ADVANCED RISK AND MAINTENANCE MODELLING IN LNG CARRIER OPERATIONS

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THE FOLLOWING FIGURES AND TABLES HAVE BEEN EXCLUDED ON INSTRUCTION FROM THE UNIVERSITY

FIGURES 2.1, 4.3, AND 6.1

TABLES 2.1 AND 2.2

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Abstract

High demand of Liquefied Natural Gas (LNG) in recent time requires LNG carriers in more frequent operations in order to meet customers' needs. To ensure that the LNG carriers are always reliable in service, it has become necessary to adopt various advanced modelling techniques such as Genetic Algorithm (GA), fuzzy logic and Evidential Reasoning (ER) for risk/safety assessment and maintenance modelling of LNG carrier operations. These advanced computational techniques can help to overcome challenges posed by uncertainties associated with the LNG carrier operations. Their usefulness is demonstrated using case studies in this research.

Firstly, two major hazards of LNG carrier operations such as "failure of LNG containment system" and "LNG spill from transfer arm" are identified and estimated as high risk ones using a risk matrix technique and expert judgement. The causes (failure modes/basic events) of these high risk hazards are analysed using a Fault Tree Analysis (FTA). The failure logics of their failure modes are established and Boolean algebra is applied to facilitate the evaluation of the failure probabilities and frequencies.

Secondly, a GA model is developed to improve the safety levels of the LNG containment system and transfer arm, to minimise their maintenance costs and to realise optimal resource management. The GA is used to optimise a risk model that is developed with exponential distribution and parameters such as failure frequencies, unit costs of maintenance and new maintenance costs of the LNG containment system and transfer arm.

Thirdly, the uncertainties of some parameters in the GA model such as unit costs of maintenance are subdued using the strength of Fuzzy Rule Base (FRB) in combination with GA. 125 fuzzy rules of LNG carrier system maintenance cost are developed, which makes it possible to facilitate the evaluation of maintenance cost in any specific LNG risk-based

operation. The outcomes of unit costs of maintenance are used in the GA based risk model to update the optimal management of maintenance cost.

Finally, the uncertainties of failure modes of the LNG containment system and transfer arm are investigated and treated based on the Formal Safety Assessment (FSA) principle using a Fuzzy ER (FER) approach. The fuzzy logic is used to estimate the safety/risk levels of those failure modes while the ER is used to synthesise them to facilitate the estimation of safety/risk levels of the top events. Risk Control Options (RCOs) are developed to manage high level risks. The costs for each of the RCOs are estimated and synthesised using ER, which facilitated the investigation of the best RCOs in risk-based decision making.

There is no doubt that the methodologies proposed possess significant potential for use in improving safety and maintenance of LNG carrier operations based on the verifications of their corresponding test cases. Accordingly, the developed models can be integrated to formulate a platform to facilitate risk assessment and maintenance management of LNG carrier systems in situations where traditional techniques cannot be applied with confidence.

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Abbreviations

ABS	American Bureau of Shipping
AHP	Analytical Hierarchy Processing
ALARP	As Low As Reasonably Practicable
BDDs	Binary Decision Diagrams
BOG	Boil-Off Gas
BV	Bureau Veritas
BWR	Boiling Water Reactor
CAS	Criticality Analysis
CBA	Cost Benefit Assessment
CCA	Cause Consequence Analysis
CM	Condition Monitoring
COLREG	Convention on the International Regulations for Preventing Collisions at Sea
DNV	Det Norske Veritas
DoB	Degree of Belief
D-S	Dempster-Shafer
ETs	Event Trees
ETA	Event Tree Analysis
ER	Evidential Reasoning
FDS	Fire Deluge System
FER	Fuzzy Evidential Reasoning
FGA	Fuzzy Genetic Algorithm
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
F-N	No of Fatalities
FPSO	Floating Production, Storage and Offloading Unit
FRB	Fuzzy Rule Base
FRB-ER	Fuzzy Rule Base-Evidential Reasoning
FSA	Formal Safety Assessment

FST	Fuzzy Set Theory
FTs	Fault Trees
FTA	Fault Tree Analysis
GC	Gas Code
GA	Genetic Algorithm
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HIP	High-Integrity Protection System
HSE	Health, Safety and Executives
IACS	International Association of Classification Societies
IDS	Intelligent Decision System
IGC	International Gas Code
ILLC	International Load Line Convention
IMO	International Maritime Organization
ISM	International Safety Management
LMD	LNG Carrier System Maintenance Duration
LMC	LNG Carrier System Maintenance Cost
LNG	Liquefied Natural Gas
LSPC	LNG Carrier System Spare Parts Cost
LTCC	LNG Carrier System Technical Consultancy Cost
MCDM	Multiple Criteria Decision Making
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
OCIMF	Oil Companies International Marine Forum
PD	Pressure Difference
PHA	Preliminary Hazard Analysis
PLL	Potential Loss for Life
PM	Preventive Maintenance
PPD	Positive Pressure Difference

PRA	Probabilistic Risk Assessment
RCM	Reliability Centred Maintenance
RCMs	Risk Control Measures
RCOs	Risk Control Options
RCT	Risk Contribution Tree
RHR	Residual Heat Removal
RM	Reactive Maintenance
ROTV	Remote Operated Towed Vehicle
ROV	Remote Operated Vehicle
SIGITTO	Society of International Gas Tanker and Terminal Operators
SOLAS	Safety of Life at Sea
STCW	Standard of Training, Certification and Watchkeeping
STI	Surveillance Test Interval
UK MCA	United Kingdom Maritime and Coastguard Agency
USCGA	United States Coast Guard Agency
WMoM	Weighted Mean of Maximum

Chapter 1 - Introduction

Summary

In this chapter, the background analysis of the research is conducted, followed by the discussion of research aim and objectives. The challenges of conducting the research, the research methodology and scope of the thesis are also described. The structure of the thesis is outlined with the view of addressing the methodologies of risk-based maintenance and subjective risk assessment of Liquefied Natural Gas (LNG) carrier operations.

1.1. Background Analysis

Liquefied Natural Gas (LNG) carriers are well designed ships that have maintained excellent safety records for years, though recently, the number of voyages per year has increased. This drastic increase in the number of voyages per year of LNG carriers, has lead to questions about the safety and reliability of the vessels while in operations because of hazards that will be introduced in meeting the world's high demand of LNG. The International Maritime Organization (IMO), Society of International Gas Tanker and Terminal Operators (SIGTTO), and International Association of Classification Societies (IACS) such as American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV), Korean Register of Shipping, and Nippon Kaiji Kyokai have put their efforts and time to ensure that risks associated with LNG facilities are mitigated in their technical design standards and operating procedures to an acceptable level. Therefore, it is necessary to assess the effectiveness of the safety features used, which is of particular significance when limited resources and assets are available.

The IMO has proven that risk assessment is effective in the maritime industry via the introduction of the Formal Safety Assessment (FSA) methodology after studying notable accidents, including the tragedy of the Herald of Free Enterprise disaster in 1987, the Piper

Alpha accident, 1988 and the Exxon Valdez accident in 1989. These catastrophic marine and offshore accidents drove the United Kingdom Maritime and Coastguard Agency (UK MCA) to propose FSA to the IMO in 1993. This can support the relevance of this study that risk assessment and maintenance modelling need to be proactively carried out on the LNG carrier operations because of the rapid increase in the number of LNG carriers used in the LNG industry. The aim of maintenance is to ensure that LNG carrier systems are reliable while in operation and minimize their downtime and maintenance cost. Different types of maintenance strategies can be applied to LNG carrier systems as stand-alone or simultaneous in a cost effective manner.

The components of a LNG value chain include natural gas production, liquefaction of natural gas, transportation of LNG, re-gasification, and distribution to end users (Foss, 2003, Sophia and Anne, 2006). In this research, there is particular emphasis on the transportation of LNG using LNG carriers for the risk assessment framework. Therefore, a generic LNG carrier is used to facilitate an understanding of the subject under study and can help identify relevant hazards. LNG is natural gas that becomes liquefied at a temperature of approximately -256^0F (-160^0C) after pretreatment for easy storage and transportation by LNG carriers. It occupies 1/600th the volume of its gaseous state. When vaporized, its flammability range is between approximately 5% and 15% by volume, i.e. a mixture with air within this range of concentrations is flammable (Vanem et al., 2008).

Thus, the framework developed in this research encompasses a generic LNG carrier and its systems and subsystems that could fail to cause a LNG spill. The greatest concerns of the LNG carrier are loss of containment, LNG spill on deck, fire and explosion, gas release, disposal of boil off, and over/under pressure. The framework is based on the generic LNG carrier and its systems and subsystems, since the difference between the carriers is the containment system, which is either membrane, spherical or prismatic tank type. Membrane tank design type is mostly used in the industry because of its relatively higher utilization of the hull volume for the cargo capacity. Although the ship dimensions are smaller than similar spherical (moss) and prismatic type LNG carriers of the same cargo capacity, the

boil-off gas amount carried by the membrane tank type vessels is higher compared to that of the spherical tank type because of the way they have been designed.
The developed framework of a generic LNG carrier can ensure the proactive safety of LNG vessels and their systems/subsystems as well as provides a basis of analysing the measures of their pollution prevention to the maritime environment by the identification of their hazards. The risks associated with the hazards will be estimated and prioritized using a risk matrix approach and expert judgement.

Fault Tree Analysis (FTA) will be adopted for Probabilistic Risk Assessment (PRA) and Genetic Algorithm (GA) will be used for maintenance modelling of the high risk LNG carrier systems. Uncertainty treatment of unit costs of maintenance of the high risk LNG carrier systems will be conducted using a combination of fuzzy logic and GA, while subjective risk assessment of the high risk LNG carrier systems based on FSA methodology will be conducted using a combination of fuzzy logic and Evidential Reasoning (ER).

1.2. Research Aim and Objectives

The aim of this research is to conduct a proactive risk assessment and maintenance modelling of LNG carrier operations under uncertainties. The methodology will be proactively based. This will be useful to the LNG industry to prevent and mitigate any prospective accidents that will cause loss of lives, great damage to LNG carrier systems and environmental pollution. To achieve this aim, the following objectives are outlined:

- Conduct a comprehensive literature search on relevant hazards of LNG carrier operations and risk prioritization using a risk matrix approach.
- Carry out PRA of a LNG containment system and a LNG transfer arm, which are areas of high risk of LNG carriers, using a FTA method.
- Carry out maintenance modelling of LNG carrier systems using a GA approach, thereby identifying their maintenance costs as a safety improvement measure.

- Develop a novel methodology for uncertainty treatment of unit costs of maintenance of a LNG containment system and a LNG transfer arm using Fuzzy Rule Base (FRB) and GA for optimization of the risk model.
- Develop a novel methodology for subjective risk assessment and control of a LNG containment system and a LNG transfer arm by employing a combination of fuzzy logic and ER, based on a FSA methodology.

The above objectives will be achieved in this research from Chapters 2 to 6. Novel methodologies are detailed in various chapters with case studies. Literature review of this research is detailed in Chapter 2, followed by Hazard Identification (HAZID) and risk priorization in Chapter 3. A combination of FTA and GA is detailed in Chapter 4, while a combination of GA and FRB is presented in Chapter 5. Chapter 6 proposes a combination of fuzzy logic and ER.

1.3. Challenges of Conducting the Research

In maintaining the outstanding safety records of LNG carriers, there are some challenges encountered while conducting risk assessment and maintenance modelling of the LNG carrier operations in this research. These challenges have been treated in both certain and uncertain environments. Novel methodologies are developed to handle the uncertain situations of LNG carrier operations with respect to risk assessment and maintenance modelling. In view of that, the challenges are outlined and handled as follows:

- HAZID of a generic LNG carrier. The hazards of generic LNG carrier operations pose to be a challenge, as this research is not based on investigation of any accident that has happened. It is a purely proactive HAZID process. This challenge is handled by thorough literature search and consultation with experienced marine professionals. The risks of the hazards are estimated using a risk matrix approach and expert judgement.
- Construction of FTA of a LNG containment system and a LNG transfer arm. The developments of causes of top events such as "failure of the LNG containment system" and "LNG spills from the transfer arm" are challenging tasks. In development of any

FTA diagram, different designers do identify various failure modes (basic events), though, the causes of the top event and their failure logic are always similar. However, effort and time is put in construction of the FTA diagrams of the LNG containment system and transfer arm failures with the assistance of marine professionals. Significant failure modes are identified.

