonmez *et al.*, (2001) the stepwise procedure of the ER algorithm is presented as follows:

- Define a decision problem in a hierarchical model.
- Allocate the weights of each criterion and their sub-criteria for the decision problem.
- Select the most appropriate method for assessing a criterion either quantitatively or qualitatively.
- Convert assessments between a criterion and the sub-criteria linked to it if they are assessed by different methods.
- Assess each alternative based on the lowest level attribute in the hierarchical model.
- Compute the qualitative assessments at the top level to obtain an aggregated result for each alternative
- The ranking process for the alternatives is based on highest aggregated result.

The ER algorithm has been verified as a very powerful tool in many decision analyses, with its applications in a risk assessment problems (Kong, *et al.,* 2015; Nwaoha *et al.,* 2013;Yan *et al.,* 2011; Nwaoha *et al.,* 2011;Yang *et al.,* 2009; Ren *et al.,* 2008; Liu *et al.,* 2005; Yang *et al.,* 2005; Yang and Xu, 2002; Sönmez *et al.,* 2001; Wang and Yang, 2001; Yang, 2001; Wang, 2000). The ER algorithm is developed into an Intelligent Decision System software package (IDS). The IDS can be used as a support tool to design a model so desired by a decision maker or risk analyst and input their own data for analysis.

2.9.6 Bayesian Networks (BN)

Bayesian Network is a probabilistic graphical approach. It is also known as Bayesian Belief Network (BBN). BN is a probabilistic cause and effect modelling approach which emerged from years of research in artificial intelligence. BN is a powerful tool for intelligent decision support in solving problems with complexity, uncertainty and probabilistic reasoning. As a probabilistic graphical model, BN is represented as a directed acyclic graph (DAG) indicating various dependencies that exist between variables (Rebai, 2010). The BN comprises of a set of nodes depicted graphically by directed edges. Every single node in a BN defines a probability distribution which is either discrete or continuous. Every single arc signifies the conditional probability dependence. The dependency of a node on another in a BN model is established by a Conditional Probability Table (CPT). Wang and Trbojevic (2007) explain that a basic BN model should be defined within the context of the problem which it is to address by describing the functions, features, characteristics and attributes associated with the problem under investigation. The construction of a BN model should contain the following steps:

- Generate nodes.
- Define relevant problem parameters.
- Define nodes and their probable states.
- Input the nodes into the network pane and label them.
- Describe the states of each node.
- Establish the link between nodes to show their relationship.
- Review the generic model.

2.9.6.1 BN structure

In a BN, a node that is conditionally dependent on other nodes is referred to as a "child node", while it direct preceding nodes are called the "parent nodes". A node without parents is a "root node" and a node without children is a "leaf node". Any node that is not a leaf node or a root node represents the intermediate node. Root nodes are conditionally independent and marginal prior probabilities is assigned to it. A child node is a conditionally dependent node, which is, defined based on the state of its parent nodes using a CPT. Proper links in a BN can be constructed in different ways under various conditions to establish the relationships between variables based on three formalize patterns, namely serial, diverging and converging connections (Fenton and Neil, 2012). Based on the three formalize pattern, a BN model allows interference based on an observable evidence and the model can be updated based on such evidence. The Bayesian's rule is used to establish update in BN in terms of new observation in accordance with a Bayesian's rule. In accordance with random variables B_1 and B_2 in a BN are expressed as follows:

$$P(B_1|B_2) = \frac{P(B_2|B_1)\ P(B_1)}{\sum_{all \ldots i} P(B_2|B_1 = v_i) P(B_1 = v_i)} \tag{2.26}$$

Assuming that variable B_2 is in the state v_j, then, the probability of B_2 value in light of a newly observed evidence is the posterior probability. This distinguishes it from the prior probability held by the analyst before the emergence of new evidence or observation. Considering each state of B_1, Equation 2.26 is utilize to compute the joint probability distribution $P(B_1|B_2 = v_j)$ (Riahi, 2010):

$$P(B_1|B_2 = v_j)\ \frac{P(B_2 = v_j|B_1) P(B_1)}{\sum_{all \ldots i} P(B_2 = v_j|B_1 = v_i) P(B_1 = v_i)} \tag{2.27}$$

2.9.6.2 Joint Probability Distribution (JPD)

The utilization of BN is not limited to depicting causal relationships; it also plays a vital function in terms of representing joint probability distributions. The compact representation of JPD in BN depends on the local JPDs connected to each variable in the network, whose function is to measure the strength of causal relationships illustrated in the BN structure. The behaviour of a variable in the network under every possible assignment of its parents can be mathematically described by the local JPDs. With a specific end goal to indicate the conduct of the variable, it is fundamental to have various parameter exponential in the quantity of parents, and since this number is generally lesser contrasted with the quantity of variables in a BN, this outcome in exponential sparing in space and time (Riahi, 2010). In order to express the clarity of the computational saving, we can hypothetically illustrate a network containing five variables (B_1, B_2, B_3, B_4, and B_5) that are all dependent on each other's influence. Hence, the evaluation of joint probability distribution for the variables based on chain rule from probability theory is stated as follows:

$$P\left(B_{1,} B_2, B_3, B_4, B_5\right) = P(B_1 | B_2 B_3\, B_4\, B_5) \times P(B_2 | B_3 B_4\, B_5\,) \times P(B_3 | B_4\, B_5\,) \times P(B_4\, | B_5\,) \times P(B_5\,) \tag{2.28}$$

Suppose that the dependencies for BN is explicitly modelled, the joint probability distribution can be computed in the following manner:

$$P\left(B_{1,} B_2, B_3, B_4, B_5\right) = P(B_1\, | B_2\,) \times P(B_2 | B_3\, B_4\,) \times P(B_3\, | B_5\,) \times P(B_4\,) \times P(B_5\,) \tag{2.29}$$

For a given BN structure with its local joint probability distribution, the joint probability distribution of the domain of "n" variables is calculated as follows:

$$P(B_{1,} B_2, \dots \dots B_n) = \prod_{i=1}^{n} P(B_i|Pa_i) \quad (2.30)$$

In the equation, Pa_i depicts the parents of variables X_i in the BN whose structure are $\mathbb{G}$. The JPD of variable X_i for a value assignment of its parents Pa_i is defined as the conditional probabilities. The conditional probabilities $Pr(B_i|Pa_i)$ can be specified by $2^{|Pa_i|}$ rather than 2^n parameters, resulting in the exponential space savings mentioned above.

2.9.6.3 History of BN application

Industries started to grow interest in the application of BN in the 90s, particularly when widespread process started to emerge in terms of interface between man and machine to speed up decisions. The development of BN over the years takes into account the integration of knowledge acquired in an observed domain with a prior knowledge of the domain. This development with BN has provided ways to improve small knowledge database. According to Riahi (2010), BN first application was mentioned in Andreassen *et al.,* (1989). Rebai (2010) also mentioned various applications of BN such as for filtering junk e-mail, assistance for blind people, traffic accident reconstruction, image analysis for tactical computer-aided decision, market research, and interaction enhancement, user assistance in software use, fraud detection, and meteorology. According to Rebai (2010) all the works were carried out by Allanach *et al.,* (2004), Cano *et al.,(*2004), Davis, (2003), Jaronski *et al.,* (2001), Lacey & MacNamara (2000), Fennell & Wishner (1998) Horvitz *et al.* (1998) Sahami *et al.,* (1998) and Ezawa and Schuermann (1995). In recent years the application of BN has been widely utilised in the field of safety and risk management of complex systems such as maritime infrastructures, maritime transport, and marine systems. There is widespread application of BN in solving problems relating to maritime to safety performance assessment for maritime safety administration, decision making in highway maintenance, navigational risk estimation, assessment of seafearers performance, knowledge management for liner shipping operator, optimum management of groundwater contamination, quantitative input for maritime risk analysis, supplier selection, accident analysis, water resources management and marine and offshore decision support solution (Salleh *et al.,* 2015; Riahi *et al.,* 2014; Zhang *et al.,* 2014; Wang *et al.,* 2013; Zhang et al., 2013; Ferreira and Borenstein, 2012; Li *et al.,* 2012; Weber *et al.,* 2012; Farmani *et al.,* 2009; Bayraktar and Hastak, 2009; Datubo *et al.,* 2006).

2.10 Conclusions

The primary focus of this chapter involves a comprehensive analysis of petroleum refinery accident, overview of petroleum refinery processes, operation and configuration. The current trend of petroleum refinery operations from a risk management perspective is examined in this chapter. Overview of the guidelines and regulations for safety in the petroleum refining industry, overview of uncertainty associated with the risk management of petroleum refinery operations and the decision perspective in risk management of petroleum refinery operations are reviewed. In this literature review, sensitive causes of risk management failure in the petroleum refining industry were revealed. Various risk/safety assessment approaches that have been employed in risk assessment in the petroleum refining industry are defined and supported with significant literatures. Furthermore, a comprehensive review of uncertainty treatment approaches used for the risk assessment and decision making process for the risk management of petroleum refinery operations in this research was presented. The applications of the uncertainty treatment techniques and their practicality on the subject under investigation are outlined in the research methodologies in Chapter 4, 5, 6 and 7. A novel scientific risk management framework developed in this research incorporate the FLPR as the uncertainty treatment techniques for risk analysis and risk ranking (see Chapter 4), integrated approach based on fuzzy set theory and evidential reasoning approach as the uncertainty treatment approach for the evaluation of the risk level of petroleum refinery operation (see Chapter 5), integrated approach fuzzy set theory and Bayesian reasoning for evaluation of probability of disruption of petroleum refinery operations (see Chapter 6) and integrated approach based on AHP-Fuzzy VIKOR was utilised in multicriteria decision making analysis for the selection of the safety improvement strategy for risk management of petroleum refinery operations.

Chapter 3 - Research Methodology

Summary

This chapter presents the conceptual framework to enhance the safety of petroleum refinery operations. The fundamentals of the methods applied in each phase of the conceptual framework are discussed.

3.1 Introduction

In this chapter the methodology that is fundamental to this research is described. The philosophical hypothesis of the adopted research methodology in each technical chapter is established in a novel conceptual framework of the research. The blue print of a research methodology employed in any investigation is the strategy or plan of action, which a researcher intend to utilise for a research activity from starting point to the conclusion. In the context of this chapter, research is a specific problem undertaking to find answers to a problem based on a structured, systematic, data based, critical, objective and scientific inquiry (Sekaran and Bougie, 2001, p.135 cited in Abubaker 2013). In terms of conducting a piece of research, there are three fundamental methods, which are the quantitative research method, qualitative research method or combination of the two. The qualitative research method places emphasis on the phenomenogicals basis of the study, meaning, an elaborate description of a phenomena or culture study (Creswell, 2003, 2009, p.142 cited in Abubaker, 2013). The qualitative research approach involves discovering and understanding meaning provide to a problem based on individual or group in terms of judgement, perspective and perception regarding the problem. Qualitative research methods can be conducted through empirical study, material case study, personal experience, brainstorming session, historical information, interviews and observation.

The qualitative research method can be constructive, interpretive and inductive in nature. Quantitative research methods are regarded as statistical studies, empirical studies or hypothesis testing research. The strategies for quantitative research methods include: self -administered questionnaire, experimental studies, quasi-experimental studies, pre-test and post-test designs, structured interview schedules and observation schedules (Polkinghorne, 2005). Basically, research methods are procedures for data collection, data analysis, and interpretation that a researcher performs during research work. In this research, the data acquisition process is based on relevant knowledge elicited from experts in the field of study. Thus, this chapter focus on the description of how the research was carried out to fulfil the aim and objectives.

3.2 Description of the research design

The basic research plan formulated to respond to a research problem is vital for the viability and the validity of the research, therefore, developing a systematic process to address important research questions depends on the research method adopted. The main strategy employed in this research is based on selection and the integration of the best qualitative and quantitative methods to provide answers to various segments of the research problem. In an effective research design, close link should be established between research questions, methodology, data collection approach, the nature of data and data analysis process (Hox and Boeije, 2005). The research design is defined in term of the ideology of a conceptual framework with a specific theoretical perspective that accommodate qualitative and quantitative data. Bearing in mind that no particular method fits to respond appropriately to all research questions, therefore, it is expedient to solve a research problem by incorporating several methods since various methods are not mutually exclusive. The application of the research methods and data collection techniques involves the use of multiple theories, collection and amalgamation of qualitative and quantitative data in a single research design to balance the flaw of one method with the strength of the other. In this research the acquisition of data and their justification was established based on the use of questionnaire, literature survey, expert opinion, brainstorming/interview and case study (Gill et al., 2008).

3.3 Sampling frame

A researcher can make a decision on the type of informants or respondents that can be involved in a research project, when the main research question is identified. This process will assist the researcher to establish what type of question to ask the respondent or participant in the research (Harrell and Bradley, 2009).

Due to the high risk of operational activities in the petroleum refinery, choosing the right experts in the investigation of risk of disruption associated with petroleum refinery operations is paramount to this research. Expertise are drawn from operators, managers and consultants in the petroleum refining industry. The collection of qualitative data in this study is determined by selecting the best sample of respondents from major crude oil producing countries, with expertise in petroleum refinery operations. The random sampling involves the consultation with professional and specialist with wealth of knowledge and vast experience on petroleum refinery operations. Hence, the selected experts based on the random sampling are aware of the importance of elements of risk with which they are involved. The capability of each of the selected expert to define and compare which elements of risk has the higher impact in the disruption of a petroleum refinery operation, justify their selection for this research. The criteria for the random selection of the experts is based on their academic qualifications, skills, years of experience in the petroleum refining industry and the position attained (for more details on the experts see Chapter 4, 5, 6 and 7). Based on this sampling process, valid data is collected for risk assessment and decision support for risk management of petroleum refinery operations. In this thesis, the sample size range is between 5-6 experts, consisting of senior managers, process/mechanical/maintenance engineers and consultants in the petroleum refining industry. This sample size is considered because of the fact that specialist in sample field is expected to share certain common values, which justifies the need for less huge sample size. According to Saaty (2001) quoted by Mokthari 2011, a small sample size (i.e.$< 10\,response$) was necessary if data acquisition is from the experts. In this research, these justification provide the convenience of utilising the gathered data from experts.

3.4 Data collection method

Deciding the most suitable method for data collection involve considering the uncertainty of the data in the process of answering a research questions. There are two prominent data collection methods, which are the primary data collection and secondary data collection. The primary data collection involve fresh data collected for a specific research aim, while secondary data collection entails the collection of already existing data in order to be reused for current research (Harrell and Bradley, 2009). The data collection methods are considered as qualitative and quantitative research methods.

The qualitative data collection methods have been generally utilised in research to answer many research questions. The method is introduced where there is a need to understand complexity, interpretations, ideas, values or beliefs as well as experience, which can be utilised to produce inference in a research. The data acquisition process when using the qualitative approach involves acquisition of evidence through report/ document studies, literature review, case studies, brainstorming session/ interview and experts judgement

(Hox and Boeije, 2005). On the other hand, quantitative data collection is characterised by gathering numerical data.

The process of primary data gathering for this research is based on literature review, questionnaire survey, brainstorming session with experts and expert's judgement. The data collected based on expert's judgement are qualitative data. Such data have certain level of uncertainty which are treated by utilising uncertainty treatment technique like fuzzy set theory. Furthermore, the qualitative data based on the expert judgement can be transformed into quantitative data which can be utilised in various phases of the research (i.e. risk/hazard identification and ranking, risk assessment and risk mitigation). The credibility of this research is based on using both qualitative and the quantitative approach for data collection in scientific and consistent manner to enhance the accuracy, validity and reliability of the research findings.

3.5 Data analysis

When a data is collected for a research purpose, it is either to propose a hypothesis and/or deny a hypothesis in order to pursue the scientific theory that clarifies the observed behaviour of a subject under investigation. Therefore, the quality and the depth of the data collected should be verified to enrich the quality of the research finding. The in-depth analysis of data collected for a research purpose should provide a rich descriptions of perceptions and experiences which are valuable complement to the data. In this research, data was gathered based on experts' judgement through the use of survey questionnaire and brainstorming session with the experts. Based on this kind of approach of data acquisition, there will be challenges relating to incompleteness of information, biased judgement and uncertainties in the availability of knowledge possessed by the experts in term of delivering a quality response. This challenges are dealt with in this research with the application of techniques that can check the consistency of the responses and treat uncertainties.

3.6 Research conceptual framework

The generic framework proposed in this research, provides the holistic view of this research work. It is the basis upon which the research methodology will be directed. The generic framework was developed by utilising knowledge of various methods, which was studied, understood, justified and carefully implemented at each phase of the research. The background ideology for the conceptual framework are from extensive review of safety/risk assessment for process industry, risk management with application to the offshore oil and gas industry, process safety management and current practice in petroleum refining industry. The idea behind this conceptual framework is to provide a robust risk management framework for optimising petroleum refinery operation. Adoption of the conceptual framework will provide decision makers in petroleum refineries with a robust risk evaluation and decision support tool to improve their risk management process. Furthermore, the framework can help decision makers in petroleum refineries to intuitively deal with the uncertainties associated with making a risk inform decisions under fuzzy situations. The robustness of the framework was demonstrated based on test case which was utilised in these research. This research framework takes into account the weakness in knowledge and lack of reliable safety data for risk management of petroleum refinery operation.

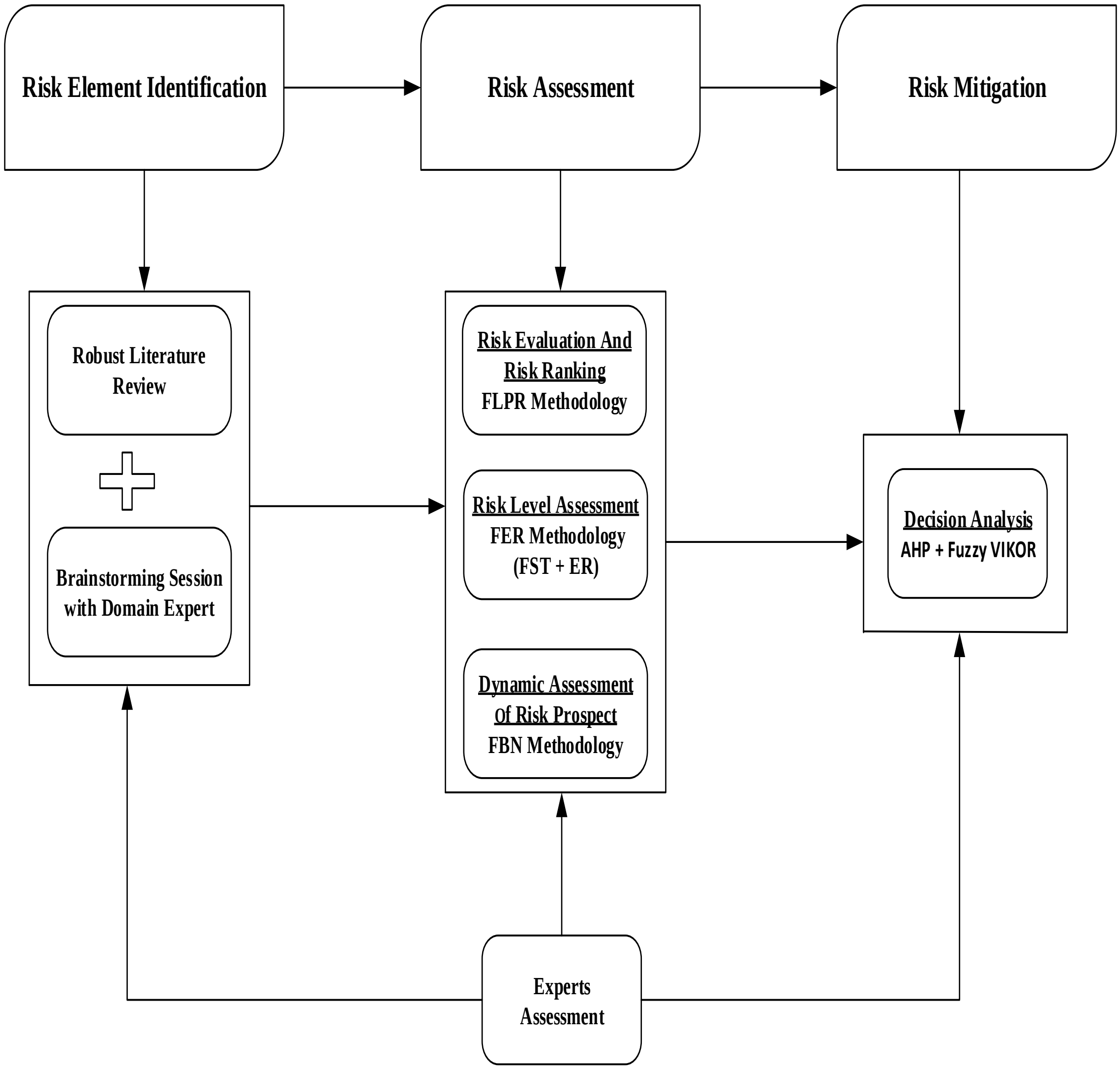

Figure 3.1: A Generic Conceptual Framework for enabling safety improvement of petroleum refinery operations

3.6.1 Risk element identification phase

The risk management framework comprises of the literature review on the existing risk elements associated with the disruption of petroleum refinery operation (see Chapter 2). A brainstorming session with knowledgeable and experienced experts in petroleum refinery operation will be carried out for proper screening of the most significant risk elements and their attributes. The outcome of the screening process based on the experts' opinion will provide the basis for developing a dynamic hierarchical model which will be utilised in the risk assessment phase (see Chapter 4).

3.6.2 Risk assessment phase

The risk elements and their attributes that are identified in Chapter 4 will be depicted in a hierarchical model to establish the interrelationship among them. The risk element and their attribute will be assessed and weighted in order to prioritise and rank them using the FLPR method. The FLPR methodology is fully presented in the Chapter 4.

The second phase of the risk assessment is discussed in Chapter 5. The risk elements prioritised in the Chapter 4 will be further analysed in depth in order to evaluate the disruption risk level associated with petroleum refinery operation. The evaluation process will be carried out using a dynamic methodology based on a fuzzy ER in the assessment process. The Intelligent Decision Software (IDS) software will be utilised in the assessment process.

In Chapter 6 of the research, the possibility of disruption of petroleum refinery operations will be analysed based on utilising a flexible and dynamic approach based on BN technique and FST. The Netica software was used to compute the possibility of disruption of petroleum refinery operation. These assessment process will provide an in depth understanding of the convergent effect of the risk elements and their attributes in terms of their prospect of causing the disruption of petroleum refinery operations.

3.6.3 Risk mitigation phase

In Chapter 7, the strategy to prevent, mitigate and control the most significant attributes of the risk elements that can result in the disruption of the petroleum refinery operations will be determined from a set of proposed alternatives. This will be achieved through the application of multicriteria decision making methodology based on AHP-Fuzzy VIKOR, motivated to consider the complexity and uncertainties with decision making for risk management of petroleum refinery operations. The most significant alternative will be selected using expert elicitation in the evaluation of the proposed alternatives. Based on the evaluation process the chosen alternative is established as the best strategy to improve safety of petroleum refinery operation.

3.7 An analytical framework for evaluating and ranking disruption risks of process unit operation

This Chapter is the first phase in the risk assessment process. Firstly, risk elements and their attributes with the potential to cause disruption to petroleum refinery operations, are screened based on preference and decision of experts after a brainstorming process. The risk element and their attributes are depicted in a hierarchical model to establish the relationship between the risk elements and their attributes. In the next step, the FLPR methodology was utilised in the prioritising process, first by obtaining the weights of the risk elements and their attributes and then ranking them according to their significant level. The FLPR methodology involves the following steps:

Step 1: Problem definition.

Step 2: Identification of risk elements and attributes.

Step 3: Develop the hierarchical structure.

Step 4: Linguistic assessment of risk elements and attributes.

Step 5: Apply (FLPR) approach to determine the weight of all risk elements and attributes in the hierarchical structure.

Step 6: Ranking decision on each risk elements and attributes according to the decreasing order of values.

Expert elicitation was utilised in the assessment process where there is lack of data. Quantifying the expert's opinion allows a systematic analysis of significance of the risk elements and their attribute with the potential to cause disruption of operation in a petroleum refinery.

3.8 A risk modelling approach for the optimization of complex petroleum refinery operations

This chapter present the investigation of the risk level of the risk elements and their attributes which was assessed and ranked in Chapter 4. The use of fuzzy ER methodology tailored to risk assessment to provide decision support in the risk management of petroleum refinery operation, presents an advanced technique to evaluate the risk level of petroleum refinery operations. The summary of the methodology is as follows:

- Establish the relative importance of the risk elements and attributes with potential to cause disruption of operation.
- Determine the fuzzy ratings of all the attributes associated with each risk element.
- Fuzzy risk estimate of all the attributes associated with each risk element.
- Transformation of fuzzy estimates into a belief structure with the same set of evaluation grades.
- Analyse the hierarchical model based on the fuzzy ER methodology to determine disruption risk level of petroleum refinery operations.
- Determine the crisp value of the overall risk level using an expected utility approach.
- Perform sensitivity analysis for partial validation of the result.

3.9 An Application of Fuzzy-BN modelling to evaluate the possibility of disruption of petroleum refinery operations

Chapter 6 of this research presents a risk evaluation approach to investigate the possibility of disruption of petroleum refinery operation based on a fuzzy BN model. The relationship among the risk elements and the attributes whose weights are most significant to cause disruption of petroleum refinery operations are evaluated as a variables in the fuzzy BN model. The variables are utilised to construct the causal network in order to quantify their interrelationship under a dynamic condition and to determine the possibility of disruption of a petroleum refinery operations. The major steps in the fuzzy BN methodology is as follows:

- Establish the relative possibility of the risk elements attributes
- Develop the BN model
- Analyse the model
- Validate the model

3.10 Application of a Compromise Decision Support Model for Strategic Selection of the Optimal Risk Management Strategy for PRPU Operations.

In Chapter 7, the outlines for the selection of the most appropriate strategy from a proposed set of alternatives to improve the risk management of petroleum refinery operations is presented. The AHP-Fuzzy VIKOR is a multicriteria decision approach that provides the basis for decision support in the selection of a proactive risk management option for petroleum refinery operations. Based on the assessment conducted in Chapter 4, 5 and 6, the methodology for the decision support to improve risk management of the most significant attributes is presented as follows:

- Determine the decision weight of evaluation criteria by aggregation based on experts' preference opinion.
- Determine the rating of alternatives with respect to each criteria.
- Develop a fuzzy decision matrix.
- Defuzzified the decision matrix.
- Construct a normalized matrix.
- Estimate the overall value of each alternative based using the separate measures parameters.
- Determine the ranking of each alternative based on the decreasing order of overall value of the separate measure parameters.

3.11 Rational for the use of the methodologies proposed in this research.

It is envisaged that the acquisition of historical failure data/information for modelling and the analysis of PRPU complex risk scenarios is uncertain. Therefore, there is a need to utilise methodologies that are flexible and comprehensive as possible to handle the inherent fuzziness of information concerning risk parameters. Due to the fact that randomness and uncertainty are inherent problems of risk modelling and decision making on real-life complex risk scenarios in the petroleum refinery domain, the methodologies applied in this research are justified based on the following reasons:

- The methodologies incorporated into the developed framework, provides flexibility that allows the use of experts' subjective assessment to quantify the criticality level of disruption risk elements and their attributes efficiently without any loss of useful information in the assessment process.

- The methodologies can cope with the growth of the interactive complexity that can exist in terms of risk and decision modelling of complex scenarios based on hierarchical propagation of evidences between different levels in a model. The methodologies provide a suitable way to deal with incomplete knowledge of the state of the relationship between variables within a given domain. In addition, the methodologies were selected because of their credibilities in terms of their applications in various fields of engineering and medical research (*i.e.* utilised for medical prognosis, application for risk modelling of marine and offshore systems and application for decision modelling of risk management criteria). The methodologies can provide a practical and clear, unambiguous interpretation of uncertainty in risk analysis of complex systems, where relevant data is scarce.

3.12 Conclusion

The brief outline of the research methods adopted for investigation in each phase of this research is presented. The philosophy of the research was illustrated in the conceptual framework, which was used to depict the research perspectives. Various sections of this chapter discussed the research design, sampling frame, data collection method, data analysis and data source were explained. This chapter further provides the summary of the application of the research methods in each phase of the research work to justify the conceptual framework.

Chapter 4 - An Analytical Methodology for Evaluating and Ranking Disruption Risks of a Petroleum Refinery Operations

Summary

This chapter produces a novel application of FLPR methodology for the evaluation and the ranking of the disruption risks of a petroleum refinery operations. FLPR methodology was applied to a case study of a complex petroleum refinery operations. The methodology provides a proactive approach which can be utilised by risk analysts and decision makers in the petroleum refinery domain to determine the relative weights and the importance of risks associated with their operations. This methodology will enhance risk managers ability in the petroleum refinery domain, to channel resources for adequate prioritisation of the importance risks.

4.1 An overview of PRPU risk management

Petroleum refinery process units, as a complex system, require efficient scientific knowledge and understanding of different issues relating to technical, organizational and operational problems which can result in high risk of accident. Irrespective of the continuous development in safety design methods and operating procedures to overcome the high risks, which pose significant threat to life of personnel in PRPU environment, recordable losses due to major accidents still occur (Reniers and Amyotte, 2012; Vinnem *et al.,* 2012; Knegtering and Pasman, 2009). In order to mitigate high risk of PRPU accident, it is important to analyse and prioritise the significant root causes of disruption of PRPU operations, in order to improve the risk management process in a PRPU domain. Therefore, critical risk elements and their associated attributes that can cause the disruption of a PRPU operation must be analysed and prioritise in order to determine their level of influence in contributing to the disruption. The outcome of the evaluation and the prioritization process can provide a salient risk information to decision makers and duty holders operating a PRPU in order to allocate resources efficiently, for risk mitigation and control.

4.2 Refineries process unit risk elements

The process of investigating and identifying critical risk elements for major hazard facilities like petroleum refinery process units is very rigorous due to the complexity and diversity of their operations. The most significant root causes of disruption of petroleum refinery process unit operations are investigated and the significant risk elements and their attributes of refinery process units are identified. The selection of the most critical risk elements and their attributes is carried out based on a comprehensive literature review and brainstorming session with field experts in petroleum and gas refinery operations. The risk elements and their associated attributes are represented in a hierarchical model. The model is an illustrative structure that depicts the common interactions of risk elements and their attributes, in order to analyse the disruption risk of PRPU operation. The overall effects of the risk elements and their attribute on PRPU operations can be quantify by incorporating effective risk modelling methodology. The hierarchical model shows the interactions, such that the attributes at the lower level are linked to the risk elements at higher level. For instance, attributes at lower levels, such as process equipment failure, is a subset of the technical risk element at a higher level. For the purpose of this study the term 'element' is used to describe part of something, particularly situations or activities that can initiate hazardous events (Wu *et al.*, 2015). The most significant risk elements that can cause interruption of petroleum refinery process units' safety and effectiveness in operation is enumerated in Table 4.1 and are further discussed in details in Sections 4.2.1 to 4.2.4. Figure 4.1 presents the detailed hierarchical model for petroleum refinery, process units' disruption risk.

4.2.1 Technical risk elements

In a major hazard facility like petroleum refineries, a variety of potentially hazardous products are being produced from crude oil, therefore, it is very important that the technical reliability of functional assets used in refinery process units perform at an optimum level to enable smooth operations. Any failure or deficiency in technical measures and performance can cause significant issues, such as process equipment failures, instrument failure, piping failure and utility system failure, which can interrupt smooth operations of refinery process units and cause huge financial consequences. Due to the complexity of technology to control and maintain operational reliability of refinery process units and other interconnected structures, there is a need to consider the aforementioned risk issues in order to identify and understand their synergies and influence with other potential hazards that can lead to accidents.

4.2.2 Operational risk elements

Refinery process units consist of several interconnections of complex equipment and machinery which operate in extreme conditions. Any deterioration in operating performance of the equipment and machinery under severe conditions in the refinery process unit environment, can result in a terrible operational hazard that can sometimes affect operations such as start-up, shutdown, maintenance, processing and storage. If a significant operational hazard is not critically addressed in an appropriate fashion, it may increase the probability of operational risks which may result in higher operating costs, production loss and dangerous situations that could cause a serious accident. In order to reduce high risk of operational failure and boost refinery process units operational availability and reliability, focus must be on operational risk elements which are considered as important initiator of disruptions to refinery process unit operations. Attributes such as deviations from operational procedure, operator incompetency, inadequate communications and inadequate maintenance procedure are identified as the most critical root causes of high risk with serious consequences to refinery process units operational reliability and availability.

4.2.3 Organizational risk elements

Organization safety alertness and focus is crucial to proactive evaluation and management of safety in a high risk critical system like a petroleum refinery. High risk of process unit operations needs to be anticipated and appropriate organizational safety management approach should be adopted in a systematic manner to prevent the risk or to mitigate the consequences of risk. In a petroleum refinery, organizational safety management under-performance, is a critical issue that has wreaked havoc by contributing to major refinery accidents. For example, the BP Texas refinery accident in 2005 and Chevron Richmond refinery accident in 2012 provides a clear view of the significant impact of organizational safety management under-performance, as a major factor in the build-up to the accident. In order to maintain a high level of organizational safety performance in petroleum and gas refineries, it is important to consider some significant root causes of organizational risk elements. As such are inappropriate management procedure, inappropriate decision making, inadequate staffing, poor safety monitoring and auditing, and lack of safety training and drills and their impact on effective risk management of petroleum refinery process unit operation.

4.2.4 External risk elements

To reduce the risk of petroleum refinery process unit accidents or mitigate the consequences, there is a need to address core external risk elements which have contributed significantly to accidents in the past, in petroleum and gas refineries. Root causes of external risk element, such as natural hazards, sabotage and terrorist attacks have contributed to disruption of PRPU operations.

Table 4.1 Significant risk elements and attributes

Level 2 risk element	Level 3 attributes
E_1 Technical risk element	E_{11} process equipment failure
	E_{12} instrument failure
	E_{13} piping system failure
	E_{14} utility system failure
E_2 Organizational risk element	E_{21} inappropriate management policy/procedure
	E_{22} inappropriate decision making
	E_{23} inadequate staffing
	E_{24} poor safety monitoring/auditing
	E_{25} lack of safety training/drill
E_3 Operational risk element	E_{31} deviation from operation procedure
	E_{32} operator incompetency
	E_{33} inadequate communication
	E_{34} inadequate maintenance procedure
E_4 External risk element	E_{41} natural hazard
	E_{42} sabotage
	E_{43} terrorist attack

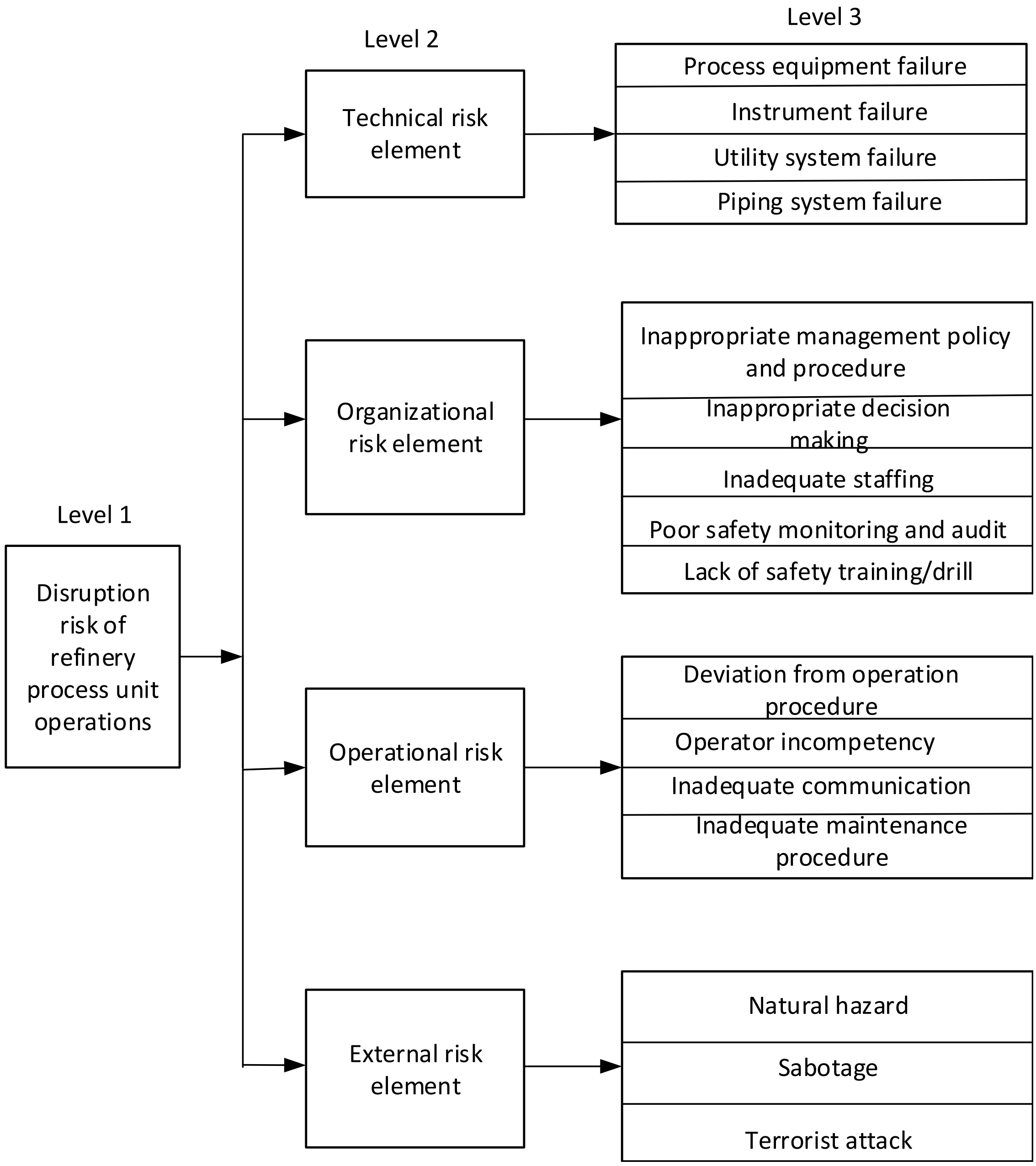

Figure 4.1 Hierarchical model for disruption risk of petroleum refinery process unit operation

4.3 Linguistic assessment of risk elements and attributes

Linguistic variables are regarded as expressions in natural or artificial language which can be implemented to indicate the preference value of one criteria over another in a decision-based hierarchical model. For the purpose of this study, the idea of using the linguistic assessment variables is to deal with complexity or inconsistency of decision maker's opinion in order to express it in a quantitative manner. Linguistic expressions such as; absolutely not important, very strongly not important, essentially not important, weakly not important, equally important, very strongly important and absolutely important are used for pairwise comparisons of risk elements and attributes of disruption risk of PRPU operations. The linguistic expressions can be expressed in fuzzy numbers based on the Triangular Fuzzy Number (TFN) proposed by (Chen and Hwang, 1992). Triangular fuzzy number (TFN) is a fuzzy set function that can be adopted to deal with the uncertainty and vagueness associated with decision makers' opinion in terms of solving practical problems. TFN provides decision makers' with a reasonable way to represent subjective and imprecise information in a logical manner. For a fuzzy number, $\tilde{P}$, TFN can be denoted by $\tilde{P} = (l, m, u)$ where l, m and u are expressed as lower, upper and median bounds of the fuzzy number. Based on operational laws of TFN number in Wang and Chen (2008), the algebraic operations of any two triangular fuzzy numbers $\tilde{P}_1$ and $\tilde{P}_2$ or a real number r and a triangular fuzzy number can be expressed in the following manner:

Addition operation $\oplus$:

$$\tilde{P}_1 \oplus \tilde{P}_2 = (l_1,\ m_1,\ u_1) \oplus (l_2,\ m_2,\ u_2)\ = (l_1 + l_2\ ,\ m_1 + m_2,\ u_1 + u_2\ ) \quad (4.1)$$

Subtraction operation $\ominus$:

$$\tilde{P}_1 \ominus \tilde{P}_2 = (l_1,\ m_1,\ u_1) \ominus\ (l_2,\ m_2,\ u_2) =\ (l_1 - u_2\ ,\ m_1 - m_2, u_1 - l_2\ ) \quad (4.2)$$

Multiplication operation $\otimes$:

$$\tilde{P}_1\ \otimes \tilde{P}_2\ = (l_1,\ m_1,\ u_1) \otimes (l_2,\ m_2,\ u_2) = (l_1 l_2\ , m_1 m_2, u_1 u_2\ )\ \cong \text{for } l_1 > 0, m_1 > 0, u_1 > 0. \quad (4.3)$$

Division operation $\oslash$:

$$\tilde{P}_1 \oslash \tilde{P}_2 = (l_1, m_1, u_1) \oslash (l_2, m_2, u_2) \cong \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2}\right) \text{ for } l_1 > 0, m_1 > 0, u_1 > 0 \quad (4.4)$$

Logarithm operation:

$\log_k(\tilde{P})$ = ($\log_k l$, $\log_k m$, $\log_k u$,) k is base. (4.5)

Reciprocal operation:

$(\tilde{P})^{-1} = (l, j, u)^{-1} \cong$ for $l, m, u > 0$ (4.6)

The TFN membership function is expressed in Equation (4.7). In addition, Figure 4.2 shows a triangular fuzzy member function.

$$\mu_{\tilde{p}} = f(x) = \begin{cases} \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0, & \end{cases} \quad (4.7)$$

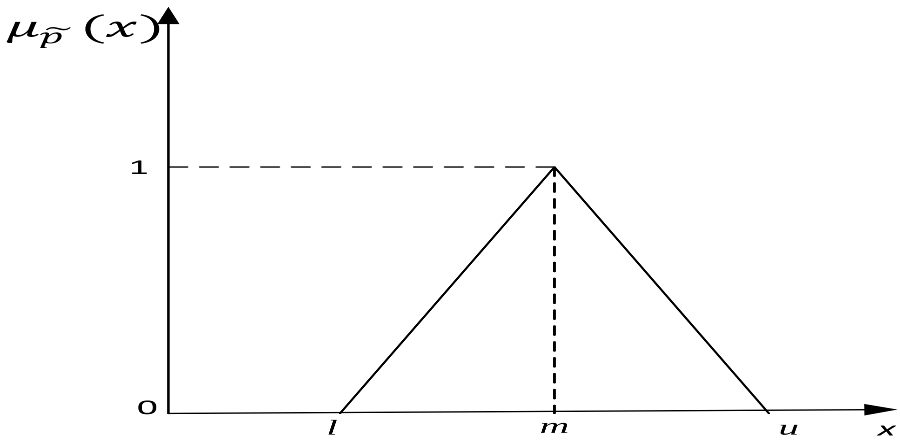

Figure. 4. 2 Triangular fuzzy membership function

4.3.1 Triangular fuzzy conversion scale for pairwise comparison

Appropriate selection of fuzzy scale for pairwise comparisons of fuzzy opinions of experts is adopted from Wang and Chen (2011). The pairwise comparison scale is used in this study to establish the intensity of risk elements of petroleum refineries process units disruption risk based on expert judgement, which are represented using linguistic terms with corresponding triangular fuzzy value as shown in Table 4.2. Also, Figure 4.3 shows the triangular fuzzy importance scale.