- Formulation of an objective function (risk model) for maintenance optimization using GA. To form a mathematical relationship among all the needed parameters of a LNG containment system and a LNG transfer arm for optimal risk control solution is a difficult task. This problem is solved by using the risk formula for the LNG containment system and transfer arm, time-cost relationship, and the relationship between the budgeted maintenance cost of high risk LNG carrier systems and maintenance cost of each of the high risk systems.
- Development of a novel methodology for uncertainty treatment of unit costs of maintenance of a LNG containment system and a LNG transfer arm. This challenge is tackled by employing the FRB method. The 125 rules of the FRB are developed with the antecedents (technical consultancy cost, maintenance duration and spare part cost) as well as with the consequent (maintenance cost). Relevant rules are fired and fuzzy values of unit costs of maintenance of the LNG containment system and transfer arm are identified. The fuzzy values are defuzzified to crisp values using Weighted Mean of Maximum (WMoM).
- Development of a novel methodology for uncertainty treatment of failure modes of a LNG containment system and a LNG transfer arm. This challenge is solved by using the FER approach, based on a FSA methodology. The fuzzy set manipulation formula is used to estimate the degree of beliefs (DoBs) of different categories of safety levels of failure modes of the LNG containment system and transfer arm, while the ER is used to synthesise their results to ascertain the safety levels of the systems.

1.4. Research Methodology and Scope of Thesis

The research methodology carried out in this thesis is risk assessment of LNG carrier operations and its maintenance modelling for safety improvement in the LNG industry. The risk assessment is carried out in both certain and uncertain environments. In the uncertain environments, the FSA principle is adopted in the risk assessment process of the LNG carrier operations. Eight chapters are established to realize this research methodology.

In Chapter 1, the background of this research is explained together with the research aim and objectives, challenges of conducting the research and the structure of this thesis. This chapter is well organized for a clear idea of the subject under investigation.

In Chapter 2, a thorough and comprehensive literature review of safety and maintenance issues relating to LNG carriers is conducted. This involves an investigation of the properties of LNG and various LNG accidents/incidents that can assist in improvement of safety of the LNG carriers. Regulations governing safety of LNG shipping that have contributed to safe operations of the LNG carriers for years are also reviewed. Maintenance is studied, including advantages and disadvantages of different types of maintenance strategies. In view of these reviews, and the current and future status of LNG carrier operations due to high energy demand, the needs for this research arise. Risk assessment and a FSA methodology are introduced as the way forward. The usefulness of GA, fuzzy logic and ER as risk-based modeling techniques is identified and presented, followed by the justification for this research.

In Chapter 3, HAZID of LNG carrier operations is conducted, which is the first step to providing a solution to potential accidents/incidents of LNG carriers. The hazards are identified after a thorough literature search and brainstorming of experts. The risk matrix approach is adopted for priorization of risks of the hazards. In the risk matrix technique, the occurrence likelihoods of hazards are described with linguistic terms such as frequent, probable, occasional and remote while the consequences of hazards are described using linguistic terms such as catastrophic, critical, marginal and negligible. The mechanism of the risk matrix technique is used to assign scores to hazards for effective mapping on the risk matrix table, which facilitates the estimation of high risk hazards by expert judgements. The high risk hazards of the LNG carrier operations are identified as "failure of the LNG containment system" and "LNG spill from the transfer arm" and are represented using FTA diagrams with undeveloped events for comprehensive risk assessment in the following chapters.

Chapter 4 explains the application of FTA and GA to risk-based maintenance of high risk LNG carrier systems. The FTA of the LNG containment system and transfer arm that are in a undeveloped event form in Chapter 3, is developed in basic event (failure mode) form and has top events such as "failure of the LNG containment system" and "LNG spill from the transfer arm" for PRA. The PRA is conducted with the assumption of failure modes being independent to estimate the failure probabilities of the LNG containment system and transfer arm. The failure frequencies of the LNG containment system and transfer arm are also calculated. A mathematical (risk) model is developed using parameters such as hazard severity weight, failure probabilities, failure frequencies, unit cost of maintenance, new cost of maintenance, time of maintenance and budgeted cost of maintenance of the LNG carrier systems. To identify the new costs of maintenance of the LNG containment system and transfer arm for a safety improvement measure, GA is used to optimize the risk model, satisfying the constraints of the objective function that is made up of unit costs of maintenance, new cost of maintenance and budgeted maintenance cost. Validations of results are conducted to ascertain the new cost of maintenance of the LNG containment system and transfer arm.

Chapter 5 details how the FRB method is used to treat uncertainties of unit costs of maintenance of the LNG containment system and transfer arm in the optimization of the risk model using GA. The resultant unit costs of maintenance are used to substitute the former ones of the LNG containment system and transfer arm in the risk model in Chapter 4. The risk model is minimized using GA to identify the new costs of maintenance of the LNG containment system and transfer arm. All the maintenance costs used and produced in optimization of the risk model are noted and compared with all the previous maintenance costs in Chapter 4. The maintenance cost differences are noted and the advantages of FRB method are revealed. The FRB is used to combine different experts' opinions of unit costs of maintenance of the LNG containment system and transfer arm.

In uncertain situations of failure modes of the LNG containment system and transfer arm due to lack of data of failure frequencies, Chapter 6 provides a step by step solution for such problems based on the FSA methodology. Firstly, safety/risk levels of the identified failure modes of the developed FTA of the LNG containment system and transfer arm in Chapter 4 are estimated using the mechanism of the fuzzy set manipulation formula in the HAZID and risk assessment phases. The estimated safety levels of failure modes of the LNG containment system and transfer arm are synthesised using the mechanism of ER to ascertain their respective safety levels.

In Risk Control Option (RCO) and Cost Benefit Assessment (CBA) phases, three RCOs are forecasted for the LNG containment system and transfer arm respectively. The cost of using any of the RCOs in the risk reduction is estimated by four experts and their judgements are systhesised using ER to obtain the actual estimated cost of a particular RCO. The safety level of the LNG containment system is synthesised with the estimated cost for each RCO and mapped onto utility space for the decision making phase. A similar process is applied to estimate the safety level of the LNG transfer arm.

In decision making, the preference degree for each RCO is calculated using DoB of the utility space, and the highest preference degree can be noted. The RCO with the highest preference degree is the one needed to improve the safety of the LNG containment system. In this case, the RCO is to carrying out maintenance activities. In a similar way, the most preferable RCO for the LNG transfer arm is also to carrying out maintenance activities. Other RCOs of the LNG containment system are "regular inspection of the system per voyage" and "training of crew members on new technology and change of operating procedures in loading of LNG to the containment system". The RCOs of the LNG transfer arm that are not selected as the best ones are "use of well experienced personnel in loading/unloading of LNG" and "redesign of the system".

In Chapter 7, discussions of the results produced in Chapters 3, 4, 5 and 6 are detailed. The strengths and weaknesses of the methodologies used in these chapters are described. The industries that can use this research are identified.

In Chapter 8, discussion of the conclusion of this research is detailed. The pathway of achieving the main aim of this research is discussed, while limitation of the research is also outlined. New areas in the LNG industry where the methodology of this research will be useful are recommended for future studies.

1.5. Structure of the PhD Thesis

The research is structured from Chapters 1 to 8. The name of each chapter is listed in Table 1.1. The information flow diagram of this research is illustrated in Figure 1.1. The flow of information is started in Chapter 1, the introduction to this research. This gives rise to Chapter 2, which is literature review of all relevant subjects under investigation. The information produced from Chapter 2 is used to develop other chapters.

Table 1.1: Summary of the Chapters in this Research

Chapter No.	Title
1	Introduction
2	Literature Review
3	Hazard Identification and Risk Prioritization of Liquefied Natural Gas Carrier Operations using a Risk Matrix Approach
4	Application of Genetic Algorithm to Risk-based Maintenance Operations of Liquefied Natural Gas Carrier Systems
5	A Fuzzy Genetic Algorithm Approach to Analyse Maintenance Cost of High Risk Liquefied Natural Gas Carrier Systems under Uncertainty
6	A New Fuzzy Evidential Reasoning Method for Risk Analysis and Control of Liquefied Natural Gas Carrier Systems
7	Discussion
8	Conclusion

Chapter 3 identifies hazards and prioritizes risks of LNG carrier operations, which provides a foundation for solution to other chapters. Chapter 4 exploits the information provided from Chapter 3 for effective risk-based maintenance operations of the LNG carrier systems. Its aims are re-examined in Chapters 5 and 6 due to/in event of existence of uncertainties of unit costs of maintenance and failure modes of the LNG carrier systems as a result of ambiguity and lack of data respectively. Chapter 7 discusses the results produced in other chapters, and the advantages and disadvantages of the methods used in these chapters. Finally, the conclusion of this research is drawn in Chapter 8.

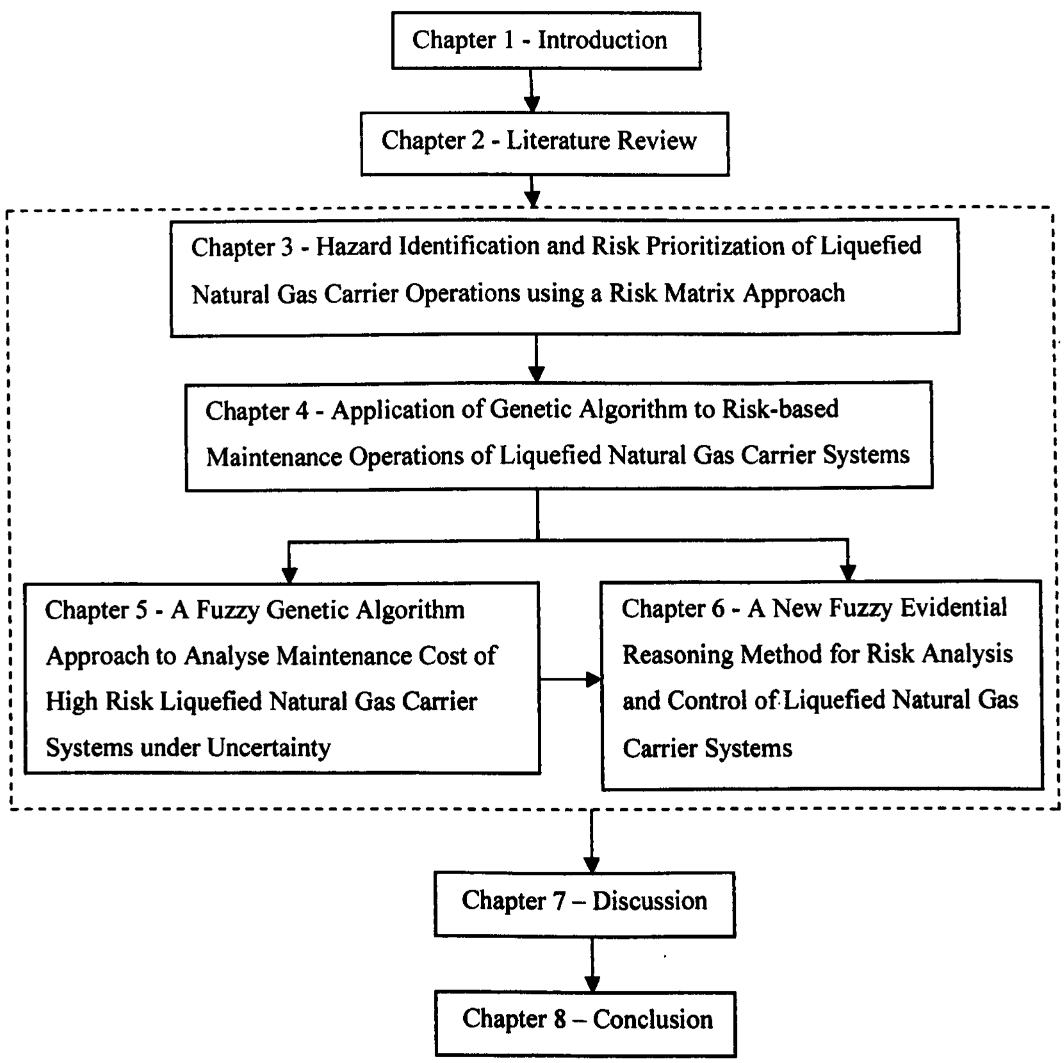

Figure 1.1: Structure of the Research

Chapter 2 - Literature Review

Summary

This chapter provides a thorough literature review of safety/risk assessment and the maintenance modelling of LNG carrier operations. This includes safety, properties and hazards of LNG, overview of LNG carrier including the incidents/accidents and the regulations governing safety of the shipping, an overview of FSA of ships and overview of maintenance. Different modelling techniques such as GA, Fuzzy Logic and ER are also reviewed. Their usefulness in the LNG industry in areas of risk assessment and maintenance modelling is identified. Justification of carrying out this research is established.

2.1. Introduction

The literature review plays a vital role in this research. LNG carriers are expensive and complex engineering structures for which there is need for proactive risk assessment of their operations because catastrophic accidents such as cargo loss cannot be tolerated. The literature review is carried out to investigate the properties of LNG and its carriers, and also various LNG accidents/incidents. Such an investigation can assist in the improvement of safety of LNG shipping operations with particular emphasis on safety/risk assessment using probabilistic and subjective (possibilistic) approaches and on maintenance modelling using optimization techniques. Various risk assessment tools are discussed and the efficient approaches are adopted in this research. FSA is also discussed. The maritime industry adopted FSA in 1990s as a proactive tool to tackle various marine accidents. FSA has changed the traditional reactive regulatory framework towards a risk-based and goal-setting regime (Godaliyadde, 2008). The concept of maintenance in the maritime and LNG industry is outlined. Reliability Centred Maintenance (RCM) and types of maintenance strategies are discussed. The differences among the maintenance strategies are noted and their relevance is outlined.

There is a need to carry out regular risk assessment of LNG carrier operations and maintenance modelling using a proactive approach due to a rapid increase in number of voyages per year. Such increases in number of voyages per year are as a result of high demand of LNG. A PRA is conducted using a risk assessment tool such as FTA, and maintenance modelling conducted for safety improvement using the GA. Novel approaches are proposed to deal with uncertain situations. The FRB is employed to treat uncertainties of unit costs of maintenance of the LNG containment system and transfer arm, while FER is used to treat uncertainties of failure modes of the LNG containment system and transfer arm based on the FSA methodology.

2.2. Safety of LNG

The safety record of the LNG industry is outstanding compared to other petroleum/process industries. The excellent safety record is proven by the few incidents and accidents that have happened since 1912, when the first LNG plant was built in West Virginia. The success of the LNG industry in terms of safety is because of the following factors (Foss, 2003):

- The industry has technically and operationally evolved to ensure safe and secure operations. Technical and operational advances include everything from the engineering domain that underlies LNG facilities to operational procedures and technical competency of personnel.
- The physical and chemical properties of LNG and its associated hazards and risk are well understood and incorporated into their technology and operations.
- The high standards and regulations that are applied to the LNG industry.

Safety is defined as freedom from unacceptable risk or personal harm (Wang and Trbojevic, 2007). This is applied to LNG facilities, including LNG carriers because of the potential hazards that might affect their operations. A hazard is a physical situation or condition with a potential for injuries/deaths, property damage, damage to the environment or some combinations of these (Wang and Trbojevic, 2007). Risk mitigation and hazard prevention measures are applied to a LNG value chain in Figure 2.1. Risk mitigation measures are used to reduce the consequences of hazards, while hazard preventive measures prevent the occurrence of hazards and their undesirable consequences. Risk is defined as a combination of the probability of occurrence of an undesired event and the degree of its possible consequences, or a term which combines the chance that a specified undesired event will occur and the severity of the consequences of the event (Wang and Trbojevic, 2007).

Figure 2.1: LNG Value Chain (Foss, 2003)

Though various safety measures secure the operations of the LNG value chain in Figure 2.1, they are still prone to accidents. An accident on a particular component of a LNG value chain can affect another component. For example, an accident/incident on the LNG carrier operations during loading/unloading of LNG can affect the LNG storage tank via the pipelines. The LNG carrier operational hazards can be identified using a brainstorming technique, after analyzing the safety features of the components that make up the LNG value chain. The LNG value chain has five main functions. These are (Naturalgas Online, 2010):

- Natural gas production.
- Liquefaction of natural gas.
- Transportation of LNG.
- Re-gasification.
- Distribution.

2.2.1. Natural Gas Production

After discovering of viable quantities of natural gas on a particular area, a natural gas well is drilled and "completed" to allow for the flow of petroleum or natural gas out of the formation and up to the surface (Naturalgas Online, 2010). This process includes strengthening the well hole with casing, and evaluation of the pressure and temperature of the formation, before installation of the proper equipment for an efficient flow of natural gas out of the well (Naturalgas Online, 2010). During natural gas production in the gas field, workers need to wear safety boots, hand gloves, goggles, helmets and an overall for mitigation of consequences of the hazards. The natural gas produced is channelled to the next LNG value chain component (i.e. liquefaction facility).

2.2.2. Liquefaction of Natural Gas

Liquefaction of natural gas is the process of converting natural gas to its liquid state. It reduces the natural gas from its original volume for easy transportation using LNG carriers. Safety features of the liquefaction facility are identified as:

- Secondary containment of the LNG storage tanks have the ability to keep LNG isolated in event of an accident.
- Automatic shutdown of LNG facilities and activation of fire alarm in undesirable conditions.
- Practice of the Health and Safety Executive (HSE) policies and regulations that are applied to liquefaction facilities and their processes.

2.2.3. Transportation of LNG

Transportation of LNG is the shipment from a containment tank to another containment tank using LNG carriers. The containment systems of LNG carriers have more than four layers that secure LNG, coupled with their double hull systems that reduce the risk of gas spills. With the increase of LNG demands and distributions, the safety concern of LNG shipping is increasingly growing, attracting more and more research.

2.2.4. Re-gasification

Re-gasification is the process of converting the LNG back to its gaseous phase by use of vaporizers. The produced natural gas from the re-gasification process is transported to end users via pipelines. HSE policies and industrial safety rules and regulations are practiced to avoid environmental pollution and expose of the workers to risk (HSE, 2011).

2.2.5. Distribution

The LNG that is converted to its gaseous state for easy distribution is channelled through intrastate or interstate gas pipelines to the end users. These pipelines are constantly inspected to ensure safe distribution of natural gas. Pipeline inspection reveals the safety level of the pipelines so that appropriate action or correction will be taken if anything has gone wrong. The pipeline inspection is carried out using inspection techniques such as internal (magnetic flux leakage, ultrasonic, geometry/calliper and eddy current tool), external (Remote Operated Towed Vehicle (ROTV) and Remote Operated Vehicle (ROV)) and diver inspection.

2.3. Properties of LNG

LNG is natural gas that is produced from the wellhead and becomes liquefied at a temperature of approximately -256^0F (-160^0C) after pretreatment for easy storage and transportation using LNG carriers. It occupies $1/600^{th}$ the volume of its gaseous state. The raw natural gas that is converted to LNG comes from three types of wells. These are (Naturalgas Online, 2010):

- Oil wells.
- Gas wells.
- Condensate wells.

Natural gas from these wells is mainly composed of methane, propane, ethane, pentanes, water vapour, hydrogen sulphide, carbondioxide, helium, nitrogen and other compounds. Typical compositions of natural gas with its percentage before it is refined are illustrated in Table 2.1. The natural gas is pretreated to have a pipeline quality using four basic processes such as (Naturalgas Online, 2010):

- Oil and condensate removal.
- Water removal.
- Separation of natural gas liquids.
- Sulphur and carbondioxide removal.

Table 2.1: Composition of Natural Gas (Naturalgas Online, 2010)

These processes make the LNG a clear, cold, odourless, non-corrosive, non-toxic, cryogenic liquid at normal atmospheric pressure. LNG has other properties that make it a unique gas. These include:

- The density of LNG is about 450Kg/m^3 compared to the density of water, which is about 1000Kg/m^3 (Foss, 2003). Thus, LNG floats on top of water if spilled, and vaporizes rapidly because it is lighter than water.
- The vapour of LNG is flammable because it is composed mainly of methane. Methane occupies about 70 to 90% of LNG.
- The LNG vapour at ambient temperature is lighter than air and its specific gravity relative to air is 0.55, once thermal equilibrium is reached (ABS Consulting, 2004).
- At a pressure of 1 atmosphere and temperature of -259°F (-162°C), its normal boiling point, LNG can evaporate and form vapour that has a specific gravity of 1.7 (ABS Consulting, 2004).

- LNG vapour tends to stay near the surface of the ground or water for less than a minute, until it mixes with air and warms to a temperature of approximately -162°F (-108°C), at which it will become less dense than air and tend to rise and disperse more rapidly (ABS Consulting, 2004).
- The vapour of LNG does ignite whenever there are LNG spills and a source of ignition such as an open flame, spark or a source of heat of 540^0C and above (Foss, 2003).

2.4. Hazards of LNG

The properties of LNG determine the type of hazards associated with it in onshore and offshore environments. Safety systems are used to mitigate and prevent the consequences of hazards on its value chain systems. Failures of LNG carrier operations are the main factor that results in consequences such as LNG hazards, which cause pollution of the environment. Such LNG hazards are:

- Explosion.
- Vapour clouds.
- Rollover.
- Freezing liquid.
- Rapid phase transition.
- Pool fire.

2.4.1. Explosion

Explosion is an LNG hazard that occurs when LNG changes its chemical state by ignition or uncontrollable release from its pressurized state (Foss, 2003). The release of LNG without control is probably a result of structural failure. Structural failure mainly occurs as a result of external attack on the tank (i.e. induced failure) or the stress in the inner part of the tank. Structural failure will not lead to immediate explosion because the LNG liquid is stored at atmospheric pressure.

2.4.2. Vapour Cloud

Vapour clouds become hazardous if there is a source of ignition when the LNG is within 5-15% flammability limit. The LNG warms up and returns to a gaseous state once it leaves the container where it is stored at very low temperature of about -256^0F (-160^0C). It mixes with the surrounding air and begins to disperse after the creation of a fog (Foss, 2003). Fire caused by a LNG vapour cloud, burns gradually until it reaches the source (LNG spills) and continues to burn as a pool fire (IMO, 2007).

2.4.3. Rollover

Loading of LNG with multiple densities into a tank, causes formation of various layers. This is a result of the LNG not mixing up initially (IMO, 2007). The density of the lower layer of LNG is changed by heat applied by the normal heat leak until it becomes lighter than the upper LNG layer (Foss, 2003). During this process, liquid rollover would occur with a sudden vaporization of LNG that may be too large to be released through the normal tank pressure release valves (Foss, 2003). The pressure release valve settings depend on the designed pressure of the tank. The pressure release valve value could be 2413165.1 N/m^2, if the designed pressure of the tank is 2068427.2 N/m^2. The stabilization of the LNG causes overpressure in the tank (IMO, 2007). The resultant effect of the overpressure may be cracks on the inner tank (primary containment).

2.4.4. Freezing Liquid

This is one of the hazardous effects of LNG spillage. Any human contact with LNG will freeze that part of the body. Freezing liquid is prevented by use of containment systems to surround the LNG storage tank. In addition, all personnel working on the LNG facility must wear gloves, facemasks and other protective clothing when entering potentially hazardous areas, including the areas where freezing liquid occurred (Foss, 2003).