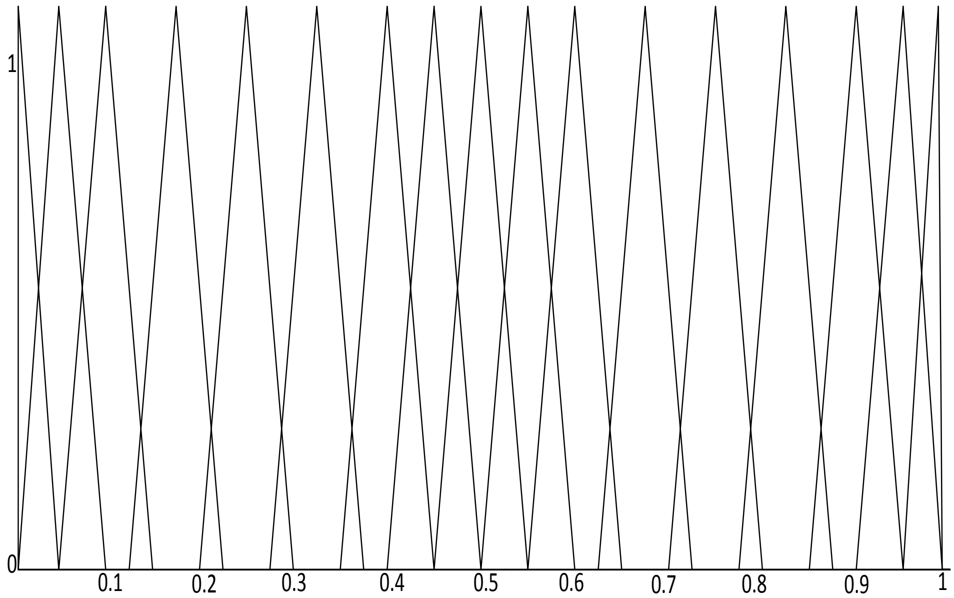

Figure. 4.3 Triangular fuzzy importance scale adapted from Wang and Chen, 2011

Table 4.2: Fuzzy linguistic assessment variables

Linguistic variables	Triangular fuzzy number	Triangular fuzzy reciprocal scale
Equally important (EQ)	(0.45, 0.5, 0.55)	
Intermediate value between EQ and WK (WE)	(0.5, 0.55, 0.6)	(0.4, 0.45, 0.5)
Weakly more important (WK)	(0.55, 0.6, 0.65)	(0.35, 0.4, 0.45)
Intermediate value between WK and strongly more important ST (WS)	(0.625, 0.675, 0.725)	(0.275, 0.325, 0.375)
strongly more important (ST)	(0.7,0.75, 0.8)	(0.2, 0.25, 0.3)
Intermediate value between ST and VS (VT)	(0.775, 0.825, 0.875)	(0.125, 0.175, 0.225)

Table 4.2-Continued

Very strongly more important (VS)	(0.85,0.9,0.95)	(0.05, 0.1, 0.15)
Intermediate value between VS and AB (VA)	(0.9, 0.95, 1)	(0, 0.05, 0.1)
Absolutely important (AB)	(0.95, 1, 1)	(0, 0, 0.05)
The inverse of the linguistic variables are (LWE), (LWK), (LWS), (LST), (LVT), (LVS), (LVA), (LVS), and (LAB). These inverse linguistic variables are represented as the triangular fuzzy reciprocal values.		

4.3.2 Determining the weight of experts

It is important in decision making to determine the weight of a group of experts employed, to give their subjective opinion on risk elements or attributes that can affect the reliability of a system under investigation. Therefore, the reliability and quality of experts' subjective opinion is based on assigned weights of each expert using criteria such as knowledge proficiency and experience, qualifications, industrial and, academic position. Based on the aforementioned criteria, the experts' weights can be calculated in a simple manner by using the Delphi method to obtain the weight score of expert based on Equation 4.8.

$$W_{ei} = E_{ip} + E_{ke} + E_{aq}$$
$$W_{ef} = \frac{W_{ei}}{\sum_{i=1}^{n} W_{ei}} \qquad (4.8)$$

where W_{ei} is the weighting factor of which E_{ip}, E_{ke}, and E_{aq} are the industrial position score, knowledge, proficiency/experience score and an academic qualification score for each expert, respectively. W_{ef} is the weight of expert and in this study, the Delphi method is adopted to obtain the weights of 'm' experts in order to aggregate their fuzzy judgement from *n* – 1 pairwise comparison values $\{\bar{\tilde{p}}_{12\,,}\ \bar{\tilde{p}}_{23}\ \ldots\ \bar{\tilde{p}}_{(n-1)n}\}$;

$$\bar{\tilde{p}}_{ij} = W_{ef} \otimes (\tilde{p}_{ij}^{1} \oplus \tilde{p}_{ij}^{2} \oplus \tilde{p}_{ij}^{3} \oplus \ldots\ldots \oplus \tilde{p}_{ij}^{m}) \qquad (4.9)$$

Table 4.3: Weighting scores for experts

Criteria	Categories	Score
Industrial position	Petroleum refinery manager/ Refinery Consultant	5
	Senior (refinery engineer/process engineer/ process safety manager)	4
	Process safety analyst	3
	Junior engineer	2
	Technician	1
Experience / knowledge proficiency	$\geq$ 20 years	5
	11- 20 years	4
	6-10 years	3
	1-5 years	2
	None of the above	1
Academic qualifications	PhD	5
	Master degree	4
	Bachelor degree	3
	HND	2
	HNC	1

4.4 Application of Fuzzy linguistic preference relation (FLPR) process for weight estimate

In this study, the assessment of the relative weight of the risk elements and their attributes that can cause the disruption of a petroleum refinery process unit operations is important, in order to prioritize the risk elements and their attributes according to their level of significance. The process will enhance the understanding of their impact in terms of disruption of PRPU operations. The FLPR procedure which was presented in Section 2.9.4 is utilised to evaluate and rank PRPU risk elements and their associated attributes, in order to determine the degree of their importance.

The FLPR procedure lessens the difficulty and the inconsistency associated with the evaluation of a complex and sensitive hierarchical model problem (Wang and Chen, 2011). In terms of utilising the FLPR procedure in the estimation of the importance weights of the PRPU risk elements and their attributes, it provides the benefit of maintaining consistency of a pairwise comparison matrix of experts judgement or preferences (Wang and Chen, 2008; Wang and Lin, 2009; Chen and Chao, 2011; Chen *et al.*, 2011). In order to avoid uneven deductions in the assessment and ranking process of PRPU risk elements and their attributes, the FLPR procedure provides the flexibility for consistent comparability of the decision makers' preference by using fuzzy linguistic assessments variables.

When using the FLPR approach, it is quite easy to avoid exasperation in collecting a consistently sound judgement without prejudice from experts when using a questionnaire. Using FLPR approach is much more convenient and reasonable to avoid a complex pairwise comparison and to check for inconsistencies in the decision matrices. The schematic of the FLPR methodology is presented in Figure 4.4.

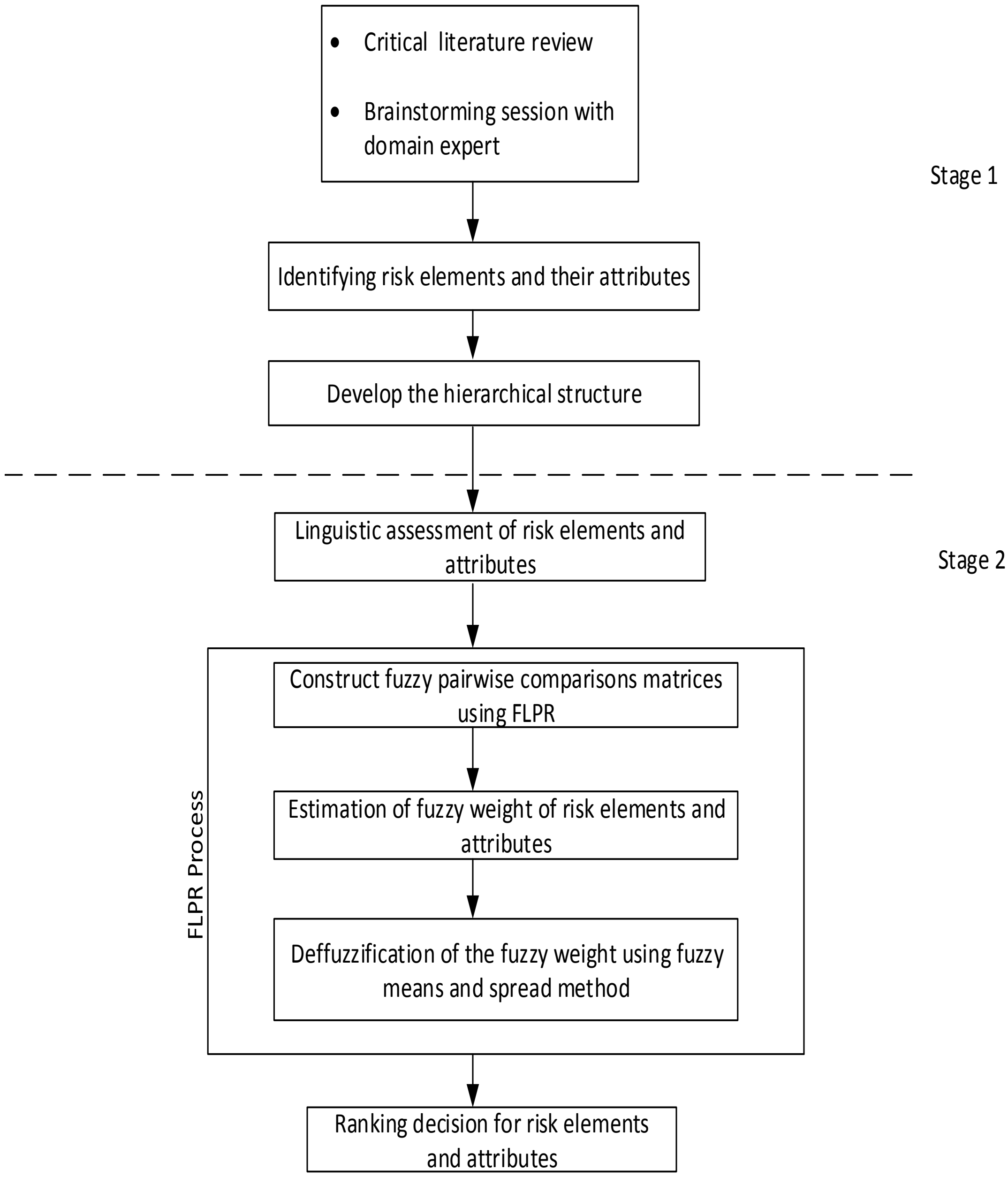

Figure 4.4: Schematic of FLPR methodology for evaluation and ranking of disruption risks PRPU operation

4.5 Case study

A generic case study of an onshore complex petroleum refinery, with over 20 years of operation, reasonable management of change in organizational structure and policies, and fairly reliable safety standards is considered for investigation. With the aim of reducing high risk of disruption of PRPU operation, the major challenge is how to determine the importance level of the risk elements and their attributes which has been identified and approved by an expert as the significant causes of disruption of PRPU operations. For the purpose of this study six experts are successfully convinced to participate in the assessment process.

- Step 1: Problem definition

To investigate and evaluate important risk elements and attributes that can cause disruption to the smooth operations of petroleum refinery process units.

- Step 2: Identify risk element and attributes associated with the disruption of PRPU operation

Critical literature review and brainstorming sessions with experts and scholars having comprehensive understanding of petroleum refinery process unit operations and years of practical experience. This will provide the basic information for identification of significant risk element and attributes that are observed and perceived to be a significant threat to PRPU operations. In this study, four major risk elements and sixteen attributes are considered as the major threat to PRPU operations.

- Step 3: Develop the hierarchical structure

The relationship between the four major risk elements and sixteen attributes which are identified is presented in the hierarchical structure. The hierarchical structure provides reliable information for the risk evaluation process in order to enhance effective risk management of PRPU operations.

- Step 4: Linguistic assessment of risk elements and attributes

The linguistic variable for pairwise comparison rating for the risk elements and their attributes are presented in Table 4.2. The pairwise comparisons of risk elements and their attributes in the hierarchical structure are established based on the experts' judgement. A questionnaire was provided to experts with 5 to 20 or more years' of experience, in order to obtain their opinion on the disruption risk of complex refinery process unit operations. The experts conduct the pairwise comparisons of the risk elements with respect to the goal. They also compared the attributes with respect to the risk elements. The weights of the experts that gave the judgements on the pairwise comparisons of the risk elements and their attributes are obtained. Table 4.4 shows the expert weight based on Delphi evaluation procedure (see Section 4.3.2).

Table 4.4: Weight of experts

Position	Experience/ knowledge proficiency	Qualification	Weighting factor	Weight of experts
Consultant	10 years	PhD	5+3+5 = 13	$\frac{13}{74}$ = 0.176
Senior engineer	5 years	Masters	4+2+4 = 10	$\frac{10}{74}$ = 0.135
Senior engineer	Over 20 years	Bachelor degree	4+5+3 = 12	$\frac{12}{74}$ = 0. 162
Senior manager	Over 20 years	PhD	5+5+5 = 15	$\frac{15}{74}$ = 0.2
Senior engineer	5 years	Masters	4+2+4 = 10	$\frac{10}{74}$ = 0.135
Senior manager	Less than 20 years	PhD	5+4+5 = 14	$\frac{14}{74}$ = 0.19
			74	1

To determine the overall value of experts for the pairwise comparison of risk elements and their attributes, the weight of each expert and the rating was aggregated. The six expert judgments assigned to the pairwise comparison of risk elements is used to calculate the overall experts' judgement on each risk element and their attributes' in the hierarchical model. Table 4.5 shows the linguistic variables assigned by the experts for pairwise comparisons of the risk elements with respect to the goal; the judgment of the six experts for the pairwise comparison of risk elements as well as the aggregated value of the six expert judgement for risk elements with respect to the goal is presented in Tables 4.6 and 4.7. Furthermore, expert's linguistic judgment of all the attributes in regard to risk elements is presented in Table 4.8.

Table 4.5: The linguistic terms of expert judgement for pairwise comparisons of risk elements

	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	
E_1	LST	ST	EQ	VS	LST	WS	E_2
E_2	VS	WS	LST	LVT	VS	EQ	E_3
E_3	LVT	ST	LST	ST	VS	VS	E_4

Table 4.6: Judgement of six experts for risk elements

	Expert1(0.176)	Expert 2 (0.135)	Expert 3 (0.162)	Expert 4 (0.2)	Expert 5 (0.135)	Expert 6 (0.19)	
E_1	(0.2, 0.25, 0.3)	(0.7, 0.75, 0.8)	(0.45, 0.5, 0.55)	(0.85, 0.9, 0.95)	(0.2, 0.25, 0.3)	(0.625, 0.675, 0.725)	E_2
E_2	(0.85, 0.9, 0.95)	(0.625,0.675, 0.725)	(0.2,0.25,0.3)	(0.125, 0.175, 0.225)	(0.85, 0.9, 0.95)	(0.45, 0.5, 0.55)	E_3
E_3	(0.125, 0.175, 0.225)	(0.7, 0.75, 0.8)	(0.2, 0.25, 0.3)	(0.7, 0.75, 0.8)	(0.85, 0.9, 0.95)	(0.85, 0.9, 0.95)	E_4

Table 4.7: Aggregated value of experts on pairwise comparisons of risk elements with respect to goal

Risk elements	Aggregated expert value	Risk elements
E_1	(0.52,0.57,0.62)	E_2
E_2	(0.49,0.54,0.61)	E_3
E_3	(0.56,0.61,0.67)	E_4

Table 4.8: The linguistic terms of expert judgement for pairwise comparisons of attributes (FLRP)

		Expert1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	
E_1	E_{11}	LVS	LST	EQ	VS	LST	EQ	E_{12}
	E_{12}	ST	VS	AB	EQ	VS	VS	E_{13}
	E_{13}	VS	ST	LVS	VT	VS	WS	E_{14}
E_2	E_{21}	VS	EQ	LST	ST	VT	VT	E_{22}
	E_{22}	ST	ST	VS	WS	EQ	VS	E_{23}
	E_{23}	LST	LST	VS	VS	LVS	LST	E_{24}
	E_{24}	LVS	WS	VS	EQ	LVS	LAB	E_{25}
E_3	E_{31}	LVS	EQ	VS	ST	VS	LST	E_{32}
	E_{32}	VA	EQ	LST	VS	VS	LWS	E_{33}
	E_{33}	LST	EQ	VS	ST	LST	ST	E_{34}
E_4	E_{41}	ST	LWS	ST	WS	LST	ST	E_{42}
	E_{42}	VS	LST	WS	EQ	VS	EQ	E_{43}

- Step 5: Application of FLPR process to determine the weight of each risk element and their attributes in the hierarchical structure

The weight of the risk elements and attributes of the disruption risk of PRPU operations are estimated using fuzzy linguistic preference relation method (FLPR). Based on the application of FLPR procedure, the subjective response of experts can be transformed into quantitative variables to estimate the weight of risk elements and attributes presented in the hierarchical structure and rank them according to their level of importance.

The feedback from the experts is utilised to construct an incomplete FLPR matrix for a set of *n*-1 preference values as stated in the FLPR process. The incomplete FLPR matrix values are represented in triangular fuzzy importance scale values as detailed in Table 4.2. The complete FLPR matrix is established using the step 2 of FLPR procedure for weighing and ranking in Section 2. 9.4.

The whole procedure for establishing FLPR pairwise comparison matrix and the process of obtaining risk elements weights is illustrated in this study by presenting the evaluation of attributes with respect to a technical risk element as an example. The attributes defined as E_{11}, E_{12}, E_{13} and E_{14}, has only three pairwise comparison judgements ($\tilde{p}_{12,}\ \tilde{p}_{23}\ \tilde{p}_{34}$), which means comparisons from E_{11} to E_{12}, from E_{12} to E_{13} and from E_{13} to E_{14} is required to construct the fuzzy linguistic preference relation matrix. The pairwise comparison matrix structure for the attributes relating to the technical risk element is shown in Table 4.9.

Due to the differences in preferences and competencies of the experts, a questionnaire designed based on linguistic assessment variables is used to obtain fuzzy data on pairwise comparisons of the attributes relating to the technical risk element. The fuzzy data obtained from the experts is converted into triangular fuzzy values to construct the initial FLPR matrix as shown in Table 4.10. The whole calculation for the FLPR matrix of attributes relating to the technical risk elements is based on the proposition stated in Section 2.9.4 (see Appendix E for details of the calculations).

Table 4.9: Pairwise comparison matrix structure for attributes relating to technical risk element

Technical risk element	E_{11}	E_{12}	E_{13}	E_{14}
E_{11}	P_{11}	P_{12}	P_{13}	P_{14}
E_{12}	P_{21}	P_{22}	P_{23}	P_{24}
E_{13}	P_{31}	P_{32}	P_{33}	P_{34}
E_{14}	P_{41}	P_{42}	P_{43}	P_{44}

Table 4.10: Incomplete FLPR pairwise comparison matrix of attributes with respect to technical risk element

Technical risk element	E_{11}	E_{12}	E_{13}	E_{14}
E_{11}	(0.5, 0.5, 0.5)	(0.39, 0.43, 0.48)	P_{13}	P_{14}
E_{12}	P_{21}	(0.5, 0.5, 0.5)	(0.76, 0.81, 0.85)	P_{24}
E_{13}	P_{31}	P_{32}	(0.5, 0.5, 0.5)	(0.64, 0.69, 0.74)
E_{14}	P_{41}	P_{42}	P_{43}	(0.5, 0.5, 0.5)

Based on the FLPR, for element p_{ij} which signifies the intensity ratio for preference of one risk element over another, certify the condition that p_{ij} = 0.5 if there is no difference between two risk elements after pairwise comparison. Similarly the condition applies to the diagonal elements P_{11}, P_{22}, P_{33} and P_{44} in the matrix structure whereby value is presented in equivalent to the triangular fuzzy number (0.5, 0.5, 0.5) as shown in Table 4.10. Also, P_{12}, P_{23} and P_{34} indicate the $n-1$pairwise comparison of four attributes with respect to the technical risk element. Hence, the unknown elements in the matrix which are P_{13}, P_{14}, P_{21}, P_{24}, P_{31}, P_{32}, P_{41}, P_{42} and $P_{43}$are calculated using the FLPR propositions.

The complete FLPR matrix for the calculations above is shown in Table 4.11. The FPLR matrix has certain values which are not in the interval [0, 1], therefore, the FPLR matrix is transformed using the transform function as stated in Section 2.9.4 to preserve the reciprocity and additive consistency of the matrix. Table 4.12 shows the transformed FLPR matrix.

Using the same steps in the FLPR procedure, the FPLR matrices for other attributes with respect to their risk elements and that of the risk element with respect to the goal are estimated and presented in Tables 4.13, 4.14, 4.15, 4.16, 4.17, 4.18 and 4.19. Furthermore, the average values $(\widetilde{A_i})$, the weights$(\widetilde{W})$, and the deffuziffied values of all risk elements and their attributes are calculated and presented in Table 4.20. Defuzzified values are obtained based on the fuzzy mean and spread method to perform ranking of the risk elements and their attributes according to the level of their importance.

Table 4.11: Complete FLPR pairwise comparison matrix of attributes with respect to technical risk element

	E_{11}	E_{12}	E_{13}	E_{14}
E_{11}	(0.50,0.50,0.50)	(0.39,0.43,0.48)	(0.65,0.74,0.83)	(0.79,0.98,1.07)
E_{12}	(0.52,0.57,0.61)	(0.50,0.50,0.50)	(0.76,0.81,0.85)	(0.90,1,1.09)
E_{13}	(0.17,0.26,0.35)	(0.15,0.19,0.24)	(0.50,0.50,0.50)	(0.64,0.69,0.74)
E_{14}	(-0.07,0.28,0.46)	(-0.09,0,0.10)	(0.26,0.31,0.36)	(0.50,0.50,0.50)

Table 4.12: Transform FLPR matrix of technical risk element attributes

	E_{11}	E_{12}	E_{13}	E_{14}
E_{11}	(0.51,0.51,0.51)	(0.41,0.45,0.50)	(0.64,0.72,0.79)	(0.76,0.92,1.0)
E_{12}	(0.53,0.57,0.60)	(0.51,0.51,0.51)	(0.73,0.78,0.82)	(0.85,0.94, 1.0)
E_{13}	(0.22,0.30,0.38)	(0.21,0.24,0.28)	(0.51,0.51,0.51)	(0.63,0.67,0.72)
E_{14}	(0.02,0.09,0.25)	(0,0,0.16)	(0.30,0.34,0.38)	(0.51,0.51,0.51)

Table 4.13: Incomplete FLPR matrix with respect to goal

Risk element	E_1	E_2	E_3	E_4
E_1	(0.5,0.5,0.5)	(0.52,0.57,0.62)	P_{13}	P_{14}
E_2	P_{21}	(0.5,0.5,0.5)	(0.49,0.54,0.61)	P_{24}
E_3	P_{31}	P_{32}	(0.5,0.5,0.5)	(0.56,0.61,0.67)
E_4	P_{41}	P_{42}	P_{43}	(0.5,0.5,0.5)

Table 4.14: Complete FLPR pairwise comparison matrix of risk elements with respect to goal

	E_1	E_2	E_3	E_4
E_1	(0.50,0.50,0.50)	(0.52,0.57,0.62)	(0.51,0.61,0.73)	(0.57,0.72,0.9)
E_2	(0.38,0.43,0.48)	(0.50,0.50,0.50)	(0.49,0.54,0.61)	(0.55,0.65,0.78)
E_3	(0.27,0.39,0.49)	(0.39,0.46,0.51)	(0.50,0.50,0.50)	(0.56,0.61,0.67)
E_4	(0.10,0.28,0.5)	(0.22,0.35,0.45)	(0.33,0.39,0.44)	(0.50,0.50,0.50)

Table 4.15: Complete FLRP pairwise comparison matrix attributes with respect to organizational risk element

	E_{21}	E_{22}	E_{23}	E_{24}	E_{25}
E_{21}	(0.50,0.50,0.50)	(0.63,0.68,0.73)	(0.83,0.93,1.03)	(0.74,0.87,1.04)	(0.52,0.81,0.91)
E_{22}	(0.27,0.32,0.37)	(0.50,0.50,0.50)	(0.70,0.75,0.80)	(0.61,0.71,0.81)	(0.39,0.53,0.68)
E_{23}	(-0.03,0.07,0.17)	(0.20,0.25,0.30)	(0.50,0.50,0.50)	(0.41,0.46,0.51)	(0.19,0.28,0.38)
E_{24}	(-0.04,0.13,0.26)	(0.19,0.29,0.39)	(0.49,0.54,0.59)	(0.50,0.50,0.50)	(0.28,0.32,0.37)
E_{25}	(0.09,0.19,0.48)	(0.32,0.47,0.61)	(0.62,0.72,0.81)	(0.63,0.68,0.72)	(0.50,0.50,0.50)

Table 4.16: Transformed FLRP matrix for organizational risk element attributes

	E_{21}	E_{22}	E_{23}	E_{24}	E_{25}
E_{21}	(0.50,0.50,0.50)	(0.62,0.67,0.71)	(0.81,0.90,0.99)	(0.72,0.84,1.0)	(0.52,0.79,0.88)
E_{22}	(0.29,0.33,0.38)	(0.50,0.50,0.50)	(0.69,0.73,0.78)	(0.60,0.69,0.79)	(0.40,0.54,0.67)
E_{23}	(0.09,0.10,0.19)	(0.22,0.27,0.32)	(0.50,0.50,0.50)	(0.41,0.46,0.51)	(0.21,0.30,0.39)
E_{24}	(0,0.16,0.28)	(0.21,0.31,0.40)	(0.49,0.54,0.58)	(0.50,0.50,0.50)	(0.31,0.33,0.38)
E_{25}	(0.12,0.21,0.48)	(0.33,0.47,0.60)	(0.61,0.70,0.79)	(0.62,0.67,0.70)	(0.50,0.50,0.50)

Table 4.17: Complete FLPR pairwise comparison matrix of attributes with respect to operational risk element

	E_{31}	E_{32}	E_{33}	E_{34}
E_{31}	(0.50,0.50,0.50)	(0.50,0.55,0.60)	(0.56,0.71,0.76)	(0.69,0.74,0.89)
E_{32}	(0.40,0.45,0.50)	(0.50,0.50,0.50)	(0.56,0.61,0.66)	(0.09,0.19,0.29)
E_{33}	(0.24,0.29,0.44)	(0.34,0.39,0.44)	(0.50,0.50,0.50)	(0.53,0.58,0.63)
E_{34}	(0.11,0.26,0.41)	(0.71,0.81,0.91)	(0.37,0.42,0.47)	(0.50,0.50,0.50)

Table 4.18: Complete FLPR pairwise comparison matrix of attributes with respect to external risk element

	E_{41}	E_{42}	E_{43}
E_{41}	(0.50,0.50,0.50)	(0.56,0.61,0.66)	(0.61,0.71,0.81)
E_{42}	(0.34,0.39,0.44)	(0.50,0.50,0.50)	(0.55,0.60,0.65)
E_{43}	(0.19,0.29,0.39)	(0.35,0.40,0.45)	(0.50,0.50,0.50)

Table 4.19: Complete FLPR decision matrix for risk elements and attributes of PRPU operations

	E_1	E_2	E_3	E_4
E_1	(0.50,0.50,0.50)	(0.52,0.57,0.62)	(0.51,0.61,0.73)	(0.57,0.72,0.9)
E_2	(0.38,0.43,0.48)	(0.50,0.50,0.50)	(0.49,0.54,0.61)	(0.55,0.65,0.78)
E_3	(0.27,0.39,0.49)	(0.39,0.46,0.51)	(0.50,0.50,0.50)	(0.56,0.61,0.67)
E_4	(0.10,0.28,0.5)	(0.22,0.35,0.45)	(0.33,0.39,0.44)	(0.50,0.50,0.50)

E_1	E_{11}	E_{12}	E_{13}	E_{14}
E_{11}	(0.51,0.51,0.51)	(0.41,0.45,0.50)	(0.64,0.72,0.79)	(0.76,0.92,1.0)
E_{12}	(0.53,0.57,0.60)	(0.51,0.51,0.51)	(0.73,0.78,0.82)	(0.85,0.94, 1.0)
E_{13}	(0.22,0.30,0.38)	(0.21,0.24,0.28)	(0.51,0.51,0.51)	(0.63,0.67,0.72)
E_{14}	(0.02,0.09,0.25)	(0,0,0.16)	(0.30,0.34,0.38)	(0.51,0.51,0.51)

E_2	E_{21}	E_{22}	E_{23}	E_{24}	E_{25}
E_{21}	(0.50,0.50,0.50)	(0.62,0.67,0.71)	(0.81,0.90,0.99)	(0.72,0.84,1.0)	(0.52,0.79,0.88)
E_{22}	(0.29,0.33,0.38)	(0.50,0.50,0.50)	(0.69,0.73,0.78)	(0.60,0.69,0.79)	(0.40,0.54,0.67)
E_{23}	(0.09,0.10,0.19)	(0.22,0.27,0.32)	(0.50,0.50,0.50)	(0.41,0.46,0.51)	(0.21,0.30,0.39)
E_{24}	(0,0.16,0.28)	(0.21,0.31,0.40)	(0.49,0.54,0.58)	(0.50,0.50,0.50)	(0.31,0.33,0.38)
E_{25}	(0.12,0.21,0.48)	(0.33,0.47,0.60)	(0.61,0.70,0.79)	(0.62,0.67,0.70)	(0.50,0.50,0.50)

E_3	E_{31}	E_{32}	E_{33}	E_{34}
E_{31}	(0.50,0.50,0.50)	(0.50,0.55,0.60)	(0.56,0.71,0.76)	(0.69,0.74,0.89)
E_{32}	(0.40,0.45,0.50)	(0.50,0.50,0.50)	(0.56,0.61,0.66)	(0.09,0.19,0.29)
E_{33}	(0.24,0.29,0.44)	(0.34,0.39,0.44)	(0.50,0.50,0.50)	(0.53,0.58,0.63)
E_{34}	(0.11,0.26,0.41)	(0.71,0.81,0.91)	(0.37,0.42,0.47)	(0.50,0.50,0.50)

E_4	E_{41}	E_{42}	E_{43}
E_{41}	(0.50,0.50,0.50)	(0.56,0.61,0.66)	(0.61,0.71,0.81)
E_{42}	(0.34,0.39,0.44)	(0.50,0.50,0.50)	(0.55,0.60,0.65)
E_{43}	(0.19,0.29,0.39)	(0.35,0.40,0.45)	(0.50,0.50,0.50)

Table 4.20: Evaluated weight and ranking of risk elements and attributes of PRPU operations

Risk elements (level 2)	Average	Fuzzy weight	Deffuzified values	Normalized Crisp values	Ranking	
E_1	(0.53,0.60,0.69)	(0.23,0.30,0.40)	0.31	0.30	1	
E_2	(0.48,0.53,0.59)	(0.21,0.27,0.34)	0.27	0.26	2	
E_3	(0.42,0.49,0.52)	(0.19,0.25,0.30)	0.25	0.24	3	
E_4	(0.57,0.72,0.9)	(0.13,0.19,0.27)	0.20	0.20	4	
Attributes (Level 3)					**Global weight**	**Global ranking**
E_{11}	(0.58,0.65,0.7)	(0.26,0.32,0.38)	0.28	0.30	0.090	2
E_{12}	(0.65, 0.7, 0.71)	(0.30,0.35,0.39)	0.35	0.36	0.1080	1
E_{13}	(0.39,0.43,0.47)	(0.12,0.19,0.26)	0.19	0.20	0.0600	7
E_{14}	(0.21,0.24,0.33)	(0.10,0.12,0.18)	0.13	0.14	0.0420	14
E_{21}	(0.63,0.93,1.02)	(0.21,0.34,0.47)	0.34	0.33	0.0858	3
E_{22}	(0.50,0.56,0.62)	(0.16,0.21,0.29)	0.22	0.21	0.0546	9
E_{23}	(0.27,0.33,0.38)	(0.09,0.12,0.18)	0.13	0.13	0.0334	16
E_{24}	(0.33,0.37,0.43)	(0.12,0.14,0.20)	0.15	0.14	0.0364	15
E_{25}	(0.44,0.51,0.61)	(0.14,0.19,0.28)	0.20	0.19	0.0494	13
E_{31}	(0.56,0.63,0.69)	(0.25,0.31,0.39)	0.32	0.31	0.0744	5
E_{32}	(0.39,0.44,0.49)	(0.17,0.22,0.27)	0.22	0.22	0.0528	11
E_{33}	(0.40,0.44,0.50)	(0.18,0.22,0.28)	0.23	0.23	0.0522	12
E_{34}	(0.42,0.50,0.57)	(0.19,0.24,0.32)	0.25	0.24	0.0576	8
E_{41}	(0.56,0.61,0.66)	(0.34,0.40,0.48)	0.40	0.40	0.0800	4
E_{42}	(0.46,0.50,0.53)	(0.28,0.33,0.39)	0.33	0.33	0.0660	6
E_{43}	(0.35,0.40,0.45)	(0.21,0.26,0.33)	0.27	0.27	0.0540	10

- Step 6: Ranking decision

The calculation of weight and ranking of risk elements and their attributes according to their importance level is presented in Table 4.20. Based on the result obtained, the trend of the ranking in descending order of risk elements in level 2 of hierarchical model indicates that $E_1 > E_2 > E_3 > E_4$. Also, the trend of ranking of attributes in level 3 indicates that $E_{12} > E_{11} > E_{21} > E_{41} > E_{31} > E_{42} > E_{13} > E_{34} > E_{22} > E_{43} > E_{32} > E_{33} > E_{25} > E_{14} > E_{24} > E_{23}$.

4.6 Discussion

The ranking order sign indicates that technical and organizational risk elements are more important in terms of causing disruption risk of PRPU operations. Instrumentation failure, process equipment failure, inappropriate management policy, inappropriate decision making, deviation from operation procedure, inadequate maintenance procedure and natural hazard are considered as the most significant attributes in relation to the risk elements. Although piping system failure and inadequate communication are attributes that have contributed to disruption risk, according to literatures review and expert views, both attributes have not been identified as major root causes with high level consequences and their ranking position substantiate this fact. Thus, external risk element, utility system failure, inadequate staffing, operator incompetency and terrorist attack are ranked the lowest. This suggests that they are less likely to initiate disruption risk of PRPU operations.

4.7 Conclusion

Due to the complexity of PRPU systems, addressing the issue of disruption risk of PRPU operations is very crucial in order to prevent the risk of catastrophic accidents in PRPU. This study presents a novel methodology using fuzzy linguistic preference relation approach to evaluate the risk elements and attributes which can cause disruption risk of PRPU operations. The fuzzy linguistic preference relation is utilised to analyse the hierarchical structure of disruption risk of the PRPU operations and to determine the weights of risk elements and attributes, and to obtain the final ranking. Also, fuzzy linguistic preference relation effectively addresses the uncertainty and the imprecision from subjective judgements of domain experts.

The subjective judgement of multiple experts on four risk elements and sixteen attributes of PRPU disruption risk is represented as fuzzy linguistic assessment variables, which are expressed by triangular fuzzy values to overcome vagueness or ambiguity of the judgements and for easy computation process. Using the FLPR approach provides the most convenient way to reduce the number of pairwise comparisons of risk elements and attributes in a questionnaire sent to domain experts. The questionnaire allows experts to express their response in a consistent manner without prejudice. The result in this study provides valuable reference to duty holders and stakeholders of petroleum refineries to improve their perception about how risk elements and attributes can be critically prioritised in the risk management process. The methodology proves to be a dependable evaluation procedure in terms of its flexibility and ease of application, when compared to other hierarchical modelling methods like fuzzy AHP, which requires more information and consistency check in the decision making process. Finally, this study has demonstrated that the proposed methodology provides a resourceful and yet flexible approach to solve a risk problem in a practicable manner.

Chapter 5 - A Risk Modelling Approach for the Optimization of Complex Petroleum Refinery Operations

Summary

An innovative risk modelling methodology for the assessment of the disruption risk level of a petroleum refinery operations is presented. A holistic hierarchical model for petroleum refinery operations is developed to establish the interrelationships among the risk elements and their associated attributes that has been investigated in chapter 4. A fuzzy evidential reasoning approach was used to analysis the model in order to determine the disruption risk level of petroleum refinery operations.

5.1 Determining the potential disruption risk level in PRPU environment

Determining the level of potential disruption to PRPU operations is a complex process. This is because the decision makers assessment of risks are sometimes characterized by uncertainty due to incomplete knowledge about the real life scenario of system operational failure, vague information about system operation, ill-defined view about the likelihood of risks and their consequence severity, and lack of anticipation to express opinions with a certain degree of confidence. Based on these challenges, a risk modelling methodology which incorporates a fuzzy based evidential reasoning approach will be utilised in this study, in a systematic manner such that qualitative and quantitative information of potential causes of disruption of PRPU operations can be analysed. This approach has been proved resourceful based on John *et al.,* (2014), Mokhtari *et al.*, (2012), Yang *et al.,* (2009), Ren *et al.,* (2008) and Liu *et al.,* (2005) in terms of modelling of complex systems. In addition, the approach is suitable in terms of avoiding the loss of useful information in inference processes for risk modelling of a complex system operation. The proposed fuzzy based evidential reasoning methodology will provide a logical approach to support risk assessors and decision makers in investigating the threat of risk elements associated with petroleum refinery operations. Furthermore, the proposed methodology will provide a tangible support for effective decision making, in order to implement a reliable risk management process for petroleum refinery process unit operations.

5.2 Background: considered measures for effective risk investigation in PRPU environments.

Based on the literature review, the measures that are considered in terms of the risk investigation of PRPU operation are: years of operation of refinery process units, the complexity of safety technology to optimise operations and uncertainties associated with different facet of the risk management process. The aforementioned measures are important in terms of developing a comprehensive methodology which will incorporate key learning from incidents and near misses for risk management of PRPU operation. The measures will provide the basis for comprehensive modelling of the critical events sequence and structure, to develop an understanding of their significance to PRPU operation safety, considering their probable hazardous consequences and risk level. Furthermore, identification of the areas of focus based on the aforementioned measures, will help in developing a predictive model which allows the updating of knowledge to demonstrate the probabilities of critical events, for safety related decision making to prevent or mitigate the disruption of PRPU operation.

5.3 Representation of the significant causes of disruption of PRPU operation

Determining the importance of PRPU risk elements and their attributes based on their relative weight is the first step in the fuzzy based evidential reasoning methodology. The application of the methodology is focused on the analysis of the potential risk level of disruption to PRPU operation in an uncertain situation (whereby engineering judgement based on experts' opinion is utilised due to inadequacy of risk modelling data). The most significant risk elements and attributes with high degree of complex interrelationships that can result in the disruption of PRPU operation, are presented together with their relative important weights in Table 5.1. The relative weights assigned to the risk elements and their attributes is obtained based on the previous work in chapter 4 of this research. The scheme of the fuzzy based evidential reasoning methodology is presented in Figure 5.1.

Table 5.1: An illustration of disruption risk elements and their attributes along with the weights

Goal level 1	Level 2 risk elements	Relative weight	Level 3 attributes	Relative weight
Disruption of PRPU operation	Technical risk element	(0.30)	Process equipment failure	(0.30)
			Instrument failure	(0.36)
			Piping failure	(0.20)
			Utility system failure	(0.14)
	Organizational risk element	(0.26)	Inappropriate management policy/procedure	(0.33)
			Inappropriate decision making	(0.21)
			Inadequate staffing	(0.13)
			Poor safety monitoring and auditing	(0.14)
			Lack of safety training/drill	(0.19)
	Operational risk element	(0.24)	Deviation from operational procedure	(0.31)
			Operator incompetency	(0.22)
			Inadequate communication	(0.23)
			Inadequate maintenance procedure	(0.24)
	External risk element	(0.20)	Natural hazard	(0.40)
			Sabotage	(0.33)
			Terrorist attack	(0.27)

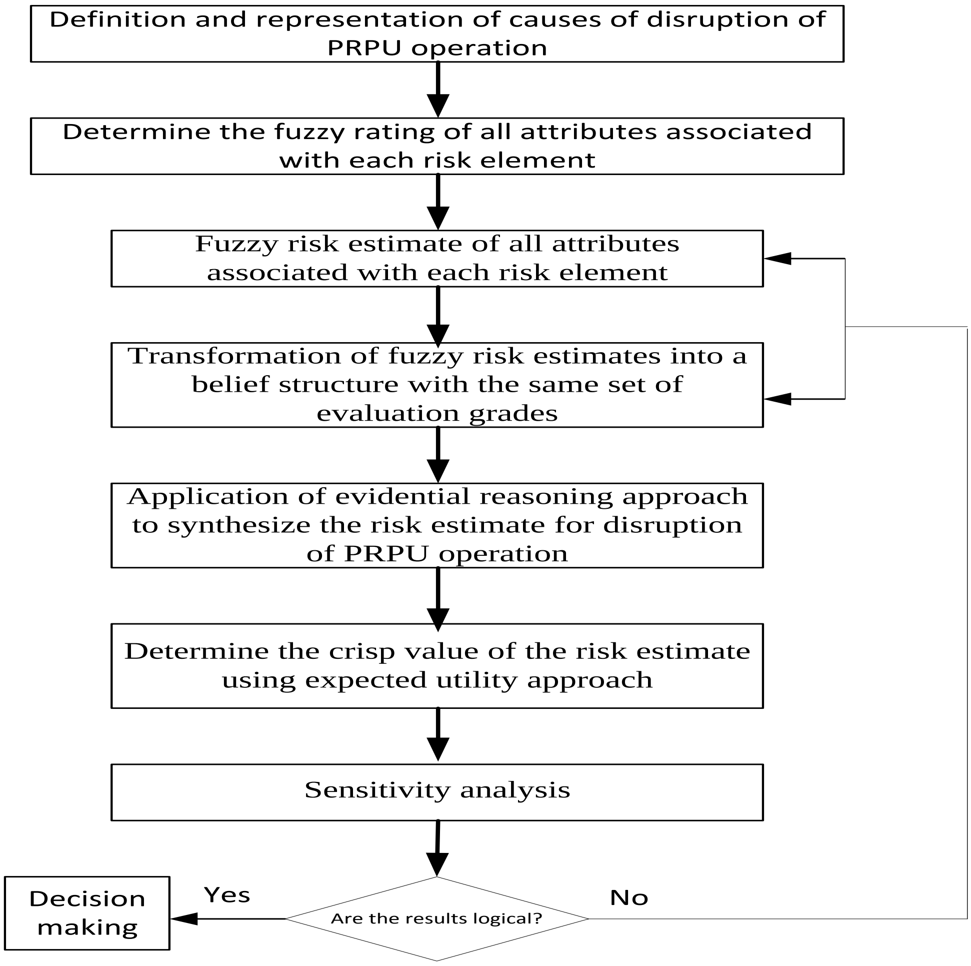

Figure 5. 1: Flowchart of the fuzzy based evidential reasoning methodology

5.4 Determine the fuzzy rating of risk elements and attributes

In a risk evaluation process for a complex PRPU operation, it is important to determine the fuzzy risk level of the attributes that are associated with each risk element that have been identified as the causes that can lead to disruption of PRPU operation. The primary risk parameters that are applicable in terms of rating the risk elements and attributes includes occurrence likelihood (**L**) and consequence severity (**S**). The occurrence likelihood describes the number of unexpected or undesired hazardous events per unit time and consequence severity describes the magnitude of loss when the undesired event or accident happens (Mokhtari *et al.*, 2012; Liu and Liao, 2007). The two risk parameters will be used to estimate the risk level of a PRPU operation.