2.4.5. Rapid Phase Transition

Rapid phase transition occurs when LNG is released on water. The LNG floats on top of water and normally vaporizes immediately if the LNG is of large volume, thereby causing rapid phase transition. Water temperature and the presence of substances other than methane also affect the likelihood of a rapid phase transition (Foss, 2003). Rapid phase transitions range from small pops to blasts that can damage lightweight structures (Foss, 2003). Rapid phase transition constitutes a minor hazard to nearby people and structures, in event of LNG release (IMO, 2007).

2.4.6. Pool Fire

Pool fire is a hazard associated with LNG that cannot be extinguished until all the LNG is consumed. LNG spillage in presence of an ignition source causes evaporating gas within its flammability limit to burn above the LNG pool. The resulting pool fire spreads as the LNG pool expands from its source and continues to evaporate. A pool fire on water is more hazardous than a pool fire on land due to thermal effects. The thermal radiation from a pool fire can injure unprotected people and damage property at considerable distance away from the fire (IMO, 2007). The pool fire contributes in causing global warming by emission of carbondioxide and methane into the atmosphere.

2.5. Overview of LNG Carriers

The LNG industry started using LNG carriers to transport LNG as far back as 1959, when the Normarti, an ex-world war II tanker was converted to carry LNG and renamed Methane Pioneer. Since then, the LNG shipping industry has been showing a remarkable safety record because of stringent safety practices in the LNG industry (Chang et al., 2009). The LNG carriers have been designed, constructed and equipped to carry cryogenic LNG stored at a temperature of -162°C and at atmospheric pressure (Moon et al., 2009). The most important concern in the transportation of LNG is to maintain the structural integrity of the cargo containment system (Moon et al., 2009).

In view of that, LNG carriers are constructed with double hulls, which provide a significant measure of protection against LNG release in event of external damage. In addition, the International Gas Code (IGC) requires LNG carrier tanks to be protected from damage due to collision or grounding by locating the tank at a specified minimum distance inboard from ship's shell plating (ABS Consulting, 2004). Inner tank and outer hull are more than 2m apart, so that if there is a large hole in the hull, it will result in a smaller one in the inner tank (Bubbico et al., 2009). Most LNG carriers have six storage compartments.

The three main types of LNG carriers have the same features but with different tank designs. The LNG carrier tank design is either a self-supporting or supporting tank design. The self-supporting tank does not depend on ship's hull for support and has three categories such as (ABS Consulting, 2004):

- Type A. It is designed primarily using recognized standards for classical ship structural analysis procedures.
- Type B. It is designed using model tests, refined analytical tools, and analysis methods to determine stress levels, fatigue life, and crack propagation characteristics.
- Type C. It is designed for specific vapour pressure criteria and the tanks meet pressure vessel criteria (not typically applicable to the LNG carriers).

Membrane tank design is classified as a supporting tank design while the spherical (moss) and structural prismatic tank designs are classified as self-supporting tank designs. The membrane tank design is supported by the hold it occupies (Pitblado et al., 2004, Sandia National Laboratory, 2005). It is made up of a layer of metal (primary barrier), layer of insulation, liquid-proof layer, and finally another layer of insulation. The multiple layers are attached to the walls of the external framed hold. The primary and secondary barriers are sheets of invar, which is an alloy of 36 percent nickel steel. The layers of insulation are plywood boxes holding perlite. Membranes are built up from the surface of a hold using discrete units of insulation called panels that are anchored to the hold. Special insulation is inserted around the anchors called studs. The joints between panels are sealed using special methods.

The spherical (moss) tank design has a spherical shape (Pitblado et al., 2004, Sandia National Laboratory, 2005). The sphere tank design is constructed using aluminium with a minimum thickness of 29 mm and is installed in the hold of a double hull ship. A steel cylinder is used to support the tank, which makes the tank independent of the ship's hull. The covered insulation surrounding the spherical tank design channels any leakage to a drip tray.

The structural prismatic tank is similar to the spherical (moss) tank because it is a self-supported tank (Pitblado et al., 2004; Sandia National Laboratory, 2005). It is constructed with stainless aluminum or 9-percent nickel steel or 304 stainless steel. The tanks are installed in the hold of a double hull ship and are insulated with covered polyurethane foam that can channel any leakage to drip trays in a similar way to spherical (moss) tank design. The prismatic tank is not popular in the LNG industry, as it accounts for only 2% of the world's LNG fleet (Foss, 2003).

The membrane and spherical tank designs are the most popular tank designs and account for 98% of the world's LNG carrier fleets (Foss, 2003). The insulation of these tanks cannot keep the LNG cold enough. To overcome this challenge, LNG is stored in the tank using auto- refrigeration. In this process, the LNG is subjected to constant temperature and pressure to keep it cold by allowing the Boil-Off Gas (BOG) to leave the tank. The BOG can be used as fuel or re-liquefied and returned to the tank.

Traditionally, LNG carriers have been propelled by steam turbine, which has been proved to be a simple and reliable solution for consuming natural BOG (Moon et al., 2009). Alternative propulsion systems have been considered in recent times, due to the continuous increase in the size of LNG carriers. Therefore, other design options for the propulsion systems such as dual fuel steam mechanical, dual fuel diesel electric, dual diesel turbine electric, dual fuel diesel mechanical propulsion with reliquefaction, and the cargo handling systems for the LNG carriers have been and continue to be developed (Moon et al., 2009).

2.5.1. LNG Carriers Accidents

Since the use of the LNG carriers in transportation of LNG, few incidents have happened and only one accident claimed 6 lives of personnel in 1996. Some notable accidents and their causes have been listed in Table 2.2. The accidents of LNG carriers in Table 2.2 are the ones that caused LNG spills. Other notable accidents of LNG carriers are listed in Appendix B1.

Table 2.2: Notable Incidents/Accidents of LNG Carriers (Østvik, et al., 2005)

1977	LNG Aquarius	The tank was overfilled during loading operations and there was a spillage of LNG. No casualty was recorded.
1979	Mostefa Ben Boulaid	There were valve leakage and deck fractures during unloading of LNG, which caused LNG spillage. There was no injury or fatality of personnel.
1979	Pollenger (LNG Challenger)	There were a valve leakage and tank cover plate fractures during unloading of LNG. The spilled LNG did not cause any injury/fatality of personnel.
1989	Tellier	During loading of the LNG, there were broken moorings, hull and deck fractures. LNG spilled and explosion occurred thereafter. Several injuries were experienced.
2001	Khannur	There was LNG leak through a vent during unloading. There were cracks in tank dome and over-pressurization of cargo in No. 4 tank. A LNG spill was experienced.
2002	Mostefa Ben Boulaid	A spillage resulted in a cracked deck. Thought to be human error as the alarm that should alert personnel had been isolated. No one was hurt.

2.5.2. Risk Assessment of the LNG Carriers

The safety and reliability of LNG carriers have been outstanding so far in the marine industry, which is achieved because of the safety features that are in place to avoid unwarranted release of LNG from their containment systems and other related marine facilities. Risk assessment is a comprehensive estimation of the probability and the degree of the possible consequences in a hazardous situation in order to select appropriate safety measures (Wang and Trbojevic, 2007). Before carrying out a risk assessment, all parties involved should have a common understanding of the goals of the exercise, the methods to be used, the resources required, and how the results will be applied (ABS, 2000).

The main safety concern of LNG carriers is the release of large amounts of LNG or its vapour. Risks associated with hazards that will cause injury to people, damage to LNG carrier systems and the environment need to be estimated and reduced. Risk assessment of LNG carriers can be carried out using qualitative or quantitative risk analysis depending on the requirements of LNG safety analysts and the available historical LNG incidents data. The process can be proactive and includes new risks estimated because of improvement in technology of the LNG carriers. A quantitative risk analysis approach has been applied to a generic LNG carrier using the FSA principle (IMO, 2007; Vanem et al., 2008). Event Tree Analysis (ETA) method was used to identify the consequences of collision, grounding, contact, fire/explosion and loading/unloading risks of LNG carrier operations in the FSA process. Collision risk was found to be the highest and the As Low As Reasonably Practicable (ALARP) principle was applied. Other researchers have carried out qualitative and quantitative risk analysis of LNG carrier systems and LNG terminals, including the works of Bubbico et al. (2009), Hyo et al. (2005), Moon et al. (2009), Østvik et al. (2005), Pitblado et al. (2004) and Vanem et al. (2006).

In bublico et al. (2009)'s work, a preliminary risk analysis of LNG carriers approaching the Panigaglia maritime terminal was conducted. The intentional damages of the containment systems of the LNG carriers by terrorist attacks caused pool fires. The consequence analysis showed that dangerous thermal effects were expected within a radius of 700-1500m in the location under examination. The impact on residential population was negligible while that of anchorage was marginal. Similar risk and consequence analysis of accidental failures such as terrorist attacks on LNG carriers approaching a generic LNG terminal in USA was investigated by Pitblado et al. (2004).

According to Hyo et al. (2005)'s work, a quantitative risk assessment of the Korea onshore LNG storage tank was carried out using a Fault Tree analysis (FTA) method. They considered events involved during the loading and unloading of LNG carriers as one of the six accident categories that could cause a LNG spill from the Korea onshore LNG storage tank. Various FTA diagrams for the identified six accident categories were developed and their failure probabilities were evaluated. Another study of risk assessment of a LNG carrier was conducted by Østvik et al. (2005). A qualitative risk assessment technique was used to estimate risks of identified hazards of a 138000m^3 membrane type LNG carrier under construction by Navantia. They considered various operational phases of LNG vessels while identifying the hazards and estimated the risks of the hazards using expert judgements.

Moon et al. (2009) conducted risk assessment of different gas turbine propulsion system designs for LNG carriers with the aim of identifying hazards associated with each design and the most significant contributors to such hazards. The causes of gas release were investigated, focusing on novel features of the gas turbine propulsion systems. Further investigations were conducted to identify ways to reduce the risks of causes of gas release. From the previous studies, it has been seen that the risks associated with LNG carrier operations are managed/reduced to a great extent using the safety features such as double hull construction, high strength steel in critical areas, double wall walled piping system, redundant steering systems, highly trained specialized crews, gas detection systems, inert inter-barrier spaces, water spray, dry chemical, CO_2 fire fighting systems and emergency cargo evacuation systems that are incorporated in the LNG carriers. Irrespective of the safety features already in place on the LNG carriers and other LNG facilities, hazards that might affect the proper functioning of the LNG carrier systems and subsystems may not be eliminated, especially with the development and implementation of new technologies. The experts in the LNG industry can conduct comprehensive risk assessment of LNG carriers and other related marine facilities using safety/risk analysis techniques such as:

- Event Tree Analysis.
- Risk Matrix.
- Fault Tree Analysis.
- Failure Mode, Effect and Critical Analysis.
- Preliminary Hazard Analysis.
- Hazard and Operability study.
- What If Technique.
- Cause Consequence Analysis.

2.5.2.1. Event Tree Analysis

ETA is a safety/risk analysis technique used in the LNG industry to deduce the consequences of an accident, unintended event or abnormal function of a system. This involves the study of the complex relationships among the subsystems of the system given the occurrence of an initiating event (Wang and Trbojevic, 2007). ETA is developed diagrammatically using inductive bottom-up logic (Halebsky, 1989; Wang and Trbojevic, 2007). ETA assigns probabilities to each branch of an event using historical data or expert judgement. For example, to determine how possible each consequence occurs when a LNG spill (initiating event) happens, involves defining the possible routes along which the consequence could occur and assign probabilities to their routes. ETA can be used to identify possible outcomes of a LNG spill occurrence. For instance, if a LNG spill occurred and there is no ignition source, the consequence will be negligible in terms of fire risk. If there is an ignition source, then check if the gas detection system failed. If not, the consequence will be minor damage, otherwise check the status of the fire alarm system. If the fire alarm system did not fail, the consequence will be major damage, otherwise injuries/deaths will be caused. ETA can be employed to investigate unknown effects from known causes (Godaliyadde, 2008; Villemeur, 1992). ETA enables quantitative analysis to be carried out to estimate the occurrence probability of each possible consequence.