In this study, the risk parameters **L** and **S** are described using linguistic variables because of the subjective nature of the information or incompleteness associated with the task of measuring the parameters precisely. Also, the linguistic variables can describe the risk parameters in a more convenient way. For instance, the occurrence likelihood of any risk element can be rated by using the following linguistic variables: “very low”, “low”, “medium”, “high” and “very high”. Similarly, consequence severity can be rated using the following linguistic variables: “negligible”, “minor”, “moderate”, “critical” and “catastrophic”. The linguistic variables are further defined in terms of fuzzy membership functions. A membership function is a curve that defines how each point in space is mapped to a membership value from 0 to 1. Linguistic variables for the risk parameters can be defined in terms of a simple membership function which can be either triangular or trapezoidal in nature. A membership function is expected to be flexible in term of its definition to suit various circumstances in order for risk analysts to conveniently interpret subjective information represented as input variables. According to novel literatures on risk assessment in a fuzzy situation, triangular and trapezoidal membership functions are the most commonly used for delineating input variables because of their simplicity. It is worth mentioning that designing a membership function of the risk parameters depends on a psychometric scale chosen by the model builder, based on their subjective knowledge of a system problem, historical records and consultation with experts (Liu *et al*, 2004; Liu *et al*, 2005; Sii *et al*, 2005). The psychometric scale, is a subjective scale with a range of granularity and fine detail. In this study, the membership function that represents the knowledge of a situation used in the assessment for the expression of the risk level of disruption to PRPU operation, is developed based on expert consultation and knowledge acquisition through literatures (Liu *et al,* 2005). The level of granularity of the membership function which is constructed from a set of overlapping curves, is based on careful consideration of multiple expert responses.

After the definition of linguistic variables of risk parameters associated with risk element and attributes that can cause disruption of PRPU operation, then the fuzzy risk estimate is determined, based on the multiplicative relationship between risk occurrence likelihood and the consequence severity as demonstrated by Equation 5.1.

$$P = L \times S \tag{5.1}$$

In the above equation, P is used to describe the fuzzy risk estimate of each attribute associated with each risk element in relation to disruption of PRPU operation. The linguistic rates of L and S are defined in terms of membership function which are quantified with triangular fuzzy numbers. Tables 5.2 and 5.3 display the linguistic variables for the risk parameters and their corresponding membership function. Also, Table 5.4 displays the qualitative description of the risk level.

Table 5.2: Linguistic variable for risk parameters

Risk parameters	Linguistic terms	Membership function
Occurrence likelihood (L)	Very low	(0.0, 0.10, 0.20)
	Low	(0.15, 0.275, 0.40)
	Medium	(0.35, 0.475, 0.60)
	High	(0.55, 0.725, 0.90)
	Very High	(0.85, 0.90, 1.0)
Consequence Severity (S)	Negligible	(0.0, 0.10, 0.20)
	Minor	(0.10, 0.25, 0.40)
	Moderate	(0.35, 0.475, 0.60)
	Critical	(0.55, 0.70, 0.85)
	Catastrophic	(0.80, 0.90, 1.0)

Table 5.3: Linguistic variables for risk level estimate

Risk parameters	Linguistic terms	Membership function
Risk (R)	Very low	(0.0,0.125, 0.25)
	Low	(0.15, 0.25, 0.35)
	Medium	(0.30, 0.50,0.70)
	High	(0.65, 0.75, 0.85)
	Very High	(0.80, 0.90,1.0)

Table 5.4: Qualitative description of risk levels (R).

Very low	If likelihood of hazardous event is very low and consequence severity is negligible.
Low	If likelihood of hazardous event is low and the consequence severity is minor.
Medium	If likelihood of hazardous event is medium and the consequence severity is moderate.
High	If likelihood of hazardous event is high and the consequence severity is critical.
Very high	If the likelihood of hazardous event is very high and the consequence severity is catastrophic.

5.5 Fuzzy risk estimate of the risk elements and attributes.

The fuzzy rating of risk elements and attributes associated with risk parameters for evaluation of the risk level of PRPU operation, is obtained from expert judgement. The fuzzy rating is based on five linguistic grade adapted from Ngai and Wat, (2005); Pillay and Wang, (2003). As stated earlier in this chapter, the fuzzy estimate of the risk level for each risk element and attribute of the PRPU operation is determined by two independent risk parameters; occurrence likelihood of hazard (L) and consequence severity (S), and the product of the two parameters is equal to the fuzzy risk level estimate. Basically, this is the product of fuzzy rating of L and S represented by two triangular fuzzy numbers (TFN) indicated as TFN_L = L = (a_l, b_l, c_l) and TFN_S = S = (a_s, b_s, c_s), whereby a_l, b_l, c_l represent the lower least values, most likely values and upper least likely values of the triangular fuzzy numbers associated with L. Also, a_s , b_s and c_s are defined as the lower least values, most likely values and upper least likely values of the triangular fuzzy numbers associated with S. The two parameters are used to obtain the anticipated fuzzy risk estimate for the attributes that are associated with each risk element as illustrated in the equation below.

$$TFN_{LS} = TFN_L \otimes TFN_S = (a_l \otimes a_s,\ b_l \otimes b_s,\ c_l \otimes c_s) \quad (5.2)$$

The TFN is adopted because of its computational simplicity in terms of quantifying the subjective and vague uncertainty associated with expert opinion. Experts can provide judgment concerning a risk problem based on their knowledge of the system under investigation. For instance, risk can be assigned an occurrence likelihood rating TFN_L as medium (0.4, 0.5, 0.6) and a consequence severity rating TFN_S as low (0.15, 0.25, 0.4), then the corresponding fuzzy risk estimate is TFN_{LS} (0.06, 0.125, 0.24). The calculated value TFN_{LS} is the fuzzy risk estimate.

5.6 Transformation of fuzzy estimates into a belief structure with the same set of evaluation grade

After determining the fuzzy risk estimate for attributes of each risk element, it is essential to transform the fuzzy risk estimate into a belief structure, with the same set of evaluation grades. Due to the fact that the analyst cannot always provide an exact estimate in risk modelling of any complex system operation, especially in a fuzzy situation, transforming fuzzy risk estimate into a belief structure, provides a linguistic risk level with the same set of evaluation grades to represent the risk profile of the attributes associated with each risk element. A risk level with a belief structure generally represents the strength to which a risk estimate is believed to be true in a risk analysis and it must express the degree of expectation or confidence that an attribute of a risk element will yield an anticipated outcome that can lead to disruption of PRPU operation. The transformation process helps to capture any ambiguity, uncertainty and imprecision associated with the fuzzy risk level estimate because subjective judgements of experts in risk modelling cannot always be 100% certain.

Based on Mokhtari *et al.,* (2012), the fuzzy risk estimate can be converted to a belief structure with the same set of evaluation grades when measuring the risk level of disruption of PRPU operation. Using the explanation in Section 5.5, the obtained fuzzy risk result TFN_{LS} is mapped over TFN_P (i.e. 5 grades defined over the universe of discourse of risk (VL, L, M, H and VH) is shown in Figure 5. 2. TFN_P is a fuzzy triangular membership function which is developed based on multiple experts' knowledge of risk level. Based on Figure 5. 2, the point where the newly mapped TFN_{LS} overlaps each linguistic variable of TFN_P are spotted, and the maximum values are used at points where TFN_{LS} and a linguistic variable of TFN_P overlap at more than one point, and the illustration of the overlap is presented in Figure 5. 3. The overlapping points in the mapping are denoted as Z_P which is normalized to obtain a Z (i.e. Z, linguistic variables with their membership degrees). The normalized risk result (Z) from the mapping process is used as input data in the evaluation of the risk level that can lead to the disruption of PRPU operation. Finally, the overall risk level for the disruption of PRPU operation can be synthesized using an Intelligent Decision Software (IDS) package, with an embedded evidential reasoning algorithm for the aggregation of both normalized risk level result (Z) for attributes of each risk element, and their weights. The transformation of the fuzzy risk estimate (i.e. TFN_{LS}) into a belief structure with the same set of evaluate grades, which represent the fuzzy risk level is presented as follows:

- Mapping the estimated value of TFN_{LS} over TFN_P (i.e. 5 grades defined over the universe of discourse of risk (VL, L, M, H and VH).

- The point of intersection at which the newly mapped FTN_{LS} overlaps each linguistic term of the TFN_P is determined.
- Choosing the maximum value if TFN_{LS} and a linguistic term of TFN_P intersect at more than one point.
- Establish a set of intersecting points (Z_P) that defines a non-normalised 5 grades in the form of fuzzy sets.
- Normalising the (Z_P) (5 non-normalised grades) to obtain a Z (5 normalised grades) which is known as the belief structure.

5.7 Application of the evidential reasoning algorithm for risk level estimate of disruption to PRPU operation

In order to obtain the disruption risk level estimation for a PRPU operation, the ER algorithm will be utilise to analyse the hierarchical model of a PRPU risk problem. The process involve the synthesis of the risk level estimates of the attributes or criteria at the lowest level in the hierarchical model to obtain to the risk level estimates of the risk elements in the upper level of the hierarchical model. Also, the aggregation of the risk level estimates for the risk elements produces the disruption risk level estimate of PRPU operation. In order to perform the aggregation process, Intelligent Decision Software (IDS) which is embedded with the ER algorithm is utilised. The hierarchical model is developed in the software and the risk estimates of the attributes of each risk element and their weights are used as input data in the model to obtain the disruption risk level estimate. The ER algorithm is elucidated in the following manner based on the explanation in Yang and Xu, 2002:

Let ‘‘R’’depict the set of the five grade of expressions for belief degree of risk which can be obtained from two subsets R_1 and R_2 provided by two experts. R = (γ^1 Very Low, γ^2 "Low", γ^3 "$Moderate$", γ^4 "$High$", γ^5 "$Very\ High$")

R_1 = (γ_1^1 Very Low, γ_1^2 "Low", γ_1^3 "$Moderate$", γ_1^4 "$High$", γ_1^5 "$Very\ High$")

R_2 = (γ_2^1 Very Low, γ_2^2 "Low", γ_2^3 "$Moderate$", γ_2^4 "$High$", γ_2^5 "$Very\ High$")

The risk expressions in the two subsets indicated as “Very Low”, “Low”, “Moderate, “High” and “Very High” are associated with their corresponding belief degrees. The assumption is that the relative weights of the two experts expressions which is synthesised to R in the risk evaluation process is given as ω_1 and ω_2 (ω_1+ω_2). Suppose the relative weight of the two experts can be estimated using any of the established pairwise comparison methods, then the hypothesis that the risk evaluation is confirmed to the i^{th} risk expression in the estimate of two subsets R_1 and R_2 is established based on their probability mass or weight belief degree. The probability mass is described as follows:

$$\ddot{M}_1^k = \omega_1 \times \gamma_1^k$$
$$\ddot{M}_2^k = \omega_2 \times \gamma_2^k \qquad (5.3)$$
$$\text{where } k = 1, 2, 3, 4, or\ 5$$

Assuming H_1 and H_2 are the remaining probability mass unassigned to any of the individual risk expressions, then H_1 and H_2 are decomposed into the following expression (Yang, 2001):

$$H_1 = \dot{H}_1 + \ddot{H}_1$$
$$H_2 = \dot{H}_2 + \ddot{H}_2 \qquad (5.4)$$

where $\dot{H}_1 = 1 - \omega_1$ and $\dot{H}_2 = 1 - \omega_2$ express the extent to which other decision makers contribute their part in the assessment while considering the possible incompleteness in the subsets R_1 and R_2 which is stated as follows:

$$\ddot{H}_1 = \omega_1\left(1 - \sum_{k=1}^{5} \gamma_2^k\right)$$
$$\ddot{H}_2 = \omega_2\left(1 - \sum_{k=1}^{5} \gamma_2^k\right) \quad (5.5)$$

Assume $\gamma_{U(2)}^k$ $(k = 1, 2, 3, 4, or\ 5)$ depicts the non-normalised degree to which risk evaluation is confirmed to the i^{th} risk expression as a result of the synthesis of judgment provided by decision makers 1 and 2. $\acute{H}_u$ is assumed to be the remaining non normalized belief unassigned to any of the risk expressions as a result of synthesis of decision makers 1 and 2's judgments. Hence, the ER algorithm is stated in the following manner based on Yang and Xu, 2002:

$$\gamma_{U(2)}^k = \mathrm{K}\left(\ddot{M}_1^k \ddot{M}_2^k + \ddot{M}_1^k H_2 + \ddot{M}_2^k H_1\right) \quad (5.6)$$

$$\dot{\acute{H}}_u = \mathrm{K}\left(\dot{H}_1 \dot{H}_2\right) \quad (5.7)$$

$$\ddot{\acute{H}}_u = \mathrm{K}\left(\ddot{H}_1 \ddot{H}_2 + \ddot{H}_1 \dot{H}_2 + \dot{H}_1 \ddot{H}_2\right) \quad (5.8)$$

$$\mathrm{K} = \left[1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} \ddot{\mathrm{M}}_1^{\mathrm{T}} \ddot{\mathrm{M}}_2^{\mathrm{R}}\right]^{-1} \quad (5.9)$$

Based on the above aggregation, the combined belief degrees γ^i of the overall assessment are determined by assigning $\dot{\acute{H}}_u$ back to the risk expressions based on the following normalization process in Equation 5.10. Also, H_U is the unassigned degree of belief that represents the extent of incompleteness in the overall assessment.

$$\gamma^i = \gamma_{U(2)}^k / \left(1 - \dot{\acute{H}}_u\right) \text{ (k = 1, 2, 3, 4, or 5)} \quad (5.10)$$

$$H_U = \ddot{\acute{H}}_u \,/\, \left(1 - \dot{\acute{H}}_u\right) \quad (5.11)$$

5.8 Obtaining crisp value for the goal using concept of expected utility

In order to obtain a single crisp value for the goal (top level criterion) in a hierarchical model of a decision problem, a distributed description cannot sufficiently produce an appropriate numerical value equivalent to the distributed assessment of the goal. Hence, a concept based on expected utility can be applied to define such numerical values in the following manner: $u(H_n)$ represents the utility value of the evaluation grade H_n and $u(H_{n+1}) > u(H_n)\ if\ H_{n+1}$ is preferred to H_n (Yang, 2002). The term $u(H_n)$ can be estimated based on decision makers' preference. When it is quite certain that no preference information exists, it is reasonable to assume that the utility of the evaluation grades can be a centremost distribution in a normalised utility space. In a normalised utility space, the equidistant distribution of the utilities of evaluation grade is estimated as follows:

$$u(H_n) = \frac{V_n - V_{min}}{V_{max} - V_{min}} \tag{5.12}$$

In the above utility equation, V_n represents the ranking value of the linguistic term which is considered as H_n, while V_{max} is considered as the ranking value of the best preferred linguistic term H_N, and V_{min} is the ranking value of the least preferred linguistic term H_1. The expected utility of a top criterion in a hierarchical framework of a decision problem is represented as $u(S(E))$. The following conditions are true in the assessment if $\gamma_H \neq 0$ (i.e. the assessment is incomplete, $(\gamma_H = (1 - \gamma_H \sum_{n=1}^{N} \gamma_n$) there is a belief interval [γ_n, $(\gamma_n + \gamma_H)$] , which indicates the possibility that S(E) is assessed to H_n. Without loss of generality, it is presumed that the least preferred linguistic term having the lowest utility is denoted by u(H_n) and the most preferred linguistic term having the highest utility is represented by u(H_n). Subsequently, the equations for minimum, maximum and average utilities of S(E) are defined as follows.

$$u_{min}(S(E)) = \sum_{n=2}^{N} \gamma_n \, u(H_n) + (\gamma_1 + \gamma_H)u(H_n)$$
$$u_{max}(S(E)) = \sum_{n=1}^{N-1} \gamma_n \, u(H_n) + (\gamma_N + \gamma_H)u(H_n) \quad (5.13)$$
$$u_{average}(S(E)) = \frac{u_{min}(S(E)) + u_{max}(S(E))}{2}$$

If it is certain that if all assessment is complete, then $\gamma_H = 0$ and the maximum, minimum and average utilities $S(E)$ will be equal. In this case, $u(S(E))$ can be estimated as:

$$u(S(E)) = \sum_{n=1}^{N} \gamma_n \, u(H_n) \quad (5.14)$$

It is noteworthy to emphasise that the above utilities are basically meant for characterising an assessment and not applicable in attribute aggregation.

5.9 Model validation process

In order to validate the consistency of a risk based model, it is important to perform sensitivity analysis for the purpose of establishing the reliability of the model. The sensitivity analysis goal is to test the sensitivity of a proposed model in terms of its output or conclusion with respect to any change in the model input. Due to the fact that uncertainty is an inherent problem of a model input, in terms of sensitivity analysis, a relative change may be a variation of the parameters of the model or changes in belief degrees assigned to the linguistic terms used to describe the parameters of the model. In this way, a systematic approach is established in order to provide a quantitative evaluation, to determine any weakness in the model and seek for improvement in the designed model. If the methodology provides a logical inferences reasoning, then the following three precepts must at least be reflected in the sensitivity analysis.

Axiom 1: A minor decrement/increment of the input data i.e. belief degrees related to a risk oriented linguistic variables of the lowest criteria should result in a corresponding decrement/increment in the model output which is the risk level.

Axiom 2: If the belief degrees connected and the highest preference linguistic variable of a lower level criterion are reduced by ‘m’ and ‘n’, in the same manner the belief degrees associated with its lowest preference linguistic variable are increased by m and n (1 > n > m), then, the utility value of the model’s output is assessed as U_m and U_n respectively. U_m should be greater than U_n.

Axiom 3: If ‘a’ and ‘b’ (b < a) criteria from all the lowest level criteria are carefully chosen and the degree of belief associated with the highest preference linguistic variables of such ‘a’ and ‘b’ criteria are reduced by the same amount (i.e. concurrently, the degrees of belief associated with the lowest preference linguistic terms of such ‘a’ and ‘b’ criteria are increased accordingly by the same amount), the utility value of the model’s output will be estimated as U_a and U_b; then, U_b should be greater than U_a.

5.10 Case study

In this section, a case of a complex petroleum refinery with over 20 years of operation, with a reasonable management of change in organizational structure and policies and fairly reliable safety standard is analysed. In the petroleum and gas industry, the risk management process of PRPU operation is mostly based on the observation and experiences of refinery managers and PRPU operators. Making decisions on how risk can be prioritized and managed is highly demanding for managers and operators in the petroleum and gas refinery, simply because of the level of responsibility and uncertainty associated with the routine operations of PRPU. Such situation sometimes creates indistinctness in the measure of risk level, when available information for risk update is inconsistent. Also, inconsistent risk update can result in low level perception about risk under fuzzy situations. As a result, estimating the risk level of multiple attributes of risk elements that can trigger disruption of PRPU operation will provide support for the decision making process in terms of risk management. Hence, an advanced risk evaluation framework for decision support in terms of the risk management process is important to assist managers under uncertain conditions.

- Step 1: Identification and description of risk attributes associated with PRPU operation

In this risk evaluation process, 16 attributes are associated with the four risk elements are selected as the risk evaluation criteria for PRPU operation. These attributes are process equipment failure, instrumentation failure, Piping failure, utility system failure, deviation from operation procedure, inadequate communication, inappropriate maintenance procedure, operator incompetency, inappropriate management policy and procedure, inappropriate decision making, inadequate staffing, poor safety monitoring, lack of safety training/drill, natural hazard, sabotage and terrorist attack. The relative weights of all the risk elements and their attributes for PRPU disruption risk evaluation are shown in Table 5.1.

- Step 2: Fuzzy ratings of risk elements and attributes

Suppose the disruption risk of PRPU operation is considered under fuzzy situation in a complex refinery, the evaluation process involves five experts who gave their fuzzy rating for risk attributes in terms of disruption to PRPU operation. Basically, the ratings are expressed in TFN in order to precisely enable data collection and allow capture of experts' preference in a reliable manner. The selected experts for the case study give their rating regarding each of the attributes using the linguistic variables or evaluation grades (see Table 5.2). The experts' judgements are nominated based on the fact that they all have the same level of qualifications, positions and years of experience in petroleum and gas refinery operations. All the chosen experts have a PhD qualification, 11-20 years' experience, and are consultants, senior engineers or managers in petroleum and gas refinery. Based on the above criteria, these experts are assumed to be of equal weights.

- Step 3: Fuzzy estimate of risk level for attributes associated with each risk element of PRPU operation

As discussed earlier in Section 5.5, Table 5.6 shows the result for a combination of two risk parameters, occurrence likelihood and consequence severity to determine the fuzzy estimate of the risk level of all attributes associated with each risk element that can cause disruption to PRPU operation. The aggregated expert rating for the occurrence likelihood and consequence severity is determined by using the weighted average method. The method allows aggregation of conflicting rating provided by five experts. The weighted average equation for the five experts is defined as:

$$\tilde{P}_i = \frac{\sum_{l=1}^{m} w_l P_{i,l}}{\sum_{k=1}^{m} w_l} \quad i = 1,2,3 \ldots \ldots, n \tag{5.15}$$

$P_{i,l}$ is the fuzzy rating of parameters obtained from expert i, m is the number of attributes associated with the parameters, w_l is the weighting factor assigned expert i and n is the number of experts.

Table 5.5: Fuzzy risk estimate for disruption

Risk attributes	Aggregated expert rating for FTN_L	Aggregated expert rating for FTN_S	FTN_{LS} Fuzzy risk estimate
E_{11}	(0.16,0.295,0.4)	(0.47,0.60,0.75)	(0.08,0.18,0.3)
E_{12}	(0.16,0.295,0.4)	(0.66,0.77,0.89)	(0.11,0.23,0.36)
E_{13}	(0.1,0.215,0.32)	(0.66,0.77,0.89)	(0.06,0.17,0.28)
E_{14}	(0.31,0.465,0.58)	(0.46,0.61,0.76)	(0.14,0.28,0.44)
E_{21}	(0.16,0.295,0.4)	(0.43,0.55,0.7)	(0.07,0.16,0.28)
E_{22}	(0.2,0.33,0.44)	(0.52,0.64,0.78)	(0.10,0.21,0.34)
E_{23}	(0.35,0.525,0.64)	(0.30,0.41,0.56)	(0.11,0.22,0.36)
E_{24}	(0.24,0.365,0.48)	(0.42,0.56,0.71)	(0.10,0.20,0.34)
E_{25}	(0.16,0.295,0.4)	(0.56,0.69,0.83)	(0.09,0.20,0.33)
E_{31}	(0.16,0.295,0.4)	(0.51,0.65,0.8)	(0.08,0.19,0.32)
E_{32}	(0.37,0.49,0.6)	(0.29,0.42,0.57)	(0.11,0.21,0.32)
E_{33}	(0.27,0.41,0.52)	(0.42,0.54,0.7)	(0.11,0.21,0.36)
E_{34}	(0.19,0.335,0.44)	(0.47,0.6,0.75)	(0.09,0.21,0.33)
E_{41}	(0.03,0.14,0.24)	(0.52,0.64,0.78)	(0.016,0.09,0.19)
E_{42}	(0.03,0.14,0.24)	(0.56,0.69,0.83)	(0.016,0.10,0.20)
E_{43}	(0.0,0.1,0.2)	(0.7,0.82,0.94)	(0.0,0.08,0.19)

- Step 4: Transformation of fuzzy risk level estimates into a belief structure with the same set of evaluation grades

In order to measure the disruption of PRPU operation, it is important to transform the risk level of all attributes associated with each risk element into a belief structure with the same set of evaluation grades. Therefore, the approach proposed in Section 5.6 is utilized for the transformation process. Figure 5.2 depict the fuzzy triangular membership function for the PRPU risk level and Figure 5.3 shows an example of the transformation of a fuzzy risk estimate into a fuzzy risk level, with a belief distribution of five linguistic grades. The non-normalised and the normalised belief structures for all the attributes associated with each of the risk element are presented in Tables 5.6 and 5.7.

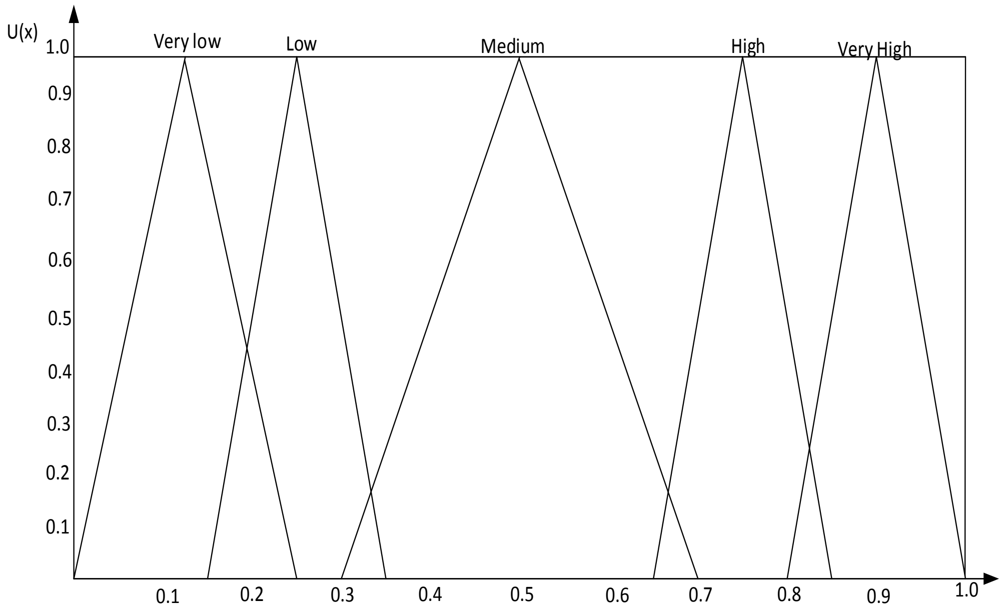

Figure 5. 2: Fuzzy triangular membership function for PRPU risk level

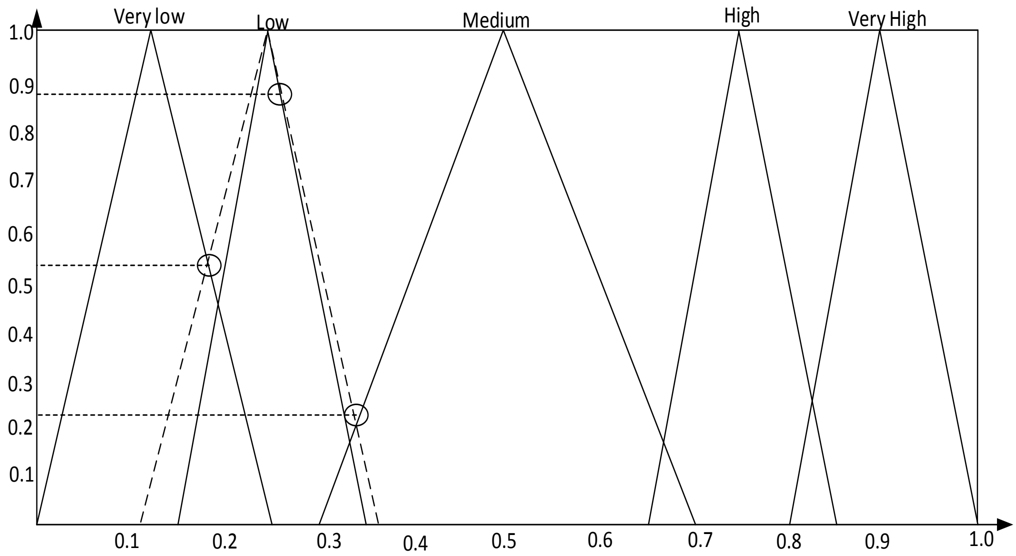

Figure 5. 3: An example of transformation of fuzzy risk level estimate

Table 5.6: An illustration of the transformation of fuzzy risk estimate E_{12} into fuzzy risk level with 5 evaluation grades

FTN_{LS}	0.11,	0.23,	0.36		
Grade	VL	L	M	H	VH
Z_P	0.55	0.88	0.23	0	0
Z	0.33	0.53	0.14	0	0

Table 5.7: Non-normalised transformation result of disruption risk attributes

	Z_P				
Risk attributes	VL	L	M	H	VH
E_{11}	0.72	0.65	0	0	0
E_{12}	0.55	0.88	0.23	0	0
E_{13}	0.68	0.65	0	0	0
E_{14}	0.42	0.85	0.35	0	0
E_{21}	0.72	0.65	0	0	0
E_{22}	0.58	0.82	0.12	0	0
E_{23}	0.55	0.85	0.15	0	0
E_{24}	0.58	0.85	0.10	0	0
E_{25}	0.60	0.85	0.10	0	0
E_{31}	0.60	0.80	0.05	0	0
E_{32}	0.55	0.80	0.05	0	0
E_{33}	0.55	0.8	0.15	0	0
E_{34}	0.6	0.8	0.1	0	0
E_{41}	0.5	0.92	0	0	0
E_{42}	0.36	0.85	0	0	0
E_{43}	0.8	0.15	0	0	0

Table 5.8: Normalised risk level estimates for risk attributes

Risk attributes	Z (Normalised value)				
	VL	L	M	H	VH
E_{11}	0.53	0.47	0	0	0
E_{12}	0.33	0.53	0.14	0	0
E_{13}	0.51	0.49	0	0	0
E_{14}	0.26	0.52	0.22	0	0
E_{21}	0.53	0.47	0	0	0
E_{22}	0.38	0.54	0.08	0	0
E_{23}	0.36	0.54	0.1	0	0
E_{24}	0.38	0.55	0.07	0	0
E_{25}	0.39	0.55	0.06	0	0
E_{31}	0.42	0.55	0.03	0	0
E_{32}	0.39	0.57	0.04	0	0
E_{33}	0.37	0.53	0.1	0	0
E_{34}	0.4	0.53	0.07	0	0
E_{41}	0.35	0.65	0	0	0
E_{42}	0.3	0.7	0	0	0
E_{43}	0.84	0.16	0	0	0

- Step 5: Aggregating assessment using the evidential reasoning approach

ER is introduced to solve basic assessment problem in terms of aggregation of all risk results for attributes to obtain an assessment for each of the risk element that can cause disruption of PRPU operation. In the same manner, the result of the assessment of all the risk elements can be aggregated to obtain the disruption risk of PRPU operation. The ER algorithm has been integrated into a software package called intelligent decision system (IDS), a demonstration version of IDS was first utilised by Yang J.B. (2002). To obtain a precise assessment, the relative importance of all the attributes associated with each risk element needs to be assigned weights. Given the weights of the attributes and their corresponding risk level estimates as shown in Tables 5.1 and Table 5.5, a detailed aggregation is yielded for assessment of the risk elements using the IDS software. The same step can be repeated for aggregation of the risk elements to obtain an assessment for risk of disruption to PRPU operation. To demonstrate the implementation of the ER algorithm, the basic calculation for aggregation of three attributes relating to the external risk element is presented using equations 5.2 to 5.13. Based on

Table 5.8, the belief degrees of the three attributes are:

Natural hazard: $\gamma_1^1 = 0.35$ $\gamma_1^2 = 0.65$ $\gamma_1^3 = 0$ $\gamma_1^4 = 0$ $\gamma_1^5 = 0$

Sabotage: $\gamma_2^1 = 0.3$ $\gamma_2^2 = 0.7$ $\gamma_2^3 = 0$ $\gamma_2^4 = 0$ $\gamma_2^5 = 0$

Terrorist attack: $\gamma_3^1 = 0.84$ $\gamma_3^2 = 0.16$ $\gamma_3^3 = 0$ $\gamma_3^4 = 0$ $\gamma_3^5 = 0$

Suppose the weights of the three external risk element attributes, ω_1,ω_2, and ω_3, in The scheme of the fuzzy based evidential reasoning methodology is presented in Figure 5.1.

Table 5.1 are 0.40, 0.33 and 0.27. The basic probability mass formulae in Section 5.7 are then applied. The result of the estimation of the probability mass for each of the attributes based on their belief distributions and weights are presented in Table 5.9.

Table 5.9: Probability masses for the attributes related to external risk elements

		$\ddot{M}_1^k$ for natural hazard		
$\ddot{M}_1^1 = 0.14$	$\ddot{M}_1^2 = 0.26$	$\ddot{M}_1^3 = 0$	$\ddot{M}_1^4 = 0$	$\ddot{M}_1^5 = 0$
$\dot{H}_1 = 0.60$	$H_1^{\cdot\cdot} = 0$	$H_1 = 0.60$		
		$\ddot{M}_2^k$ for sabotage		
$\ddot{M}_2^1 = 0.099$	$\ddot{M}_2^2 = 0.231$	$\ddot{M}_2^3 = 0$	$\ddot{M}_2^4 = 0$	$\ddot{M}_2^5 = 0$
$\dot{H}_2 = 0.67$	$H_2^{\cdot\cdot} = 0$	$H_2 = 0.67$		
		$\ddot{M}_3^k$ for terrorist attack		
$\ddot{M}_3^1 = 0.2268$	$\ddot{M}_3^2 = 0.0432$	$\ddot{M}_3^3 = 0$	$\ddot{M}_3^4 = 0$	$\ddot{M}_3^5 = 0$
$\dot{H}_3 = 0.73$	$\ddot{H}_3 = 0$	$H_3 = 0.73$		

The combined probability masses of the first two attributes in the assessment of the external risk element is generated based on Equations 5.5 to 5.8. ‘K’ is a normalising factor for the estimation of the combined probability masses for natural hazard and sabotage. The combined probability masses of natural hazard and sabotage is presented in Table 5.10.

Table 5.10: Aggregation of the probability masses of natural hazard and sabotage

Aggregation result of the probability masses of natural hazard ($\ddot{M}_1^k$) and sabotage ($\ddot{M}_2^k$).				
The normalising factor K for the combined probability mass of natural hazard and sabotage is calculated as 1.0616.				
$\gamma_{U(2)}^1$ =0.1773	$\gamma_{U(2)}^2$= 0.3958	$\gamma_{U(2)}^3 = 0$	$\gamma_{U(2)}^3$= 0	$\gamma_{U(2)}^5$= 0
$\dot{\acute{H}}_1$= 0.4267	$\acute{\acute{H}}_1$ = 0	$\acute{H}_1 = 0.4267$		

The above result for combination of natural hazard and sabotage is aggregated with the probability mass of terrorist attack to obtain the assessment for external risk element. 'K (2)' is the normalization factor for combination of the result obtained above and terrorist attack. The overall result for the combined probability masses of the three attributes is presented in Table 5.11.

Table 5.11: Aggregation of the combined probability masses for the three attributes

Aggregation result of the combined probability masses of natural hazard ($\ddot{M}_1^k$), sabotage ($\ddot{M}_2^k$) and terrorist attack ($\ddot{M}_3^k$).				
The normalising factor K (2) for the combined probability mass of natural hazard, sabotage and terrorist attack is calculated as 1.1079.				
$\gamma_{U(3)}^1$ =0.2953	$\gamma_{U(3)}^2$= 0.3595	$\gamma_{U(3)}^3$ = 0	$\gamma_{U(3)}^3$= 0	$\gamma_{U(3)}^5$= 0
$\dot{\acute{H}}_2$= 0. 3451	$\acute{\acute{H}}_2$ = 0	$\acute{H}_2 = 0.3451$		

Using Equations 5.9 and 5.10, the combined degree of belief for aggregation of the three attributes are estimated and the result are presented in Table 5.12.

Table 5.12: Aggregation result for external risk element

Combined degree of belief for the aggregation of the three attributes.				
Very low	Low	Medium	High	Very high
$\gamma^1 = 0.4509$	γ^2 = 0.5491	γ^3= 0	$\gamma^4 = 0$	$\gamma^5 = 0$

The aggregation of the three attributes for assessment of external risk element is given as S (external risk element) = {(very low, 0.4509), (low, 0.5491)}.

- Step 6: Obtain overall crisp result for risk level of PRPU operation

The risk level of PRPU operations is estimated based on the aggregation of the risk elements (see Table 5.13).

To obtain a single value for the overall assessment of the risk level of disruption of PRPU operation, the utility value associated with each evaluation grade of the risk level has to be estimated based on equations 5.10 to 5.12. The result presented in Table 5.13, indicates a belief distribution that shows disruption risk level for PRPU operation is slightly at medium level. Hence, the crisp value for disruption risk of PRPU operation was evaluated as 0.1571 (see Table 5.14). This result indicates that a probable risk level of disruption of a PRPU operation is 15.71%. This result implies that the convergent effect of the interrelationship between the risk elements and their attributes in a fuzzy situation can lead to the disruption of a PRPU operation.

Table 5.13: Aggregation of the risk elements

Risk elements	Very low	Low	Medium	High	Very high
Technical risk element	0.4113	0.5207	0.0680	0.0000	0.0000
Organizational risk element	0.4266	0.5347	0.0387	0.0000	0.0000
Operational risk element	0.3856	0.5676	0.0468	0.0000	0.0000
External risk element	0.4509	0.5491	0.0000	0.0000	0.0000
Disruption risks' result	0.4060	0.5595	0.0345	0.0000	0.0000

Disruption risks' result {(Very low, 0.4060), (Low, 0.5595), (Medium, 0.0345) (High, 0.0000), (Very high, 0.0000)}.

Table 5.14: Estimation of disruption risk

H_n	Very low	Low	Medium	High	Very high
V_n	1	2	3	4	5
$u(H_n)$	$\frac{1-1}{5-1} = 0$	$\frac{2-1}{5-1} = 0.25$	$\frac{3-1}{5-1} = 0.5$	$\frac{4-1}{5-1} = 0.75$	$\frac{5-1}{5-1} = 1$
γ_n	0.4060	0.5595	0.0345	0.0000	0.0000
$\sum_{n=1}^{N} \gamma_n =$	$0.4060 + 0.5595 + 0.0345 + 0.0000 + 0.0000 = 1 \rightarrow \gamma_H = 0$				
$\gamma_n \times u(H_n)$	= 0.0000	0.1398	0.0173	0.0000	0.0000
$\sum_{n=1}^{N} \gamma_n u(H_n)$ = 0.1571					

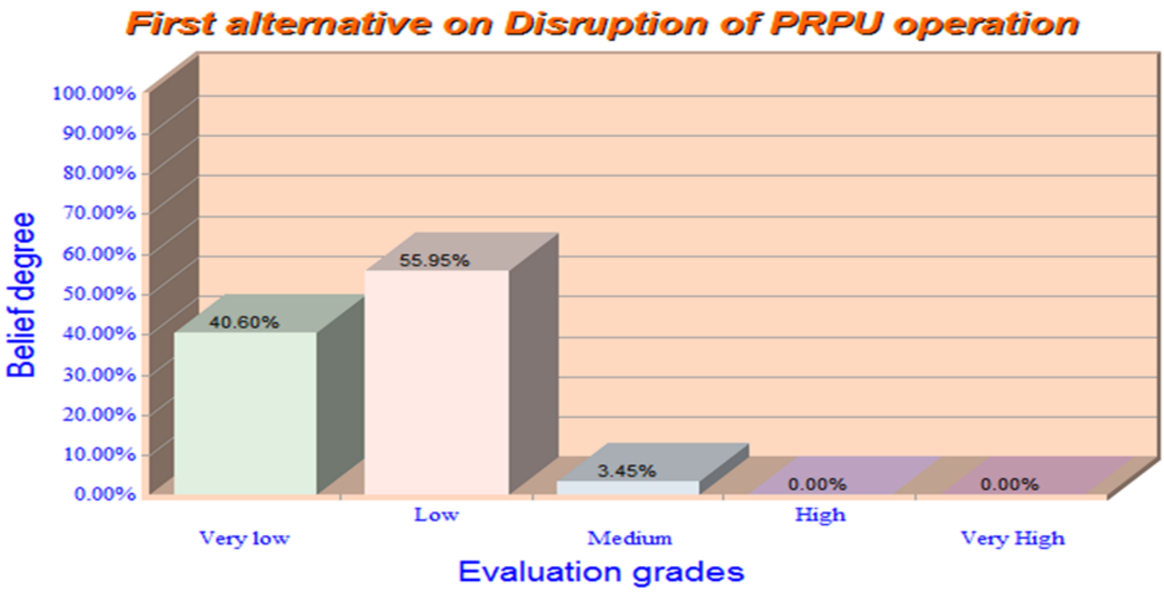

Figure 5. 4: Graphic demonstration of the risk level estimate for disruption of PRPU operation

- Step 7: Sensitivity analysis (SA)

In this study, the SA provides a systematic approach in both a statistical and analytical manner to allow the variation of one or more input data at a time in order to evaluate the contributions of each risk element and their associated attributes to disruption of PRPU operation. The variety of input data provides a means of deducing the highest level of threat from any risk element or their attributes. SA is utilised to substantiate the validity of the proposed framework for evaluation of disruption risk of PRPU operations. The sensitivity analysis is conducted using the precept explained in Section 5.9. The precept involves three axioms which are used as a measure to assess the logicality of the risk result in terms of analysing the disruption risk of PRPU operation. Also, the axioms are utilised to identify the most significant system risk elements that can spontaneously trigger the disruption of PRPU operation.

In the sensitivity study, the belief degrees associated with the highest preference linguistic grades of each attribute are decreased by ‘k’ and concurrently, the belief degrees associated with the lowest preference linguistic grades of the corresponding attributes are increased by ‘k’; hence, the results are obtained.

It is worth mentioning that when reducing the belief degree of the highest preference linguistic grades of a risk element by ‘k’, at the same time the belief degree of its lowest preference linguistic grades must be increased by ‘k’. Thus, if any of the belief degree associated with the highest preference linguistic grades, which is to be reduced by ‘k’ is less than ‘k’, then the remaining belief degree (i.e.γ_r) can be obtained from the belief degree of the next linguistic grade. This process continues until k is expended.

The result in Table 5.15 shows the utility values for each attribute after performing the SA process (i.e. decrement of the belief degrees associated with the highest preference linguistic grades by 10%, 20% and 30% respectively). The values selected for the sensitivity analysis are based on the consideration of uncertain condition whereby any of the attributes that are associated with each of the risk element can occur randomly. The sensitivity of the result is displayed by the utility graph in Figure 5.5. It is noteworthy to mention that all the results obtained are in accordance with Axioms 1 and 2.

a) When the belief degrees associated with the highest preference linguistic grades of all the attributes is decreased by 30% and the belief degrees associated with the lowest preference linguistic grades of all the attributes is increased by 30%, the overall utility value for the disruption of the PRPU operation is estimated at 0.5516.

b) When 11 attributes in the model were selected at random (instrument failure, piping failure, process equipment failure, inappropriate management policy/procedure, inadequate staffing, lack of safety training/drill, deviation from operation procedure, operator incompetency, inadequate maintenance procedure, sabotage and terrorist attack) to perform the SA process where the highest preference linguistic grades of all the attributes is decreased by 30% and the belief degrees associated with the lowest preference linguistic grades of all the attributes is increased by 30%, the overall the utility value for disruption of PRPU operation is evaluated at 0.6805.

By comparing the two results between (a) and (b), the overall utility value 0.6805 is larger than 0.5516, thus (b) is more significant than (a). Therefore, this result is in harmony with axiom 3. The analysis reflects that the model validation is sound and logical.

Table 5.15: Sensitivity result for decrement/increment of input data

	Increment/decrement of the input data for sensitivity analysis			
Attributes	0%	10%	20%	30%
Process equipment failure	0.1571	0.1658	0.1713	0.1792
Instrument failure	0.1571	0.1704	0.1847	0.2004
Piping failure	0.1571	0.1611	0.1653	0.1698
Utility system failure	0.1571	0.1608	0.1647	0.1669
Inappropriate management policy/procedure	0.1571	0.1639	0.1711	0.1787
Inappropriate decision making	0.1571	0.1624	0.1662	0.1738
Inadequate staffing	0.1571	0.1599	0.1631	0.1663
Poor safety monitoring and auditing	0.1571	0.1602	0.1636	0.1670
Lack of safety training/drill	0.1571	0.1617	0.1689	0.1717
Deviation from operational procedure	0.1571	0.1649	0.1734	0.1822
Operator incompetency	0.1571	0.1620	0.1671	0.1725
Inadequate communication	0.1571	0.1623	0.1677	0.1736
Inadequate maintenance procedure	0.1571	0.1626	0.1684	0.1744
Natural hazard	0.1571	0.1627	0.1688	0.1754
Sabotage	0.1571	0.1614	0.1661	0.1711
Terrorist attack	0.1571	0.1599	0.1621	0.1649

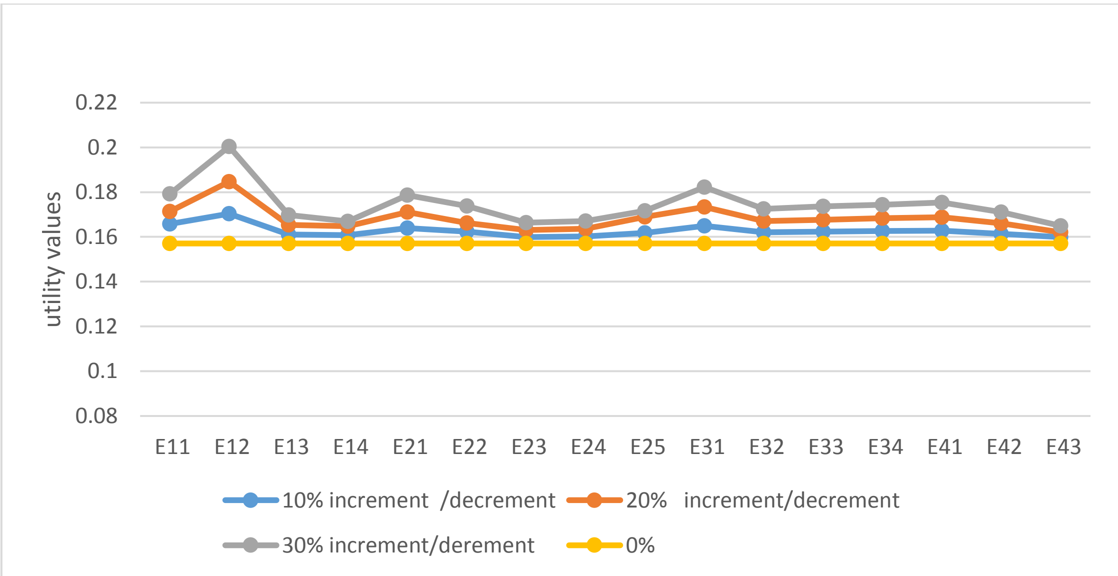

Figure 5.5: Sensitivity of model output to variation in model input

5.11 Discussion

In this study, the assessment of the risk level in terms of investigating the disruption of PRPU operation has been established and the results are shown in Table 5.14. Based on the assessment, the risk level result provides the highest belief degree value of 55.95% for low, 40.60% for very low and 3.45% for medium. The overall crisp value for the risk level is 0.1571.

However, the evidence from the sensitivity analysis indicates that under a dynamic condition, any moderate change in the risk level of any of the attributes used in the assessment for disruption of PRPU operation will affect the risk level estimate. For instance, if the belief degrees for the highest preference linguistic grades "low" and "very low" for instrument failure are decreased by 30% and at the same time their lowest preference linguistic grades "high" and "very high" are increased by 30%, the assessment result shows a swift change from 0.1571 to 0.2004. This change indicates that instrument failure is a sensitive attribute that can trigger a high level disruption to PRPU operation. In view of the sensitivity analysis, instrument failure is ranked as the most sensitive attribute. Also, deviation from operation procedure (ranked 2), inappropriate management policy/procedure (ranked 3), process equipment failure (ranked 4), and natural hazard (ranked 5) are the sensitive attributes among the lower level criteria used to determine the risk level of PRPU operation. The risk levels of these sensitive attributes must be a centre of focus in a risk management process for the petroleum refinery operations. Therefore, it is necessary to provide a robust decision support strategy that can be implemented effectively, to mitigate or control the risk levels of these attributes. This process will provide support in terms of the risk management of PRPU operations and reducing any other threat of operational uncertainties.

5.12 Conclusion

An inclusive generic assessment framework based on fuzzy set theory and an evidential reasoning approach for risk modelling of PRPU operation in a complex refinery environment is presented. The methodology was effectively used for the evaluation of disruption risk level of PRPU operation whereby the measures of risk elements and their associated attributes are vague and imperfect because of their subjective nature. In the risk evaluation process, the lack of real data is overcome by processing the subjective judgement of experts into a flexible and reasonable fuzzy value with a belief structure. The subjective evaluation of risk elements and their associated attributes based on multiple expert knowledges are well represented in a reliable manner. In the analysis, the fuzzy risk level estimate of attributes associated with each risk element is determined by two parameters occurrence likelihood and consequence severity. The expert ratings for the parameters associated with attributes of risk elements are expressed in triangular fuzzy numbers. The fuzzy risk estimates for all the attributes are transformed into a belief structure with the same set of evaluation grades based on the transformation approach proposed by Sadiq *et al.*, (2008). Then, an evidential reasoning approach was utilised as an aggregation procedure for synthesis of the transformed risk level estimates of all the attributes to obtain the overall risk level that can lead to disruption of PRPU operation in a complex refinery environment.

Finally, this proposed methodology has provided an understanding and a reliable risk analysis approach in a complex refinery environment, after it has been utilised to investigate the risk level that can cause a disruption case study of a complex petroleum refinery that has been in operation for 20 years. Hence, this assessment framework can be utilised as a risk assessment tool by risk managers and decision analyst in petroleum refinery to boost risk assessment process where available information can sometimes be vague or incomplete for risk analysis.

Chapter 6 - An Application of Fuzzy-BN for Risk Modelling of Petroleum Refinery Operations

Summary

A fuzzy Bayesian Network methodology is presented in this chapter to predict the prospect of disruption of petroleum refinery operations. The risk elements and attributes that can lead to the disruption of petroleum refinery operations are assigned in a BN model. The conditional dependence among the variables in the BN model are established using the symmetric model approach. In the assessment process, the subjective judgement of experts were transformed into crisp values based on a fuzzy based approach. In the application of the fuzzy Bayesian Network methodology, a sensitivity analysis was conducted to test the dynamism of the BN model. The proposed fuzzy BN methodology provides the capabilities for a systematic modelling of risk problems relating to petroleum refinery operations.

6.1 Fuzzy Bayesian Network (FBN) Approach

Extensive research has been conducted in the maritime and offshore sector based on the application of FBN. This has shown that the Fuzzy-Bayesian network is a reliable approach, which can be utilised as a robust risk modelling approach to enhance an assessment of disruption level in a petroleum refinery operation environment. FBN provides a more convincing inference process in a domain where causal factors are depict as discrete variables. The significance of (FBN) methodology is that they can be exploited in a logical fashion to enhance modelling and reasoning in terms of risk evaluation of a system failure.

In order to establish a reliable evaluation of risk as a function of occurrence likelihood for disruption of petroleum refinery operations using FBN approach, the uncertainty associated with the assessment of the probabilities of risk parameters needs to be dealt with. The uncertainties practically emanated from lack of access to real life data from a reliable source and the challenges of incorporating qualitative data from experts, to establish the probability of risk parameters in a BN model.

Qualitative data collected from experts may partly suffer uncertainties due to incompleteness and conflicts of knowledge, which may lead to inconsistency of consensus among experts. However, the uncertainties associated with the experts' assessment of risk parameters expressed in a linguistic manner, can be represented numerically by fuzzy values from a membership function design based on Fuzzy Set Theory (FST). Furthermore, an algorithm for the transformation of the experts' assessment to reach consensus values for likelihood of the risk parameters in the BN model will be introduced based on Hsu and Chen, (1996).

In order to ascertain a smooth BN inference process, the conditional probability distribution for the BN model will be determined via the Kernel of symmetric model by Riahi, (2010). In this way, the required probability distribution of the input variable in the BN inference process is produced. Hence, the objective of this chapter is to present a comprehensive novel risk-model, which focuses on the analysis of the prospect of disruption to PRPU operations. The proposed model will provide a holistic view of a predictive quantitative mechanism for disruption of PRPU operations based on fuzzy Bayesian Network (BN). This approach will enhance the representation of the causal factors relationship graphically and depict how they can trigger the disruption risk of PRPU operation.

In this study, the symmetric model is the adopted approach to develop the Conditional Probability Table (CPT) for the BN model developed to evaluate the prospect of disruption of a petroleum refinery operation. The symmetric model concept depends on employing the relative importance of each parent node for their associated child node. The strength of direct dependence of each child node to its associated parent nodes is defined by the normalised weight of the parent nodes.

6.2 The Fuzzy-Bayesian Network methodology for risk modelling of disruption of a petroleum refinery operations.

The most significant risk elements and attributes that are associated with petroleum refinery operations, outlined in chapter four are utilised as the basis for the BN model. The BN model provides a graphical approach to analyse the causal links or relationship between the risk elements and their attributes, which are represented as a set of variables in the BN model. The main reason for developing the BN model is to analyse the prospect of disruption of PRPU operations under binary-state condition.

In the BN, each node operates as a binary-state variable in order to provide a dynamic and a more realistic situation in term of determining occurrence probability for disruption of PRPU operations. The prior probability for each root node in the BN is determined based on the subjective expert judgments and transforming them into quantitative data. The data provide the input for all the root nodes in the BN model. The conditional dependence of the child node to its parent nodes in the BN is established based on conditional probability distributions.

The CPT for the child nodes in the BN model is determined using symmetric model. The symmetric model is used to generate the CPT by synthesizing the normalised value of the relative importance of each parent node to their child node in the BN model. The symmetric model deals effectively with the conditional probability combination of binary-state parent nodes. The propagation of the input through the BN enables the computation of the likelihood of disruption of PRPU operations. The proposed FBN methodology steps of petroleum refinery operations is described as follows:

6.2.1 Develop a BN model for assessing the prospect of disruption of petroleum refinery operations

In order to build the BN model, it is vital to clearly define the domain that it is supposed to represent. The nodes in the BN should be well depicted and their states must be adequately defined in order to avoid misinterpretation. It is important to establish the relationship between the nodes by establishing adequate links of the nodes and the probability distribution that shows the level of influence between the nodes. A BN model for the assessment of the prospect of disruption of PRPU operations is developed by assigning PRPU risk elements and their corresponding attributes as a nodes in the BN (see Table 6.1). What each node represent in the BN must be determined, i.e. parent node or root node, child node and target node. The root nodes is not directly influenced by any other node in the BN and it is defined as a level-1 node (first stage). The child node is defined as a level 2 node (second stage) and the target node is defined as the level 3 node (Third stage).

This process of building the BN graph continues in a hierarchical order until all the parent-child links and the target node directional influences are established by the edge of the graph. After defining what each node represents in the BN model, the next step is to define the possible states of all the nodes i.e. “Yes” and “No”. The BN model diagram for assessing the likelihood of disruption of petroleum refinery operation is presented in Figure 6.1.

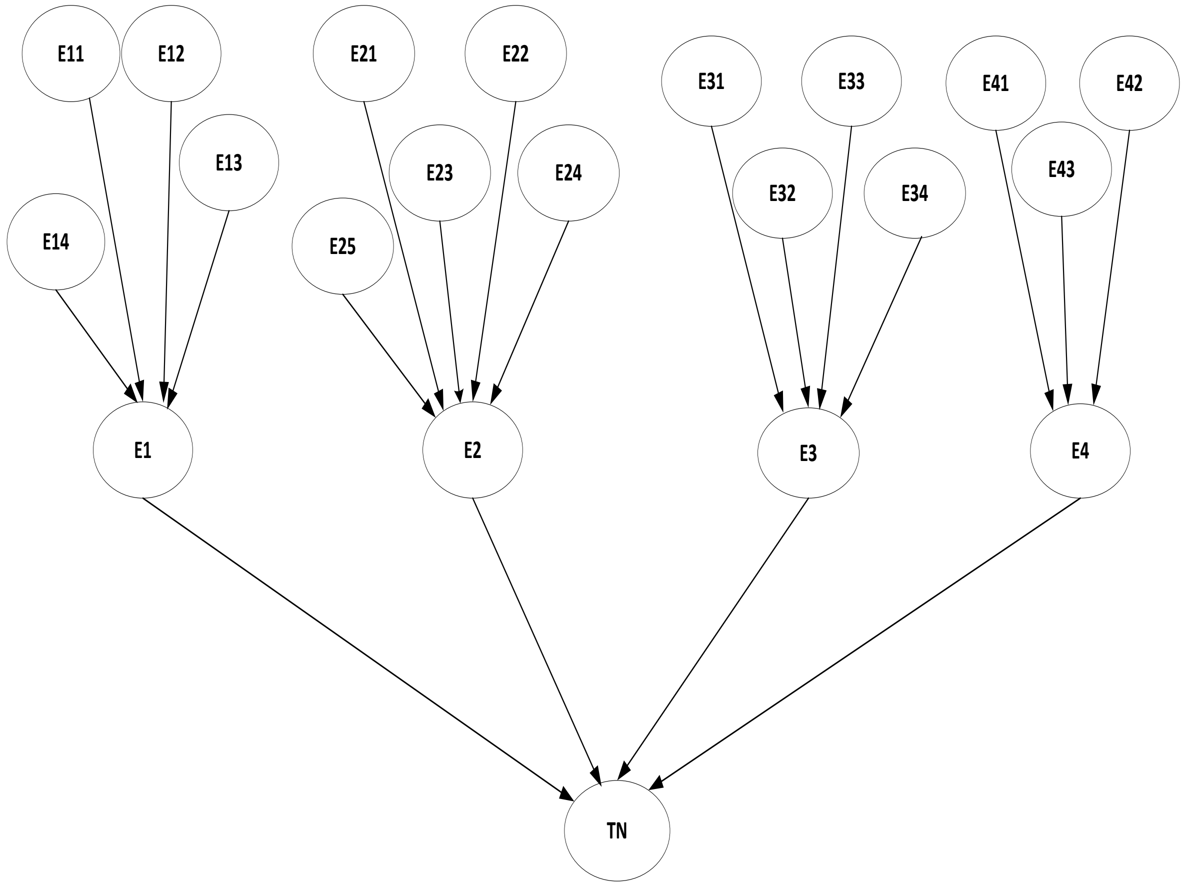

Figure 6.1: BN model for evaluation of disruption risk of petroleum refinery operations

Table 6.1: Nodes representation for the BN model

Node type	Abbreviation	Node description
Target node	Disruption	Disruption of PRPU operations
Child node	E1	Technical risk element
Parent node	E11	Process equipment failure
Parent node	E12	Instrumentation failure
Parent node	E13	Piping failure
Parent node	E14	Utility system failure
Child node	E2	Organizational risk element
Parent node	E21	Inappropriate management policy and procedures
Parent node	E22	Inappropriate decision making
Parent node	E23	Inadequate staffing
Parent node	E24	Poor safety monitoring and auditing
Parent node	E25	Lack of safety training/drill
Child node	E3	Operational risk element
Parent node	E31	Deviation from operation procedure
Parent node	E32	Operator incompetency
Parent node	E33	Inadequate communication
Parent node	E34	Inadequate maintenance procedure
Child node	E4	External risk element
Parent node	E41	Natural hazard
Parent node	E42	Sabotage
Parent node	E43	Terrorist attack

6.2.2 Fuzzy data transformation

All expert judgement expressed using linguistic terms are converted to fuzzy values in order to capture the subjectivity and the imprecision in the judgement.

The expert rating of each root node in a BN model can be characterised by a fuzzy set defined on a universe of discourse (U) of membership function with interval values ranging from zero to one. The membership function for the fuzzy set is a triangular fuzzy scale or a trapezoidal fuzzy scale that is represented either by a triangular fuzzy number or by a trapezoidal fuzzy number. A triangular fuzzy membership scale of PRPU operations is presented in Table 6.2.

The ratings from a homogenous group of experts is aggregated to reach a consensus value. Then, the aggregated experts' rating is defuzzified into a crisp value (fuzzy possibility score) using appropriate algorithm. Furthermore, the fuzzy possibility score for each node is transformed into unconditional prior probabilities. The fuzzy based transformation process, used to obtain the input data for the purpose of this study, is established based on the following steps:

- Step 1. Rating state: In this stage the subjective judgement from experts is categorise using fuzzy linguistic scales which are in the form of linguistic terms such as 'very high', 'high', 'medium' 'low,' and 'very low'. The linguistic terms are very reliable in terms of handling fuzzy situations. The linguistic terms are transformed into their corresponding fuzzy numbers based on a defined fuzzy membership function of an appropriate linguistic scale. In this chapter, a triangular fuzzy membership function based on a five linguistic term is adopted for rating each root node in the BN model.
- Step 2. Aggregation state: Experts response to a subject matter is influenced by their experience and knowledge; therefore, it is necessary to aggregate different subjective assessments of experts into a single one. There are various methods to aggregate different opinions of expert's to reach consensus. The algorithm for aggregation of fuzzy opinion under group decision-making, proposed by Hsu and Chen (1996) is employed. The algorithm can aggregate subjective judgement of homogeneous and heterogeneous group of experts to reach a consensus. The algorithm is based on the following sub-steps:

(1) Evaluate the degree of similarity is $s(\tilde{A}_i , \tilde{A}_j)$ of the subjective judgements $\tilde{A}_i$ and $\tilde{A}_j$ between each pair of experts E_i and E_j , where $s\left(\tilde{A}_i , \tilde{A}_j\right) \in [0, 1]$. Based on Chen and

Chen (2003) approach, assume that the opinions of the experts are represented by trapezoidal fuzzy numbers $\tilde{X}_i = (a_1\, a_2\, a_3\, a_4)$, $\tilde{X}_j = (b_1\, b_2\, b_3\, b_4)$, then the degree of similarity $s(\tilde{A}_i\,, \tilde{A}_j)$ between the two fuzzy numbers can be evaluated as follows:

$$s(\tilde{A}_i\,, \tilde{A}_j) = 1 - \frac{\sum_{i=1}^{4}|a_i - b_i|}{4}\,. \quad (6.1)$$

If $\tilde{X}_i$ and $\tilde{X}_j$ are triangular fuzzy numbers, the degree of similarity can be calculated in the following manner:

$$s(\tilde{A}_i\,, \tilde{A}_j) = 1 - \frac{\sum_{i=1}^{3}|a_i - b_i|}{3}\,. \quad (6.2)$$

The larger the degree of similarity between these two fuzzy numbers, the greater the similarity.

(2) Compute the average degree of agreement of expert $DA(E_i)$, where

$$DA(E_i) = \frac{1}{n-1} \sum_{i \neq j}^{n} s(\tilde{A}_i\,, \tilde{A}_j) \quad (6.3)$$

(3) Compute the relative degree of agreement $RDA(E_i)$ of each expert.

$$RDA(E_i) = \frac{DA(E_i)}{\sum_{i=1}^{n} DA(E_i)} \quad (6.4)$$

(4) Compute the consensus coefficient degree $\mathrm{CC}(E_i)$ of expert, $E_i(i = 1,2,3 \ldots, n)$:

$$\mathrm{CC}(E_i) = \beta . W(E_i) + (1-\beta). RDA(E_i) \quad (6.5)$$

where β $(0 < \beta < 1)$ is the relaxation factor of the proposed approach, it indicates the importance of weight of expert $W(E_i)$ over $RDA(E_i)$. If $\beta = 0$, then no importance is given to $W(E_i)$ and homogeneous group of expert is used (Miri Lavasani *et al.*, 2014; Hsu and Chen, 1996). If $\beta = 1$, the consensus degree coefficient of the expert is the same as important weight of the expert. Hence, the relative worthiness of each expert's judgement can be evaluated based on the value of the consensus degree coefficient *(*Celik *et al.,* 2010*)*. The value assigned to β is determined based on the decision maker perspective.

(5) The aggregation result of experts' judgement can obtained as follows:

$$R_{ag} = CC(E_1) \times R_1 + CC(E_2) \times R_2 + \cdots + CC(E_m) \times R_m \qquad (6.6)$$

- Step 3. Defuzzification process: The aggregated fuzzy rating from a subjective assessment of experts is transformed into a defuzzified value regarded as the Fuzzy Possibility Score (FPS). The FPS is defined as the most possible extent of the expert assessment of a node in a BN model. The aggregated fuzzy rating is fuzzy numbers, which must be defuzzified to crisp values. The centre of area defuzzification technique is adopted for this study for ease of computation of the fuzzy values (Miri Lavasani *et al*., 2011). The centre of area defuzzification technique is defined as:

$$X^* = \frac{\int \mu_i(x) x dx}{\int \mu_i(x)} \qquad (6.7)$$

X^* is defined as the defuzzified output, $\mu_i(x)$ is the overall value of the aggregated fuzzy rating based on expert opinions and x is the output variable. The centre of area formulae can be utilised to defuzzify aggregated values of a triangular fuzzy number and a trapezoidal fuzzy number. A triangular fuzzy number A^* = (a_1, a_2, a_3) is deffuzzified as follows:

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} x dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x dx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} dx} = \frac{1}{3}(a_1, a_2, a_3) \qquad (6.8)$$

A trapezoidal fuzzy number A^* = (a_1, a_2, a_3, a_4) is deffuzzified as follow:

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} xdx + \int_{a_2}^{a_3} xdx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} xdx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} dx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} dx} = \frac{1}{3} \frac{(a_4+a_3)^2 - a_4a_3 - (a_1+a_2)^2 + a_1a_2}{(a_4+a_3-a_1-a_2)} \quad (6.9)$$

6.2.3 Analyse the BN model for disruption of petroleum refinery operation

In a BN model, defining each node and their possible states is important in order to establish the dependencies of each child node to its associated parent nodes by using prior information from available data or from expert's opinion. The relative important influence of each parent node to it child node is determined based on the CPT for each child node in the BN. The CPT quantifies the strength of direct dependence of each child node to its associated parent nodes (Riahi *et al.*, 2014). When the prior probability estimate for each parent node in the Bayesian network model is determined based on step 2 of the methodology, then, the CPT for each child node in the network is generated by exploiting the kernel of the symmetric model, which is described as follows:

In a normalized space, the relative influence of each parent node in terms of defining the conditional probability of child node A, given the parent node, B_r , where $r = 1, 2, \dots \dots n$ can be estimated as follows:

$$P(A = present | B_1 = present) = \omega_1$$

$$P(A = present | B_2 = present) = \omega_2$$

$$\vdots$$

$$P(A = present | B_n = present) = \omega_n$$

$$\sum_{r=1}^{n} \omega_r = 1 \quad (6.10)$$

Based on Equation (6.11) in the context of the symmetric model (i.e. normalised space), the probability of a child node A conditional upon "n" parent nodes, B_r where $r = 1, 2, \ldots\ldots n$, can be estimated as follows:

$$P(A|B_1B_2 \ldots\ldots B_n) = \sum_{r=1}^{n} \widetilde{\omega}_r \tag{6.11}$$

$\widetilde{\omega}_r = \omega_r$: If the state of the "r^{th} parent node" is identical to the state of its child.

$\omega_r = 0$: If the state of the "r^{th} parent node" is different from the state of its child.

The important influence of each parent node to their child node is estimated as a relative weight, which is determined by transforming the subjective judgement of experts. The normalisation process for the relative weight is calculated as follows:

$$P(A = present|B_1 = present) = P(\dot{C}_1) = \frac{P(C_1)}{\sum_{m=1}^{n} P(C_m)} \tag{6.12}$$

$$\vdots$$

$$P(A = present|B_n = present) = P(\dot{C}_n) = \frac{P(C_n)}{\sum_{m=1}^{n} P(C_m)}$$

$$P(C_1) + P(C_2) + P(C_3) + \cdots + P(C_n) = 1$$

whereby the $P(A = present|B_1 = present) = P(\dot{C}_1)$ represents the relative influence of the first parent node for its associated child node in the absence of all other variables. The normalised weight obtained from the normalization process provides the input value, which determines the unconditional probability distribution for the root node or parent node in the BN model. Once the CPTs for the entire child nodes in the BN model are determined, BN software can draw inferences in order to determine the occurrence probability for disruption of petroleum refinery operation.

The symmetric model terminology for the relative influence justification in normalised space is based on axioms of probability theory, due to normalisation and in normalised space $\dot{C}_1$, $\dot{C}_2$, $\dot{C}_3$…& $\dot{C}_n$ remain disjointed (Riahi, 2010):

$$P(\dot{C}_1 \cap \dot{C}_2) = P(\dot{C}_2 \cap \dot{C}_3) = \cdots = 0$$

$$\therefore \; P(\dot{C}_1 \cup \dot{C}_2 \cup \dot{C}_3 \cup \ldots \cup \dot{C}_n) = P(\dot{C}_1) + P(\dot{C}_2) + P(\dot{C}_3) + \cdots + P(\dot{C}_n) \qquad (6.13)$$

Based on equation 6.11, the following probability distribution can be obtained:

$$P(A = Yes|B_1, B_1, \ldots \ldots . B_n = No) = 0$$

$$P(A = No|B_1, B_2, \ldots \ldots .. B_n = No) = 1$$

$$P(A = Yes|B_1, B_2, \ldots \ldots . B_n = Yes) = 1$$

$$P(A = No|B_1, B_2, \ldots \ldots .. B_n = No) = 0$$

6.2.4 Validation of the BN model

In order to test the consistency of the BN model, sensitivity analysis (SA) approach is adopted in the validation process. SA is a process that helps to provide a reasonable amount of confidence in the result obtained by analysing the sensitivity of a BN model output to any slight variation in probability of the input node. The following Axioms are utilised in the validation process:

Axiom 1: A slight increment/decrement in the rate or probability of occurrence associated with any state of an input variable should result in a relative increment/decrement of the model output.

Axiom 2: If the rate or occurrence probability associated with highest preference state of an input variable can be decreased by A and B (i.e. simultaneously the rate or probability of occurrence associated with the lowest preference states should be increased by A and B ($1 > B > A$). Then, the utility value of the model output is determined by U_a and U_b accordingly, where U_a should be greater than U_b.

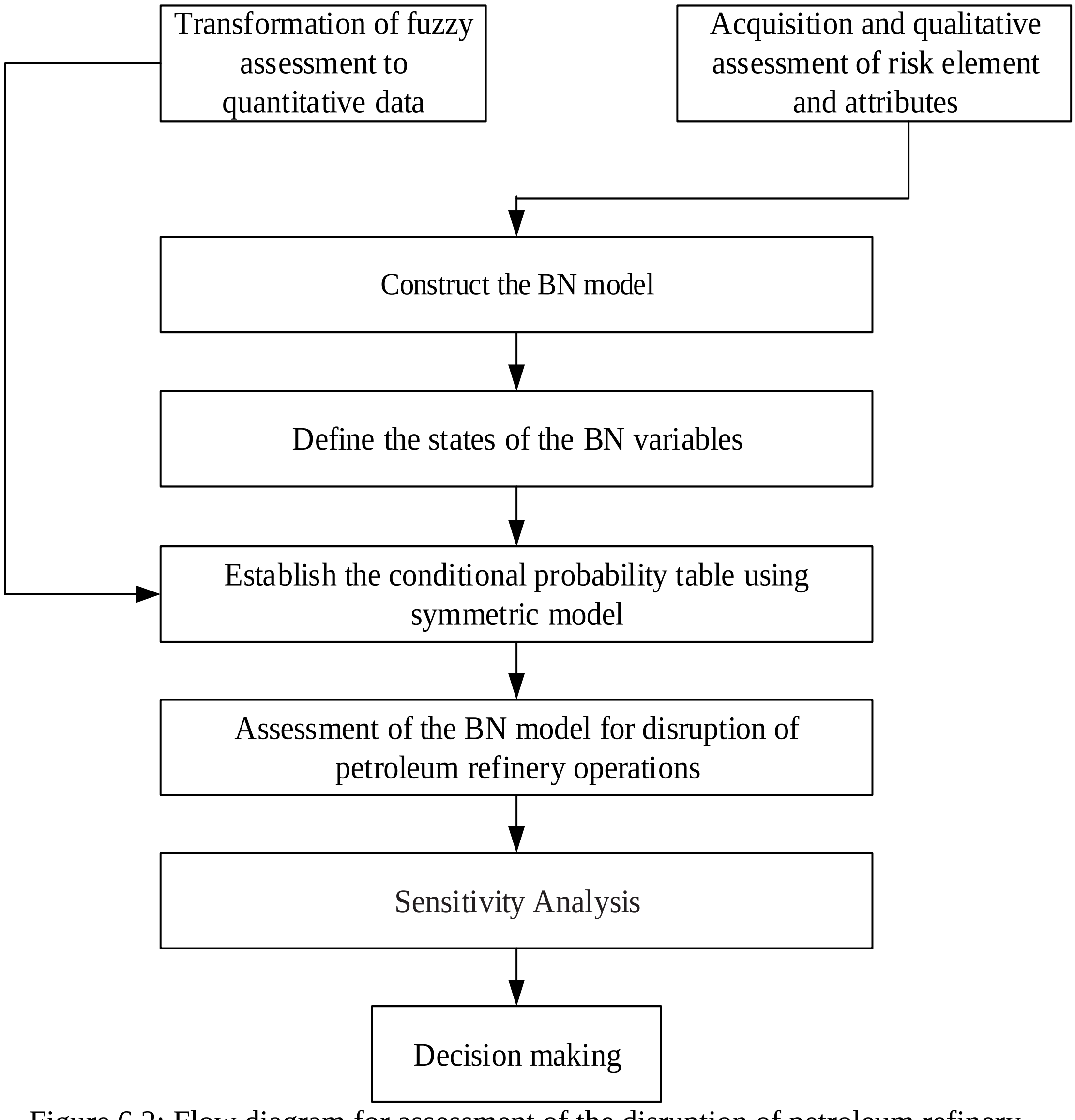

Figure 6.2: Flow diagram for assessment of the disruption of petroleum refinery operations

6.3 Case study

The methodology presented in this study is utilised to investigate the prospect of risk scenario on the smooth operation of a petroleum refinery operation. A case study is used to demonstrate how the methodology can be implemented to assess the likelihood of disruption of petroleum refinery operation. A BN model was developed based on available information on the key risk elements and their corresponding attributes, which have been identified based on literature review and brainstorming with experts with a background in petroleum refinery operations. A case of a complex petroleum refinery, which has been in operation for 20 years, is considered.

6.3.1 Generic BN model for assessing the prospect of disruption of petroleum refinery operation (step 1)

The generic BN model developed presents a clear picture of the systematic build-up of the risk scenario under investigation. The model consists of the two levels of interrelationship, where all the risk elements and their corresponding attributes are presented as child nodes and parent nodes in the BN model as illustrated in Figure 6.1.

6.3.2 Fuzzy based data transformation (step 2)

- Step 1: Rating state

Due to lack of quantitative data to define the occurrence likelihood for each of the attribute represented as a root node in BN model, expert subjective judgement is used to quantify the occurrence likelihood of each node. In this study, five experts were selected to give their responses. The nominated experts' all have the same level of qualifications, positions and years of experience in petroleum and gas refinery operations. All the experts have a PhD qualification, 11-20 years' experience, and they are a consultant, senior engineers or managers in a petroleum and gas refinery. In this case, the experts are of equal weights. The subjective judgment from each expert is transformed into a fuzzy number based on the fuzzy linguistic scale presented in Table 6.2. The expert judgments on the likelihood of each root node in the BN and their corresponding fuzzy values are presented in Tables 6.3 and 6.4.

Table 6.2: Fuzzy linguistic scale

Linguistic terms	Triangular fuzzy numbers
Very Low (VL)	(0, 0.10, 0.20)
Low (L)	(0.15, 0.275, 0.4)
Medium (M)	(0.35, 0.475, 0.6)
High (High)	(0.55, 0.725, 0.9)
Very High (VH)	(0.85, 0.9, 1.0)

Table 6.3: Expert linguistic ratings

Nodes	Expert Linguistic rating				
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
E11	L	VL	L	M	L
E12	L	VL	M	VL	M
E13	L	L	VL	L	M
E14	L	L	M	M	H
E21	L	L	VL	L	M
E22	L	L	VL	M	M
E23	L	M	L	H	H
E24	M	L	VL	M	M
E25	M	VL	L	L	L
E31	L	VL	L	L	H
E32	M	L	L	VH	M
E33	L	L	M	M	M
E34	M	L	L	L	L
E41	VL	VL	VL	L	VL
E42	VL	L	VL	VL	VL
E43	VL	VL	VL	VL	VL

Table 6.4: Fuzzy value of Experts' ratings

Nodes	Fuzzy value of Experts' Ratings				
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
E11	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0.35,0.475,0.6)	(0.15,0.275,0.4)
E12	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0.35,0.475,0.6)
E13	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.35,0.475,0.6)	(0, 0.10, 0.20)	(0.35,0.475,0.6)
E14	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.35,0.475,0.6)	(0.35,0.475,0.6)	(0.55,0.775,1.0)
E21	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0.35, 0.475,0.6)
E22	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.35,0.475,0.6)	(0.35, 0.475,0.6)
E23	(0.15,0.275,0.4)	(0.35, 0.475,0.6)	(0.15,0.275,0.4)	(0.55,0.775,1.0)	(0.55,0.775,1.0)
E24	(0.35,0.475,0.6)	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.35,0.475,0.6)	(0.35, 0.475,0.6)
E25	(0.35, 0.475,0.6)	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.15,0.275,0.4)
E31	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.55,0.775,1.0)
E32	(0.35, 0.475,0.6)	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.15,0.275,0.4)
E33	(0.35, 0.475,0.6)	(0.15,0.275,0.4)	(0.35,0.475,0.6)	(0.35,0.475,0.6)	(0.35, 0.475,0.6)
E34	(0.35, 0.475,0.6)	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.15,0.275,0.4)	(0.15,0.275,0.4)
E41	(0, 0.10, 0.20)	(0, 0.10, 0.20)	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0, 0.10, 0.20)
E42	(0, 0.10, 0.20)	(0.15,0.275,0.4)	(0, 0.10, 0.20)	(0, 0.10, 0.20)	(0, 0.10, 0.20)
E43	(0, 0.10, 0.20)	(0, 0.10, 0.20)	(0, 0.10, 0.20)	(0, 0.10, 0.20)	(0, 0.10, 0.20)

- Step 2: Aggregation state

The fuzzy likelihood value provided based on the five expert assessment of all subjective attributes represented in the BN model has been presented in Table 6.4.The aggregation of the experts assessments will provide a sound and a tolerable consensus to overcome the conflict of knowledge in terms of each expert opinion. The aggregation approach presented in Section 6.2.2 is utilise to reach the consensus for all the experts' assessments. For instance, the aggregation of expert judgement for E31 is obtained based on aggregation step described in Section 6.2.2.

Step 2a: Estimate of degree of similarity $s(\tilde{A}_i, \tilde{A}_j)$ of the subjective judgements $\tilde{A}_i$ and $\tilde{A}_j$ is presented as follow:

$$s(\tilde{A}_i, \tilde{A}_j) = 1 - \frac{\sum_{i=1}^{3}|a_i - b_i|}{3}$$

$$s(\tilde{A}_i, \tilde{A}_j) = 1 - \frac{|a_1-b_1|+|a_2-b_2|+|a_3-b_3|}{3} = 1 - \frac{|0.15-0|+|0.275-0.10|+|0.4-0.2|}{3} = 0.825$$

Tables 6.5: Degree of similarity of experts' subjective judgments

$s(\tilde{A}_i, \tilde{A}_j)$	$\tilde{A}_1$	$\tilde{A}_2$	$\tilde{A}_3$	$\tilde{A}_4$	$\tilde{A}_5$
$\tilde{A}_1$	0	0.825	1	1	0.55
$\tilde{A}_2$	0.825	0	0.825	0.825	0.375
$\tilde{A}_3$	1	0.825	0	1	0.55
$\tilde{A}_4$	1	0.825	1	0	0.55
$\tilde{A}_5$	0.55	0.375	0.55	0.55	0

Step 2b: Calculation of the Average Agreement Degree $A(E_i)$ for each of the experts' are presented as follows:

$$A(E_1) = \frac{s(\tilde{A}_1, \tilde{A}_2) + s(\tilde{A}_1, \tilde{A}_3) + s(\tilde{A}_1, \tilde{A}_4) + s(\tilde{A}_1, \tilde{A}_5)}{4} = \frac{0.825+1+1+0.55}{4} = 0.8437$$

$$A(E_2) = \frac{s(\tilde{A}_2, \tilde{A}_1) + s(\tilde{A}_2, \tilde{A}_3) + s(\tilde{A}_2, \tilde{A}_4) + s(\tilde{A}_5, \tilde{A}_5)}{4} = \frac{0.825+0.825+0.825+0.55}{4}$$

$$= 0.7125$$

$$A(E_3) = \frac{s(\tilde{A}_3, \tilde{A}_1) + s(\tilde{A}_3, \tilde{A}_2) + s(\tilde{A}_3, \tilde{A}_4) + s(\tilde{A}_3, \tilde{A}_5)}{4} = \frac{1+0.825+1+0.55}{4} = 0.8437$$

$$A(E_4) = \frac{s(\tilde{A}_4, \tilde{A}_1) + s(\tilde{A}_4, \tilde{A}_2) + s(\tilde{A}_4, \tilde{A}_3) + s(\tilde{A}_4, \tilde{A}_5)}{4} = \frac{1+0.825+1+0.55}{4} = 0.8437$$

$$A(E_5) = \frac{s(\tilde{A}_5, \tilde{A}_1) + s(\tilde{A}_5, \tilde{A}_2) + s(\tilde{A}_5, \tilde{A}_3) + s(\tilde{A}_5, \tilde{A}_4)}{4} = \frac{0.55+0.375+0.55+0.55}{4} = 0.5063$$

Step 2c: Computation of the Relative Degree of Agreement $RDA(E_i)$ of each expert is as follows:

$$RDA(E_1) = \frac{DA(E_1)}{\sum_{i=1}^{n} DA(E_1)} = \frac{0.8437}{3.7499} = 0.2250$$

$$RDA(E_2) = \frac{DA(E_2)}{\sum_{i=1}^{n} DA(E_2)} = \frac{0.7125}{3.7499} = 0.1900$$

$$RDA(E_3) = \frac{DA(E_3)}{\sum_{i=1}^{n} DA(E_3)} = \frac{0.8437}{3.7499} = 0.2250$$

$$RDA(E_4) = \frac{DA(E_4)}{\sum_{i=1}^{n} DA(E_4)} = \frac{0.8437}{3.7499} = 0.2250$$

$$RDA(E_5) = \frac{DA(E_5)}{\sum_{i=1}^{n} DA(E_5)} = \frac{0.5063}{3.7499} = 0.1350$$

Step 2d: Estimate for Consensus Coefficient Degree CC(E_i) of all the experts is as follows:

In this case, the degree of importance of each expert is zero ($\beta = 0$) because all the experts are considered equal in weight. In this case, $RDA(E_i) = \mathrm{CC}(E_i)$

CC(E_1) = $\beta.W(E_1) + (1-\beta).RDA(E_1)$ = $0 \times 0 + (1-0) \times 0.2250$ = 0.2250

CC(E_2) = $\beta.W(E_2) + (1-\beta).RDA(E_2)$ = $0 \times 0 + (1-0) \times 0.1900$ = 0.1900

CC(E_3) = $\beta.W(E_1) + (1-\beta).RDA(E_1)$ = $0 \times 0 + (1-0) \times 0.2250$ = 0.2250

CC(E_4) = $\beta.W(E_1) + (1-\beta).RDA(E_1)$ = $0 \times 0 + (1-0) \times 0.2250$ = 0.2250

CC(E_5) = $\beta.W(E_1) + (1-\beta).RDA(E_1)$ = $0 \times 0 + (1-0) \times 0.1350$ = 0.1350

Step 2e: The aggregation result of experts' judgement can obtained as follows:

$$R_{ag} = CC(E_1) \times R_1 + CC(E_2) \times R_2 + CC(E_3) \times R_3 + CC(E_4) \times R_4 + CC(E_5) \times R_5$$

$$R_{ag} = 0.2250 \times (0.15, 0.275, 0.4) + 0.1900 \times (0, 0.10, 0.20) + 0.2250 \times (0.15, 0.275 + 0.225 \times (0.15, 0.275, 0.4 + 0.135 \times (0.55, 0.775, 1.0)$$

R_{ag} = (0.1755, 0.3025, 0.4295)

- Step 3: Defuzzification state

The centre of area approach is utilised to defuzzify the aggregated fuzzy opinions of the five experts. The output value for the defuzzification of the aggregated result of the expert judgements for the variable E31 is as follows:

$$X^{*} = \frac{1}{3}(a_1 + a_2 + a_3) = \frac{1}{3}(0.1755 + 0.3025 + 0.4295) = 0.3025$$

Hence, the defuzzified values of all the experts' aggregation and their normalized values are presented in Table 6.6. The defuzzified values represent the relative weight of the root nodes in Table 6.6, whereby their normalization values provide the input for the unconditional probability of each root node.