2.5.2.2. Risk Matrix

Risk matrix is a qualitative assessment method which can be used to estimate risk in the LNG industry. It is used as a pre-comprehensive risk assessment of a system because the mechanism can be used to screen high risk hazards that need to be further evaluated using other risk/safety analysis techniques. The analysts focus on those high risk hazards for facilitation of the risk assessment process. It is mostly used as a first choice for HAZID and risk prioritization for large engineering systems as detailed failure rate values are not needed.

This technique uses a tabular format to estimate risks associated with the hazards (Halebsky, 1989; Eleye-Datubo, 2006; IMO, 2007; Military Standard, 1993; Tummala and Leung, 1995). The table of a risk matrix technique has probability of failure on the horizontal axis and consequence of that failure on the vertical axis. The points of intersection of the horizontal and vertical axis are the risks of the hazards. The probability of failure is categorized and scored, as well as consequence of that failure. The summations of their scores at the points of intersection on the risk matrix table are described as estimated risks of hazards (failures). The success of this method depends heavily on the multi-disciplinary team experience of the system under investigation. The benefit of this technique has been taken to carry out the study in Chapter 3.

2.5.2.3. Fault Tree Analysis

FTA is a safety/risk analysis technique commonly used to assess the probability of failure of a system. Since the early 1970s, the FTA technique has been utilised as a tool in risk assessment methodologies (Godaliyadde, 2008; Kumamoto and Henley, 1992). This technique is a process of deductive reasoning which can be applied to a system of any size for risk assessment purposes (Ang and Tang, 1984; Godaliyadde, 2008; Wang and Trbojevic, 2007).

The FTA technique represents the failure logic of a system in an inverted tree structure and provides very good documentation of how the failure logic of the system is developed (Andrews and Ridley, 2002). The pathways through the Fault Tree (FT) diagram represent all the events which give rise to the top event, are known as cut sets or implicant sets. The minimal cut set is defined as the irreducible pathways leading to the occurrence of a top event (Wang and Trbojevic, 2007). It can be used in qualitative and quantitative assessment. The quantitative assessment is carried out successfully on any system that the failure probabilities of the basic events are known. If the basic events probabilities are not known, a subjective method can be adopted.

The FTA technique is used for the PRA of LNG carrier systems followed by the maintenance modelling using GA in Chapter 4. It is also used in subjective risk assessment of the LNG carrier systems adopting the FSA methodology in Chapter 6.

2.5.2.4. Failure Modes, Effect and Criticality Analysis

Failure Modes, Effects and Criticality Analysis (FMECA) is a safety/risk analysis technique used in HAZID and risk estimation. It was created and developed in the United States in the early 1960s and used by NASA during the development of the Apollo Project (Carmignani, 2009). It can be carried out from any indenture level required to examine the failure modes of a component (subsystem) and its possible consequences. FMECA systematically details, on a component by component basis, all possible failure modes and identifies their resulting effects on the system (Godaliyadde, 2008; Kumamoto and Henley, 1992). FMECA is an inductive process which involves the compilation of reliability data that is available for individual components (Godaliyadde, 2008; Wang and Trbojevic, 2007). It can provide regulators with insight into the system features and how they contribute to overall system safety (Buzzatto, 1999). This safety/risk analysis technique is made up of Failure Mode and Effects Analysis (FMEA) and Criticality Analysis (CAS). The performance of an FMEA is the first step in generating FMECA (Pillay and Wang, 2003). FMEA is the identification of potential failure modes of the constituent components and the effect on system performance by identifying the potential severity of the effect (Pillay and Wang, 2003). The CAS produces the criticality ranking of the components under investigation. The CAS helps analysts to know which component to give maximum attention. FMECA can be used in qualitative and quantitative analyses. FMECA produces information that can be used in the development of FTs and boolean representation tables (Godaliyadde, 2008; Wang and Trbojevic, 2007; Wang et al., 1998).

2.5.2.5. Preliminary Hazard Analysis

Preliminary Hazard Analysis (PHA) is a safety analysis technique that is performed to identify all the possible hazards that could be created by the system being designed. This is the first step used to identify the hazards of a LNG carrier starting from when the ship is about to be designed. Results of PHA enable system designers to avoid many potential safety problems (Dowlatshahi, 2001). A collective brainstorming technique is employed during which the design or operation of the system is discussed on the basis of experience of the participants (Godaliyadde, 2008). PHA is a qualitative approach which involves a mixture of inductive and deductive logic (Wang and Trbojevic, 2007). Checklists are commonly used to assist in identifying the hazards and the results are presented in a tabular format (Godaliyadde, 2008). When sufficient information is not available for particularly rigorous analyses, PHA serves as a valuable aid (Dowlatshahi, 2001). The procedures of a PHA are (Czerny et al., 2005):

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

2.5.2.6. Hazard and Operability Study

Hazard and Operability (HAZOP) study is an inductive technique for identifying hazards and problems associated with the operation of a process plant in the LNG industry. The HAZOP technique was developed in the 1970s by loss prevention engineers working for Imperial Chemical Industries at Tees-Side UK (Godaliyadde, 2008; Smith, 2005; Villemeur, 1992). This is a collective brainstorming technique in which the system is examined systematically, component by component, to determine how deviations from the design intent can occur, the consequences of such deviations and the preventive/mitigative measures that are required (Godaliyadde, 2008). It is also an extended FMECA. The aim of the HAZOP is to carry out a qualitative analysis in the intermediate stages of the design process to predictable hazards, thus it is an exploratory technique (Godaliyadde, 2008; Mauri, 2000). It is used in detailed examination of components within a LNG system to determine what would happen if the components were to operate outside their normal design mode conducted by a group of specialists headed by a hazard analyst. Each LNG component will have one or more parameters associated with its operation such as “pressure”, “flow”, “temperature”, “composition”, “relief”, “level”, “phase” and “instrumentation”.

The HAZOP study looks at each parameter in turn and uses guide words to list the possible off-normal behaviour. The guide words are "no", "low", "high", "as well as", "reverse", "other than" and "part of". An example of the combination of a parameter like "no" and a guide word like "flow" is used in loading or unloading of LNG from an onshore containment tank to a LNG containment tank through a pipeline. If LNG is not or has stopped flowing through the pipeline, the team involved in HAZOP studies will give the deviation "no flow". The team then focuses on listing all the credible causes of a "no flow" deviation beginning with the cause that can result in the worst possible consequences. Once the causes are recorded, the team lists the consequences, safeguards and any recommendations deemed appropriate. The process is repeated for the next deviation until completion of the node before the team moves to the next node and repeats the process depending on the type of process being considered. Information produced from HAZOP studies can be used in cause consequence analysis, FMECA and Boolean representation analysis (Wang and Trbojevic, 2007).

2.5.2.7. What-IF Analysis

What-If analysis helps to identify potential LNG hazards. It uses brainstorming techniques to ask question, "What If" in the lifecycle of a system. The intention of "What If" is to ask questions which will cause a team to consider potential failure scenarios and ultimate consequences that such failures might create (CCPS, 1992; Eleye-Datubo, 2006; Wang and Trbojevic, 2007). The possible hazards are identified, existing safeguards are noted, and qualitative severity and likelihood ratings are assigned to help in risk assessment. This technique assures that all hazards that may or may not occur in the future are known because well experienced personnel are involved in the HAZID process. Assembling an experienced and knowledgeable team is probably the single most important element in conducting a successful "What If" analysis. Their experience in the design, operation, and servicing of the involved systems is essential. Their knowledge of design standards, regulatory codes, past and potential operational errors as well as maintenance difficulties brings a practical reality to the review. To minimize the chances that potential problems are not overlooked, all the potential hazards are identified before recommendations on those hazards are made. It uses a mixture of inductive and deductive logic (Wang and Trbojevic, 2007).

2.5.2.8. Cause–Consequence Analysis

Cause-Consequence Analysis (CCA) is the combination of ETA and FTA. The ETA shows consequence and the FTA shows causes, hence deductive and inductive analysis is combined. The CCA was developed at RISO national laboratories, Denmark, in the 1970's to specifically aid in the reliability and risk analysis of nuclear power plants in Scandinavian countries (Andrews and Ridley, 2002; Andrews and Ridley, 2001; Villemeur, 1992). Many authors have used the CCA as the main analysis tool for a safety assessment (Andrews and Ridley, 2002; Pauperas, 1991; Valaityte et al., 2009; Vyzaite et al., 2006). The purpose of the CCA is to identify chains of events that can result in undesirable consequences. The CCA diagram documents the failure logic of a system (Andrews and Ridley, 2001). It is used to identify hazards (FTA) and consequences of the hazards (ETA) for easy eradication of risk. The "consequence tracing" part of the CCA involves taking the initial event and following the resulting chains of events through the system (Wang and Trbojevic, 2007). The "cause identification" part of the CCA involves drawing the FT and identifying the minimal cut sets leading to the identified critical event (Wang and Trbojevic, 2007). The diagram of the CCA normally starts with choice of critical event. This technique is advantageous in safety analysis as it can work forward using ETs and backward using FTs.

2.6. Overview of Maintenance

Maintenance is defined as the combination of all technical and administrative actions, including supervision actions, intended to retain an entity in, or restore it to a state in which it can perform a required function (Pillay and Wang, 2003; Wang and Trbojevic, 2007). The ultimate goal of maintenance is to provide reliability to equipment, machines or processes that meets the business needs of a company (Jones, 2009). Reliability is defined as the ability of a machine or components or equipment to perform a required function under specified conditions and for a given period of time without failing (BS EN 292; Jone, 2009; Wang and Trbojevic, 2007). Maintenance of the LNG carrier systems is of upmost importance in the LNG industry to avoid loss of LNG and ensure safety of the crew members onboard the vessel. Once a risk-based check is conducted, system maintenance is recommended as a preventive or mitigative measure for any identified hazard that the consequence could be catastrophic, marginal or critical. However, the system maintenance is prioritized based on the consequences of their failures and the manufacturers' instructions. Various maintenance techniques have been developed and industries have proved their usefulness on engineering systems. Reliability Centred Maintenance (RCM) is a procedure for determining maintenance strategies based on reliability techniques and encompasses FMECA (Pillay and Wang, 2003). The RCM focuses the maintenance resources only on those items that affect the system reliability, thereby making the maintenance programme cost effective in the long run (Mokashi et al., 2002; Pillay and Wang, 2003). Maintenance involves planned and unplanned activities being carried out to ensure an acceptable state of operation of a system. Selection of a maintenance strategy will depend on one or a combination of the following criteria (Pillay and Wang, 2003; Savic et al., 1995; Wang and Trbojevic, 2007):

- Maximisation of reliability.
- Minimisation of downtime.
- Minimisation of total maintenance cost.

In the maritime industry, any selected maintenance strategy must take into account cost, safety, environmental and operational consequences. The prime objective of a maintenance programme is to:

- Minimise costs.
- Meet safety and environmental goals.
- Meet operational goals.

A maintenance model is successfully developed in the maritime industry after considering the problems associated with the maintenance of a ship and its systems and subsystems such as (Wang and Trbojevic, 2007; Pillay and Wang, 2003):

- The high cost of a ship's system out of service.
- Severe safety and insurance conditions, necessitating rigorous survey requirements.
- Ships' personnel are operators as well as maintainers.
- The frequency with which personnel join and leave ships, creating a need for continuity of ships maintenance plans.

- The high degree of isolation from repair and spares facilities.
- The high cost of transport unit (i.e. the ship).
- Varying costs, availability and quality of labour and spares throughout the world.

Maintenance of the LNG carriers and their systems and subsystems can be carried out using any of the maintenance techniques as stand-alone or in combination with other maintenance techniques to produce a sound maintenance regime in a cost effective manner. Some maintenance activities are carried out onboard the vessel depending on the experience of crew members. If the failures of the LNG carrier systems that affect the operations of the vessel cannot be maintained by the crew members, a tugboat will be used to tow the vessel to a nearby port for maintenance. The importance of maintenance is demonstrated by the fact that it is the only shipboard activity to have one whole element assigned to it (i.e International Safety Management (ISM) Code element 10) (IMO, 1997). The types of maintenance commonly used are:

- Preventive Maintenance.
- Reactive Maintenance.
- Predictive Maintenance.
- Proactive Maintenance.