Tables 6.6: The defuzzification of all experts' aggregation

Nodes	Aggregation of subjective judgment of experts	Defuzzification value (relative weight)	Normalised weight (unconditional prior probability)
E11	(0.1582, 0.2787, 0.3991)	(0.2787)	0.2165
E12	(0.1582, 0.2787, 0.3991)	(0.2787)	0.2165
E13	(0.1691, 0.2842, 0.3992)	(0.2842)	0.2208
E14	(0.3025, 0.4650, 0.5692)	(0.4456)	0.3462
E21	(0.1582, 0.2787, 0.3991)	(0.2787)	0.1591
E22	(0.2027, 0.3412, 0.4438)	(0.3292)	0.1879
E23	(0.3486, 0.4931, 0.6376)	(0.4931)	0.2814
E24	(0.2518, 0.3720, 0.4935)	(0.3724)	0.2125
E25	(0.1582, 0.2787, 0.3991)	(0.2787)	0.1591
E31	(0.1755, 0.3025, 0.4295)	(0.3025)	0.2074
E32	(0.1848, 0.3098, 0.4348)	(0.3098)	0.2124
E33	(0.3310, 0.4463, 0.5680)	(0.4484)	0.3074
E34	(0.2728, 0.3978, 0.5228)	(0.3978)	0.2728
E41	(0.02661, 0.131, 0.2354)	(0.1310)	0.3569
E42	(0.03084, 0.136, 0.2411)	(0.1360)	0.3706
E43	(0.0000, 0.1000, 0.2000)	(0.1000)	0.2725

6.3.3 Evaluation of the BN model and result *(Step 3)*

In order to evaluate the likelihood of disruption of petroleum refinery operation, the Netica software provides a convenient way to build the BN and carry out the probabilistic inference. The probability distribution of the child nodes in the BN model is synthesized using the symmetric model approach. The relative weights for all the root nodes in the network are determined based on the four stages presented in step 2 of the methodology. The evaluation of the relative weight of the root node E31 is presented as an example. Table 6.6 provides the relative weights that are utilized to determine the unconditional probability values for all the root nodes in the BN model. The relative influence of each parent node to their associated child node or the strength of direct dependence of a child node to its parent node is revealed based on populating the CPT through the concept of the symmetric model. In this study, the concept of the symmetric feature of the CPT for the child node E4 (External risk element) based on the relative importance of its set of parent nodes E41, E42 and E43 is presented in an intelligent manner. In view of the above, the calculation of the normalized weight for all the set of parent nodes for E4 is illustrated below to obtain the values of the probability distribution.

$$\omega_1 = \frac{w_1}{w_1+w_2+w_3} \approx 0.3569, \quad \omega_2 = \frac{w_2}{w_1+w_2+w_3} = \frac{0.1360}{0.367} \approx 0.3706,$$

$$\omega_3 = \frac{w_3}{w_1+w_2+w_3} = \frac{0.100}{0.367} \approx 0.2725$$

$$P(\dot{C}_1) + P(\dot{C}_2) + P(\dot{C}_3) = 1 \quad \therefore 0.3569 + 0.3706 + 0.2725 = 1$$

Table 6.7: Populated CPT for E4 using the symmetric model

	E41 (Yes)				E41 (No)			
	E42 (Yes)		E42 (No)		E42 (Yes)		E42 (No)	
	E43 (Yes)	E43 (No)	E43 (Yes)	E43 (No)	E43 (Yes)	E43 (No)	E43 (Yes)	E43 (No)
$\Omega(Ext)$	1	0.7274	0.6294	0.3569	0.6341	0.3706	0.2725	1
$\Omega(\neg Ext)$	0	0.2726	0.3706	0.6431	0.3569	0.6294	0.7274	0

where, $\emptyset(Ext) = P(Ext = Yes|E41, E42, E43)$

$\emptyset(\neg Ext) = P(Ext = No|E41, E42, E43)$

The marginal probability of likelihood of the child node E4, which represent external risk element (Ext) described in Table 6.1 is determined based on the principle of Bayes chain rule:

$P(Ext = Yes|E41, E42, E43)$ = 0.5

$P(Ext = No|E41, E42, E43)$ = 0.5

The amount of data that is required as input to populate all the CPTs of the child nodes in the BN model are determined using equation (6.12), as $2^5, 2^6, 2^5, 2^4, 2^5$ (i.e. 176 data). It is important to emphasize that the above calculation is true for the target scenario and the same approach applies to any other scenario regardless of the number of parent nodes. Hence, if there is uncertainty about the validity or non-validity of a child's parents, then there should be uncertainty regarding the validity or non-validity of the child itself. In general, it is worth mentioning to note that the Bayesian conclusion for the BN model relies on the above as a background for probability distributions, which are defined based on prior input at the root node. The Netica software was utilized for the process of probability propagation or inference for the BN model to determine the prior probability at the Target Node (TN). In addition, the BN model proved dynamic in term of its capability to review target node probability in the light of newly observed evidence. The experiment performed based on the application of the case study to the BN model provide a result at the target node, which is represented in Figure 6.3 as: Disruption = (Yes, 0.293 or 29.3%), (No, 0.707 or 70.7%). In the process of introduction of newly observed evidence with 100% certainty, the result of the target node provides a significant effect in term of change in occurrence probability. For instance, three scenarios were assumed, whereby the observed evidence for the first scenario with node E14, E41 and E42 are 100% certain, the second scenario involves observed evidence for E14, E23, E33 and E42 are 100% certain and the third scenario present E11, E23, E33 and E43. For the first scenario, the likelihood of disruption is estimated at 48.9%. For the second and third scenarios, their total likelihood probability is estimated at 49.8% and 52.3%. The three results presented in Figures 6.4, 6.5 and 6.6 indicate an average increase of 20% more than the original analysis result. This experiment presents the dynamism of the BN model base on the consideration of different risk scenario, to test the sensitivity of the BN variables in terms of their conditional dependence influence in the assessment process.

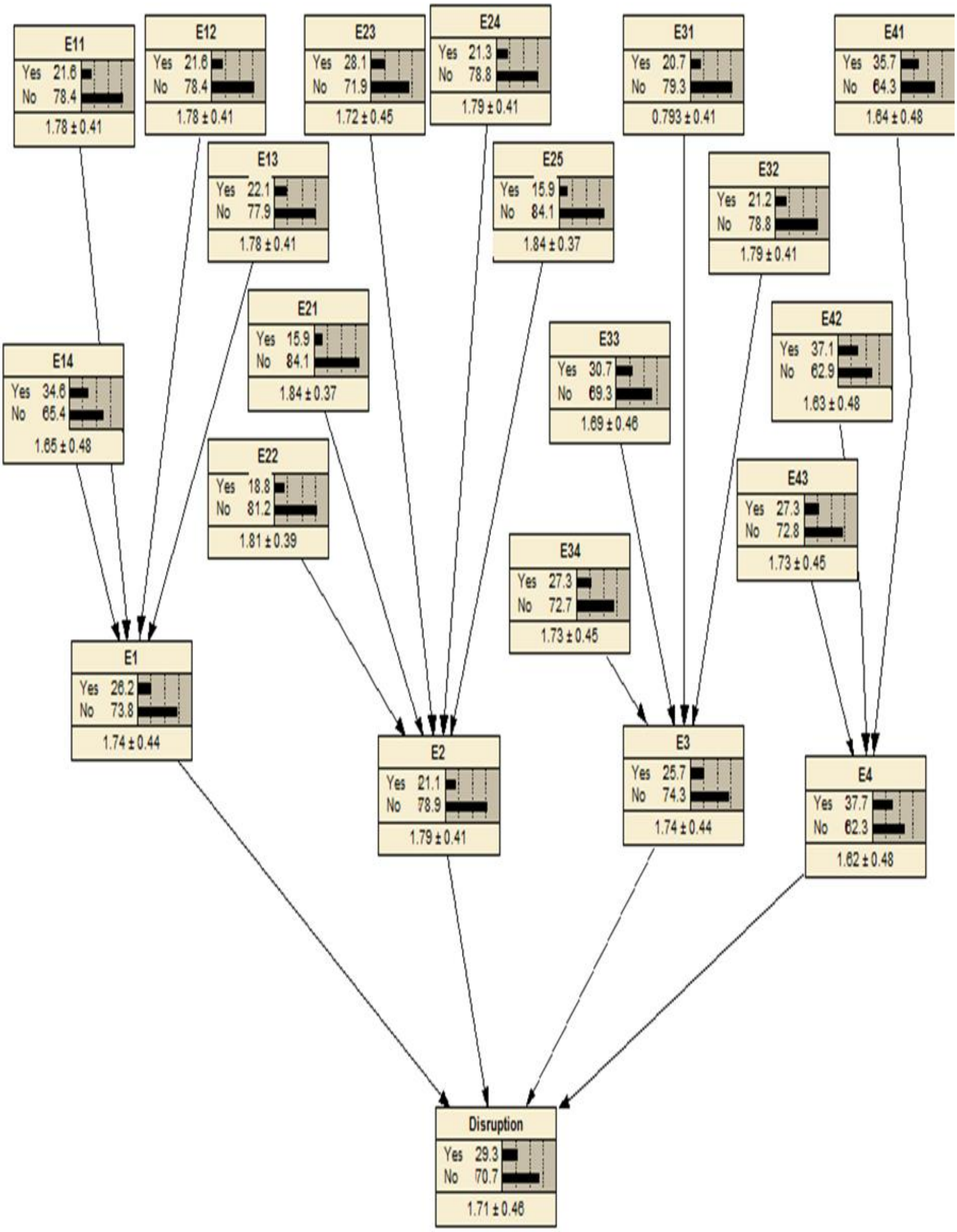

Figure 6.3: Evaluation of likelihood of disruption of petroleum refinery operations
(Source: Netica software)

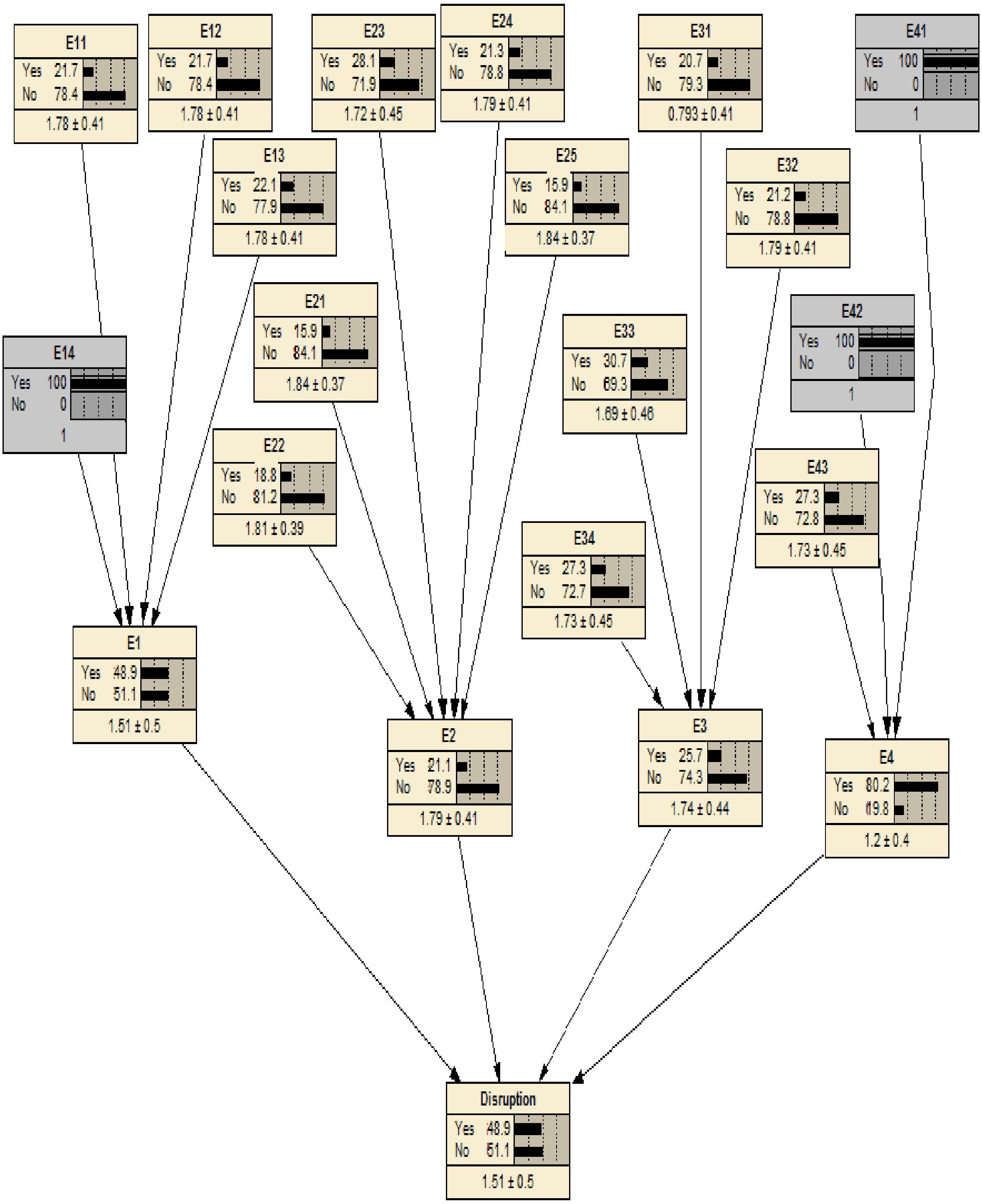

Figure 6.4: The effect of E14, E41 and E42 on the probability of disruption of petroleum refinery operations (Source: Netica software)

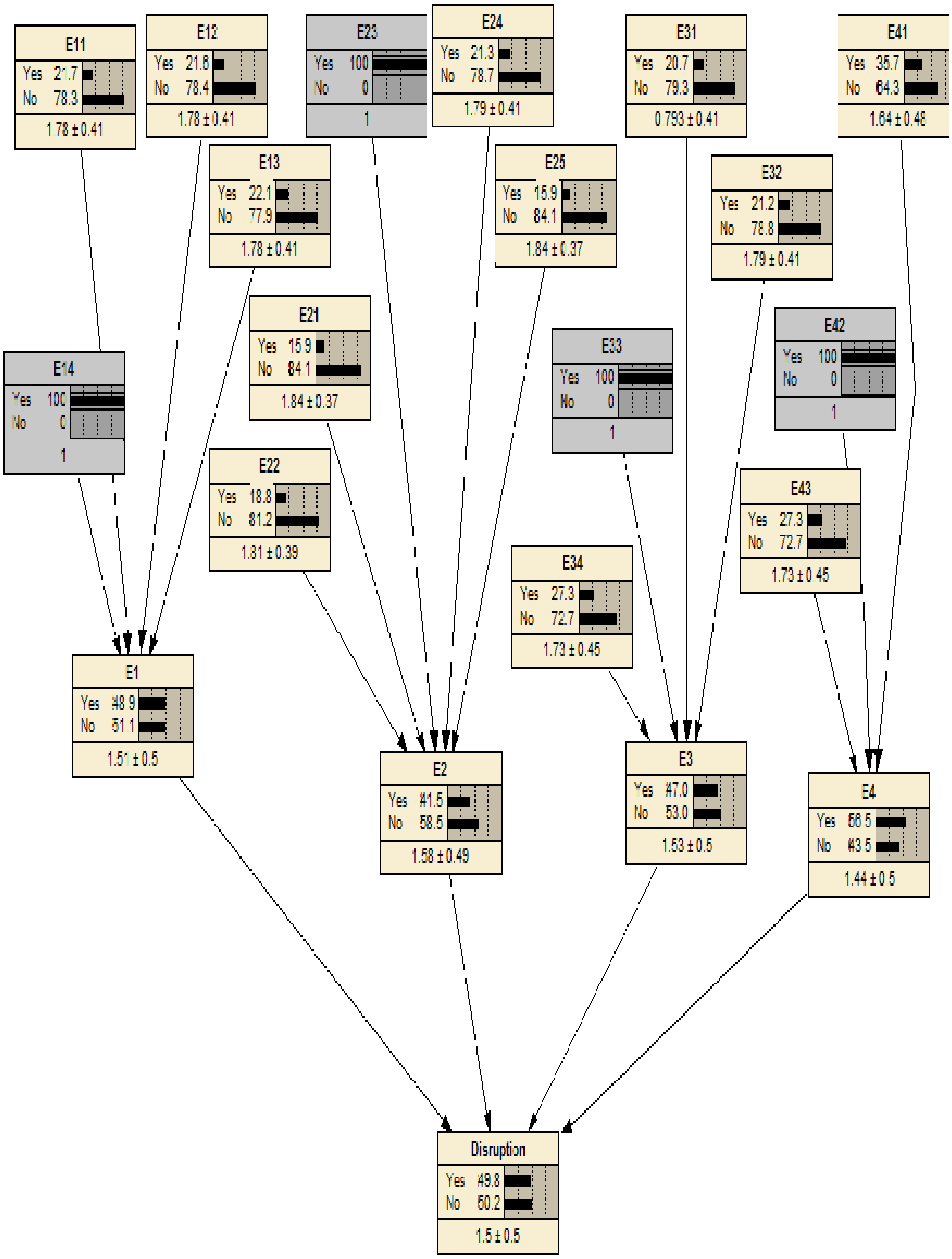

Figure 6.5: The effect of E14, E23, E33 and E42 on probability of disruption of petroleum refinery operations (Source: Netica software)

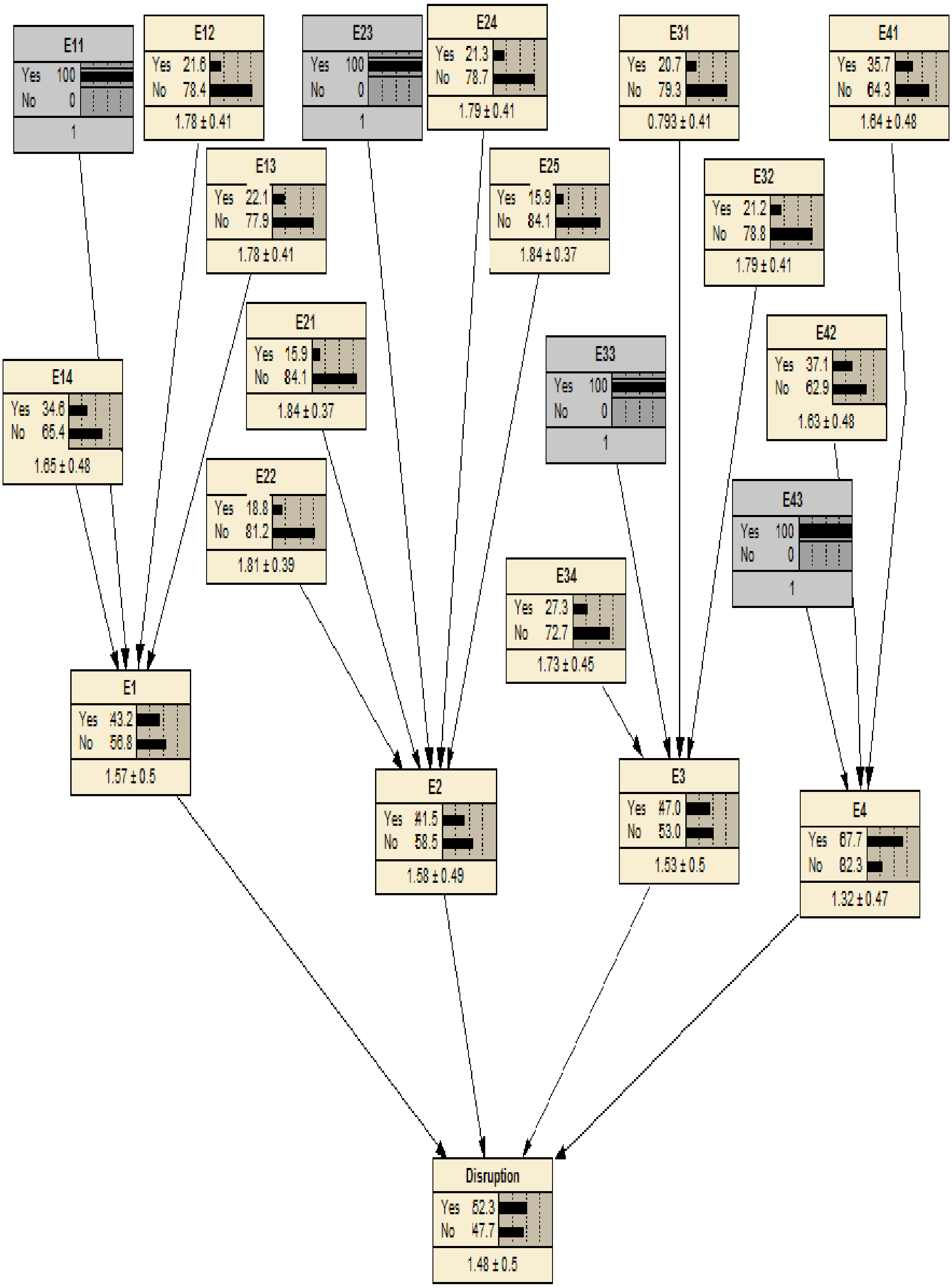

Figure 6.6: The effect of E11, E23, E33 and E43 on the probability of disruption of petroleum refinery operations (Source: Netica software)

6.3.4 Sensitivity Analysis (SA)

Sensitivity Analysis is used to authenticate the robustness of the BN model. Two axioms are used in the SA to identify the influence of various nodes on the output in the target node, in order to establish the logicality of the analysis result. A reasonable way to conduct the analysis is by systematic variation of the input values of the BN variables based on the two axioms discussed in Section 6.2.4. The input value for all the root nodes in the network are varied by gradual increment/decrement of 10%, 20% and 30% and the results are obtained. The values for the sensitivity scope are selected to test the behaviour of any of the root nodes in the BN model in order to understand the threshold for significant action to reduce the threat of the variables. It is worth mentioning that when the input data for the highest preference states for each of the sixteen root nodes in the BN model are increased by 10%, 20% and 30%, the lowest preference state for the root nodes are decreased in the same manner.

Base on the SA, the node E43 (Terrorist attack) state "Yes" was increased by 30%, the model output (disruption) is estimated at 33.4% or 0.334 "Yes" and the "No" probability is 66.6%. This indicates that the initial likelihood probability of the model output increased by 4.1%. On the other hand, when the "Yes" for E34 is reduced by 30%, the probability of the model output decreased from 29.3% to 25.5%. Thus, the process is carried out for all the other root nodes and the results are presented in Tables 6.8 and 6.9. The analysis validates the extent of the influence of each root node in the BN model under varying condition and in accordance with axioms 1 and 2. In addition, any of the root nodes that is insensitive under the varying conditions explained above is not considered as a significant node and it can be eliminated in order to have a reliable and a coherent BN model.

The sensitive behaviour of each root node under varying conditions is illustrated in Figures 6.7. The correlation of the sensitivity behaviour of each root node based on the increment/decrement shows the probability range for the occurrence of disruption under the influence of each root node in the BN model. This outcome provides confidence in terms of determining the threshold for significant action to be taken to effectively decrease the probability for disruption of petroleum refinery operations.

Table 6.8: Increment of the parent nodes prior probability

Attributes	Sensitivity Analysis (Increment)		
	10%	20%	30%
E11	0.298	0.303	0.308
E12	0.298	0.303	0.308
E13	0.298	0.303	0.309
E14	0.301	0.309	0.318
E21	0.296	0.300	0.303
E22	0.297	0.301	0.305
E23	0.299	0.305	0.311
E24	0.298	0.302	0.306
E25	0.296	0.300	0.303
E31	0.298	0.302	0.307
E32	0.298	0.303	0.308
E33	0.300	0.307	0.314
E34	0.299	0.305	0.313
E41	0.3004	0.314	0.323
E42	0.3004	0.314	0.325
E43	0.3007	0.321	0.334

Table 6.9: Decrement of parent nodes for prior probabilities

Attributes	Sensitivity Analysis (Decrement)		
	-10%	-20%	-30%
E11	0.288	0.283	0.282
E12	0.288	0.283	0.282
E13	0.288	0.283	0.282
E14	0.285	0.277	0.268
E21	0.290	0.288	0.288
E22	0.289	0.286	0.286
E23	0.288	0.282	0.277
E24	0.289	0.285	0.284
E25	0.290	0.288	0.288
E31	0.288	0.283	0.283
E32	0.288	0.284	0.283
E33	0.286	0.280	0.272
E34	0.287	0.280	0.276
E41	0.283	0.272	0.263
E42	0.283	0.274	0.260
E43	0.281	0.265	0.255

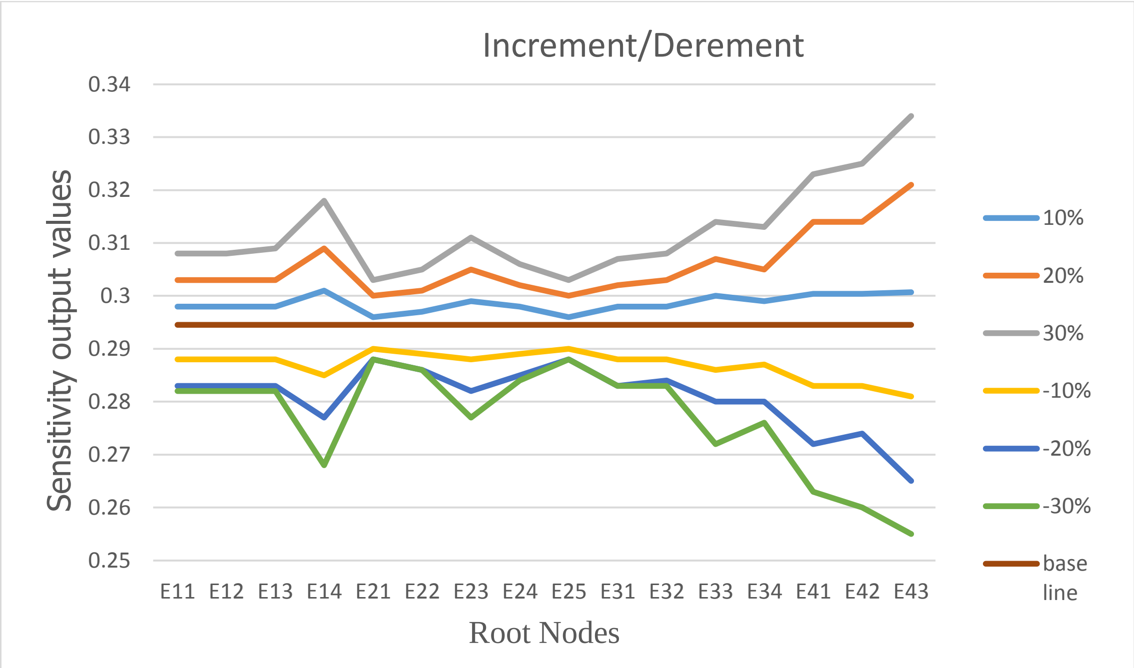

Figure 6.7: Sensitivity of the model output based on increment variation

6.4 Discussion and Conclusion

This chapter has demonstrated that a BN model can provide an effective approach for dynamic risk modelling of petroleum refinery operations. The BN model incorporates a holistic view of the inter-relationship between risk elements and their attributes (causal factors) that can trigger the disruption of petroleum refinery operations. The conditional dependencies in terms of the inter-relationship between the causal factors in the BN model are determined based on a symmetric model approach, which provides the kernel for the conditional probability distribution. This chapter demonstrates the unique application of the BN model as a dynamic approach to forecast the prospect of disruption to a petroleum refinery operations and to update the likelihood of PRPU disruption in the light of new evidence. A case study was introduced to analyse the BN model in order to determine the prospect of disruption of PRPU operations. Then sensitivity analysis was utilised to partially validate the BN model. Due to the unavailability of real data for this study, experts' subjective assessment was introduced as a source of information for the assessment process. For the reason that experts' knowledge and their perceptions toward assessment of a system's problem can sometimes be biased, a consensus approach for the aggregation of the experts' judgments was introduced to obtain reliable input data for analysis in the BN model. The validation of the BN model based on the SA assisted in identifying the most influential contributing input variables, to the target node in the BN model.

Based on the BN model analysis result, the prospect of disruption to petroleum refinery operations is estimated at 29.3%. In this study, the analysis of the behaviour of the input variables (i.e. E43, E42, E41, E14, E23 and E33) in the BN model under 100% certainty presented in Figures 6.5, 6.6, 6.7 and 6.8 contributed to the significant increment of the probability at the target node. The details of the SA results in Tables 6.8 and 6.9 indicate that when the input values for the sixteen root nodes are varied in the same range of increment/decrement probability, the most sensitive of the root nodes are E43 (Terrorist attack), E14 (Utility system failure), E23 (Inadequate staffing), E33 (Inadequate communication), E42 (sabotage) and E41(Natural hazard). The analysis result presents a sound and coherent understanding of the originality of the BN model in terms of its application to predict the prospect of disruption of a petroleum refinery operation. The methodology steps in the analysis of the BN model have provided a platform for which experts' assessment can be utilised by decision makers and risk analysts in the absence of real data for risk modelling in a simplistic manner. Hence, the methodology has provided an advanced approach for assisting decision makers in the petroleum refinery domain, to understand the risk impact of disruption to petroleum refinery operation and to improve their perception and anticipation towards decision-making strategies for risk management of their operations.

Finally, it is worth mentioning that the credibility and the robustness of the BN model, is demonstrated in the fact that it can accommodate the use of expert-knowledge elicitation, as an exploratory decision for complementing and updating uncertain information in a distinctive manner.

Chapter 7 - Application of AHP-Fuzzy VIKOR Methodology for Strategic Selection of the Optimal Risk Management Strategy for Petroleum Refinery Operations

Summary

A hybrid approach based on AHP-Fuzzy VKOR methodology was presented in this chapter for strategic selection of the optimum risk management strategy for prevention, mitigation and control of the disruption risks associated with petroleum refinery operations. Various alternatives that have been identified as a potential safety improvement strategy were integrated and assessed to determine the best alternative or to obtain an ideal solution. The AHP approach was utilised to obtain the weight of the assessment criteria, while the Fuzzy VIKOR approach was used to determine the ranking order of the risk management alternatives incorporated in the assessment process for optimum safety of a petroleum refinery operations.

7.1 Introduction

The decision making process for the selection of an appropriate risk management strategy for the optimization of petroleum refinery operations, is a multi-criteria decision making problem. Decision makers in petroleum refineries, sometimes execute poor decisions in a fuzzy situation, because of many conflicting criteria that need to be considered. Poor decisions can be as a result of incomplete information about an alternative strategy for risk/hazard prevention, control and mitigation. Decision makers' perspective about available risk information determines the basis for making robust decisions in regards to major accident risk (Yang and Haugen, 2016). Furthermore, lack of resolution in the collective knowledge of decision makers about a system problem can result in a bias outcome or conflict of interest in a decision process. Therefore, it is vital in a decision making process for decision makers to consider data in the form of a qualitative assessment or quantitative assessment or both. Thus, handling both qualitative and quantitative data for the selection of an alternative strategy is based on the choice of the decision making algorithm (Opricovic, 2009).

In order to implement an effective strategy that can be utilised to improve the risk management of petroleum refinery process unit operations, appropriate decisions must be made based on consistent evaluation of proposed alternatives, using a robust and yet flexible decision making algorithms. In this chapter, an advanced decision methodology is presented as part of the risk based framework (see Chapter 3) to improve safety of petroleum refinery process unit operations. The decision methodology will provide a systemic approach for the selection of a robust strategy, feasible to prevent, mitigate and control the attributes that contribute to the disruption risk of petroleum refinery operations. Potential risk elements and their associated attributes that can cause the disruption of petroleum refinery process unit operations have been identified and analysed in the previous Chapters of this research. Based on the previous Chapters, risk modelling approach based on Fuzzy Evidential Reasoning (FER) and Fuzzy Bayesian Network (FBN) were utilised to assess the disruption risk level of petroleum refinery operations. In this chapter, a multi-criteria decision support methodology based on AHP-Fuzzy VIKOR is implemented to determine the optimum strategy among the available alternatives proposed to improve the risk management of petroleum refinery process unit operations.

7.2 Multi-Criteria Decision Making (MCDM)

A multi-criteria decision-making (MCDM) is the gateway for the decision analyst to solve complex system decision problem. Over the years MCDM has been developed and has been made flexible and robust through the use of various mathematical methods as tools to choose the best alternative, to solve a complex system problem. Some of the most popular MCDM methods involve techniques such as Analytical Hierarchical Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Analytic Network Process (ANP), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), and Elimination Et Choix Traduisant la Realité (ELECTRE) (Dagdeviren, Yavuz, & Kilinc, 2009; Rezaei, 2015). These techniques have been recommended as decision making approaches for choosing, ranking, or sorting of the best options in a decision making situation. It is important to develop all the best alternatives relating to a problem under investigation before deciding the most appropriate MCDM method to use. The main focus of this chapter is developing a robust and flexible strategic decision support to assist decision makers in a petroleum refinery to select the optimal safety improvement strategy among various risk management alternatives. Furthermore, a chosen MCDM method for solving the problem of selection of the optimum alternative for petroleum refinery process unit operations, should be dynamic in handling any subjectivity, uncertainty and ambiguity in the assessment process. It is difficult to determine which of the MCDM method is the most reliable or worse in terms of applications, but some methods better suit some decision making circumstances than others. In the applications of MCDM methods, the deployed algorithm should specify how criteria information can be processed to acquire the most suitable alternative for investment (John *et al.,* 2014). The utilization of any MCDM method should be consistent with the comparison of the criteria with respect to the alternative for efficient trade off.

Due to the complexity of decision making in terms of dealing with risk management of a petroleum refinery process unit operations, MCDM method that can facilitate the selection of a better and optimum risk management strategy should consider variations in decision makers' preferences for the criteria and their conflicting knowledge in a systematic manner (John *et al*, 2014). In the line of common practice of obtaining a decision solution for MCDM problem, the basic information in a MCDM procedure is always defined as a matrix as presented below:

$$(C_1 \; C_2 \; \cdots C_m \;)$$

$$(W_1 \; W_2 \; \cdots W_m \;)$$

$$Z = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} x_{11} & x_{11} & \cdots & x_{11} \\ x_{11} & x_{11} & \cdots & x_{11} \\ \cdots & \cdots & \ddots & \vdots \\ x_{11} & x_{11} & \ldots & x_{11} \end{bmatrix}$$

In the MCDM approach, the four main parts for each decision matrix are summarized as follows:

- Alternatives.
- Criteria or Attributes.
- Weight of experts or relative importance of each criteria.
- Performance measure of alternatives with respect to criteria.

where $\{A_1 \;\; A_2 \ldots A_n\}$ is a set of assumed or feasible actions (alternatives), $\{C_1 \;\; C_2 \ldots C_m\}$ represents a set of criteria to measure the performance of the alternatives and $W_j\left(W_j \geq 0, \sum W_j = 1\;\right)$ is the assigned weight of $j^{th} criterion \;\; (j = 1,2, \ldots m)$. The decision matrix for the MCDM problem contain essential elements, which must be normalized to the same units so that all the criteria can be dealt with in a resourceful manner to avoid computational difficulty. There are four means of normalization in an MCDM problem, the two most popular methods are linear normalization and vector normalization (Lavasani *et al.*, 2012). In an MCDM problem, the actual decision making procedure is illustrated as follows:

- Definition and context of the decision problem.
- Presenting the objective and evaluation criteria.
- Generating alternatives to attain the goals.
- Assessment of the alternative in terms of the evaluation criteria
- Providing a consensus decision approach as a compromise method.
- Decision making on the optimum alternative.
- If the alternative is not approved, collection of new evidence and review of the iteration process of the decision making procedure.

7.3 Assessment of Petroleum Refinery Process Unit operations for optimum risk management of disruption.

The disruption risk of petroleum refinery process unit operations can be prevented/or mitigated based on a robust risk management strategies, which are carefully synthesized, implemented and updated by decision makers and stakeholders in a petroleum refinery. The strategies are developed based on the quality of risk information provided, in order to formulate alternatives that cut across all aspects of PRPU operations. In the previous chapters of this research, comprehensive risk information is obtained from risk modelling of key risk attributes that contribute to a major disruption of petroleum refinery operation. Following the intensive investigation based on the risk-modelling approaches in the previous chapters, the next step is to develop a decision making model, which can be utilised to establish the most appropriate decision strategy from a set of proposed alternatives, based on the decision makers' perspectives in terms of improving the risk management of petroleum refinery process unit operations.

The decision making approach will provide decision makers in petroleum refinery with a robust approach to complement engineering judgment in terms of risk management. In order for decision makers to determine the most appropriate strategy among a proposed set of alternatives, it is essential to measure the importance of each of the alternatives by a set of distinctive criteria. The criteria can be determined based on the consideration of key performance characteristics that are associated with the alternatives. Then, a decision making aid based on an MCDM approach can be utilised to determine the best strategy among available alternatives to reduce the risk level of a petroleum refinery process unit's operation.

7.4 Identification of Decision Making Criteria for Selection of the Best Alternative Strategy for PRPU Operations.

The acquisition of the most relevant criteria to evaluate a set of alternatives provided by a decision analyst in a decision making process is obtained based on extensive and robust literature review and brainstorming session with a group of experts. The set of selected criteria is summarized in Table 7.1. The background literatures for the selected criteria are summarized as follows:

- Reliability (Kolmjenovic et al., 2016; John *et al.,* 2014; Lavasani *et al.,* 2012; Wang and Gao, 2012; Qinfeng *et al*., 2011; Aven, Vinnem and Wiencke, 2007).
- Survivability (HSE KP3, 2007).
- Safety (Lavasani *et al.*, 2012; Zhaoyang *et al.,* 2011; Aven, Vinnem and Wiencke, 2007; Mearns & Flin, 1995).
- Redundancy (Azadeh *et al.,* 2014).

- Consequence (Yang and Haugen, 2016 ; Lavasani *et al.*, 2012 ; John *et al.*, 2014 ; OGP, 2011)
- Investment cost (Zhaoyang *et al.*, 2011; Mendeloff et al., 2013; John et al, 2014)
- Cognitive adaptability (Mearns & Flin, 1995).
- Availability (Yang & Haugen, 2016; Wang and Gao, 2012; Qinfeng *et al*., OGP, 2008; OGP, 2011; Vinnem *et al.*, 2006).
- Security (Knowles *et al.*, 2015; Moore, 2013; Leith and Piper, 2013; Srivastava and Gupta, 2010).

Table 7.1: Evaluation criteria

Evaluation criteria	Description
Reliability (B_1)	To measure the ability of the alternative to perform the required functions accurately when it is needed.
Survivability (B_2)	The ability of the alternative to improve the survival level of the system which they are designed to protect against incidents.
Safety (B_3)	Level of safety guaranteed by the alternative to prevent MAH.
Redundancy (B_4)	The ability of provision of system warning before the occurrences of structural breakdown. The duplication of a system component or functions that performs with the intention of increasing reliability.
Consequence (C_1)	Consideration of consequence of alternative in terms of short or long term effect.
Investment cost (C_2)	Anticipated cost of implementation of alternative.
Cognitive Adaptability (B_5)	Ability of the alternatives to be dynamic, flexible, and amendable at any slight introduction of changes given dynamic and uncertain task environments.
Availability (C_3)	The ability of the alternative to function well when implemented for a targeted period before update or beyond to reduce the downtime of operations.
Security (B_6)	Protection of infrastructure system from sabotage, terrorism and/or malicious acts.

7.5 Determination of the Elements of Decision Alternatives

The general property of a decision making strategy for an advance risk management of a petroleum refinery process unit operation is based on utilization of three major approaches and other recommended safety practice, which have been applied for major accident hazard prevention, mitigation and control in the oil and gas industry. The three main elements are asset integrity management, process safety management and operations integrity management. These approaches provide the basis for developing the risk management strategies for optimizing the safety of petroleum refinery process unit operations. The three elements adopted are described as follows:

Asset Integrity Management (AIM): Asset integrity is the capability of an asset to remain functional effectively and efficiently. Management of asset integrity involves ensuring that people, systems, processes and resources that delivers integrity are maintained and are available to perform throughout the life cycles of an asset (Kolmjenovic et al., 2016; Hassan and Khan, 2012). The primary objective of Asset Integrity Management is to preserve asset in a fit for the service condition while extending the asset life in the most reliable, safe and cost effective way. Asset integrity management have been in practice in the oil and gas industry as a solution for management of critical assets in the oil and gas industry. UK HSE KP 3 report published in 2007 is directed at asset integrity management of offshore oil and gas installation, with the purpose to prevent, control or mitigate major accident hazards. Oil and Gas UK 2009 report focuses on asset integrity management in order to deal with underlying issues and common failure in the past, such as a Texas City refinery accident. International Association of Oil and Gas Producers (IOGP) report 2008, proposed a guide to help oil and gas organizations reduce major accident risks by focusing on asset integrity management.

Process Safety Management (PSM): Process safety is a discipline that responds to managing the integrity of operating systems and processes handling of hazardous materials (IOGP, 2008). Process safety management deals with the prevention and control of process safety events that involves the release of hazardous materials and energy. The application of PSM involves critical management artifact that includes Plan, do, check and act in order to be efficient. On 17 July, 1990, US Occupational Safety and Health Administration (OSHA) published a proposed standard for Process Safety Management of Highly Hazardous Chemicals. The proposed standard comprises of requirements for the management of hazards associated with processes using highly hazardous chemicals. The OSHA process safety management standard has been the bedrock of improving process operations risk management in the petroleum refining and oil production industry based on a comprehensive management program that integrate appropriate technologies, procedures, and management practices. OGP 2011 report, focus on the need for process safety key performance indicators to prevent unplanned hazardous material releases, which can lead to a major accident. American National Standard Institute (ANSI) and the American Petroleum Institute (API) introduce recommended practice 756 (2010), which focuses on process safety performance indicators for the refining and petrochemical industries to manage process events, in order to prevent unintended loss of hazardous substances. In addition, the UK HSE, 2006 publication on process safety management provides systematic guides to develop process safety performance indicators.

Operations Integrity Management (**OIM**): This is a framework that contains underlying principles for processes, evaluation and implementation of operational integrity of a business. The OIM framework was developed by ExxonMobil Corporation in 1992. The aims of OIM framework is to reduce the risk of safety, health, and environmental events in order to enhance operational organizations to conduct their main activities in a formal, regulated way. Operations integrity addresses major aspect of operations that can affect personnel, process safety, security, health, and environmental performance. Important elements of the OIM framework focus on management leadership and commitment, risk assessment and management, personnel, operation and maintenance, management of change, incident investigation and analysis, community awareness and emergency preparedness and operations integrity assessment.

In addition to the aforementioned approaches, other supplementary literature on risk management studies for oil and gas industry operations was also utilized as a reasonable contribution in formulating alternatives based on organizational and security management in the decision making process. Literature sources (i.e. Andrew Hopkin, 2011; Amyotte et al., 2007; Kongsvik, Almoklov, and Fenstad, 2010; Pasman et al., 2009; Khan & Amoyotte, 2007; Kwon, 2006; Paul Baybutt, 2003), provide comprehensive information about the organization and security management, which contributed to the development of the alternatives.

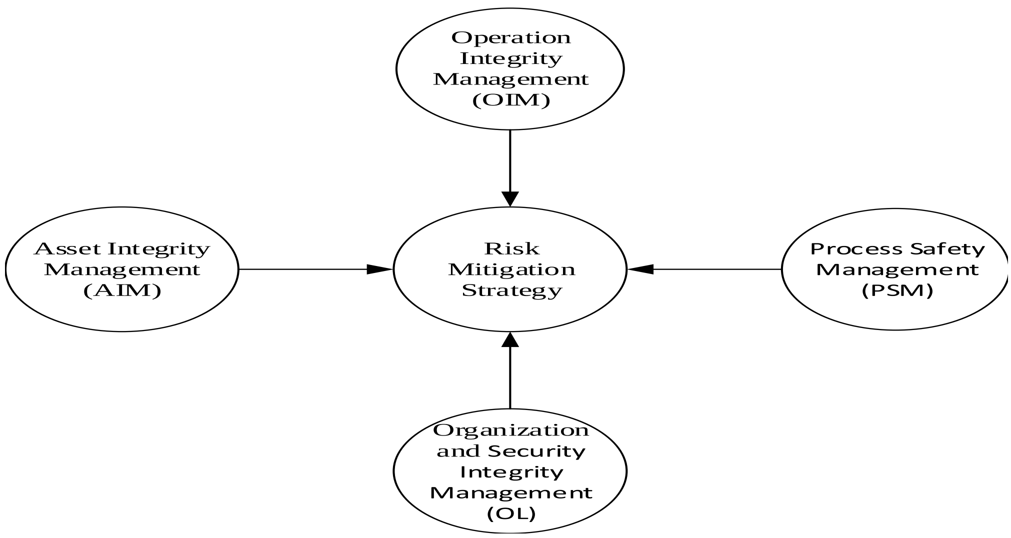

Figure 7. 1: Elements of decision alternatives

7.6 Description of decision support strategies to improve risk management of petroleum refinery operations.

7.6.1 Process safety management

The key strategies that have been identified in process safety management discipline as elements of decision making alternatives, which can contribute to the enhancement of risk management of a petroleum refinery operations are presented as follows (Cefic, 2011; IOGP, 2011; API, 2010; CPS, 2007; Kwon, 2006):

- **Implementation of robust Integrity Operating Windows for monitoring process equipment integrity (PS 1):** Integrity Operating Windows (IOWs) are those predetermined limits that are established for process variables that need to be implemented in order to prevent potential breaches of control of process conditions, which can systematically result in unexpected or unplanned deterioration or damage to process equipment. Exceedance of the preset limit based on the IOW, could result in accelerated damage from any one or more of the several damage mechanisms prescribed by the American Petroleum Institute recommended practice (API RP 571). The identified damage mechanisms included in the API 571 are localized corrosion, mechanical or metallurgical damage, high temperature corrosion and environmentally assisted cracking. Implementation of a robust IOW that can be integrated into the distribution control system or Supervisory Control and Data Acquisition (SCADA) system in a petroleum refinery will enhance the development and monitoring of the operating envelopes and boundaries to track changes to process unit equipment condition in real-time. IOW is a real-time information dashboard that provides warning of changing operating conditions that could affect the integrity of process unit equipment or validation of the current inspection plan to enable operator's to make a risk-informed decision when taking corrective actions.