2.6.1. Preventive Maintenance

Preventive Maintenance (PM) is a maintenance strategy carried out on equipment before its failure. PM is usually conducted on repairable systems to improve the overall reliability of these systems (Sun et al., 2009). PM can be defined as actions performed on a time based schedule that detect, preclude or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level (Sullivan et al., 2002). The PM technique maximizes/increases the reliability of LNG carriers and their systems and subsystems by detection and prevention of incipient failures, before they become major failures. PM involves the repair, replacement and maintenance of equipment in order to avoid unexpected failure during use (Khanlari et al., 2008, Pillay and Wang, 2003). The objective of a PM programme is to minimize the total cost of inspection, repair and equipment downtime (Khanlari et al., 2008). PM decrease the number of failures but does not guarantee that catastrophic failure will not occur. Carrying out a PM programme as the equipment designer envisioned, extends the life of the equipment closer to the original design (Sullivan et al., 2002). PM with inspection intervals is a commonly used maintenance strategy (Crocker, 1999; Ben-Daya and Hariga, 1998; Lofsten, 1999; Pillay and Wang, 2003; Wang and Trbojevic, 2007). This maintenance technique has advantages such as (Sullivan et al., 2002):

- Cost effective in many capital intensive processes.
- Flexibility allows for the adjustment of maintenance periodicity.
- Increases component life cycle.
- Energy savings.
- Reduces system or component or process failure.
- Cost savings over reactive maintenance programme.

The disadvantages of a PM programme are outlined as:

- It is always labour intensive.
- Occurrence of catastrophic failures cannot be ruled out on the systems or components.
- Sometimes, there is introduction of problems on the systems or components because of unneeded maintenance.

2.6.2. Reactive Maintenance

Reactive Maintenance (RM) is a maintenance strategy that involves reacting to failures of equipment as they occur by carrying out maintenance as necessary to rectify the equipment. No actions are taken to maintain the equipment as the designer originally intended to ensure the design life of the equipment is reached (Sullivan et al., 2002). It could be called break down, fix-when-fail, run to failure or corrective maintenance. In RM programme, procedures that can be used to influence the equipment survivability are ignored. It only consists of actions applied on equipment when they break down (Samrout et al., 2009). When failures of equipment are not critical, RM becomes necessary (Arunraj et al., 2010). Equipment that can be reactively maintained must be non-critical and will not pose any serious hazards or affect the operation of the system as a whole (Pillay and Wang, 2003). A RM programme is applied in many industries because of the following:

- Cost effective for small and non-critical equipment.
- Limited number of personnel is needed to carry out maintenance activities throughout the design life of the equipment.

The major downsides of RM programme are (Sullivan et al., 2002):

- Increased cost due to unplanned downtime of equipment.
- Increased labour cost, especially if overtime is needed.
- Cost is involved with repair or replacement of equipment.
- Possible secondary equipment or process damage from equipment failure.
- Inefficient use of personnel resources.
- A large material inventory of repair parts is required since equipment is run to failure.

2.6.3. Predictive Maintenance

Predictive maintenance can be defined as measurements that detect the onset of a degradation mechanism, thereby allowing casual stressors to be eliminated or controlled prior to any significant deterioration in the component physical state (Sullivan et al., 2002). It can provide an increase in safety, quality and availability of a system (Carnero, 2006). It is also called Condition Monitoring (CM). A predictive maintenance programme can be used to detect whether or not to maintain a system according to its state (Chu et al., 1998). The continuous analysis of equipment condition monitoring data allows planning and scheduling of maintenance or repairs in advance of catastrophic and functional failure (Pillay and Wang, 2003). Basically, predictive maintenance differs from preventive maintenance by basing maintenance need on the actual condition of the equipment rather than on some preset schedule (Sullivan et al., 2002). Predictive maintenance saves cost over preventive maintenance because tasks are performed only when warranted. This maintenance strategy has advantages such as (Sullivan, et al., 2002):

- Allows for pre-emptive corrective actions.
- Increases component operational life/availability.
- Decrease in equipment or process downtime.
- Decrease in costs for parts and labour.
- Better product quality.
- Improves worker and environmental safety.
- Energy savings.
- Cost savings over preventive maintenance programme.

The disadvantages of applying predictive maintenance are (Sullivan et al., 2002):

- Increase investment in diagnostic equipment and in personnel training.
- Savings potential not readily seen by management.

2.6.4. Proactive Maintenance

Proactive maintenance is a maintenance strategy that determines the root causes of repeated failures. The root cause failure analysis is the determination of the mechanisms and causes of equipment faults. It is a natural part of proactive maintenance process (EPRI, 2001). The fundamental causes of equipment failures can be identified and the failure mechanisms can be corrected. Proactive maintenance improves maintenance through better design, installation, maintenance procedures, workmanship and scheduling (Pillay and Wang, 2003). This maintenance strategy is a daily process that complements the maintenance work process and the predictive maintenance process (EPRI, 2003). The techniques used in proactive maintenance to extend machinery life are proper installation and precision rebuild; failed-part analysis; rebuild verification; age exploration and recurrence control (Pillay and Wang, 2003). Proactive maintenance can be used to reduce the failure probability of equipment (Swanson, 2001). The proactive maintenance has attributes such as (Pillay and Wang, 2003):

- Maintaining a feedback loop from maintenance to design engineers, in an attempt to ensure the design mistakes made in the past are not repeated in future designs.
- Viewing maintenance and supporting functions from a life-cycle perspective. This perspective will often show that reducing maintenance activity to save money in the short term often cost in long term.
- Constantly re-evaluating established maintenance procedures in an effort to improve them and ensure that they are being applied in the proper mix.

The advantages of proactive maintenance are:

- The design life of equipment is extended.
- The root causes of problems are addressed.
- Reduces maintenance costs beyond predictive levels.

The major disadvantage of proactive maintenance is:

- High cost.

2.7. Overview of Formal Safety Assessment of Ships

Several accidents in the maritime industry prompted the IMO to question the safety of operations of ships. For safety of the public and environment, the IMO decided to adopt the FSA methodology after studying notable accidents that have affected the lives of people onboard vessels and caused great damage to the environment. One of the accidents was the capsize of the Herald of Free Enterprise that happened on 6th March, 1987, which claimed 193 lives. The investigation of the capsize of the Herald of Free Enterprise led by Lord Carver brought changes to marine safety related regulations, demonstrated by the adoption of the enhanced damage stability and watertight closure provisions in the Safety of Life at Sea (SOLAS'90) (Wang, 2002; Wang and Trbojevic, 2007). The introduction of the ISM Code for the safe operations and pollution prevention, and the development of the FSA framework in shipping industry are also adopted as marine safety related regulations (Wang, 2002; Wang and Trbojevic, 2007). Introduction of a more structured risk analysis process through the FSA procedure; compelled regulators to examine potential hazards and introduce appropriate measures or standards before a catastrophic accident occurs.

The submission of Lord Carvers report on the investigation of the capsize of the Herald of Free Enterprise, which was published in 1992, caused the United Kingdom Maritime Coastal Agency (UK MCA) to immediately improve the safety of ships by proposing to the IMO in 1993 that FSA should be applied to ships to ensure a strategic oversight of safety and pollution prevention. The IMO accepted the proposal and sanctioned the application of FSA in relation to ship design and operation. The UK MCA has proved FSA's practicability by carrying out trial applications to safety of high speed catamaran ferries (IMO, 1997a; IMO, 1998a) and bulk carriers (IMO, 1998f; IMO, 2000; IMO, 2002a; IMO, 2002b). FSA has been successfully applied to various ships and marine facilities using probabilistic and subjective (possibilistic) assessment approaches. The ship and marine facilities include:

- Fishing vessels (Pillay, 2001; Loughran et al., 2003).
- Ports (Trbojevic, 2002; Ung et al., 2006; Ung, 2007).
- Marine transportation (Soares and Teixeira, 2001).
- Offshore support vessels (Sii, 2001).
- Containerships (Wang and Foinikis, 2001).
- LNG ships (IMO, 2007; Vanem et al., 2007).
- Ship Hull Vibration (SHV) (Godaliyadde, 2008)
- Cruising ships (Lois et al., 2004).
- Liner shipping (Yang et al., 2005; Yang, 2006).
- Trial study on passenger roro vessels with dangerous goods (IMO, 1998g).
- Trial study on high speed crafts (IMO, 1997b; IMO, 1998b; IMO, 1998c).
- Trial study on oil tankers (IMO, 1998d; IMO, 1998e).

The applications of FSA to ship design and operation offer great incentives that could (Eleye-Datubo, 2005):

- Improve the performance of the current fleet, being able to measure the performance change and ensure that new ships are good designs.
- Ensure that experience from the field is used in the current fleet and that any lessons learned are incorporated into new ships.
- Provide a mechanism for predicting and controlling the most likely scenarios that could result in incidents.

FSA is a process of identifying hazards, assessing the associated risks, studying alternative ways of managing those risks, carrying out Cost Benefit Assessment (CBA) of alternative management options and finally making decisions on which option to select (MSA, 1993). The five basic steps of the FSA methodology are applied to ships and marine systems step by step. The steps are HAZID (Step 1), Risk Assessment (Step 2), Risk Control Option (RCO) (Step 3), CBA (Step 4) and Decision Making (Step 5). The steps interact with each other to ensure that the best RCO is chosen based on the CBA during decision making. The incentives offered by FSA have been demonstrated in Chapter 6 of this thesis by applying its methodology to LNG carrier operations using a subjective approach. The subjective approach is successful by employing a FER algorithm, which treats the uncertainties associated with the failure modes of LNG carrier systems.

2.8. Overview of Regulations Governing Safety of LNG Shipping

The IMO was created in 1958, with the aim of functioning as a body that contributes to the standardization of the legislations and regulations related to safety of shipping. The IMO was formerly called the Inter-governmental Maritime Organization (IMCO). The international safety based marine regulations have been driven by serious marine accidents (Godaliyadde, 2008). The regulations for gas carriers concerning the construction, equipment and operations of gas carriers are contained in the IMO "Gas Codes". The three Gas Codes that have evolved for the LNG shipping industry are (Walker et al., 2003):

- The code for existing ships carrying liquefied gas in bulk (existing ship code – IMO).
- The code of construction and equipment of ships carrying liquefied gas in bulk (The GC code – IMO).
- The international code of construction and equipment of ships carrying liquefied gas in bulk (The IGC code – IMO). .

The IMO has implemented international conventions for the safety of shipping such as (ABS, 2000):

- International Standard of Training, Certification and Watchkeeping (STCW), 1995. It is aimed at providing unified standards for training and certification of seafarers.
- International Convention for the Prevention of Pollution at Sea, 1973 and protocol of 1978 (MARPOL 73/78). It is aimed at preventing and minimizing pollution at sea from oil, noxious liquid substances, noxious substances in packaged forms, sewage, garbage, and air pollution.
- International Load Line Convention (ILLC), 1966. It is aimed at standardizing the procedures for assignment of load lines to ships and the conditions of assignment, such as intact and damage stability, the protection of openings in the watertight boundaries and protection of crew at sea, etc.
- Convention on the International Regulations for Preventing Collisions at Sea (COLREG), 1972. It is aimed at providing "rules of the road" at sea, such as maintaining proper lookout, safe speed, lights and signals to be displayed, etc.
- International Convention for the Safety of Life at Sea (SOLAS), 1974. It is aimed at providing adequacy in ship structural design (albeit by specifying compliance with classification rules); safety of mechanical and electrical systems onboard; damage stability; fire safety; radio communication and search and rescue; safety of navigation and prevention of collision; the provision of life saving appliances, the safe carriage of dangerous cargoes; and safety management.

The International Association of Classification Societies (IACS) was formed in 1969 and is made of 10 members and 2 associate members. The members of IACS such as Lloyd's Register, American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV), Korean Register of Shipping, and Nippon Kaiji Kyokai classify LNG ships using the regulations of the IMO conventions and their own rules. Their rules and the IMO conventions have contributed in improving the safety of LNG carriers. Other bodies such as the Society of International Gas Tankers and Terminal Operators (SIGTTO) provide guidelines for the safe operation of gas tankers and terminals, after putting their effort and time to ensure that risks associated with LNG facilities are mitigated in their technical design standards and operating procedures to a maximum level.

2.9. Genetic Algorithm

GA was developed by John Holland in the 1970s as an optimization technique that uses the principle of a natural genetic. A GA maintains a population of candidate solutions, where each candidate solution is usually coded as a binary string called a chromosome (individuals) (Yen and Langari, 1999). GA establishes a fitness function for facilitation of the formation of an initial population. The fitness of the chromosomes that make up the initial population is assessed for selection of the best ones for the next generation. The chromosomes that are not selected for the next generation using the selection operator are replaced by the reproduced offspring. The offspring are reproduced by the parents (the selected chromosomes from the initial population) using the crossover operator. Premature convergence is overcome by the use of a mutation operator and a new population is formed, maintaining the population size of the initial population. This process continues until an optimal solution is found or a fixed number of generations is reached. There are different methods of GA used in solving engineering problems. These methods of GA include:

- Binary Genetic Algorithm.
- Continuous Genetic Algorithm.
- Steady State Genetic Algorithm.
- Multiobjective Genetic Algorithm.

2.9.1. Binary Genetic Algorithm

It is a GA that works with finite parameter space (Harikumar et al., 2004). The value of the chromosome (structure or potential solution) is represented using binary numbers (0 or 1). The bit (0 or 1) represents the gene that makes up the chromosome. The usual representation scheme for the GA is that each potential solution is coded as a string of parameter values, usually in binary code (Andrew and Bartlett, 2003). The main aspect of this method is the representation of the parameter as strings of binary digits of 0 or 1 (Harikumar et al., 2004). In this method, GA operators are:

- Selection.

- Crossover.
- Mutation.
- Elitism.

2.9.1.1. Selection

The operator is a process of choosing parents for reproduction based on their fitness (Haupt and Haupt, 2004). It attempts to apply pressure upon the population in a manner similar to that of natural selection found in biological systems (Colley, 1999). The selection operators use the fitness values in the current population to create a breeding pool for the next generation (Alim et al., 2007). A selection operator occurs at each iteration of the algorithm to allow the population of chromosomes to evolve over the generations to fit chromosomes (members) as defined by the fitness (objective) function. The selection operators are a roulette wheel selection (Colley, 1999; Mitchell, 1996; Haupt and Haupt, 2004; Man et. al., 1999), stochastic universal sampling selection (Colley, 1999; Man et. al., 1999, Mitchell, 1996), and tournament selection (Man et. al., 1999, Mitchell, 1996; Haupt and Haupt, 2004).

2.9.1.2. Crossover

It allows solutions to exchange information in a way similar to that used by a natural organism undergoing sexual reproduction (Colley, 1999). It is an operator that forms a new chromosome from two parent chromosomes by combining part of the information from each according to Haupt and Haupt, (2004). The operator switches gene between two genotype to generate offspring. The crossover operators include a single point crossover (Colley, 1999; Mitchell, 1996; Haupt and Haupt, 2004), two point crossover (Colley, 1999; Mitchell, 1996; Haupt and Haupt, 2004; Sakawa, 2002), and multipoint crossover (Colley, 1999; Man et al., 1999; Sakawa, 2002).

2.9.1.3. Mutation

Mutation is a reproduction operator that randomly alters the values of genes in a parent chromosome (Haupt and Haupt, 2004). A mutation operator provides diversity in the population by making changes randomly in a selected genotype and the percentage of genes (bits) in a population that is mutated in each generation of GA is lower than that of the crossover operator. In other words, mutation is applied with a lower probability than the crossover probability (Alim et al., 2007).

2.9.1.4. Elitism

This is an operator that ensures that the GA retains the best chromosomes at each generation because sometimes a selection operator does not guarantee that the fittest chromosomes as defined by the fitness function are selected for the next generation. Without this operator, the likelihood of losing the best chromosomes is high during selection, crossover and mutation. In many applications, the search speed can be more effective by not losing the best members known as elite members.

The application of binary GA to engineering problems is of great benefit. These include:

- Optimization of continuous variables by encoding them to binary numbers.
- Simple application of crossover and mutation.
- Optimization of mixed-integer problems.

However, difficulties are also encountered during the GA process. Some of the difficulties are:

- Hybridization with other algorithms is difficult.
- It wastes time because of conversion of variables with real numbers to binary numbers prior to application of GA.
- Variables with a long number of bits occupy space in the computer.
- It is not that efficient compared to continuous GA, if the binary bits are many.

2.9.2. Continuous Genetic Algorithm

A continuous GA is an algorithm that uses real numbers to encode the variables. It follows the same steps of GA that is used in the binary GA. Although they share the same steps, significant differences have been revealed. The difference in the continuous parameter GA occurs in the computation of the fitness function and the crossover and mutation operators (Harikumar et al., 2004). Some of all these features have allowed continuous GA to be equipped with more advantages, including:

- It enables faster calculation compared to the binary GA because the chromosomes do not need to be decoded before evaluation of the objective function.
- It gives exact or approximate optimal solution compare to binary GA because it uses internal precision of the computer and round off to define the precision of the chromosomes (values) during the computational processes.
- It has less storage data space than binary GA because it is not represented by a number of bits. The variables are represented by a single floating number.
- Continuous GA can be easily hybridized with other algorithms.
- It can solve a multiobjectives optimization problem.

Although showing some attractiveness, the continuous GA still exposes a weakness such as applications of crossover and mutation operators being not natural and real.

2.9.3. Steady State Genetic Algorithm

A steady state GA is either a single or multiobjective GA with its ability of solving one or more objective function(s). It can be binary based or continuous based, depending on the encoding of the constraints of objective function(s) as a result of the problem formulation. In steady-state selection, only few chromosomes (individuals) are replaced in each generation. Usually a small number of the least fit chromosomes (individuals) are replaced by offsprings resulting from crossover and mutation of the fittest individuals (Mitchel, 1996). Elitism is introduced to ensure that some of the fittest individuals are not lost during the generation processes. The fraction of individuals replaced is called the generation gap (Colley, 1999). Steady-state GAs are often used in evolving rule-based systems in which incremental learning (and remembering what has already been learned) is important and in which members of the population collectively (rather than individually) solve the problem at hand (Mitchel, 1996). Firstly, the initial population is formed from the problem formulation. This initial population is allowed to evolve in successive generations through the following steps (Podofillini et al., 2006):

- Selection of a pair of individuals as parents.
- Crossover of the parents, with generation of two children.
- Replacement in the population, so as to maintain the population number constant.
- Genetic mutation.

The new population formed is ranked and updated after the evaluation of the objective functions. This ranking is used in the selection procedure which is performed in such a way that in the long run the best individuals will have a greater probability to be selected as parents, in resemblance to the natural principles of "survival of the fittest" (Podofillini et al., 2006). The iteration will continue until convergence is achieved and sufficient genetic diversity should be used, if it is needed to avoid premature convergence or no convergence. Steady-state GA has the advantages of continuous and binary GAs.

2.9.4. Multiobjective Genetic Algorithm

When more than one objective function is involved, single objective GA becomes multi-objective GA. This solution solves problems simultaneously and helps to identify the effectiveness of minimising the objective functions to the benefit of the constraint and vice versa. The comparison of two solutions with respect to several objectives can be achieved by introducing the concepts of Pareto Optimality and dominance, which enable solutions to be compared and ranked without imposing any prior measure as to the relative importance of individual objectives, neither in the form of subjective weights nor arbitrary constraints (Marseguera et al., 2004). This GA has the following specific characteristics (Torres-Echeverria and Thompson, 2007):

- Ranking based on Pareto dominance.
- Fitness sharing performed in the objective space.
- Mating restriction.

- Suggest the first truly progressive preference-based method, incorporating the decision maker through goals and priority levels.
- Parallel coordinates for visualization of the trade-off surface in two dimensions.

Pareto optimal means the dominance of a solution with respect to objective functions in the search space. The population of chromosomes created will be ranked according to their Pareto dominance. The multi-objective GA starts with finding all nondominated chromosomes of population and gives them a rank of one (Haupt and Haupt, 2004) as the best ones. These best ones are removed from the population for identification of the next group of nondominated chromosomes, which will be ranked as two. The rank two nondominated chromosomes are also removed, to find the next group of nondominated chromosomes. This process continues until all the nondominated chromosomes/solutions have been ranked. The selection and replacement procedures of multi-objective GA are based on the ranking in which every chromosome belonging to the same rank class has to be considered equivalent to any others to be selected as its parents and surviving the replacement (Podofillini et al., 2006). It also uses niching on the objective function to distribute the population over the Pareto-optimal region. A Nondominated Sorting GA (NSGA) ranks chromosomes in the same manner as a multiobjective GA (Haupt and Haupt, 2004). Therefore, NSGA is used to calculate a uniqueness value, which is related to the distance between each solution and its closest neighbours. The distance known by calculating the variables or costs is scaled between 0 and 1 and subtracted from the cost. NSGA is effective because of the following reasons (Haupt and Haupt, 2004):

- Reduces the computational complexity of the nondominated sorting.
- Introduces elitism.
- Replaces sharing with crowded-comparison to reduce computations and the need for a user-defined sharing parameter.

Multiobjective GA can be recognized with the following features:

- It has the ability of solving multi-objective problems effectively.
- It has the ability of solving both continuous and binary GA.

- It helps the designer to determine the effectiveness of one objective function to the other.
- It has very high computational complexity.
- It is likely to converge at a single point, if niche strategy called sharing is not used.

There are other optimization techniques such as particle swarm optimization, ant colony optimization and simulated annealing (Haupt and Haupt, 2004). According to Matlab Version 7.7 (R2008b), binary integer programming, multiobjective goal attainment optimization, single-variable nonlinear minimization, constrained nonlinear minimization, minimax optimization, unconstrained nonlinear minimization, semi-infinite minimization, nonlinear equation solving, single-variable non-linear equation, linear programming, nonlinear curve fitting, constrained linear squares, nonlinear linear squares, nonnegative linear least square, pattern search, quadratic programming, neural network and threshold acceptance algorithm are recognized as optimization techniques. Monte Carlo simulation is also an optimization technique (Rubinstein and Kroese, 2007). GA is used in minimization of the risk model in Chapters 4 and 5 because of its ability to:

- Ensure that there is genetic diversity, thereby increasing the search space to produce best optimal risk solution.
- Ensure that the search is probabilistic and not deterministic.
- Ensure that the search is conducted in a generated population of points and not at a single point at each iteration, which improves efficiency and accuracy of GA.

2.10. Fuzzy Set Theory

Fuzzy Set Theory (FST) is first presented by Lofti Zadeh in 1965. The theory is a mathematical formalization which enables representation of degrees of membership of members in sets (Eleye-Datubo, 2006). Fuzzy logic is the term used for ad-hoc applications of rules based on a simplified FST (Eleye-Datubo, 2006). The fuzzy logic is a versatile tool that is tolerant of imprecise, ambiguous and vague data/information, and one for which its reasoning builds understanding into a process. It mainly uses the concept of linguistic variables, and provides a framework for dealing with such variables in a systematic way. There are various techniques of fuzzy logic such as discrete and continuous fuzzy sets, and FRB, which have been used in uncertainty treatments in the maritime industry (Eleye-Datubo, 2006; Godaliyadde et al., 2009; Pillay, 2001; Pillay and Wang, 2002; Pillay and Wang, 2003; Wang et al., 1995; Wang et al., 1996; Wang, 1997; Wang, 2000; Sii et al., 2001; Ung et al., 2006; Yang et al., 2005). The usefulness of fuzzy logic has also been proved in other industries (Durga Rao et al., 2007; Gao et al., 2008., Hatiboglu et al., 2010., Markowski and Mannan, 2009; Moreno and Pascual, 2009; Prato, 2007; Soman and Misra, 1993; Soh and Yang, 1996; Sun and Collins, 2007; Yang and Soh, 2000).