- **Implementation of adequate conditional monitoring and inspection for safety critical equipment (PS 2):** Adequate condition monitoring and inspection provides an instantaneous indication of a safety critical equipment conditions in order to maintain them in top condition in a way that will benefit the maintenance regime. The advantages of implementing a sound condition monitoring and inspection are to provide early warning of any critical equipment failure; to reduce the danger of disruption of process operations; reduction of system downtime. Refinery process unit operators can depend on conditional monitoring and inspection process to detect and take corrective action against incidents that are associated with the safety critical equipment such as vibration, signs of leakage, unusual noises, insulation deterioration, a relief device having opened, distortion, denting, temperature excursions, presence of under insulation corrosion, or other barriers or crevices.
- **Implementation of a clearly defined management of change (MOC) and safety review policy (PS 3):** A clearly defined MOC procedure and safety review policy for a petroleum refinery operation needs to address issues that involve changes to operating procedure, process unit control, process equipment, personnel's supporting a process unit operation and maintenance. For instance, any changes that cover process control system hardwares, process control softwares, alarm management and operating modes, and operating conditions should be strictly managed under the appropriate MOC procedure for a process unit to operate on a continuous basis. The MOC procedure must include

appropriate risk assessment in regards to any changes to be made and appropriate training of personnel to understand the procedure and their specific responsibilities. In addition, the key performance indicators raised for the MOC and the safety review policy must be reviewed from time to time (i.e. monthly, quarterly and annually) by the refinery process safety management committee.

- **Risk assessment and compliance audit (PS 4)**: Appropriate risk assessment and compliance audit should be conducted regularly by a team of knowledgeable personnel. The objective is to review compliance to standard and guidelines for safe operation in a petroleum refinery environment (i.e. PSM standards, API RP). Risk assessment review of all identify possible hazards in different process units and/or activities should be carried out based on Process Hazard Analysis (PHA), which should be conducted every few years of operational life of a process unit. Hazard and operability analysis should be included in any MOC process conducted within the 5 year of operation of a process unit. This process will help to mitigate the impact of failure and the effect of process change. Also, the process will enhance the fitness for service reviews to identify the effect of ageing mechanisms in the process equipments based on time to time hazard indexing and ranking.
- **Implementing continuous development program for personnel for prevention and control of process safety incidents (PS 5):** This include competency assessment, continuous training to improve the process operation knowledge and understanding of the most critical risk control procedures. The approach will improve the reliability of personnel in terms of their ability to

proactively tackle process safety failures before it leads to any catastrophic consequences.

- **Robust enforcement of compliance to process safety management standards (PS 6):** Effective compliance to process safety management standards will enhance the sustainability of process unit equipment reliability, operation running times and process efficiencies. Enforcement of process safety management standards on a daily basis for operators, supervisor level and technicians can be followed through leadership commitment to process safety.
- **Implementation of robust process safety culture assessment (PS 7):** An effective assessment of process safety culture can be provided by administering questionnaires and supporting interviews that involves the commitment of personnel's time and resources. The process is to provide time-interval diagnosis of the perceptions, attitude and motivations of refinery personnel, in order to understand and evaluate their level of commitment to process safety management. The assessment can provide resourceful information about personnel's competences and awareness level toward compliance to process safety standards and current regulatory requirements, incidents and near miss reporting and documentations and maintenance of operational discipline. The assessment of process safety culture will empower the process safety team in a petroleum refinery to make appropriate decisions, which involves personnel participation for improvement of standards in terms of process hazard recognition and control in a timely manner.
- **Implementation of a robust emergency response drills procedure (PS 8):** This involves an emergency response awareness program scheduled at intervals to

equip and educate the process unit personnel. An effective emergency response awareness to respond to incidents before it can escalate beyond normal control (i.e. training on appropriate response to safety critical leak detection and response systems, emergency shutdown systems, and fire and gas leak/area detection) to improve operations safety atmosphere.

- **Incorporate risk-based integrity program that systematically evaluate damage mechanisms of petroleum refinery process unit equipment's (PS 9):** This includes an RBI assessment for systematic evaluation of both the probability of failure and the consequence of failure of process unit equipment in accordance with API standards (i.e. API 580 and API 581). Incorporating RBI assessment will enhance the identification and evaluation of potential damage mechanisms based on the effective assessment of the past and current equipment condition. RBI assessment of damage mechanism can assist in determining the extent of process unit equipment damage and equipment downtime. This process will enhance refinery process unit personnel to set up inspection intervals and updates each time process or hardware changes are made, that could facilitate damage rates and any unanticipated failure that can occur due to a damage mechanism. Some of the potential damage mechanisms that can be covered in the RBI process, in a petroleum refinery process unit should include mechanical fatigue cracking; thermal fatigue cracking; hydrogen induced cracking; high-temperature hydrogen attack creeps/stress rupture and hydrogen embrittlement. Based on the RBI approach, an inspection plan can be developed utilising the most appropriate sources of information. In addition, the inspection plans shall be reviewed and amended as needed when variables that may impact damage mechanisms and/or deterioration rates are identified, such as those contained in inspection reports or MOC documents.

7.6.2 Asset integrity management

The main strategies identified based on the principle of asset integrity management as elements of decision alternatives toward enhancing the risk management of a petroleum refinery operations are presented as follows (SGS, 2017; Petsec, 2014; Hassan and Khan, 2012; Horrock et al., 2010; Oil and Gas UK, 2009: International Oil and Gas Producer, 2008; HSE, 2007):

- **Mechanical integrity program (AIM 1)**: A comprehensive mechanical integrity program that covers process equipment, piping systems, relief and vent system and devices, emergency shutdown systems and controls (i.e. alarms, sensors, interlocks and monitoring devices) needs to be implemented. The mechanical integrity program should contain a written procedure that allows refinery personnel to identify and report potentially faulty or unsafe condition of process equipment. This will enhance personnel to record observations and suggestion in writing, in order to engage any reportable unsafe operating condition in a timely manner by the concerned mechanical integrity program team. The mechanical integrity program should include provision of training for maintenance personnel in the application of the written procedures relevant to reviews of all changes in a refinery process unit, according to MOC process. In addition, the procedure extends to the aspect of quality control for verification of maintenance materials, spare equipment and part design to meet specifications. Overall, the mechanical integrity program should incorporate evaluation systems for compliance with testing, inspecting, calibrating and monitoring of critical process unit equipment.

- **Provision of a well organised and a comprehensive maintenance management and inspection system that interfaces with operations (AIM 2):** Adequate maintenance planning is the absolute key to the management of safety-critical equipment in a petroleum refinery. The maintenance management system should include a safety report that relates to maintenance practices, and maintenance policy documentation for safety-critical equipment. A proactive maintenance strategy should provide clear evidence that maintenance backlog is being properly managed. Operational inspection regime should pay attention to identifying damage mechanisms such as corrosion, wear, erosion, external damage, pressurisation, atmospheric exposures, vibration, impingement of harmful releases, identification of dead legs etc.
- **Provision of adequate inspection and maintenance safeguarding systems (AIM 3):** In order to actively prevent or manage refinery process incidents, it is important to preserve and maintain safeguards systems such as fire protection equipment's (i.e. deluge system, fire extinguishers), alarms for emergency evacuation, fire, and interlocks. The safeguarding system should be subjected to weekly operation, monthly visual inspection and monthly functional activation test.
- **Implementation of condition-based maintenance scheme (AIM 4):** can be utilized efficiently to implement a maintenance action that can significantly reduce unnecessary operation downtime and to eliminate scheduled or unscheduled, unnecessary preventative and corrective maintenance task, in order to extend the operational life of the refinery process unit critical systems.

- **Implementation of a proactive conditional monitoring strategy (AIM 5):** to measure probable degradation rates related to corrosion, cracking and embrittlement mechanisms within each area of the refinery process unit's critical systems and assess their locations degradation threats.
- **Reliability and risk based inspection (RBI) plan (AIM 6)**: to identify the potential impact of degradation in an operating refinery process unit. RBI provides a systematic evaluation of a process unit equipment reliability and the causes of operational downtime. Based on RBI, appropriate inspection planning process to identify susceptible damage mechanisms for process equipment in operation can be easily implemented. In addition, the damage mechanism inspection intervals along with inspection procedures and techniques can be utilized as a risk ranking information in terms of inspection scheduling analysis for the execution of the RBI plan that will improve operational efficiency. The more effective the RBI plan, the lower the refinery process unit operations risk.
- **Fitness for service evaluations (AIM 7)**: provides a quantitative engineering evaluation to check the structural integrity of an in service safety critical components of a refinery process unit system. Fitness for service evaluation can be utilized to make run-repair-replace decisions, in order to assist refinery operators to determine the degradation level of equipments and to assess how long the equipments can operate safely. Fitness for service evaluation level should be conducted in accordance with API and ASME guidelines.
- **Corrosion risk assessment (AIM 8):** implementation of a sound corrosion science and engineering to identify problems and manage the risks and inspection of piping systems and process equipment's.

7.6.3 Operations Integrity Management

The principal elements that underpin the practice of operational integrity management, which is adopted as an element of a decision alternative to improve the risk management of petroleum refinery operations are presented as follows (ExxonMobil, 2009):

- **Operations integrity valuation (OIM 1)**: this process involves the assessment of operations in petroleum refinery process units by a multidisciplinary team of experts and the findings from the assessment is utilized to improve decision making in terms of management of risk level of operations and performance history of critical safety equipment's. In addition, periodical review of the assessment process and findings can be used to make improvement.
- **Implement policies that address managements of change (OIM 2):** Changes of petroleum refinery operation that can involve changes to processes, operation procedure or modification of a process unit need to be assessed and managed in order to effectively communicate the risk associated with the changes and to reduce operations integrity risk to an acceptable level.
- **Management commitment and accountability (OIM 3)**: Operations integrity assurance requires credible demonstration of management leadership commitment to the provision of adequate resources and workforce with adequate skills and knowledge to address operations integrity expectations to the highest standard for operational excellence.
- **Defining clear code of role and extent of responsibilities toward operation integrity management (OIM 4):** Establish clear safety goals and objectives of operations whereby the whole workforce can actively operate as a unit by sharing

relevant operations integrity information and learnings to maintain effective communication, cooperation and coordination at all levels of operations.

- **Implementation of appropriate and periodic operations integrity training programs (OIM 5):** Provision of periodic refresher training to equip refinery process units' operators to meet job and legal requirements, in order to enhance their technical expertise and understanding of how to take defensive measures to prevent/mitigate potential operations integrity hazards.

7.6.4 High Level Organization and Security Management

In past accounts of petroleum refinery accidents, organisational deficiencies have led to loss of organizational integrity of relational issues such as poor lines of communication and cooperation between management and the personnel to establish effective safety management systems. The core of safety ideology to drive an internal continuous improvement of organizational safety climate and continuity of safety leadership is very important. Furthermore, the threat of external events such as sabotage and terrorist attacks has driven the need to improve security integrity in the petroleum industry. For instance, a disgruntled employee in a petroleum refinery with access to an IT infrastructure can utilize a cheap PDA to connect a Wi-Fi in the corporation to obtain sensitive information to access a facility or disrupt safety critical infrastructure (Srivastava and Gupta, 2010). In the United State of America chemical facility anti-terrorism standards were introduced in April 2007 to boost the physical security of high-risk chemical facilities such as petroleum, gas and petrochemical refineries. Owners and operators in the petroleum industry have not effectively utilized the standards in their security plans. Therefore, it is important in decision making for improving risk management of petroleum refinery operation, to consider the inclusion of a comprehensive and high level organization and security management strategies to alleviate the risk of disruption to petroleum refinery process unit operations. The following are the decision support strategies that are synthesis based on the aforementioned literatures indicated in Section 7.5.

- **High level organizational safety condition management (OL 1)**: This involves implementing an organizational safety culture that applies to management of routine work schedules and high workload period to avoid short or long term effect of fatigue that can result in human error.
- **Provision of high level shift handover communication system (OL 2)**: It is very important to develop a systematic reporting structure that can deliver a reliable shift relief information and communication between personnel working within operations, setting, through accurate provision of sufficient information regarding process system conditions in the work schedule database.
- **Provision of organizational safety situation awareness (OL 3):** This will enhance personnel's capability for accurate perspective on the safety situation in their work area. Provision of adequate safety situation awareness will improve personnel attitude toward commitment to the management of safety measures and their consistencies to regulatory compliance and to enhance good organization safety practice.
- **Adequate and proportionate improvement of staffing level and staff competencies level (OL 4)**.
- **Provision of an Integrated Safe System of Work (OL 5):** In a petroleum refinery environment, work management and authorization system can be software-based system to provide automatic and consistent guidance on suitable

task precautions, which can include system isolations, de-isolation and integrity management.

- **Implementation of policies that can be utilized for management of work fatigue (OL 6):** Organization policies that can be appropriately utilized as a tool to check against work fatigue based on the record of the percentage of overtimes, number of consecutive shifts worked and numbers of extended shifts worked by personnel.
- **Implementation of all-inclusive safe work system (OL 7):** The development and the implementation of an effective and safe work practices that includes implementation of an effective work permit system to enhance employee and contractor to control hazards (i.e. hot works, confined space entry, lockout, and access control for support personnel etc.).
- **Job continuity plans to retain job knowledge and operational skills (OL 8):** This process involves provision of relevant training (knowledge and skills) for competence in each role to be managed to successfully execute job tasks. Provide for refresher training every 3 years or as required to enhance employee's competence in terms of complying with requirement such as PSM standard, environmental management regulations, API RP and RAGAGEP. This process will explicitly degenerate personnel error in terms of decision making under critical circumstances whereby appropriate reaction is important.
- **Provision of security awareness training and site intrusion detection security surveillance (OL 9):** Refinery employees should be provided with awareness and training that covers emergency response, hostage situation, bomb threat and first aids. Personnel should be enlightened in awareness concerning reporting the

presence of unknown personnel, unidentified vehicle, abandoned packages or parcel on site and any other suspicious activities within the refinery environment. Provision of intrusion detection and perimeter protection devices such as microphone sensor linked to perimeter fencing and hyper frequency sensors. In addition, the installation of video surveillance at sensitive routes and key points can be utilized to provide response of pre and post alarm digital event recording for a refinery central control station.

- **High integrity Supervisory Control and Data Acquisition (SCADA) system to manage safety critical infrastructure in the refineries (OL 10):** Provision of SCADA system provides real time intelligent control of process operations in a refinery environment. SCADA provides a security solution in terms of offering secure encryption of operations vital data to protect critical refinery infrastructure.
- **Provision of adequate process security management (OL 11)**: Process control system in a petroleum refinery needs to be securely guarded in order to prevent unauthorized manipulation of the process, including the deliberate release of hazardous materials or sabotage of process control system during operation to cause intentional runaway reactions. The process control information system needs to be intelligently protected from outside interference (i.e. cyber-hacking) through the provision isolation process. In addition, process security management will provide appropriate backup for critical equipment's and system in case of any deliberate impairment or sabotage, terrorism acts and natural events such as earthquake, hurricane, torrential rain and flooding.

7.7 An integrated AHP and Fuzzy VIKOR methodology for strategic decision modelling for selection of appropriate strategy for petroleum refinery operations.

In this study, decision making on the best alternative to improve risk management of petroleum refinery operations is the primary focus. The aspiration of an operator of a process unit operation in a petroleum refinery is to achieve a set production targets as well as reducing operating downtimes. In this case, strategic decision making in respect of operational safety on a daily basis is the most critical challenge in terms of petroleum refinery operation. In the previous chapter of this research, the feasible causes of disruption risk to petroleum refinery operations have been investigated. Afterwards, an advanced risk modelling methodologies has been applied to assess the risk level and the likelihood of disruption of operations in petroleum refinery. In this chapter, a decision support methodology based on AHP and fuzzy VIKOR will be utilized to select the most appropriate strategy from a set of alternatives to improve risk management of petroleum refinery operations. The functionality of AHP and fuzzy VIKOR approach is to deal with the accuracy in evaluating the importance weights of decision criteria and the ratings of alternatives in relation to the evaluation criteria in a consistent, productive and systematic way (Kaya and Kahraman, 2010). This approach provides an evaluation of higher and lower performance ratings of feasible alternatives, which are presented to improve risk management of the important attributes of risk elements assessed in the previous chapter of this research. In the application of the methodology, the importance of weights of the chosen criteria and final ranking of alternative based on each criterion, determine a compromise solution with minimum individual regret for decision makers. This methodology is appropriate for capturing and handling experts' appraisal subjectivity and ambiguity by utilization of fuzzy sets (triangular fuzzy number), which gives the decision analyst the room to incorporate unquantifiable, incomplete, and partial information into a decision support model. The AHP and fuzzy VIKOR algorithm is as follows:

Step 1: Definition of the problem scope for the decision making process

The main objective of the decision making process is the selection of a safety improvement strategy for risk management of risk attributes, which can actually result in the disruption of petroleum refinery process unit operations.

Step 2: Determination of the evaluation criteria and alternatives

The safety improvement strategies are defined in the alternatives and the criteria assigned to evaluate the alternatives are defined in Table 7.1. The strategies in the alternatives are presented in Section 7.6. The permutated strategies in the chosen alternatives are regarded as the most significant strategies targeted at improving safety of PRPU operations. These decision strategies are formulated based on Section 7.5.

Step 3: Develop a collaborative decision model

Based on the available information in Table 7.1 and Section 7.6, a hierarchical model for decision making on the most appropriate strategy to improve risk management of petroleum refinery operations is presented in Figure 7.1. The hierarchical model establishes the relationship between the criteria and the decision alternatives in order for the decision goal. The objective is presented in the first level of the decision model and the criteria are depicted in the second level, while all the approve strategies for petroleum refinery risk management are displayed in the third level. This decision model is utilized to simplify the complexity of the decision analysis. This decision model will provide decision makers in the petroleum and gas refinery with strategic insight to establish a logical decision making process in terms of finding optimum solutions.

Step 4: Determine the weight of each criterion using AHP method

The weight of each criterion assigns for evaluation of alternatives is determined by using the AHP method in aggregating the opinion of decision makers' base on appropriate pairwise comparison of the criteria. A dimensional square $n \times n$ pairwise comparison matrix is developed as depicted in Section 7.6 to determine the weights of all evaluation criteria.

Step 6: Linguistic assessment of alternatives using the selected criteria and the aggregation of the fuzzy ratings of the alternatives.

In this step, the appropriate linguistic variables for the fuzzy rating of alternatives can be defined and represented as a triangular fuzzy numbers as presented in Table 7.4. The linguistic variables are utilised by decision makers to express their ratings for the alternatives with respect to the established criteria. The next stage is the aggregation of the fuzzy ratings of the alternatives in order to develop a decision matrix. The aggregated fuzzy ratings of the decision makers are estimated using the Equation 2.8.

Step 7: Develop Fuzzy decision matrix for the implementation of VIKOR.

A fuzzy decision matrix is constructed and the fuzzy rating in the decision matrix can be normalized based on Equations 2.12 and 2.13. $\overline{U}_{ij}$ is the normalized rating in the decision matrix. In both Equations, B and C are define as a set of benefit and cost criteria.

Step 8: Defuzzification of the fuzzy decision matrix

The fuzzy decision matrix is defuzzified to crisp values using the graded mean integrated approach based on Equation 2.20 (Yong, 2006; Chou, 2003).

Step 9: Determine the best value $\left(\tilde{f}_j^*\right)$ and the worst value $\left(\tilde{f}_j^-\right)$ of each criterion function using Equation 2.14.

Step 10: Calculate separation measures$(\tilde{S}_i, \tilde{R}_i)$.

The calculation of the separation measure $\tilde{S}_i$ and $\tilde{R}_i$ for each alternative in the decision process is achieved based on the utilization of the criteria weights obtained based on step 4, then applying Equations 2.15 and 2.16.

Step 11: Compute $\tilde{Q}_i$ values.

$\tilde{Q}_i$ values for all the alternatives are determined using Equation 2.19 and the alternatives are ranked based on the Q_i index.

Step 12: The best alternative with the minimum of Q_i is determined.

Step 13: Conduct sensitivity study.

The AHP and Fuzzy VIKOR algorithm are a collaborative modelling procedure for structuring decisions in an easy and straightforward manner. In order to construct a decision matrix based on the methodology, the linguistic rating of experts for each alternative with respect to each of the selected criteria established based on linguistic evaluation grades found in already existing decision literatures. The concept of the linguistic rating of expert opinion is utilized in dealing with circumstances in which conventional quantitative expression cannot be represented as exact values. The linguistic grade adopted in the decision process is based on Liu et al., 2015;Tsung-Han Chang, 2014; Kannan et al., 2013; Kuo & Liang, 2011;Tolga & Kahraman, 2011; Tolga & Kahraman, 2010.

Table 7.2: Fuzzy Linguistic scale for Assessment of Alternatives

Linguistic variables	Triangular fuzzy score
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

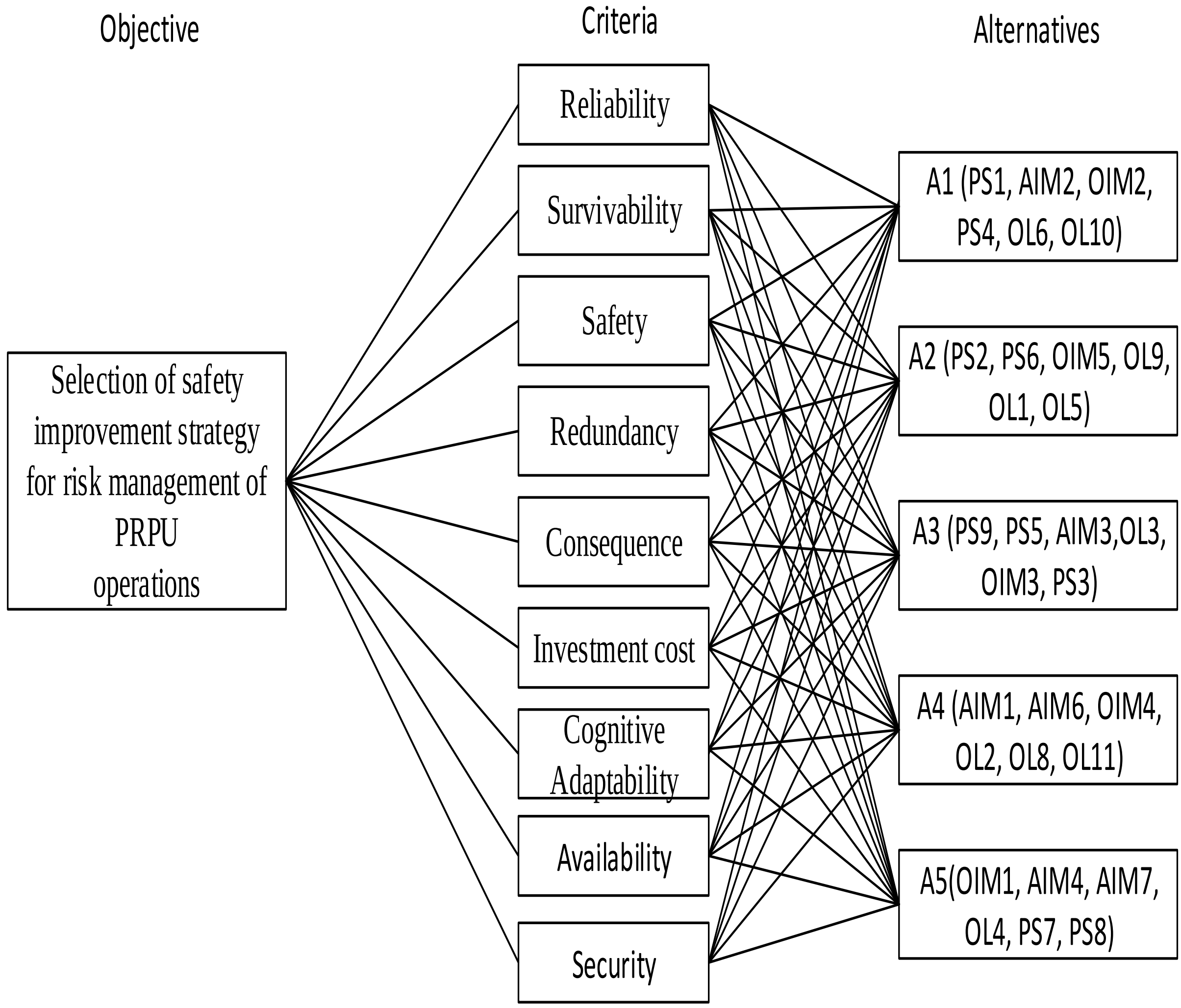

Figure 7.2: Decision model for selection of appropriate alternative for risk management of PRPU operation

7.8 Develop questionnaire for survey of experts' judgment for fuzzy decision modelling for determination of appropriate strategies for PRPU operations.

The questionnaire is formulated to obtain an expert's response on pairwise comparisons of decision criteria and the rating of alternatives with respect to the decision criteria. The questionnaire was examined by an academic expert with experience and comprehensive knowledge of decision problem relating to complex system modelling. This is to ensure clarity and appropriateness of the questionnaire. In the questionnaire, appropriate linguistic variables and scale were developed based on accumulated knowledge from literatures and brainstorming with a decision analysis specialist. The linguistic scale template was utilized to acquire the subjective responses from selected specialists with sound knowledge and experience in petroleum refinery operations. In addition ethical approval was obtained to provide authentication of the questionnaires content and participate endorsement. The questionnaire was presented as a web-based link which was e-mailed to selected expert participants.

7.9 Selecting appropriate experts for petroleum refinery operations.

The selection of experts in the survey data collection is based on consideration of the background relative to onshore and offshore refinery operations. Consultant and experts with vast experience and extensive career time in the oil and gas industrial operation. Academicians with an extensive research background of oil and gas complex system operations were also drawn as participants. The expected number of participants is at minimum of 12 and maximum of 32. For instance, the following are the background of experts that are selected to participate in the survey:

- A senior operation manager in a petroleum and gas refinery with at least 10 years' experience.

- A senior QSHE manager with comprehensive knowledge and at least 10 years' experience in petroleum refinery operation.
- A refinery engineer with at least 5 years of experience working in a petroleum refinery coupled with at least a Bachelor Degree in Engineering.
- A senior process engineer with a M.Sc. or PhD who has been involved in process safety management in relation to petroleum refinery operation for 10 years or more.
- A consultant with specialty in asset integrity management and process safety management with over 10 years of experience in consulting in the petroleum and gas industry.

7.10 A Test Case for Application of AHP-Fuzzy VIKOR methodology in fuzzy decision modelling for determination of appropriate strategies for PRPU operations.

The decision making process for the selection of the most appropriate risk management strategy for safety improvement of the petroleum refinery process unit operations is presented in Section 7.9. The real application of the aforementioned AHP-Fuzzy VIKOR methodology on the subject under investigation is demonstrated. Various risk management strategies, which have been identified from various literatures are adopted in this exercise to synthesize the alternatives presented in the decision model in Figure 7.2.

In the assessment process, feedback received from the experts' survey contains eleven participants and six of the participants completed the survey. The feedback from the survey is utilised to demonstrate how the methodology is applied to select the most appropriate alternative in order to improve the safety of a petroleum refinery process unit operations.

7.10.1 Identifying the Scope of the Decision Making Problem

Petroleum refinery operation is a complex system operation, which involves multi-faceted procedures with associated risks for technical, organizational, operational and other external viewpoints. The interactions of this risk at every phase of operations has practically led to unexpected failure modes and accidents. The elements of risks that are disruptive to petroleum refinery process unit operations have been identified and discussed in Chapter 2. In Chapter 4 and Chapter 5 all the risks are quantified and ranked, and the disruption risk level of petroleum refinery operations is evaluated. In Chapter 6, the likely probability of disruption was evaluated.

7.10.2 Assigning Evaluation Criteria and Alternatives

The criteria for the evaluation of the decision alternatives are selected based on conducting a robust literature review and brainstorming with group of decision makers with a wealth of experience and knowledge of complex systems operation in the petroleum refining industry. The selected criteria, are presented in Table 7.1. Each of the alternatives presented is synthesised based on the strategies in Section 7.6.

7.10.3 Developing a decision model

This involves organising the decision problem in a hierarchical relationship, which is in three layers as shown in Figure 7.2. This layer consists of the objective, the criteria and the alternatives. The decision model will provide a reasonable insight for decision makers on how to prioritize in the subjective assessment of their alternatives based on the selected criteria.

7.10.4 Estimation of criteria weights for selection of optimum strategy for PRPU operations

A consolidated pairwise comparison of all criteria by the chosen experts are presented in Table 7.3 and the weights of all the criteria are presented in Table 7.4.

Table 7.3: Pairwise comparison of the evaluation criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	1.0000	1.8086	1.5131	2.18225	2.80397	4.26843	3.07171	1.81712	3.1773
C_2	0.5529	1.0000	0.8909	1.20093	1.68021	2.44948	1.69838	1.06991	2.5132
C_3	0.6609	1.1224	1.0000	1.48367	1.91293	3.72882	2.28943	1.30766	2.5786
C_4	0.4582	0.8327	0.6740	1.0000	1.70997	2.41827	1.38308	1.34800	1.8859
C_5	0.3566	0.5952	0.5228	0.58480	1.0000	1.41421	0.86830	0.53636	1.5929
C_6	0.2343	0.4082	0.2681	0.41352	0.70711	1.0000	0.51125	0.33789	1.3747
C_7	0.3255	0.5887	0.4367	0.72302	1.15167	1.95598	1.0000	0.5773	1.4142
C_8	0.5503	0.9346	0.7647	0.74183	1.86441	2.95956	1.73205	1.0000	1.7042
C_9	0.3147	0.3978	0.3878	0.53023	0.62779	0.727416	0.707106	0.58677	1.0000

The consolidated pairwise comparison matrix is determined using the geometric means technique (Buckley 1985). The comparison for C_1 and C_2 for all experts is presented as follows:

Based on Decision Makers (DM) judgement obtained for C_1 and C_2, DM 1= 1, DM 2 = 7, DM 3 = 5, DM 4 = 1, DM 5 = 1, DM 6 = 1.

$$\text{Geomean} = \sqrt[6]{1 \times 7 \times 5 \times 1 \times 1 \times 1} = 1.8086$$

Table 7.4: Matrix distribution for obtaining criteria weight

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	Criteria Weight
C_1	0.2245	0.2352	0.2343	0.2463	0.2083	0.2040	0.2316	0.2118	0.1843	0.2200
C_2	0.1242	0.1301	0.1379	0.1355	0.1248	0.1171	0.1281	0.1247	0.1458	0.1298
C_3	0.1484	0.1460	0.1548	0.1675	0.1421	0.1782	0.1726	0.1524	0.1496	0.1568
C_4	0.1029	0.1083	0.1044	0.1129	0.1271	0.1156	0.1043	0.1571	0.1094	0.1158
C_5	0.0801	0.0774	0.0809	0.0660	0.0743	0.0676	0.0655	0.0625	0.0924	0.0741
C_6	0.0526	0.0531	0.0415	0.0467	0.0525	0.0478	0.0386	0.0394	0.0797	0.0502
C_7	0.0731	0.0766	0.0676	0.0816	0.0856	0.0935	0.0754	0.0673	0.0820	0.0781
C_8	0.1236	0.1216	0.1184	0.0837	0.1385	0.1415	0.1306	0.1165	0.0988	0.1193
C_9	0.0707	0.0518	0.0600	0.0598	0.0466	0.0348	0.0533	0.0684	0.0580	0.0559
SUM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

The result in Table 7.5 was obtained based on Equation 2.5. The estimate for C_1 in Table 7.4 is determined by the sum of the column as depicted in weight matrix in Equation 2.4. For instance, $W_{1,5} = 2.80397$, the sum of the column is 13.4581. Then $\frac{2.80397}{13.4581} = 0.2083$.

The weight estimate for $C_1 = \left(\left(\frac{1.000}{4.4534}\right) + \left(\frac{1.8086}{7.6882}\right) + \left(\frac{1.5131}{6.4581}\right) + \cdots \ldots \ldots \left(\frac{3.1773}{17.241}\right)\right) = 0.2200$.

The process is repeated to obtain the weights of criteria $C_2 \ldots \ldots C_9$. The consistency for all criteria pairwise comparisons is checked based on the multiplicative computation of the criteria weights with each numerical value in the columns of Table 7.5.

Table 7.5: Multiplicative computation of criteria weights for checking of the consistency ratio

	C_1		C_2		C_3		C_4		C_5		C_6		C_7		C_8		C_9
	1.0000		1.8086		1.5135		2.1822		2.8040		4.2684		3.0717		1.8171		3.1774
	0.5529		1.0000		0.8909		1.2009		1.6802		2.4495		1.6984		1.0699		2.5132
	0.6609		1.1225		1.0000		1.4837		1.9129		3.7288		2.2894		1.3077		2.5786
	0.4582		0.8327		0.6740		1.0000		1.7100		2.4183		1.3831		1.3480		1.8860
0.2200	0.3566	0.1298	0.5952	0.1568	0.5228	0.1158	0.5848	0.0741	1.0000	0.0502	1.4142	0.0781	0.8683	0.1193	0.5364	0.0599	1.5929
	0.2343		0.4082		0.2682		0.4135		0.7071		1.0000		0.5113		0.3379		1.3747
	0.3256		0.5888		0.4368		0.7230		1.1517		1.9560		1.0000		0.5774		1.4142
	0.5503		0.9347		0.7647		0.7418		1.8644		2.9596		1.7321		1.0000		1.7042
	0.3147		0.3979		0.3878		0.5302		0.6278		0.7274		0.7071		0.5868		1.0000

The result of the multiplicative computation is presented in Table 7.6 for the purpose of the consistency check.

Table 7.6: Results of the consistency check

										sum
C_1	0.2200	0.2347	0.2373	0.2526	0.2077	0.2143	0.2398	0.2167	0.1777	2.0010
C_2	0.2117	0.1298	0.1397	0.1390	0.1245	0.1230	0.1326	0.1276	0.1406	1.1784
C_3	0.1454	0.1457	0.1568	0.1717	0.1417	0.1872	0.1788	0.1559	0.1442	1.4276
C_4	0.1008	0.1081	0.1057	0.1158	0.1267	0.1214	0.1080	0.1608	0.10550	1.0527
C_5	0.0785	0.0772	0.0820	0.0677	0.0741	0.0710	0.0678	0.0640	0.0891	0.6714
C_6	0.00516	0.0530	0.0421	0.0479	0.0524	0.0502	0.0399	0.0403	0.0769	0.4542
C_7	0.0716	0.0764	0.0685	0.0837	0.0853	0.0982	0.0781	0.0688	0.0791	0.7098
C_8	0.1211	0.1213	0.1199	0.0859	0.1381	0.1486	0.1352	0.1193	0.0953	1.0848
C_9	0.0693	0.0516	0.0608	0.0614	0.0465	0.0365	0.0552	0.0700	0.0559	0.5073

The Consistency Ratio (CR) is defined in terms of the Consistency Index (CI) and Random Index using Equation 2.7. The calculation of the CI is based on Equation 2.6, which is presented below.

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

where the λ_{max} is the maximum Eigen value and n is defined as the matrix size.

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

λ_{max} is calculated as 9.0814

Then, CI is calculated as follows:

$$CI = \frac{9.0814 - 9}{9 - 1} = \frac{0.0814}{8}$$

=0.0102

The Consistency Ratio (CR) can be calculated based on Equation 2.7. The Random Index value for the nine criteria is determined using Table 2.5. CR estimate is presented as follows:

$$CR = \frac{CI}{RI} = \frac{0.0102}{1.45} = 0.0070$$

7.10.5 Linguistic assessment of alternatives using the selected criteria and the aggregation of the fuzzy ratings of the alternatives.

The assessment of each alternative is based on the feedback from the experts' survey, which consist of six completed expert responses. The linguistic assessment based on each expert opinion is presented in the Table 7.7. The next step is the conversion of each linguistic assessment into a triangular fuzzy value based on the grading in Table 7.2. Furthermore, the experts' responses are aggregated to obtain a consolidated value, which is utilise with the weights of the evaluation criteria to form a decision matrix for implementation of VIKOR. Based on completed survey from six expert, the aggregated ratings on a set of alternatives with respect to each criterion can be calculated using Equation 2.8 as follows:

Considering, the aggregation for A_1 with respect to C_1

$$\tilde{x}_{ij} = \frac{1}{N}\left[\check{x}_{ij}^{1} + \check{x}_{ij}^{2} + \cdots \check{x}_{ij}^{N}\right]$$

$$\tilde{x}_{11} = \frac{1}{6}[(7,9,10) + (5,7,9) + (7,9,10) + (7,9,10) + (7,9,10) + (7,9,10)]$$

$$\tilde{x}_{11} = (6.667, 8.667, 9.833)$$

where N represents the number of decision makers.

Table 7.7: Experts evaluation of alternatives

Alternatives	Criteria								
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
A_1	E_1: G	E_1: G	E_1: VG	E_1: G	E_1: G	E_1: H	E_1: MG	E_1: G	E_1: MG
	E_2: MG	E_2: MP	E_2: G	E_2: P	E_2: G	E_2: MH	E_2: G	E_2: MP	E_2: P
	E_3: G	E_3: MG	E_3: VG	E_3: G	E_3: VG	E_3: MH	E_3: MG	E_3: G	E_3: MG
	E_4: G	E_4: G	E_4: G	E_4: G	E_4: M	E_4: H	E_4: MG	E_4: G	E_4: G
	E_5: G	E_5: VG	E_5: MG	E_5: M	E_5: G	E_5: M	E_5: G	E_5: M	E_5: M
	E_6: G	E_6: G	E_6: MG	E_6: MG	E_6: G	E_6: M	E_6: MP	E_6: M	E_6: MP
A_2	E_1: MG	E_1: G	E_1: VG	E_1: G	E_1: VG	E_1: MH	E_1: MG	E_1: G	E_1: MG
	E_2: M	E_2: MG	E_2: MG	E_2: M	E_2: MG	E_2: M	E_2: G	E_2: M	E_2: P
	E_3: G	E_3: M	E_3: G	E_3: G	E_3: VG	E_3: MH	E_3: MG	E_3: G	E_3: MG
	E_4: G	E_4: G	E_4: G	E_4: G	E_4: M	E_4: H	E_4: MG	E_4: G	E_4: MG
	E_5: G	E_5: MG	E_5: VG	E_5: M	E_5: G	E_5: M	E_5: MG	E_5: M	E_5: MG
	E_6: G	E_6: MG	E_6: G	E_6: MP	E_6: MG	E_6: M	E_6: M	E_6: M	E_6: M
A_3	E_1: G	E_1: G	E_1: VG	E_1: MG	E_1: VG	E_1: H	E_1: G	E_1: G	E_1:MG
	E_2: MP	E_2: MP	E_2: MP	E_2: M	E_2: G	E_2: MH	E_2: MG	E_2: M	E_2: MP
	E_3: VG	E_3: MG	E_3: G	E_3: G	E_3: G	E_3: H	E_3: MG	E_3: G	E_3: M
	E_4: VG	E_4: MG	E_4: MG	E_4: G	E_4: M	E_4: H	E_4: MG	E_4: G	E_4: MG
	E_5: MG	E_5: MG	E_5: MG	E_5: MG	E_5: G	E_5: M	E_5: MG	E_5: M	E_5: MG
	E_6: MG	E_6: MG	E_6: MG	E_6: M	E_6: MG	E_6: M	E_6: M	E_6: M	E_6: M
A_4	E_1: G	E_1: G	E_1: VG	E_1: MG	E_1: G	E_1: H	E_1: G	E_1: G	E_1: G
	E_2: G	E_2: MP	E_2: MP	E_2: G	E_2: M	E_2: M	E_2: MG	E_2: MP	E_2: M
	E_3: G	E_3: MG	E_3: G	E_3: MG	E_3: VG	E_3: MH	E_3: M	E_3: MG	E_3: M

Table 7.7 continued (Experts evaluation of alternatives)

	E_4: VG	E_4: MG	E_4: MG	E_4: G	E_4: M	E_4: H	E_4: MG	E_4: G	E_4: MG
	E_5: VG	E_5: MG	E_5: MG	E_5: G	E_5: G	E_5: M	E_5: G	E_5: M	E_5: VG
	E_6: MG	E_6: G	E_6: MG	E_6: MP	E_6: G	E_6: M	E_6: MP	E_6: M	E_6: M
A_5	E_1: MG	E_1: MG	E_1: VG	E_1: MG	E_1: MG	E_1: H	E_1: MG	E_1: G	E_1: G
	E_2: G	E_2: M	E_2: VG	E_2: MG	E_2: MP	E_2: M	E_2:MG	E_2: G	E_2: M
	E_3: G	E_3: MG	E_3: G	E_3: G	E_3: G	E_3: MH	E_3: G	E_3: G	E_3: G
	E_4: MG	E_4: MG	E_4: MG	E_4: G	E_4: M	E_4: H	E_4: MG	E_4: M	E_4: MG
	E_5: M	E_5: VG	E_5: M	E_5: M	E_5: G	E_5: M	E_5: M	E_5: M	E_5: M
	E_6: G	E_6: MG	E_6: MG	E_6: MP	E_6: MG	E_6: M	E_6: M	E_6: M	E_6: M

7.10.6 Construction the decision matrix for the implementation of VIKOR

The fuzzy decision matrix for VIKOR is presented in Tables 7.8. The normalization of the decision matrix is determined using equations 7.3 and 7.4. Example of a calculation for normalization of aggregated rating of A_1 with respect to C_1 in the decision matrix is demonstrated below.

$$\bar{U}_{ij} = \left(\frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij1}}}{\tilde{\boldsymbol{x}}_{ij3}^{+}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij2}}}{\tilde{\boldsymbol{x}}_{ij3}^{+}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij3}}}{\tilde{\boldsymbol{x}}_{ij3}^{+}}\right), C_j \in B$$

$$\bar{U}_{11} = \left(\frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij1}}}{\tilde{\boldsymbol{x}}_{ij3}^{+}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij2}}}{\tilde{\boldsymbol{x}}_{ij3}^{+}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij3}}}{\tilde{\boldsymbol{x}}_{ij3}^{+}}\right) = \left(\frac{6.667}{9.833}, \frac{8.667}{9.833}, \frac{9.833}{9.833}\right)$$

$$= (0.6780, 0.8814, 1.0000)$$

$$\bar{U}_{15} = \left(\frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij1}}}{\tilde{\boldsymbol{x}}_{ij1}^{-}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij2}}}{\tilde{\boldsymbol{x}}_{ij1}^{-}}, \frac{\tilde{\boldsymbol{x}}_{\boldsymbol{ij3}}}{\tilde{\boldsymbol{x}}_{ij1}^{-}}\right) = \left(\frac{6.667}{3.667}, \frac{8.500}{3.667}, \frac{9.500}{3.667}\right) = (1.8181, 2.3179, 2.5907)$$

Table 7.8: Fuzzy decision matrix for alternatives

	C_1	C_2	C_3
W	0.2200	0.1298	0.1568
A_1	(6.667, 8.667, 9.833)	(6.000, 7.833, 9.000)	(7.000, 8.667, 9.667)
A_2	(6.000, 8.000, 9.833)	(5.333, 7.333, 9.000)	(7.333, 9.000, 9.833)
A_3	(6.000, 7.667, 8.333)	(4.667, 6.667, 8.500)	(5.333, 7.167, 8.667)
A_4	(7.333, 9.000, 9.833)	(5.000, 7.000, 8.667)	(5.333, 7.167, 8.667)
A_5	(5.667, 7.667, 9.167)	(5.333, 7.167, 9.833)	(6.667, 8.333, 9.333)

	C_4	C_5	C_6
W	0.1158	0.0741	0.0502
A_1	(6.667, 8.833, 9.833)	(6.667, 8.500, 9.500)	(5.000, 7.000, 8.667)
A_2	(4.167, 5.833, 7.000)	(6.333, 8.000, 9.167)	(4.333, 6.333, 8.167)
A_3	(5.000, 7.000, 8.667)	(6.667, 8.500, 9.500)	(5.333, 7.333, 8.833)
A_4	(5.333, 7.333, 8.833)	(6.333, 7.833, 9.000)	(4.667, 6.667, 8.333)
A_5	(5.667, 7.667, 9.167)	(4.667, 6.667, 8.333)	(4.667, 6.667, 8.333)

	C_7	C_8	C_9
W	0.0781	0.1193	0.0559
A_1	(5.000, 6.667, 8.667)	(4.667, 6.667, 8.167)	(3.500, 5.333, 7.167)
A_2	(5.000, 7.000, 8.833)	(5.000, 7.000, 8.500)	(3.833, 5.667, 7.667)
A_3	(5.000, 6.833, 8.500)	(5.000, 7.000, 8.500)	(3.667, 5.667, 7.667)
A_4	(4.167, 5.833, 7.167)	(4.333, 6.333, 8.000)	(5.333, 7.167, 8.500)
A_5	(4.667, 6.667, 8.500)	(5.000, 7.000, 8.500)	(4.333, 6.667, 8.333)

Table 7.9: Normalized fuzzy decision matrix

	C_1	C_2	C_3
W	0.2200	0.1298	0.1568
A_1	(0.6780, 0.8814, 1.0000)	(0.6101, 0.7966, 0.9153)	(0.7118, 0.8814, 0.9831)
A_2	(0.6101, 0.8136, 1.0000)	(0.5424, 0.7457, 0.9153)	(0.7457, 0.9153, 1.0000)
A_3	(0.6101, 0.7797, 0.8475)	(0.4746, 0.6780, 0.8644)	(0.5424, 0.7289, 0.8814)
A_4	(0.7457, 0.9153, 1.0000)	(0.5085, 0.7118, 0.8814)	(0.5424, 0.7289, 0.8814)
A_5	(0.5763, 0.7797, 0.9323)	(0.5424, 0.7289, 1.0000)	(0.6780, 0.8475, 0.9492)

	C_4	C_5	C_6
W	0.1158	0.0741	0.0502
A_1	(0.6780, 0.8983, 1.0000)	(1.8181, 2.3179, 2.5907)	(1.3635, 1.9089, 2.3635)
A_2	(0.4237, 0.5932, 0.7118)	(1.7270, 2.1816, 2.4998)	(1.1816, 1.7270, 2.2271)
A_3	(0.5085, 0.7118, 0.8814)	(1.8181, 2.3179, 2.5907)	(1.4543, 1.9997, 2.4088)
A_4	(0.5424, 0.7457, 0.8983)	(1.7270, 2.1361, 2.4543)	(1.2727, 1.8181, 2.2724)
A_5	(0.5763, 0.7797, 0.9323)	(1.2727, 1.8181, 2.2724)	(1.2727, 1.8181, 2.2724)

	C_7	C_8	C_9
W	0.0781	0.1193	0.0559
A_1	(0.5085, 0.6780, 0.8814)	(1.2727, 1.8181, 2.2272)	(0.3559, 0.5424, 0.7289)
A_2	(0.5085, 0.7118, 0.8983)	(1.3635, 1.9089, 2.3179)	(0.3898, 0.5763, 0.7797)
A_3	(0.5085, 0.6949, 0.8644)	(1.3635, 1.9089, 2.3179)	(0.3729, 0.5763, 0.7797)
A_4	(0.4237, 0.5932, 0.7289)	(1.1816, 1.7270, 2.1816)	(0.5424, 0.7289, 0.8644)
A_5	(0.4746, 0.6780, 0.8644)	(1.3635, 1.9089, 2.3179)	(0.4407, 0.6780, 0.8475)

7.10.7 Deffuzzification of the fuzzy decision matrix

The graded mean integrated approach is used to defuzzify the decision matrix. Based on Equation 2.20, a calculation of crisp values for element of A_1 with respect to C_1 is presented as follows:

$\tilde{C} = (c_1, c_2, c_3) = (0.6780, 0.8814, 1.0000)$

$$P(\tilde{C}) = C = \frac{c_1 + 4c_2 + c_3}{6} = \frac{0.6780 + 4(0.8814) + 1.0000}{6} = 0.8672$$

Table 7.10: Defuzzified decision matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
W	0.2200	0.1298	0.1568	0.1158	0.0741	0.0502	0.0781	0.1193	0.0559
A_1	0.8672	0.7853	0.8700	0.8785	2.2800	1.8938	0.6837	1.7954	0.5424
A_2	0.8108	0.7401	0.9012	0.5847	2.1588	1.7195	0.7090	1.8861	0.5791
A_3	0.7627	0.6752	0.7232	0.7062	2.2800	1.9752	0.6921	1.8861	0.5763
A_4	0.9012	0.7062	0.7232	0.7373	2.1209	1.8029	0.5876	1.7118	0.7204
A_5	0.7712	0.7430	0.8362	0.7712	1.8029	1.8029	0.6752	1.8861	0.6669

7.10.8 Determination of the Best ($\tilde{f}_j^*$)value and the Worst $\tilde{f}_j^-$value of each Criteria Function

The best and the worst values of each criterion function with respect to the alternatives are determined based on Equation 2.14 and presented in Table 7.11.

Table 7.11: Best values and the Worst values

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
$\tilde{f}_j^*$	0.9012	0.7853	0.9012	0.8785	2.2800	1.9752	0.7090	1.8861	0.7204
$\tilde{f}_j^-$	0.7627	0.6752	0.7232	0.5847	1.8029	1.7195	0.5876	1.7118	0.5424

7.10.9 Estimation of the Separation measures ($\tilde{S}_i, \tilde{R}_i$)

The calculation of the separation measures of each of the alternative A_i from the best values and worst values of each criterion function is determined using Equation 2.15 and 2.16. The following example is presented to demonstrate the estimation of the separation measure for A_1.

$$\tilde{S}_1 = \sum_{j=1}^{k} \frac{\tilde{w}_j \left(\tilde{f}_j^* - \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}\right)}{\left(\tilde{f}_j^* - \tilde{f}_j^-\right)}$$

$$\tilde{S}_1 = \frac{0.2200(0.9012 - 0.8672)}{(0.9012 - 0.7627)} + \cdots + \frac{0.0559(0.9012 - 0.8672)}{(0.9012 - 0.7627)}$$

$$\tilde{S}_1 = 0.2318$$

$$\tilde{R}_1 = max_j\left[\tilde{w}_j \left(\tilde{f}_j^* - \tilde{\boldsymbol{x}}_{\boldsymbol{ij}}\right)/\left(\tilde{f}_j^* - \tilde{f}_j^-\right)\right]$$

$$\tilde{\mathrm{R}}_1 = 0.0621$$

Tables 7.12: The values of $\tilde{S}_i$, $\tilde{R}_i$, $\tilde{Q}_i$

	A_1	A_2	A_3	A_4	A_5
S	0.2318	0.4260	0.6307	0.5617	0.5024
R	0.0621	0.1435	0.2200	0.1568	0.2065
Q	0.0000	0.5012	1.0000	0.7134	0.6392

7.10.10 Computation of the $\tilde{\boldsymbol{Q}}_{\boldsymbol{i}}$ values

The VIKOR index $\tilde{Q}_i$ values for the each alternatives is estimated based on Equation 2.19. The $\tilde{Q}_i$ value for A_2 is calculated as follows:

$$\tilde{Q}_i = \frac{v\left(\tilde{S}_i - \tilde{S}_i{}^*\right)}{\tilde{S}_i{}^- - \tilde{S}_i{}^*} + \frac{(1-v)\left(\tilde{R}_i - \tilde{R}_i{}^*\right)}{\tilde{R}_i{}^- - \tilde{R}_i{}^*}$$

In this case v is specified as 0.5, $\tilde{R}_2 = 0.1435$, $\tilde{R}_i{}^* = 0.0621$, $\tilde{R}_i{}^- = 0.2200$,

$\tilde{S}_2 = 0.4260$ $\tilde{S}_i{}^* = 0.2318$, $\tilde{S}_i{}^- = 0.6307$.

$$\tilde{Q}_2 = \frac{0.5(0.4260-0.2318)}{0.6307-0.2318} + \frac{(1-0.5)(0.1435-0.0621)}{0.2200-0.0621} = 0.5012$$

The same step is repeated in the calculation of $\tilde{Q}_i$ values of all other alternatives.

7.10.11 Selection of the Best Alternative by Ranking based on S, R and Q in decreasing order.

Following the estimation of the crisp values of S, R and Q for all the alternatives, the ranking order is presented in Table 7.13. In order to reach the compromise solution for ranking the alternatives, the crisp value of Q, in decreasing order is utilised as the best ranking measure to provide the best alternative with an acceptable advantage in the selection process. In addition, the selected alternative should be the best rank by S or/and R among all alternatives as the option with acceptable stability in the decision making. Finally, the ranking is in the following order $A_1 > A_2 > A_5 > A_4 > A_3$. A_1 is ranked as the best alternative and A_2 is ranked as second choice in terms of closeness to the ideal solution. Furthermore, the conditions 1 and 2 as stated in Section 2.9.3 are satisfied $\tilde{Q}_i(A_2) - \tilde{Q}_i(A_1) \geq (1/9 - 1)$ and A_1 is also the best choice based on S and R.

Table 7.13: Ranking of the alternatives

Ranking					
	A_1	A_2	A_3	A_4	A_5
S	1	2	5	4	3
R	1	2	5	3	4
Q	1	2	5	4	3

7.11 Conduct Sensitivity Analysis.

In this section the validation of the result obtained is determine based on the variation of the weight of the strategy of the maximum group utility v, which is used in the computation of $\tilde{Q}_i$ values of all the alternatives. Normally the value of v is acceptable at 0.5. Nevertheless, v can be a value in the range of 0 to 1. In order to maximize v in performing the sensitivity analysis, the variation of the v values is set in the range of 0.2, 0.4, 0.6, 0.8 and 1. Figure 7.3 illustrate the sensitivity of the rankings to the change in v.

The result of the sensitivity analysis indicates that the ranking position of each alternative is not influenced by the variation of v. This result shows that the decision making process is robust, reliable and systematic. Furthermore, the sensitivity analysis demonstrates that irrespective of the variation of the weight for the maximum group utility, yet, the compromise solution still satisfied that the selected alternative provides an acceptable advantage and acceptable stability in the decision making process.

Table 7.16: Variation of $\tilde{Q}_i$ by maximum group utility (v)

Weight of the strategy of maximum group utility (v)	$\tilde{Q}_1$	$\tilde{Q}_2$	$\tilde{Q}_3$	$\tilde{Q}_4$	$\tilde{Q}_5$
v at 0.2	0	0.5098	1	0.6452	0.6155
v at 0.4	0	0.5041	1	0.6907	0.6313
v at 0.6	0	0.4983	1	0.7361	0.6471
v at 0.8	0	0.4926	1	0.7816	0.6629
v at 1	0	0.4868	1	0.8271	0.6786

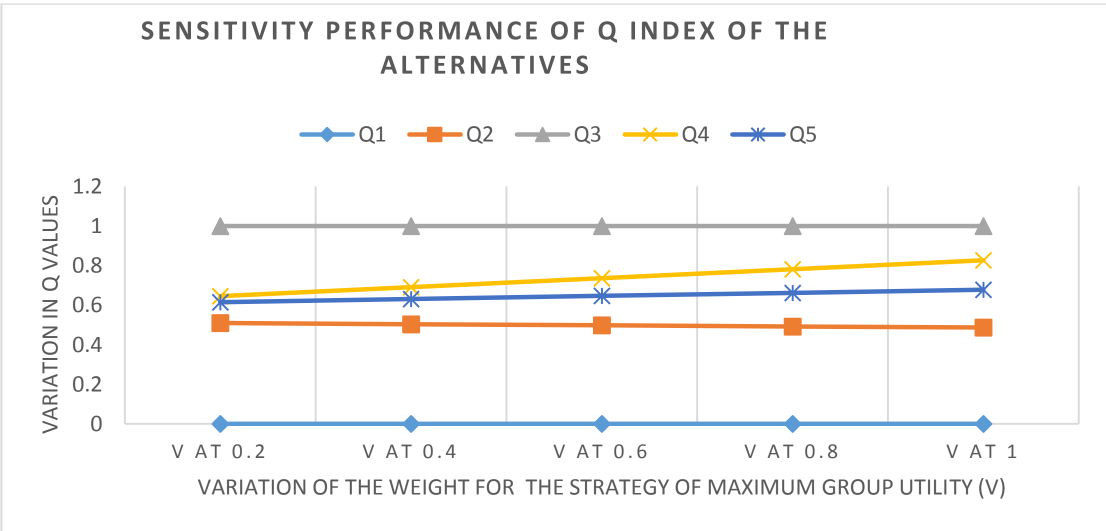

Figure 7.3: Sensitivity performance index

7.12 Discussion

The sensitivity performance of each alternative has been tested in order to investigate their stability in the ranking process, and to establish the evidence of the variation of the closeness of all the alternatives to the ideal solution. In the sensitivity analysis the variation of v for $\tilde{Q}_1$ and $\tilde{Q}_3$ has no influence on the ranking position of A_1 and A_3. This means that the ranking position of both alternatives remains absolutely stable. There is a slight change in $\tilde{Q}_2$ values for any change in v. This slight variation indicates improvement in the closeness of A_2 to the ideal solution, but it does not affect the ranking position of A_2. The sensitivity performance of $\tilde{Q}_4$ and $\tilde{Q}_5$ indicates that the variation of v has influence on A_4 and A_5 in terms of their distance away from the ideal solution. Based on the analysis, the influence of v does not affect the ranking position of all the alternatives. The changes can be observed in Figure 7.3.

Based on the result from the analysis, the risk management of petroleum refinery operation under investigation can be enhanced by employing A_1(PS1, AIM2, OIM2, PS4, OL6 and OL10):

- Implementation of a robust integrity operating windows for monitoring process equipment integrity.
- Provision of a well organised and a comprehensive maintenance management and inspection system that interfaces with operations.
- Implement policies that address managements of change.
- Risk assessment and compliance audit.

- Implementation of policies for management of work fatigue, Supervisory Control and Data Acquisition (SCADA) system to manage safety critical infrastructure in the refineries.

Selecting A_1 as a support strategy for improving the risk management of petroleum refinery operations seem to be a vital paradigm in preventing/ mitigating important risks of disruption such as instrument failure, process equipment failure, deviation from operation procedure, piping system failure, inappropriate management policy/procedure, inadequate maintenance procedure and sabotage. Given consideration to A_2 (PS2, PS6, OIM5, OL1, OL5 and OL9):

- Implementation of adequate conditional monitoring and inspection for safety critical equipment.
- Robust enforcement of compliance to process safety management standards.
- Implementation of appropriate and periodic operations integrity training programs.
- The provision of security awareness training and site intrusion detection security surveillance.
- High level organizational safety condition management and provision of an Integrated Safe System of Work, can provide an additional layer to further increase the robustness of the selected strategy to improve risk management of petroleum refinery operations. Hence, the application of the AHP and the Fuzzy VIKOR methodology has provided a platform that can help decision makers to improve their decision capability in the selection of the most reliable and resourceful alternative to enhance risk management of PRPU operation in a fuzzy situation.

7.13 Conclusions

In this chapter, an advance decision support methodology for the selection of appropriate strategies to deal with risks associated with the disruption of petroleum refinery process unit operations under fuzzy situations is presented. The proposed methodology was demonstrated with a test case, which is analysed in this study. The methodology is utilized as a collaborative modelling and strategic fuzzy multiple criteria decision making approach for a complex decision scenario, where available information, which are subjective and imprecise, are aggregated and simplified.

Due to the difficulty of acquiring real data for strategic decision support to improve the safety level of a petroleum refinery operation, strong knowledge or/and expertise of decision makers is considered in the scheme of the methodology. In view of the weaknesses and universality of uncertainty associated with the accuracy of decision makers' ratings, a functional and a robust decision modelling methodology is proposed for the selection of the appropriate strategies to improve risk management of PRPU operations. This methodology is a hybrid approach based on AHP and Fuzzy VIKOR methods.

AHP deals with the evaluation of the weights of the selected criteria, which are utilized for assessment of alternatives in the decision model, and a fuzzy VIKOR process is implemented for ranking and the selection of decision support alternative for risk management of petroleum refinery operations. Thus, an AHP and Fuzzy VIKOR methodology for evaluation and selection of decision support strategy can provide a more reliable and rational approach for decision makers and stakeholders in the petroleum refinery. Furthermore, the methodology can provide decision analysts with benefits in terms of its availability as an effective tool to assess subjective and imprecise situations in a fuzzy MCDM problem. Its application in industrial related strategic decision making provides flexibility in terms of testing the consistency and the strength of the alternatives under dynamic variation of the weight of the decision making strategy (or the maximum group utility). Finally, a strategic fuzzy decision support for the selection of appropriate strategies to tackle disruption of a petroleum refinery process unit operation is established. The methodology takes into account the sensitivity of the decision maker's expertise in the subject matter to reduce prejudice and to avoid ambiguity in the decision making process for risk management of petroleum refinery process unit operations.

Chapter 8 – Discussion and Conclusion

Summary

This research conclusion presents the adaptability and the efficacy of the conceptual framework and methodologies proposed and demonstrated with case studies. The summary of the research limitations, research contributions and future recommended for further research was logically presented in a comprehensive manner.

8.1 Discussion of results

Each of the technical chapters in this thesis has provided a brief discussion at the end, nevertheless, it is worthwhile to bring the discussion together in a more coherent way.

i) Assessment and prioritization of PRPU risk elements and their attributes

The evaluation and ranking of the PRPU risk elements and their associated attributes has been carried out in Chapter 4 of this thesis. The risk elements are ranked based on their relative weights and their associated attributes are ranked based on their global weights. The ranking result has provided useful risk information on the criticality level of the risk elements and their attributes that has been identified has threat that can lead to the disruption of petroleum refinery operations. The analysis of the PRPU risk elements and their attributes is carried out based on a generic case study and the use of experts' appraisal. The FLPR methodology was utilised in the assessment process. Using the FLPR methodology allows the analyst to obtain the weights of the risk elements and their associated attributes and to rank them according to their level of significance. The results of the ranking presents instrumentation failure, process equipment failure, inappropriate management policy, inappropriate decision making, deviation from operation procedure, inadequate maintenance procedure and natural hazard as the top priority attributes in relation to the risk elements. The result obtained in the study is useful as a vital risk information for risk analyst and stakeholders in the petroleum refining industry, to assist their risk management decisions in terms of prioritising their resource to prevent/ mitigate the risk elements and their attributes that can lead to the disruption of petroleum refinery operations. This thesis contributes an evaluation procedure based on FLPR methodology for risk evaluation and ranking in the petroleum refining industry. In this research, a generic case study was utilised, this shows the limitation of the assessment and the prioritisation of the risk elements and their attributes that are threat to PRPU operations. In the future, real world scenario case studies can be used to further improve and benchmark the ranking of the PRPU risk elements and their attributes, in order to enhance decision makers or risk managers to prioritise resources adequately for risk mitigation.

ii) Assessment of the disruption risk level of PRPU operations

Chapter 5 presents the assessment of the disruption risk level of petroleum refinery operations. This process was clearly executed using a risk modelling methodology based on Fuzzy Evidential Reasoning (FER). The result of the assessment shows the disruption risk level estimate to be {(Very low, 0.4060), (Low, 0.5595), (Medium, 0.0345) (High, 0.0000), (Very high, 0.0000)}. The result indicates the percentage of the belief degree distribution based on five assessment grades. The result shows that the disruption risk level of PRPU operation is slightly at medium level. Based on the fact that the availability of reliable risk data is not always certain, the result of the assessment is a significant contribution to knowledge in terms of providing a threshold of risk level that can lead to the disruption of petroleum refinery operations. In addition, the research has provided fairly remarkable risk management information upon which, stakeholders in the petroleum refinery can act to improve the safety of PRPU operations. The FER methodology presented in this thesis provides an evaluation procedure that contributes to knowledge in terms of risk assessment of petroleum refinery operations. The strength of the FER methodology is its capability to accommodate experts' assessment as a belief degree distribution without the loss of any information when utilising experts' assessment to define the criticality of PRPU risk elements or their attributes. The resourcefulness of the FER methodology has been indicated in its application to evaluate the risk level of offshore and marine engineering systems (Ren *et al.*, 2008).

iii) Risk modelling of prospect of disruption of petroleum refinery operations

In Chapter 6 of this thesis, the assessment to determine the prospect of disruption of a petroleum refinery operations is carried out. A BN model was developed based on FBN methodology, to depict the interaction between the risk elements and their attributes that can lead to disruption of PRPU operation. The convergent effect of the PRPU risk elements and their attributes was analysed based on the BN model and probability of disruption of PRPU operation is estimated at (yes 29%, no 71%). This result indicates that the likelihood of the convergent effect of the risk elements and their attributes to cause disruption of PRPU operation is 29%. This result shows that in theory the probability of disruption is 29% because the analysis is only based on a generic case study of a complex petroleum refinery operation. However, this result provides useful information, which can be utilized as the basis for further analysis when a real case study is analysed. The result obtained from the real case study can be compared to the result in this thesis in order to examine the difference in terms of the determination of the actual probability of disruption of PRPU operations. According to Thomson (2013), "*any given* *refinery has about a one in ten chances of suffering a major accident during its operational life of 50 years*". This statement is an indication that the petroleum refinery operations is highly risky. Hence, the result of the analysis in this thesis is a contribution to knowledge in terms of determining the probability of disruption of petroleum refinery operation. One of the strength of the BN model is that it can be used to update assessment result, when new evidence is available. This thesis has made a contribution to knowledge in terms of the application of the FBN methodology for risk modelling of the disruption of PRPU operations. The strength of the FBN methodology is its capability to transform the subjective judgement of experts into probabilities, which provides input values for each of the variables in the BN model.

iv) Strategic selection of the optimal risk management strategy for petroleum refinery operations

In the Chapter 7 of this thesis, risk management strategies are proposed as alternatives to focus on the mitigation and control of the most significant risk attributes of disruption of petroleum refinery operations. Then a decision model was developed to analyse the alternatives proposed for the risk management of the most critical attributes of the risk elements which have been analysed in Chapters 4, 5 and 6. Basically, the risk management strategies proposed in thesis is a contribution to knowledge in terms of improving the safety of petroleum refinery operations. Also the decision model, which was developed for the purpose of determining the best alternative from the set of proposed risk management strategies also provides contribution to knowledge. The decision model is very robust in the sense that it can incorporate nine significant evaluation criteria, which have been applied for strategic decision making in various academic publications for the oil and gas industry. Based on a robust literature review and brainstorming with experts in the petroleum refining industry, to a certain extent, there is confidence that the risk management strategies propose in this research can be utilised to tackle the threat of the most critical attributes of risk elements of PRPU operations. The application of the integrated methodology based on AHP-Fuzzy VIKOR to analyse the decision model also contributes a resourceful decision evaluation procedure for strategic decision making in the petroleum refining industry. The steps within the methodology are integrated in a unique way to accommodate subjective knowledge of experts, and to quantify the separation parameter for the selection of the most appropriate alternative from the set of proposed risk management strategies. Furthermore, the result from the decision analysis seems logical to support practical situations in terms of the risk management of a petroleum refinery operations.

v) Emerging themes (criticality of the expert)

Case studies have been carried out within Chapters 4 to 7 demonstrating how the methodologies can be applied independently based on the framework designed. One of the early findings of this research is that it is difficult or almost impossible to gather a panel of experts from the same petroleum refinery to conduct assessment based on the state of their process units operations. Another important finding in this research is that it is difficult to engage or convince an expert that any information provided will be treated with confidentiality. The experts' selection process is also difficult and time consuming because of the criteria set for the entrant. However, all the experts that participated in the assessment process in this research are contacted based on recommendations from academicians with contacts in the petroleum refining industry, and contacts obtained from networking with consultants during conferences. The information gathered from experts for the purpose of this research is collected using in a well-structured questionnaire, which was first pilot tested, and then used to obtain experts subjective judgement in a more concise and coherent manner. In this thesis, the consensus degree of expert opinions was estimated in order to overcome the discrepancy of expert opinions. In this thesis, the significant contribution of experts from various regions in the world cannot be overlooked. For instance, the process of identification of risk elements and their associated attributes involved critical brainstorming with expert from Iran, United Kingdom, Greece, China and Nigeria. Also, the formulation of the decision strategies, which was proposed in the Chapter 7 of this thesis was achieve based on robust literature review and experts contributions.

The methodologies applied in this research have enormous capabilities to provide valuable risk modelling and decision making to assist risk managers, safety auditors and duty holders in the petroleum refining industry in their risk management process. Also, the methodologies can be utilised as new approaches for risk assessment in petroleum refinery because of their capability to convert qualitative information into quantitative data for the risk assessment process.

This thesis has produced methodologies that can cope with uncertainty of risk modelling parameters and lack of dynamism to adapt to the light of new evidence, which is a key issue of safety/risk modelling of petroleum refinery operations. Hence, the new conceptual framework with integrated risk and decision methodologies, can be adopted to deal with risk management process for safety improvement of petroleum refinery operations. Particularly, the conceptual framework can help as a guide for risk management professionals in petroleum refinery domains in order for them to operate a robust and a well-defined risk evaluation and management process. Taking advantage of the methodologies in all the phases of the framework will help risk managers and auditors to systematically tackle safety and risk problem associated with complex decision making concerning petroleum refinery operations.

Overall, this research has produced a significant framework for risk modelling of risk elements and their associated attributes that can interact to cause a major disruption of petroleum refinery operations. One of the important contributions of this thesis is the development of a hierarchical model based on the interrelationships of the risk elements and their attributes in order to determine the risk level associated with petroleum refinery operations.

The research outcomes can provide the threshold for which the results from real world case studies can be compared, in terms of addressing the criticality and the risk level of risk elements and their attributes that can interact to cause disruption of PRPU operations. In addition, the novel framework can be extended to other industries to deal with safety problems which are related to complex system operations.

The above recommendations are by no means exclusive, therefore, the research produced in this thesis appears to be of use at least in theory. Nevertheless, the result still provides a basis upon which other case studies result can be compared. The research presented in this thesis can be utilised to justify some decisions actions to improve the safety level of petroleum refinery operations.

8.2 Research contribution to knowledge

The principal contributions to knowledge of this research in the field of risk management of petroleum refinery operations are presented as follows:

- Comprehensive review of risk management process in the petroleum refinery domain.

- Identification of risk elements and attributes that can cause disruption of petroleum refinery operations.
- Development of a generic framework for improvement of risk management of petroleum refinery operations.
- Development of the hierarchical model that depicts the holistic view of how disruption of petroleum refinery operations can happen.
- Application of FLPR methodology for risk evaluation and ranking of risk elements and their associated attributes that can affect the safety of petroleum refinery operations.
- Application of FER methodology for assessing the disruption risk level of a petroleum refinery operations.
- Application of an FBN methodology for determining the prospect of disruption of petroleum refinery operations.
- Application of an integrated AHP-Fuzzy VIKOR multicriteria decision methodology for the selection of the appropriate risk management strategy for safety improvement of petroleum refinery operations.

8.3 Limitations of the work done

In this research there are limitations that must be acknowledged in order to provide a clear view of what is achieved in this thesis. The following issues regarding the scope this research have been identified as follows:

- The analysis conducted in this research is only based on a generic case study. This is because it is difficult to gather a panel of experts from the same petroleum refinery in order to utilise their operations as a real world case study.

- The analysis conducted throughout this thesis is based on experts' subjective judgements, irrespective of the fact that the selection of experts is based on a rigorous criteria.
- In terms of the application of the evidential reasoning algorithms in this thesis, the belief degree distribution of the experts' assessment was restricted to five evaluation grades. This is because of the complexity of the calculations that can be experienced during the analysis. For practical applications to a real world case study, it is deemed appropriate to utilise seven evaluation grade for the belief distribution of experts' assessment.
- The BN model developed in the Chapter 6 of this thesis is restricted in terms of the number of states of the nodes, in order to avoid extremely large CPTs.
- To fully validate the research outcome, no proven benchmark result has been found. This is because no quantitative assessment that focuses on technical, organizational, operational and external events in terms of risk modelling of petroleum refinery operations. Most of the research findings are more qualitative in nature and none of them has directly focused on the development of a holistic risk management framework for petroleum refinery operations.

Furthermore, the partial validation of the risk modelling methodologies in the conceptual framework can be further consolidated by conducting more industrial case studies. Finally, the confidentiality barrier behind the gathering of data for the comprehensive investigation of the identified risk elements and their associated attributes is very challenging and time consuming. Since the case study applied in this investigation has provided a logical result, the methodologies created have the potential to enhance the safety of a petroleum refinery operations.

8.4 Recommendation for future research

This thesis provides the basis for further academic research in terms of the application of the methodologies in this research.

i) Instrument failure analysis and mitigation

Based on the analysis conducted in the Chapters 4 and 5 of this thesis, the attribute which is ranked as the most critical and with the highest risk level is instrument failure. The root causes of instrument failure in the petroleum refinery should be investigated and a BN model that incorporates all the root causes can be developed and analysed using series of real case studies of a petroleum refinery operating under reliable safety condition. The outcome of the analysis can provide useful risk information to determine the threshold for action to mitigate instrument failure in a petroleum refinery domain.

ii) Enlargement of the hierarchical model for in-depth analysis of the convergent effect of disruption of petroleum refinery operations

In this thesis the hierarchical model which was developed, can be further enlarged for in depth analysis of disruption. The model can be expanded to accommodate more risk events or other probable attributes of failures that are not identified in this research. Doing this will enhance the applicability of the model to real case studies in term of conducting in-depth analysis to determine the disruption risk level of PRPU operation.

iii) Development of a BN model for in-depth analysis of process equipment failure under high uncertainty

In this thesis, process equipment failure is one of the most critical attributes that contribute to the disruption of PRPU operations. Therefore, there is a need to focus more attention on risk modelling of process equipment failure. In this case, a BN model that incorporates attributes that can lead to process equipment failure can be developed and analysed. Though, Vinnem *et al.,* (2012), has developed a BN model to analyse risk influencing factor of maintenance work on major process equipment for offshore petroleum installations. Nevertheless, developing a BN model to analyse the attributes that can lead to process equipment failure in a PRPU can be carried out. In addition to the aforementioned recommendation, the following work can be done to further enhance the applicability of the framework which was developed in this research.

- In terms of the application of a FLPR methodology in this thesis to obtain the relative weight of each of the risk elements and their associated attributes, a group of six experts was used to conduct the assessment. In future research, two group of six experts could be used in the assessment process to boost research findings and this will further substantiate the applicability of the methodology.
- The outcome of the application of AHP-Fuzzy VIKOR methodology for the selection of the optimum risk management strategy in this thesis can be further consolidated by an integrated FLPR-TOPSIS methodology. This proposed methodology can further boost the authenticity of the conclusion obtained based on the AHP-Fuzzy VIKOR methodology.
- Due to the complexity and time consuming in terms of carrying out the analysis in this research, the algorithms of each methodology used in each phase of the

novel framework can be programmed, using optimization software such as CPLEX and MATLAB. This optimization software can be utilized to conclude the analysis in a short time. The approach will allow a relatively huge number of experts' assessment to be aggregated, which can lead to more interesting outcomes in terms of the application of the novel methodologies.

- The novel framework developed in this thesis can be further extended to risk modelling and decision analysis of oil and gas drilling operations.
- The novel framework can be used in the risk management process for newly operating waste to energy plant operations where new or emerging risk problems are imminent.
- The novel framework can be utilized in the assessment of resilience factors in a high risk environment like a petroleum refinery.

8.5 Conclusion

This research is carried out to primarily focus on how to prevent the disruption of petroleum refinery process unit operations. In order to achieve this goal, this thesis, has provided a novel framework that incorporates advanced safety/risk modelling methodologies, capable of dealing with uncertainties in risk assessment and decision making. Based on a robust literature review and brainstorming with experts, it was observed that the root causes of major accident in a petroleum refinery is hardly the result of a single event, but a convergence of series of events. Based on this observation, this research started with the investigation of the threat of risk elements and their associated attributes in terms of causing the disruption of petroleum refinery process unit operations. In this thesis, the criticality of the risk elements and their associated attributes that can result in a threat to PRPU operations have been are evaluated and ranked to determine their degree of importance. The ranking result can be utilised as risk information to provide more awareness on the criticality of the risk elements and their attributes to stakeholder and decision makers in the petroleum refining industry. The FLPR methodology applied in this thesis could be adopted in the petroleum refining industry as a risk evaluation process or for hazard ranking alongside the existing qualitative risk ranking matrix method.

In this thesis, the disruption risk level of a petroleum refinery operation was analysed. The result obtained from the analysis indicates that for a petroleum refinery with a fairly reliable management of change and a fairly reliable safety standard, the risk level of operation is slightly at medium level. This result can be utilised in the petroleum refining industry to create threshold for actions to minimize the risk level of operation in petroleum refineries. The hierarchical model developed in this thesis, to analyse the risk level of PRPU operations is applicable with real world case studies, in order to consolidate with the results in this thesis. The FER methodology utilised for the assessment of the risk level of PRPU operations, in this thesis, can be adopted for quantitative risk analysis in the petroleum refinery industry to support safety audit and for risk analysis prior to management of change to operations.

The application of FBN methodology in this thesis, reveals that the convergent effect of the risk elements and their attributes can possibly lead to the disruption of petroleum refinery operations. The assessment process has demonstrated the robustness of the FBN methodology has a quantitative approach for supporting the prediction of disruptive risk scenarios in a petroleum refinery domain. The BN model can be utilised in the petroleum refining industry to predict the state of the operation of any process unit in a petroleum refinery, in order to provide risk information to support operational safety.

The risk management strategies proposed in this thesis can provide useful risk management information to stakeholder and duty holders in the petroleum refining industry. Also, the decision modelling methodology applied for the selection of the most reliable risk management alternative can be utilised in practice in the petroleum refinery industry for decision making on selection of risk management strategy.

Overall, the framework developed in this thesis can be utilised to consolidate current procedures for risk management in the petroleum refining industry. For instance the FBN methodology in the framework can be practically utilised as a process hazard analysis method like FTA to quantify the consequence probability of a process failure or process equipment failure. The methodologies can be utilised in processes such as risk analysis prior to conducting management of change to any petroleum refining process, equipment, or any operational procedure. Also the framework can be applied as assessment framework for process hazard analysis in a petroleum refinery under an uncertain condition whereby failure data or available risk information is uncertain, and expert assessment is required to examine the risk criticality level of a process or a system in a petroleum refinery domain. Furthermore, the methodologies presented in the heart of the framework can be utilised in other industrial sectors for risk evaluation and ranking of systems or components criticality level (*i.e.* manufacturing and rail transport).

In terms of the related work to this research in the petroleum refinery domain, only a few literature sources have been identified. Saidi *et al.*, (2014) present a model for the risk of process operation in the petroleum and gas refineries. The work contributes to knowledge in terms of utilising fuzzy logic system for risk modelling of process units' asset failure. However, the work done is only limited to, asset failure ranking in a petroleum refinery domain. Abdul Hameed & Faisal Khan, (2014) present a framework for a cost effective risk-based shut down in petrochemical plant and oil refineries. The work produced is limited to, maintenance planning and inspection of assets. Vinnem *et al.,* (2012), presents a risk modelling approach for analysis of risk influencing factors associated with organizational, human and technical factors. The scope of the assessment is limited to, maintenance work on major process equipment on offshore petroleum installations. Zhaoyang *et al.,* (2011), present a risk based inspection methodology to evaluate the criticality of assets in a petroleum refinery process unit. The work done is specific to the maintenance of process unit equipment's.

Bertolini *et al.,* (2009), present a risk based inspection and maintenance procedure for oil refineries. The work done only focused on turnaround and work order management in a petroleum refinery. Based on this review, it is observed that none of the aforementioned research is comparable to the work done in this thesis. This is because the scope of all the aforementioned literature sources are limited to issues such as maintenance operations, risk based inspections, analysis of risk influencing factors on maintenance of process equipment. Based on this finding, it can be said that this thesis has produced novel research that can provide an in-depth analysis for risk modelling and decision making to enhance safety of operations in the petroleum refining industry.

8.6 Concluding remark

Pasman *et al.,* (2009), stated that the state of safety of process plants can only be determine by quantifying risks based on exploiting the combination of an intuitive approaches that incorporate or integrate FST, expert opinion elicitation, influence diagrams, Bayesian belief net and advance uncertainty analysis methods for quantitative risk assessment. Based on this indication, this research has contribute to knowledge based on the fact that the methodologies proposed in thesis exhibit the quality of an intuitive approaches for advancement of quantitative risk assessment in a petroleum refinery domain.

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Appendices

Appendix A: Research Questionnaires

Dear Respondent,

A research project at Liverpool Logistics, Offshore and Marine (LOOM) Research Institute is currently being carried out on "Safety Modelling Methodology for Risk Management of a Petroleum and Gas refineries". The aim of the research is to investigate the existing safety problems in petroleum and gas refineries and to develop a flexible and integrated risk management approach that can complement existing knowledge on risk management in petroleum and gas refineries to monitor, mitigate and control the risks associated with petroleum refineries operations. The analysis will provide decision makers and stakeholders in petroleum and gas refineries with a modelling platform to critically evaluate risk attributes, in order to prioritise them according to the outcome(s) that can lead to a major disruption of petroleum and gas refineries operations.

Respondent is required to complete the questionnaire below. The scope of this questionnaire considers ***complex petroleum and gas refineries in the onshore and offshore locations, with over 20 years of operation, reasonable management of change in organization structure and Policies, and fairly reliable safety standards.***

Your response and opinion is highly appreciated and is completely voluntary. The survey takes about 20-30 minutes of your time.

In order to improve the quality and relevance of the research, the researcher would greatly appreciate your views by completing the questionnaire. The information provided and your identity will be treated with confidentiality.

For further questions or enquiries about the study, please do not hesitate to contact the researcher.

Thank you,

Yours faithfully

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Part A

Questionnaire for pairwise comparisons of risk elements that are perceived to affect the safety of refinery process units in operation.

An example of how to answer is provided.

Example

Group I: If you think the first criterion **Human error** is strongly important to affect the safety and reliability of FPSO than the second criteria **Electrical fault**, then please tick as follows:

	Scale of relative importance																	
Criterion	Absolute (8,9,9)	Intermediate (7, 8, 9)	Very strong (6, 7, 8)	Intermediate (5, 6, 7)	Strong (4, 5, 6)	Intermediate (3, 4, 5)	Weak (2, 3, 4)	Intermediate (1, 2, 3)	Equal (1, 1, 2)	Intermediate (1, 2, 3)	Weak (2, 3, 4)	Intermediate (3, 4, 5)	Strong (4, 5, 6)	Intermediate (5, 6, 7)	Very strong (6, 7, 8)	Intermediate (7, 8, 9)	Absolute (8,9,9)	Criterion
Human error					X													Electrical fault

Alternatively, if the second criterion **Electrical fault** is strongly important to affect the safety and reliability of FPSO than the first criterion **Human error**, then please tick as

	Scale of relative importance																	
Criterion	Absolute (8,9,9)	Intermediate (7, 8, 9)	Very strong (6, 7, 8)	Intermediate (5, 6, 7)	Strong (4, 5, 6)	Intermediate (3, 4, 5)	Weak (2, 3, 4)	Intermediate (1, 2, 3)	Equal (1, 1, 2)	Intermediate (1, 2, 3)	Weak (2, 3, 4)	Intermediate (3, 4, 5)	Strong (4, 5, 6)	Intermediate (5, 6, 7)	Very strong (6, 7, 8)	Intermediate (7, 8, 9)	Absolute (8,9,9)	Criterion
Human error													X					Electrical fault

follows:

NB: *Please remember to indicate using* ***X*** *for your preference for each pair of compared Main criteria and Sub criteria (risk elements) based on the scale of importance* ***on either the left or right side.***

Compare all main criteria pairwise with respect to the objective according to their importance value to each other by one-to-one and all sub-criteria pairwise according to their importance values.

Goal : Disruption risk of refinery process unit in operations																		
	Scale of relative importance																	
Main Criteria	Absolute	Intermediate	Very strong	Intermediate	Strong	Intermediate	Weak	Intermediate	Equal	Intermediate	Weak	Intermediate	Strong	Intermediate	Very strong	Intermediate	Absolute	Main Criteria
Operational risk elements																		Technical risk elements
Technical risk elements																		Organizational risk elements
Organizational risk elements																		External risk elements

Category A: Operational Risk Elements																		
	Scale of relative importance																	
Sub Criteria	Absolute	Intermediate	Very strong	Intermediate	Strong	Intermediate	Weak	Intermediate	Equal	Intermediate	Weak	Intermediate	Strong	Intermediate	Very strong	Intermediate	Absolute	Sub Criteria
Deviation from operational procedure																		Operator incompetency
Operator incompetency																		Inadequate communication
Inadequate communication																		Inadequate maintenance procedure

Category B: Technical Risk Elements																		
	Scale of relative importance																	
Sub Criteria	Absolute	Intermediate	Very strong	Intermediate	Strong	Intermediate	Weak	Intermediate	Equal	Intermediate	Weak	Intermediate	Strong	Intermediate	Very strong	Intermediate	Absolute	Sub Criteria
Process Equipment Failure																		Instrument Failure
Instrument Failure																		Piping system Failure
Piping system Failure																		Utility system Failure

Category C: Organizational Risk Elements																		
	Scale of relative importance																	
Sub Criteria	Absolute	Intermediate	Very strong	Intermediate	Strong	Intermediate	Weak	Intermediate	Equal	Intermediate	Weak	Intermediate	Strong	Intermediate	Very strong	Intermediate	Absolute	Sub Criteria
Inappropriate management policy/ procedure																		Inappropriate decision making
Inappropriate decision making																		Inadequate staffing
Inadequate staffing																		Poor safety monitoring and auditing
Poor safety monitoring and auditing																		Lack of safety training /drills

Category D: External Risk Elements																		
	Scale of relative importance																	
Sub Criteria	Absolute **(8,9,9)**	Intermediate **(7, 8, 9)**	Very strong **(6, 7, 8)**	Intermediate **(5, 6, 7)**	Strong **(4, 5, 6)**	Intermediate **(3, 4, 5)**	Weak **(2, 3, 4)**	Intermediate **(1, 2, 3)**	Equal **(1, 1, 2)**	Intermediate **(1, 2, 3)**	Weak **(2, 3, 4)**	Intermediate **(3, 4, 5)**	Strong **(4, 5, 6)**	Intermediate **(5, 6, 7)**	Very strong **(6, 7, 8)**	Intermediate **(7, 8, 9)**	Absolute **(8,9,9)**	Sub Criteria
Natural hazard																		Sabotage
Sabotage																		Terrorist attack

<table>
<tr><td colspan="5">Please indicate the Occurrence Likelihood (OL) and Consequence Severity (CS) grade for each of the risk element presented in this table based on the Assessment grade indicated at the right end of this table.</td></tr>
<tr><td></td><td>Risk Elements</td><td>Occurrence Likelihood (OL)</td><td>Consequence Severity (CS)</td><td rowspan="7">Assessment grade for OL.
1= Very low
2= Low
3= Moderate
4= High
5= Very high

Assessment grade for CS.
1= Negligible
2= Minor
3= Moderate
4= Critical
5= Catastrophic

(OL): likelihood of event to happen.
(CS): Describe the magnitude of possible consequences.</td></tr>
<tr><td>Main criteria</td><td>Technical risk element</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td rowspan="4">Sub criteria</td><td>Process equipment failure EQ</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td>Piping system failure PF</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td>Controls/instrumentation failure CIF</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td>Utility system failure UF</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td colspan="2">EQ
Heat exchanger failure, fired heater failure, distillation column failure, reactor failure pumps compressors.

CIF
Monitoring devices, sensors, alarm system failure, emergency shutdown system failure, relief and vent system failure.</td><td colspan="3"></td></tr>
</table>

Please indicate the Occurrence Likelihood (OL) and Consequence Severity (CS) grade for each of the risk element presented in this table based on the Assessment grade indicated at the right end of this table.				
	Risk Elements	**Occurrence Likelihood (OL)**	**Consequence Severity (CS)**	**Assessment grade for OL.** **1= Very low** **2= Low** **3= Moderate** **4= High** **5= Very high** **Assessment grade for CS.** **1= Negligible** **2= Minor** **3= Moderate** **4= Critical** **5= Catastrophic** **(OL): likelihood of event to happen.** **(CS): Describe the magnitude of possible consequences.**
Main criteria	**External risk element**	□ **1** □ **2** □**3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
Sub criteria	Natural hazard (**NH**)	□ **1** □ **2** □**3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
	Sabotage	□ **1** □ **2** □**3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
	Terrorist attack **NH** Lighting Flood/ Snow Earthquake Hurricane/cyclone	□ **1** □ **2** □**3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	

<table>
<tr><td colspan="5">Please indicate the Occurrence Likelihood (OL) and Consequence Severity (CS) grade for each of the risk element presented in this table based on the Assessment grade indicated at the right end of this table.</td></tr>
<tr><td></td><td>Risk Elements</td><td>Occurrence Likelihood (OL)</td><td>Consequence Severity (CS)</td><td rowspan="6">Assessment grade for OL.
1= Very low
2= Low
3= Moderate
4= High
5= Very high

Assessment grade for CS.
1= Negligible
2= Minor
3= Moderate
4= Critical
5= Catastrophic

(OL): likelihood of event to happen.
(CS): Describe the magnitude of possible consequences.</td></tr>
<tr><td>Main criteria</td><td>Operational risk element</td><td>□ 1 □ 2 □ 3 □4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td rowspan="4">Sub criteria</td><td>Deviation from operational procedure</td><td>□ 1 □ 2 □ 3 □4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td>Inadequate communication (IC)</td><td>□ 1 □ 2 □ 3 □4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td>Inappropriate maintenance procedure</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td>Operator incompetency (OC)</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td><td>□ 1 □ 2 □ 3 □ 4 □ 5</td></tr>
<tr><td colspan="2">(OC)
Inadequate training of operator
Inappropriate work practice
Lack of experience
Work fatigue</td><td colspan="3"></td></tr>
</table>

Please indicate the Occurrence Likelihood (OL) and Consequence Severity (CS) grade for each of the risk element presented in this table based on the Assessment grade indicated at the right end of this table.				
	Risk Elements	**Occurrence Likelihood (OL)**	**Consequence Severity (CS)**	**Assessment grade for OL.** **1= Very low** **2= Low** **3= Moderate** **4= High** **5= Very high** **Assessment grade for CS.** **1= Negligible** **2= Minor** **3= Moderate** **4= Critical** **5= Catastrophic** **(OL): likelihood of event to happen.** **(CS): Describe the magnitude of possible consequences.**
Main criteria	**Organizational risk element**	□ **1** □ **2** □ **3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
Sub criteria	Inappropriate management policy and procedure	□ **1** □ **2** □ **3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
	Inappropriate decision making	□ **1** □ **2** □ **3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
	Inadequate staffing	□ **1** □ **2** □ **3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
	Poor safety monitoring /auditing	□ **1** □ **2** □ **3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	
	Lack of safety training/drill	□ **1** □ **2** □ **3** □ **4** □ **5**	□ **1** □ **2** □ **3** □ **4** □ **5**	

Appendix B: Research Questionnaire for Chapter 7

Strategic decision support for risk management of petroleum refinery operations

Page 1

Dear Sir/Ma'am,

My name is Ademola Ishola, a PhD student at Liverpool John Moores University. I wish to obtain information that is important for the analysis, which is to be conducted in this research. kindly, take time to read the following information. Ask us if there is anything that is not clear or if you would like more information, please check the tooltip or rather contact Tel: 07411072180, Email:A.Ishola@2014.ljmu.ac.uk

Strategic decision making is an important work package in my research in order to establish a systematic approach for prevention, mitigation and control of disruption risk of petroleum refinery operations. The outcome of this study will be utilized to assist decision makers and stakeholders in petroleum refineries, to maximize their decision in terms of implementing the most appropriate strategies for risk management of their operations. Because you are an expert, I am inviting you to participate in this survey. The questionnaire you are about to answer will only take 20 minutes to complete. There is no risk implication to your involvement in this survey and any information provided will be treated with absolute confidentiality. However, your participation is vital to this research development. Hence, your valuable contribution will be highly appreciated. Within the next two weeks the researcher hopes to collect a significant amount of data, therefore your timely response will provide the benefit of completing the research in the next few months.

Thanks for taking time to read through this introduction.

Page 2

Decision maker rating for criteria

Give an appropriate percentage to each criterion to reflect its importance: Please enter a value between 0 and 100 (0 correspond to the left and 100 correspond to the right)

Reliability (rate the importance of this criterion)

(0) (100)

Survivability (rate the importance of this criterion)

(0) (100)

Safety (rate the importance of this criterion).

(0) (100)

Redundancy (rate the importance of this criterion)

(0) (100)

Consequence (rate the importance of this criterion)

(0) (100)

Investment cost (rate the importance of this criteria)

(0) (100)

Cognitive Adaptability (rate the importance of this criterion)

(0) (100)

Availability (rate the importance of this criterion)

(0) (100)

Security (rate the importance of this criterion)

Page 3

In this section, the strategies adopted for decision making towards risk management of petroleum refinery process unit operations are presented as alternatives (A1, A2, A3, A4, A5). Please click on the tool tips on each alternative to see the details in each of the alternative.
The Decision Maker is expected to assess the alternatives with respect to each criterion.

Reliability (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

Survivability (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

Safety (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

Redundancy (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

Consequence (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

Investment cost (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

◯ Very Low ◯ Low ◯ Medium Low ◯ Medium ◯ Medium High ◯ High ◯ Very High

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

◯ Very Low ◯ Low ◯ Medium Low ◯ Medium ◯ Medium High ◯ High ◯ Very High

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

◯ Very Low ◯ Low ◯ Medium Low ◯ Medium ◯ Medium High ◯ High ◯ Very High

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Low ◯ Low ◯ Medium Low ◯ Medium ◯ Medium High ◯ High ◯ Very High

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Low ◯ Low ◯ Medium Low ◯ Medium ◯ Medium High ◯ High ◯ Very High

Cognitive Adaptability (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

Availability (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

Security (please provide the linguistic rating of the alternatives with respect to the criterion)

A1 (PS1, AIM2, OIM2, PS4, OL6, OL10)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A2 (PS2, PS6, OIM5, OL9, OL1, OL5)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A3 (PS9, PS5, AIM3, OL3, OIM3, PS3)

○ Very Poor ○ Poor ○ Medium Poor ○ Medium ○ Medium Good ○ Good ○ Very Good

A4 (AIM1, AIM6, OIM4, OL2, OL8, OL11)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

A5 (OIM1, AIM4, AIM7, OL4, PS7, PS8)

◯ Very Poor ◯ Poor ◯ Medium Poor ◯ Medium ◯ Medium Good ◯ Good ◯ Very Good

Page 4

Please provide your career service time:

	less than 5 years	6-10 years	11-15 years	16-20 year	over 20 years
Senior operation manager	☐	☐	☐	☐	☐
Senior QSHE manager	☐	☐	☐	☐	☐
Refinery mechanical engineer	☐	☐	☐	☐	☐
Senior process engineer	☐	☐	☐	☐	☐
Oil and gas refinery consultant	☐	☐	☐	☐	☐
Academic and industrial experience	☐	☐	☐	☐	☐

Academic qualifications?

- ◯ College certification
- ◯ Diploma
- ◯ Bachelors
- ◯ Masters
- ◯ PhD
- ◯ Assistant professor
- ◯ Professor

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Appendix C: Research Questionnaire for design of membership function

Part A

This questionnaire is designed in order to obtain the opinion of experts regarding the rating for the membership degree of linguistic variable associated with risk parameters in petroleum and gas refinery domain under fuzzy situation. These linguistic variables are further defined in terms of triangular fuzzy values as described in the table below.

Table C.1: Fuzzy membership function

Risk parameters	Linguistic terms	Membership functions	Expert comment
Occurrence likelihood (L)	Very low	(0.0, 0.10, 0.20)	□ **1** □ **2** □ **3** □ **4**
	Low	(0.15, 0.30, 0.40)	□ **1** □ **2** □ **3** □ **4**
	Moderate	(0.35, 0.475, 0.60)	□ **1** □ **2** □ **3** □ **4**
	High	(0.55, 0.775, 0.90)	□ **1** □ **2** □ **3** □ **4**
	Very High	(0.85, 0.90, 1.0)	□ **1** □ **2** □ **3** □ **4**
Consequence Severity (S)	Negligible	(0.0, 0.10, 0.20)	□ **1** □ **2** □ **3** □ **4**
	Minor	(0.10, 0.25, 0.40)	□ **1** □ **2** □ **3** □ **4**
	Moderate	(0.35, 0.45,0.60)	□ **1** □ **2** □ **3** □ **4**
	Critical	(0.55, 0.70, 0.85)	□ **1** □ **2** □ **3** □ **4**
	Catastrophic	(0.80, 0.90,1.0)	□ **1** □ **2** □ **3** □ **4**
Risk (R)	Very Low	(0.0,0.125, 0.25)	□ **1** □ **2** □ **3** □ **4**
	Low	(0.15, 0.25, 0.35)	□ **1** □ **2** □ **3** □ **4**
	Medium	(0.30, 0.50,0.70)	□ **1** □ **2** □ **3** □ **4**
	High	(0.65, 0.75, 0.85)	□ **1** □ **2** □ **3** □ **4**
	Very High	(0.80, 0.90,1.0)	□ **1** □ **2** □ **3** □ **4**
			Instructions □ **1 # (Please tick if the membership function is reasonable and acceptable)** □ **2 # (Please tick if the range of membership function for each linguistic variables need to be increase by at least 0.05 and at most 0.15).** □ **3 # (Please tick if the range of membership function for any of the linguistic variable need to be reduced by at least 0.05 and at most 0.15).** □ **4 # (Please tick if membership function for any of the linguistic variable is not reasonable and kindly provide a suitable membership function for such linguistic variable) in Table 2)**

N.B: Considering the membership function define for each linguistic variable associated with the risk parameters in Table C.1, expert response is required to validate the membership function for risk evaluation. For instance, if the membership function presented in Table 1 is not acceptable, expert can provide their response in same manner as define in Table C.1 by imputing their reasonable judgment in Table C.2.

Table C.2- Linguistic variable for risk evaluation

Risk parameters	Linguistic terms	Membership functions
Occurrence likelihood (L)	Very low	
	Low	
	Moderate	
	High	
	Very High	
Consequence Severity (S)	Negligible	
	Minor	
	Moderate	
	Critical	
	Catastrophic	
Risk (R)	Very Low	
	Low	
	Medium High	
	Very High	

Appendix D: List of Petroleum refinery accidents (1975-2016)

Table D.1: Historical list of petroleum refinery accidents from the 1970s -2016. (Sources: Marsh report, 2015; Thomson, 2013; US Chemical Safety Board website; JST website and ARIA database)

Year/ location	Plant/unit	event	Death /injuries	Causes
1975 Philadephia, PA, USA,	Refinery/storage area	Explosion/fire	8/none $13 million	Storage tank overfilling cause high vapour release.
1975 Avon, CA USA	Refinery	Explosion/Fire	None /$10.37million	Instrumentation failure.
1975 10.14.75 Avon, CA USA	Refinery/coking unit	Implosion/ Fire	None/$6.37 million	Instrumentation failure.
1976 Big spring, Texas USA	Refinery	Explosion/Fire	None/$6.7million	Tank bending by use of air ignited and spread within the refinery.
1976 Chalmette, LA, USA	Refinery	Explosion	13/?	Explosion in the refining tower.
1976 Plaquemine LA, USA	Refinery/ Storage	Explosion/Fire	None/$12 million	Internal vessel failure in storage tank.
1977 Port Arthur, Texas USA	Refinery	Explosion/Fire	8/none	No details.
1977 Umm Said Qatar	Refinery /Storage	Fire	7/87/$76.4 million	Metallurgical weld failure.

Table D.1-Continued

1977 Romeoville, USA	Refinery /storage area /diesel fuel	Explosion /Fire	None/$8 million	Lightning struck a storage facility in the refinery.
1978 Texas city USA	Refinery / Alkylation unit	Fire/Explosion	7/11/$190 million	Unidentified release in tank farm leads to storage tank fire and BLEVE.
1978 Piteti Romania	Refinery	Fire/Explosion	None	Failure of piping releasing vapours and causing an explosion.
1979 Linden , NJ, USA	Refinery	Fire/Explosion	None	Failure of dead leg pipeline releasing vapour.
1979 Texas city, USA	Refinery	Vapour Cloud Explosion/ Fire	None/$47 million	Failure of piping elbow in process unit.
1979 Deer park Texas USA	Refinery	Explosion	None/$138 million	Lightning struck distillate tanker causing explosion and fire.
1979 Ponce PR, USA	Refinery	Fire	None/$10 million	Pump failure release liquid which ignited.
1979 Ras Tanura, Saudi Arabia	Refinery/Storage tank	Explosion/ Fire	2/6	No details.
1979 Geelong, Australia	Refinery/Crude distillation unit	Fire	None/$11.24 million	Pump bearing failure.

Table D.1-Continued

1980 Deer park, TX, USA	Refinery / Vacuum distillation unit	Explosion/Fire	3/12/$29 million	Pump seal failure released liquid which ignited.
1980 Sydney, Australia	Refinery	Explosion/Fire	None	The incident occurred during start-up of facility after shutdown.
1980 Borger, Texas, USA	Refinery/ alkylation unit	Vapour Cloud Explosion	?/41/$65 million	Vessel rupture and hydrocarbon release.
1980 Seadrift, TX, USA	Refinery	Explosion/Fire	None/$11.8 million	Instrumentation failure caused process upset, which resulted to internal detonation releasing flammable.
1980 Corpus Christi, TX, USA	Refinery/ Reactor	Fire	None/$17 million	Metallurgical failure of laminated reactor vessel release vapour.
1981 West Glamorgan, UK.	Refinery	Explosion	None	No details.
1981 Shuaiba, Kuwait	Refinery	Fire	None/$50 million	Tank caught fire which spread to other areas.

Table D.1-Continued

1982 Kashima, Japan	Refinery	Fire	None/$13.8 million	Hydrogen embrittlement caused piping failure.
1983 Avon, CA, USA,	Refinery/Fluid catalytic coke Unit(FCC)	Fire	None/$73 million	Rupture of slurry line in FCC unit which ignited.
1983 Milford Haven, UK	Refinery	Fire	unknown/20/$15 million	Floating roof tank seal area ignited from flare carbon particles from 350 feet away.
1984 Romeville, USA	Refinery	Explosion /Fire/BLEVEs	17/31/$275 million	Weld crack leaded propane which, ignited resulting in vapour cloud.
1984 Las piedras, Venezuela	Refinery/ Hydrogen plant	Fire	None/$89 million	Line failure due to metal fatigue, release.
1984 Ft. Mcmurray, Alberta Canada	Refinery	Fire	None/$180 million	Erosion failure of pipeline release liquid near auto ignition temperature.
1984 Kerala India	Refinery	Explosion/Fire	None/$12million	Release of vapour from leaking heat exchanger.
1985 Wood River, IL, USA	Refinery	Explosion/Fire	None/$29 million	Propane pipe ruptured and released hydrocarbon.

Table D.1-Contined

1987 Ras Tanura Saudi Arabia,	Refinery	Fire	None/$60 million	The Propane release caused fire at relief valve.
1987 Grangemouth UK	Refinery	Explosion	None/$107 million	No details.
1988 Norco, Louisiana, USA	Refinery/FCC unit	Vapour cloud explosion	None/$336 million	Corrosion of carbon steel elbow released propane vapours that exploded in FCC unit impacted utilities and firewater system.
1988 Port Arthur, TX, USA	Refinery	Explosion / Fire	None/$16 million	Failure of the propane line causes a vapour cloud release in the tank farm that ignited and impacted other product transfer lines.
1989 Baton rouge, LA, USA	Refinery	Explosion/Fire	None/$140 million	Pipeline failure led to release of combustible gases, which ignited and affected the utility services.
1989 Marinez, CA , USA	Refinery/ Hydrocracker unit	Fire	None/$190 million	High pressure jet fire due to weld failure.

Table D.1-Continued

1989 St Croix Virgin Islands USA	Refinery	Natural disaster	None/$350 million	Hurricane Hugo struck the refinery.
1990 Warren, PA, USA.	Refinery	Explosion/Fire	None/ $30 million loss	LPG released by the operator during water draining operation of debutanizer system.
1990 Rio de Janeiro, Brazil	Refinery/FCC unit	Explosion	None/$10 million loss	Boiler ruptures occur in FCC unit.
1990 Chalmette, IN, USA	Refinery	Explosion /Fire	None / $25 million	Heat exchanger shell failure released gas causing explosion and process fires.
1990 Ras Tanura, Saudi Arabia	Refinery/ Fractionation Column	Fire	1/none $40 million loss	Chemically induced corrosion failure of the main crude feed line caused fire at fractionation column for kerosene and diesel.
1991 Lake Charles, LA, USA	Refinery	Explosion/Fire	None/$28, million loss	Vessels rupture during turnaround.
1991 Port Arthur, Texas, USA	Refinery	Fire	None/$31 million	No details provided

Table D.1-Continued

1991 Beaumont, Texas, USA	Refinery	Fire	None /$18 million loss	No details provided
1991 Sweeney, Texas, USA	Refinery	Explosion	None/2 / $45 million loss	No details provided
1991 Westphalia, Germany	Refinery	Explosion/ Fire	None/$62 million loss	No details provided
1992 Eleusis, Greece	Refinery/crude distillation unit	Explosion/ Fire	14/30	Process pipework failure
1992 La Mede, France	Refinery/hydrocra cker unit	Explosion/ Fire	None/$318 million loss	No details provided
1992 Wilmington California USA	Refinery/ hydrogen processing unit	Explosion/ Fire	None/$150 million loss	Rupture of the pipe elbow in hydrogen processing unit followed by the release of Hydrocarbon – hydrogen mixture to the atmosphere.
1992 Sodegaura, Japan	Refinery/ hydrodesulphu-risation unit	Explosion/ Fire	None/$318 million loss	Heat exchanger failure in hydrodesulphu-risation unit
1993 Bilbao, Spain	Refinery/ conversion unit	Explosion	None/$8 million loss	Explosion occurred in chimney.
1993 Sicily, Italy	Refinery	Explosion/Fire	7/?	No detailed causes

Table D.1-Continued

1993 Baton Rouge, Louisiana, USA	Refinery /Coker unit	Fire	3/none $78 million	Incorrect metallurgical valve leaked coke which caused an explosion under Coker unit.
1994 Milford Haven, UK.	Refinery	Fire	None/26/$48 million loss	Pipeline failure lead to hydrocarbon release.
1994 Kawasaki, Japan	Refinery	Fire	None/ $41 million loss	No details.
1994 Ryazan Russia	Refinery/crude unit	Loss of containtment	None/$180 million	Procedural error.
1995 Roseville, Pennsylvania, USA.	Refinery	Fire	None/$46 million loss	No details.
1995 Cilacap, Indonesia	Refinery	Explosion/ Fire	None/$38 million loss	No details.
1997 Visakhapatnam, India	Refinery/ Storage	Fire/explosion	60/? /$64 million loss	No details.
1997 Martinez California USA	Refinery	Explosion/Fire	None/$22 million	No details.
1998 St. John New Brunswick	Refinery	Explosion/ Fire	None/$66 million loss	No details.

Table D.1-Continued

1998 PascagoulaMis sissippi, USA	Refinery	Natural disaster	None/$320 million loss	Hurricane
1998 Equilon Anacortes Refinery Western Washington	Refinery/ Coking unit	Fire	6/none $45 million	Inappropriate decision making.
1998 Berre L'Etang, France	Refinery	Fire	None/$23 million loss	No details.
1999 Richmond California, USA	Refinery/ Hydrocracker unit	Explosion	None /$110 million loss	Failure of a valve followed by hydrocarbon release which caused explosion.
1999 Laem, Chabang, Thailand	Refinery/ Storage	Vapour cloud explosion/Fire	7/18/$12.5 million	Tank overfilling.
1999 Korfez Turkey	Refinery/ Crude unit	Fire	None/ $330 million	Earthquake
1999 Tosco Avon Refinery Accident Martinez, CA, USA	Refinery/fractiona tion tower/naphtha	Fire/explosion	4/1/$24 million approximate	Failure in maintenance operation of Piping.

Table D.1-Continued

2000 Mina Al-Ahmadi Kuwait	Refinery/Crude unit/reformer unit	Explosion /Fire	5/ 50 / $810 million loss (Current estimate)	Attempt to isolate the leak on a condensate line caused explosion/fire
2001 Lemont Illinois, USA	Refinery /Crude Distillation unit	Pool fire	None /$370 million loss	Pool fire caused as a result of release from ruptured pipework (elbow) which was due to incorrect piping material specification.
2001 Carson City, California USA	Refinery /Coker unit	Fire	None /$190 million loss	Piping leak in Coker unit cause fire.
2001 Wickland, Aruba, Dutch Antilles	Refinery /Oil Spill/ Visbreaker unit	Fire/Explosion	None/$250 million loss	Inadequate installation of a block valve on a pump in visbreaker unit during maintenance resulted to oil spill which cause fire.
2001 Lake Charles Louisiana, USA	Refinery	Explosion/Fire	?/2/$52 million	Piping leakage released gas that ignited and caused an explosion and fire.
2001 Delaware, USA	Refinery	Fire/Toxic release	1/8	Acid spill releasing a cloud of toxic gas.

Table D.1-Continued

2001 Killingholme, UK Humber refinery	Refinery /Deethanizer overhead pipe/ ethane, propane and butane.	Vapour cloud (fireball)	None/$82 million	Pipe rupture and hydrocarbon release.
2002 Mohammedia, Morocco	Refinery / crude unit, vacuum distillation unit, reformer unit	Explosion/Fire	None /$200 million loss	Waste oil from torrential rain flooding ignited by hot equipment in the refinery.
2003 Fort McMurray, Alberta, Canada	Oil sand facility/Froth treatment unit	Explosion/Fire	?/1/$120 million loss	Hydrocarbon leakage from piping.
2004 Jamestown, New Mexico USA	Oil refinery/ Alkylation unit	Explosion /Fire	None/6/$13 million	Operator error.
2004 Valdoda India	Refinery/Slurry reactor	Explosion /Fire	2/16	No details.
2005 Texas City, USA	Refinery Isomerization unit	Vapour Cloud Explosion/Fire	15/180/$1 billion loss	Explosions occur in isomerization unit as a result of raffinate splitter release of flammable liquid and vapour.
2005 Fort McKay, Alberta, Canada	Oil sand refinery/ Upgrade 2	Fire	None/$240 million loss	Fire broke out in upgrader 2 which converts bitumen into crude oil.

Table D.1-Continued

2005 Delaware City USA	Refinery/ Reactor	Nitrogen Asphyxiation	2/none/	Lack of hazard awareness, training and proper confined space rescue actions.
2006 Mazeikiu, Lithuania	Refinery/Vacuum distillation unit	Fire	None /$140 million loss	Leak from a line on vacuum distillation column manufactured from incorrect material.
2007 PascagoulaMississippi, USA	Refinery /Crude unit	Fire	None/$240 million loss	Leakage from branch of vacuum distillation column.
2007 Valero McKee refinery, USA	Refinery/ propane deasphalting unit/propane	Fire	None	Pipe rack collapse and other pipe rupture cause propane leak.
2008 Texas, USA	Refinery/Fluid Catalytic Cracker (FCC) unit, utilities, storage tank and asphalt unit	Explosion /fire	None/2/$380 million loss	Catastrophic failure of a pump during start up in propylene splitter unit.
2008 Texas, USA	Refinery	Hurricane	None/$540 million loss	Protective barrier breached during hurricane resulting to flooding of plant with sea water.

Table D.1-Continued

2008 Priolo Gargallo Sicilly, Italy	Refinery/ Gasification unit	Explosion/Fire	None/$170 million	Electricity generating plant causes fire.
2009 Wood Cross Utah USA	Refinery/Mobil distillate dewaxing unit	Explosion	None/$87 million	Piping failure.
2009 Dunkirk France	Refinery	Explosion/Fire	1/5	No details.
2010 Cadereyta, Monterrey, Mexico	Refinery/ Hydrotreater	Explosion	1/2	Equipment failure at oil hydrotreater unit.
2010 Tesoro Anacortes Refinery Accident	Refinery/Catalytic Reformer and Naphtha Hydrotreater unit	Explosion and Fire	7/none approximately $40 million as settlement	Equipment failure (Heat exchanger).
2011 Pembroke, South Wales, UK	Refinery	Explosion	4/1	Storage tank exploded, causing devastating effect.
2011 Fort Mckey Alberta Canada	Refinery/ Oil sand upgrader	Explosion/Fire	None/5 $390 million	Plant operating on bypass condition due to process upset.
2011 Sendai Japan	Refinery	Natural disaster	None/ $600 million	Earthquake followed by Tsunami.
2011 Pulau Bakom Singapore	Refinery	Fire	None/ $150 million	Equipment failure during maintenance.

Table D.1-Continued

2011 Tula, Mexico	Refinery/ Visbreaker unit	Explosion	2/?	Process equipment failure (Visbreaker)
2012 Amuay, Venezuela	Refinery	Explosion	48/80 $330 million	Significant number of leaks in the refinery.
2012 Richmond Refinery Accident	Refinery/crude unit	Explosion/Fire	None/6	Catastrophic Piping failure in crude distillation unit.
2012 Reynosa, Mexico	Refinery/ gasification unit	Explosion	30/46	No details
2012 Bangkok Thailand	Refinery/Crude distillation unit	Fire	None $140 million	Process equipment failure.
2012 Carlifornia USA	Refinery/coking unit	Release	None	Butane and Propane leak.
2012 Evansville USA	Refinery/FCC unit	Production loss	None	Power failure.
2012 Whiting USA	Refinery/ Hydrotreating unit	Fire	None/3	Accident due to maintenance.
2012 Miushima Japan	Refinery/Vacuum distillation unit	Fire	None	Unknown

Table D.1-Continued

2012 Kurashiki Japan	Refinery	Operation loss	None	False inspection record.
2012 Falcon state Venezuela	Refinery/Naphtha reformer unit	Fire	None	Fire broke out in a compressor in the reformer unit.
2012 Carlifornia USA	Refinery/Crude distillation unit	Fire	None	Potential sulphanic corrosion.
2012 Memphis USA	Refinery/ Alkylation unit	Release	1/4	Process equipment failure.
2012 Belle chasse Louisiana USA	Refinery/ Storage	Release	None	Storm Isaac.
2013 Assam Golaghat, India	Refinery/Crude and Vacuum unit	Fire	None	An Investigation is underway.
2013 Stanlow Cheshire UK	Refinery	Fire	None /$150 million	Fire broke out from a furnace.
2013 Sohar Oman	Refinery	Fire	None/$150 million	Equipment failure (gas scrubber caught fire during heavy maintenance).
2013 La Plata Argentina	Refinery/Crude distillation unit	Explosion	None/$225 million	Flash flood during heavy rain.

Table D.1-Continued

2014 Ciudad Madero, Mexico	Refinery/Coker unit	Fire	2/11	Maintenance work on Coker unit.
2014 Bolshoy Uluy, Krasnoyarsk, Russia	Refinery	Explosion /Fire	5/7	Fire broke out as a result of gas explosion.
2015 Torrance, California USA	Refinery/ MHF Alkylation Unit	Explosion	None	Deviation from procedure of operation.
2015 Delaware City USA	Refinery/ Alkylation unit	Fire	None/1	Operator error.
2016 Baton Rouge, LA USA	Refinery/fluid catalytic cracking (FCC) unit	Fire and Explosion	None/4	Minor maintenance on Isobutane line.
2016 Jamnagar India	Refinery	Fire	2/6	Gas leakage.

Appendix E: Calculation of the unknown elements of the FLPR matrix for technical risk element.

P_{21}^{L} = 1−P_{12}^{R} = 1 − 0.48 = 0.52

P_{21}^{M} = 1−P_{12}^{M} = 1 − 0.43 = 0.57

P_{21}^{R} = 1−P_{12}^{L} = 1 − 0.39 = 0.61

P_{31}^{L} = 1.5 – P_{12}^{R} − P_{23}^{R} = 1.5 −0.48 – 0.85 = 0.17

P_{31}^{M} = 1.5 – P_{12}^{M} − P_{23}^{M} = 1.5 −0.43 – 0.81 = 0.26

P_{31}^{R} = 1.5 – P_{12}^{L} − P_{23}^{L} = 1.5 −0.39 – 0.76 = 0.35

P_{32}^{L} = 1−P_{23}^{R} = 1 − 0.85 = 0.15

P_{32}^{M} = 1−P_{23}^{M} = 1 − 0.81 = 0.19

P_{32}^{R} = 1−P_{23}^{L} = 1 − 0.76 = 0.24

P_{41}^{L} = 2 – P_{12}^{R} − P_{23}^{R} − P_{34}^{M} = 2 −0.48 − 0.85 − 0.74 = −0.07

P_{41}^{M} = 2 – P_{12}^{M} − P_{23}^{M} − P_{34}^{M} = 2 −0.43 − 0.81 − 0.74 = 0.02

P_{41}^{R} = 2 – P_{12}^{L} − P_{23}^{L} − P_{34}^{L} = 2 −0.39 − 0.76 − 0.64 = 0.21

P_{42}^{L} = 1.5 – P_{23}^{R} − P_{34}^{R} = 1.5 – 0.85 − 0.74 = −0.09

P_{42}^{M} = 1.5 – P_{23}^{M} − P_{34}^{M} = 1.5 −0.81 – 0.69 = 0

P_{42}^{R} = 1.5 – P_{23}^{L} − P_{34}^{L} = 1.5 −0.76 – 0.64 = 0.10

P_{43}^{L} = 1−P_{34}^{R} = 1 − 0.74 = 0.26

P_{43}^{M} = 1−P_{34}^{M} = 1 − 0.69 = 0.31

$P_{43}^{R} = 1 - P_{34}^{L} = 1 - 0.64 = 0.36$

$P_{43}^{R} = 1 - P_{34}^{L} = 1 - 0.64 = 0.36$

$P_{24}^{L} = 1 - P_{42}^{R} = 1 - (-0.09) = 0.90$

$P_{24}^{M} = 1 - P_{42}^{M} = 1 - 0 = 1$

$P_{24}^{R} = 1 - P_{42}^{L} = 1 - (-0.09) = 1.09$

$P_{14}^{L} = 1 - P_{41}^{R} = 1 - 0.21 = 0.79$

$P_{14}^{M} = 1 - P_{41}^{M} = 1 - 0.02 = 0.98$

$P_{14}^{R} = 1 - P_{41}^{L} = 1 - (-0.07) = 1.07$

Appendix F: Chapter 5 (Assessment of attributes of external risk element using ER algorithm)

$\ddot{M}_1^k$ for natural hazard is expressed as follows:

$\ddot{M}_1^1 = 0.35 \times 0.40 = 0.14$ $\ddot{M}_1^2$ $0.65 \times 0.40 = 0.26$ $\ddot{M}_1^3 = 0$ $\ddot{M}_1^4 = 0$ $\ddot{M}_1^5 = 0$

$\dot{H}_1 = 1 - 0.40 = 0.60$ $\ddot{H}_1 = 0.40 \times \big(1 - (0.35 + 0.65 + 0 + 0 + 0)\big) = 0$

$H_1 = \dot{H}_1 + \ddot{H}_1 = 0.60 + 0 = 0.60$

$\ddot{M}_2^k$ for sabotage is expressed as follows:

$\ddot{M}_2^1 = 0.30 \times 0.33 = 0.099$ $\ddot{M}_2^2 = 0.7 \times 0.33 = 0.231$ $\ddot{M}_2^3 = 0$ $\ddot{M}_2^4 = 0$ $\ddot{M}_2^5 = 0$

$\dot{H}_2 = 1 - 0.33 = 0.67$ $\ddot{H}_2 = 0.33 \times \big(1 - (0.3 + 0.7 + 0 + 0 + 0)\big) = 0$

$H_2 = \dot{H}_2 + \ddot{H}_2 = 0.67 + 0 = 0.67$

$\ddot{M}_3^k$ for terrorist attack is expressed as follows:

$\ddot{M}_3^1 = 0.84 \times 0.27 = 0.2268$ $\ddot{M}_3^2 = 0.16 \times 0.27 = 0.0432$ $\ddot{M}_3^3 = 0$ $\ddot{M}_3^4 = 0$ $\ddot{M}_3^5 = 0$

$\dot{H}_3 = 1 - 0.27 = 0.73$ $\ddot{H}_3 = 0.73 \times \big(1 - (0.84 + 0.16 + 0 + 0 + 0)\big) = 0$

$H_3 = \dot{H}_3 + \ddot{H}_3 = 0.73 + 0 = 0.73$

The combined probability mass is generated for the aggregation of the first two attributes in the assessment.

K is a normalising factor for the combined probability masses, then the aggregation of the combine probability masses of natural hazard and sabotage is done in the following manner:

$$K = \left[1 - \sum_{T=1}^{5}\sum_{\substack{R=1 \\ R \neq T}}^{5} \ddot{M}_1^T \ddot{M}_2^R\right]^{-1}$$

$$K = \left[1 - \left(\ddot{M}_1^1\, \ddot{M}_2^2 + \ddot{M}_1^1\, \ddot{M}_2^3 + \ddot{M}_1^1\, \ddot{M}_2^4 + \ddot{M}_1^1\, \ddot{M}_2^5\right) + \left(\ddot{M}_1^2\, \ddot{M}_2^1 + \ddot{M}_1^2\, \ddot{M}_2^3 + \ddot{M}_1^2\, \ddot{M}_2^4 + \ddot{M}_1^2\, \ddot{M}_2^5\right) + \left(\ddot{M}_1^3\, \ddot{M}_2^1 + \ddot{M}_1^3\, \ddot{M}_2^2 + \ddot{M}_1^3\, \ddot{M}_2^4 + \ddot{M}_1^3\, \ddot{M}_2^5\right) + \left(\ddot{M}_1^4\, \ddot{M}_2^1 + \ddot{M}_1^4\, \ddot{M}_2^2 + \ddot{M}_1^4\, \ddot{M}_2^3 + \ddot{M}_1^4\, \ddot{M}_2^5\right) + \left(\ddot{M}_1^5\, \ddot{M}_2^1 + \ddot{M}_1^5\, \ddot{M}_2^2 + \ddot{M}_1^5\, \ddot{M}_2^3 + \ddot{M}_1^5\, \ddot{M}_2^4\right)\right]$$

$$= \{1 - [(0.14 \times 0.231 + 0 + 0 + 0) + (0.26 \times 0.099 + 0 + 0 + 0) + 0 + 0 + 0]\}^{-1}$$

$$= 1.0616$$

$$\gamma_{U(2)}^1 = K\left(\ddot{M}_1^1\ddot{M}_2^1 + \ddot{M}_1^1 H_2 + \ddot{M}_2^1 H_1\right)$$

$$= 1.0616(0.14 \times 0.099 + 0.14 \times 0.67 + 0.60 \times 0.099)$$

$$= 0.1773$$

$$\gamma_{U(2)}^2 = K\left(\ddot{M}_1^2\ddot{M}_2^2 + \ddot{M}_1^2 H_2 + \ddot{M}_2^2 H_1\right)$$

$$= 1.0616(0.26 \times 0.231 + 0.26 \times 0.67 + 0.60 \times 0.231)$$

$$= 0.3958$$

$$\gamma_{U(2)}^3 = K\left(\ddot{M}_1^3\ddot{M}_2^3 + \ddot{M}_1^3 H_2 + \ddot{M}_2^3 H_1\right)$$

$$= 1.0616(0 + 0 + 0)$$

$$= 0$$

$$\gamma_{U(2)}^4 = K\left(\ddot{M}_1^4\ddot{M}_2^4 + \ddot{M}_1^4 H_2 + \ddot{M}_2^4 H_1\right)$$

$$= 1.0616(0 + 0 + 0)$$

$$= 0$$

$\gamma_{U(2)}^{5}$ = $\mathrm{K}\left(\ddot{M}_1^5 \ddot{M}_2^5 + \ddot{M}_1^5 H_2 + \ddot{M}_2^5 H_1\right)$

$= 1.0616(0 + 0 + 0)$

= 0

$\dot{\acute{H}}_1 = \mathrm{K}\left(\dot{H}_1 \dot{H}_2\right)$

$= 1.0616(0.60 \times 0.67)$

= 0.4267

$\ddot{\acute{H}}_1 = \mathrm{K}\left(\ddot{H}_1 \ddot{H}_2 + \ddot{H}_1 \dot{H}_2 + \dot{H}_1 \ddot{H}_2\right)$

$= 1.0616(0 + 0 \times 0.67 + 0.60 \times 0)$

= 0

$\acute{H}_1 = \dot{\acute{H}}_1 + \ddot{\acute{H}}_1$

$= 0.4267 + 0$

= 0.4267

The above result for combination of natural hazard and sabotage is aggregated with terrorist attack to obtain assessment for external risk element.

$$\mathrm{K}\ (2) = \left[1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} \ddot{\mathrm{M}}_1^{\mathrm{T}} \ddot{\mathrm{M}}_2^{\mathrm{R}}\right]^{-1}$$

K (2) is the normalization factor for combination of the result obtained above and terrorist attack.

$\mathrm{K}\ (2) = \Big[1 - \left(\ddot{M}_{1(2)}^1 \ddot{M}_3^2 + \ddot{M}_{1(2)}^1 \ddot{M}_3^3 + \ddot{M}_{1(2)}^1 \ddot{M}_3^4 + \ddot{M}_{1(2)}^1 \ddot{M}_3^5\right) + \left(\ddot{M}_{1(2)}^2 \ddot{M}_3^1 +\right.$

$\left.\ddot{M}_{1(2)}^2 \ddot{M}_3^3 + \ddot{M}_{1(2)}^2 \ddot{M}_3^4 + \ddot{M}_{1(2)}^2 \ddot{M}_3^5\right) + \left(\ddot{M}_{1(2)}^3 \ddot{M}_3^1 + \ddot{M}_{1(2)}^3 \ddot{M}_2^3 + \ddot{M}_{1(2)}^3 \ddot{M}_2^4 +\right.$

$\ddot{M}^3_{1(2)}\ddot{M}^5_2\big) + \big(\ddot{M}^4_{1(2)}\ddot{M}^1_3 + \ddot{M}^4_{1(2)}\ddot{M}^2_3 + \ddot{M}^4_{1(2)}\ddot{M}^3_3 + \ddot{M}^4_{1(2)}\ddot{M}^5_3\big) + \big(\ddot{M}^5_{1(2)}\ddot{M}^1_3 +$

$\ddot{M}^5_{1(2)}\ddot{M}^2_3 + \ddot{M}^5_{1(2)}\ddot{M}^3_3 + \ddot{M}^5_{1(2)}\ddot{M}^4_3\big)\big] = \{1 - [(0.1773 \times 0.0432 + 0 + 0 + 0) +$

$(0.39585 \times 0.2268 + 0 + 0 + 0) + 0 + 0 + 0]\}^{-1}$

= 1.1079

$\gamma^1_{U(3)}$= K (2) $\big(\ddot{M}^1_{1(2)}\ddot{M}^1_3 + \ddot{M}^1_{1(2)}H_3 + \ddot{M}^1_3\acute{H}_1\big)$

= 1.1079(0.1773 × 0.2268 + 0.1773 × 0.73 + 0.4267 × 0.2268)

= 0.2953

$\gamma^2_{U(3)}$ = K (2) $\big(\ddot{M}^2_{1(2)}\ddot{M}^2_3 + \ddot{M}^2_{1(2)}H_3 + \ddot{M}^2_3\acute{H}_1\big)$

= 1.1079(0.3958 × 0.0432 + 0.3958 × 0.73 + 0.4332 × 0.0432)

= 0.3595

$\gamma^3_{U(2)}$ = K (2) $\big(\ddot{M}^3_{1(2)}\ddot{M}^3_3 + \ddot{M}^3_{1(2)}H_3 + \ddot{M}^3_3\acute{H}_1\big)$

= 1.1079(0 × 0 + 0 × 0.73 + 0 × 0.4332)

= 0

$\gamma^4_{U(2)}$ = K (2) $\big(\ddot{M}^4_{1(2)}\ddot{M}^4_3 + \ddot{M}^4_{1(2)}H_3 + \ddot{M}^4_3\acute{H}_1\big)$

= 1.1079(0 × 0 + 0 × 0.73 + 0 × 0.4332)

= 0

$\gamma^5_{U(2)}$ = K (2) $\big(\ddot{M}^5_{1(2)}\ddot{M}^5_3 + \ddot{M}^5_{1(2)}H_3 + \ddot{M}^5_3\acute{H}_1\big)$

= 1.1079(0 × 0 + 0 × 0.73 + 0 × 0.4332)

= 0

$\dot{H}_2 \;= \text{K (2)} \left(\dot{\acute{H}}_1\, \dot{H}_3\right)$

$= 1.1079(0.4267 \times 0.73)$

$= 0.3451$

$\ddot{\acute{H}}_2 = \text{K (3)}\left(\ddot{\acute{H}}_1\, \ddot{H}_3 + \dot{\acute{H}}_1 \dot{H}_3 + \ddot{\acute{H}}_1\, \dot{H}_3\right)$

$= 1.1066\ (0 \times 0 + 0.4267 \times 0 + 0 \times 0)$

$= 0$

$\acute{H}_2 = \dot{\acute{H}}_2 + \ddot{\acute{H}}_2$

$= 0.3451 + 0$

$= 0.3451$

The combined degree of belief for aggregation of the three attributes is estimated as follows:

$$\gamma^1 = \frac{\gamma^1_{U(2)}}{\left(1-\dot{\acute{H}}_u\right)} = \frac{0.2953}{1-0.3451} = 0.4509$$

$$\gamma^2 = \frac{\gamma^2_{U(2)}}{\left(1-\dot{\acute{H}}_u\right)} = \frac{0.3595}{1-0.3451} = 0.5491$$

$$\gamma^3 = \frac{\gamma^3_{U(2)}}{\left(1-\dot{\acute{H}}_u\right)} = \frac{0}{1-0.3451} = 0$$

$$\gamma^4 = \frac{\gamma^4_{U(2)}}{\left(1-\dot{\acute{H}}_u\right)} = \frac{0}{1-0.3451} = 0$$

$$\gamma^5 = \frac{\gamma^5_{U(2)}}{\left(1-\dot{H}_u\right)} = \frac{0}{1-0.3451} = 0$$

The aggregation of the three attributes for assessment of external risk element is given as S (external risk element) = {(very low, 0.4509), (low, 0.5491).