FRB allows for the involved linguistic attributes to be specifically guided towards a justified output result. Thus, fuzzy logic can be used in application of a linguistic approach in a wide variety of problems. The significance of fuzzy variables is that they facilitate gradual transition between states and thereby possess the natural capability to express and deal with observation and measurement uncertainties (Pillay and Wang, 2003). This is beyond crisp variables. The definition of states by crisp sets is mathematically sound, though in some cases, it may be unrealistic in a situation where measurement errors cannot be avoided. This can be illustrated using a temperature reading of $600^{\circ}C$ of a LNG carrier engine, which is classified as "hot". An under-estimation of $1^{\circ}C$ would place the temperature to "warm" category. The existence of uncertainty of the temperature makes maintenance decision on the LNG carrier engine very difficult. When dealing with crisp variables, the uncertainty is ignored; the measurement is regarded as evidence for one of the states, the one that includes the border point by virtue of an arbitrary mathematical definition. The idea is that unlike crisp set, which is completely determined by an indicator function taking values in {0, 1}, a fuzzy set is characterised by a membership function with membership values ranging between 0 and 1 (Pillay and Wang, 2003). A fuzzy set whose membership function only takes on the value zero or one is called crisp.

2.10.1. Fuzzy Membership Function

A fuzzy set is represented by a membership function on the universe of discourse or universal set (X) (Zadeh, 1987). If a universe X is made up of elements of x and various combinations of these elements make up set A on the universe. For crisp sets, each element of x in the universe X is either an element of set A or is not. Crisp sets have a unique membership function whereas fuzzy sets (denoted by $\tilde{A}$) have an infinite number of memberships to represent the situation (Ross, 2004). Elements in a fuzzy set can have a continuum of degrees of membership ranging from complete membership to complete non-membership (Zadeh, 1987). A non-membership is represented by 0 and full membership is represented by 1, which means full representation of the set under consideration. A membership between 0 and 1 indicates the degree of membership $\mu(x)$. The difference between a crisp set and a fuzzy set is the membership function. Values assigned to a membership are not fixed and can be chosen by the investigator based on the application. The notation of a fuzzy set is expressed as follows:

$$\mu\tilde{A}(x) \in [0,1] \tag{2.1}$$

where $\mu\tilde{A}(x)$ represents the degree of membership of element x in a fuzzy set $\tilde{A}$. $\mu\tilde{A}(x)$ is equal to the degree to which $x \in \tilde{A}$ and $\in$ means "member of". The shape of the fuzzy set depends on the way the data is represented. The membership is indicated on the vertical axis and ranges between 0 and 1. The domain of a set is indicated along the horizontal axis. The fuzzy set shape defines the relationship between the domain and the membership values of a set. The hypothesis of using a membership function is to map the parameter constraint to membership grade between the scaled intervals (Godaliyadde, 2008).

There are different types of fuzzy membership functions used in solving engineering problems. A particular membership function chosen for solving engineering problem depends on the choice of the designer and the problem formulation. The most commonly used membership functions in engineering applications are triangular, trapezoidal, sigmoid curve, generalized bell curve and gaussian curve membership function.

2.10.2. Features of Fuzzy Set Theory

The fuzzy logic is used in this research over other alternative modelling techniques because of the following features (Eleye-Datubo, 2006):

- It is conceptually easy to understand with "natural" mathematics.
- It is tolerant to vague or imprecise data. Its use of FST is particularly adapted to the representation and manipulation of imprecision and uncertainty of the linguistic labels that define the criteria of the classes.
- It presents a flexible way of dealing with different forms of uncertainty. For example, there is a lot of freedom in choosing the membership functions of fuzzy sets.
- It is more intuitive than differential equations and enables analysts and decision-makers to capture knowledge of how the system behaves in everyday linguistic terms (i.e. based on natural language).
- Though making use of heuristics, the framework still offers a convenient way to express and make the most of the experience of experts' common sense knowledge.
- It has the ability to model any complex or highly non-linear function to any arbitrary degree of accuracy.
- It is based on rules (i.e. rule base logic) that can be specified with a natural language. Basically, the laws are naturally broken down into individual IF-THEN statements that lend themselves to parallel processing.

The FRB technique is used in combination with GA for uncertainty treatment of unit costs of maintenance of the LNG containment system and the transfer arm for optimal maintenance in Chapter 5. A discrete fuzzy set method is used in combination with ER to assess the safety/risk levels of failure modes of the LNG containment system and the transfer arm and select the best RCOs based on the safety principles of FSA in Chapter 6.

2.11. Evidential Reasoning

ER was developed in the 1990s to deal with Multiple Criteria Decision Making (MCDM) problems under uncertainty (Godaliyadde, 2008). It solves problems of both quantitative and qualitative nature with uncertainty. The ER algorithm is based on the decision theory and the Dempster-Shafer (D-S) theory of evidence, which is well suited for handling incomplete assessment of uncertainty (Yang, 2001; Yang and Singh; 1994). D-S theory is a mathematical theory of evidence that can combine different evidences together using their Degree of Beliefs (DoBs). The ER is different from other conventional MCDM methods such as the Analytical Hierarchy Processing (AHP) and additive utility function approach because it uses a belief structure to represent an assessment as a distribution. The algorithm is used to aggregate criteria from the bottom level of criteria to the top level criterion. In other words, once the assessments of the conditions of components of a system have been carried out, the overall assessment of the whole system can be obtained using the ER algorithm. The ER algorithm synthesises the conditions of the components with respect to their evaluation grades associated with the DoB.

Suppose a system has two subsystems and the subsystems have components. To assess the safety/risk level of the system, the components safety/risk levels can be synthesised using the ER approach. In such ER assessment framework, four synthesis axioms are proposed as (Godaliyadde, 2008):

- If no subsystem is assessed to an evaluation grade at all, then the system should not be assessed to the same grade either.
- If all components are precisely assessed to an individual grade, then the system should also be precisely assessed to the same grade.
- If all components are completely assessed to a subset of grades, then the system should be completely assessed to the same subset as well.
- If any component assessment is incomplete, then a system assessment obtained by aggregating the incomplete and complete component assessments should also be incomplete with the degree of incompleteness properly assigned.

The properties of ER are (Sönmez et al., 2001, Yang and Xu, 2002):

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

Practical application of ER in combination with fuzzy set has been illustrated in Chapter 6. In Chapter 6, ER is used to synthesise the safety/risk levels of failure modes of the LNG carrier containment system and transfer arm respectively, which are modelled using fuzzy set. The ER has also been proved to be a useful tool in many decision making applications (Godaliyadde et al., 2009; Liu et al., 1994; Sönmez et al., 2001; Tang et al., 2004; Wang et al., 1995; Wang et al., 1996; Wang, 1997; Wang, 2000; Wang, 2002; Wang and Yang, 2001; Yang, 2001; Yang et al., 2005; Yang and Singh, 1994; Yang and Xu, 2002; Xu and Yang, 2005; Xu et al., 2006).

2.12. Justification of Research

The operations of LNG carriers are associated with hazards estimated as high, medium, low and negligible risk hazards. The high risk hazards are threats to LNG carrier operations as the occurrence of these hazards will result in a catastrophic or critical consequence. The increase in demand and supply of LNG in recent time, poses to be a threat to the marine environment and public because high risk hazards might be inevitable, if not properly handled. The number of voyages per year has increased drastically, and is likely that the vessels will start changing routes more frequently due to "cross-trades" and "gas swaps". To maintain the LNG industry's strong safety record, potential high risk hazards need to be addressed, then there is need for this research. A proactive approach is used to conduct a probabilistic and subjective risk assessment and maintenance modelling of LNG carrier operations.

In view of that, HAZID of LNG carrier operations are conducted using a risk matrix approach. The risks associated with the hazards are prioritized to concentrate on the high risk ones. The failure modes (basic events) of high risk LNG carrier systems are identified using FTA. A PRA is conducted to identify their probabilities of failure and failure frequencies for effective maintenance modelling. Maintenance modelling is carried out using GA to reasonably assign the maintenance cost to each system for obtaining the optimal reliability improvement of the whole high risk LNG carrier systems.

In addition, the problems of uncertainties associated with the unit costs of maintenance of high risk LNG carrier systems are solved. A solution is adopted by employing the service of a FRB method. Expert judgment is used to develop 125 rules of FRB of the LNG carrier system maintenance cost with antecedents such as technical consultancy cost, maintenance duration and spare part cost; and consequent such as maintenance cost.

Furthermore, the challenges of existence of uncertainties of failure modes of the high risk LNG carrier systems are overcame using subjective (possibilistic) risk assessment approaches. The FER is incorporated with the FSA in the uncertainty treatment of the failure modes to ascertain the unacceptable safety states of the high risk LNG carrier systems, and recommend Risk Control Measures (RCMs) for improvement of the systems safety and reliability.

2.13. Conclusion

A thorough literature search has been conducted in this chapter. The detailed risk assessment of LNG carrier and various safety analysis techniques can be used in HAZID and risk estimation. Such safety analysis techniques include HAZOP, PHA, FMECA, and What-If-Technique, FTA, ETA, CCA and risk matrix. The FTA and risk matrix are adopted as qualitative/quantitative safety analysis techniques in this research. Maintenance strategies such as preventive, reactive, predictive and proactive are also explained. The FSA is reviewed and the various subjective and probabilistic applications in the maritime industry are outlined. Algorithms such as fuzzy logic, GA and ER are highlighted for solving risk assessment and maintenance modelling problems in the LNG industry in this research.

The innovative research in this thesis has been illustrated using four core chapters. The four core chapters are developed as the way forward with the aim of proposing a proactive approach for risk assessment of LNG carrier operations and maintenance modelling. These include "HAZID and Risk Prioritization of LNG Carrier Operations Using a Risk Matrix Approach (Chapter 3)", "Application of GA to Risk-Based Maintenance Operations of LNG Carrier Systems (Chapter 4)", "A Fuzzy GA (FGA) Approach to Analyse Maintenance Cost of High Risk LNG Carrier Systems under Uncertainty (Chapter 5)", and "A New FER Method for Risk Analysis and Control of LNG Carrier Systems (Chapter 6)".

Chapter 3 – Hazard Identification and Risk Prioritization of Liquefied Natural Gas Carriers Operations Using a Risk Matrix Approach

Summary

In this chapter, HAZID of LNG carrier operations is carried out using a brainstorming technique. A risk matrix approach is employed to estimate the risks of hazards associated with the LNG carrier operations using expert judgment. In the risk matrix table, the linguistic terms such as frequent, probable, occasional and remote are used to estimate the occurrence likelihoods of LNG carrier hazards, while the consequences of the hazards are estimated using the linguistic terms such as catastrophic, critical, marginal and negligible.

3.1. Introduction

The recent interest in increasing fleet of LNG carriers and expansion or building of new LNG facilities to accommodate the carriers, along with increased awareness on potential terrorist threats has caused stakeholders to raise questions about the potential consequences of incidents involving LNG carrier operations (ABS consulting, 2004). Therefore, HAZID needs to be carried out on a generic LNG carrier. The greatest concern of LNG carriers is hazards that could cause LNG spills. Some of these hazards are regarded as high risks to LNG carrier operations. Expert judgment is used to estimate the high risks hazards due to uncertainties of their failure rates. HAZID of a generic LNG carrier will proactively ensure the safety of LNG vessels and their systems/subsystems if acted upon, as well as provide a basis of analysing the measures of their pollution prevention to the maritime environment.

In this work, components of a LNG value chain are identified and described with particular attention on the transportation of LNG using LNG carriers in a qualitative risk analysis framework. Natural gas production, liquefaction of natural gas, transportation of LNG, re-gasification, and distribution to end users are described as the five main components of a LNG value chain (Foss, 2003; Sophia and Anne, 2006). The properties of LNG determine its hazards such as explosion, vapour clouds, rollover, freezing liquid, rapid phase transition, and pool fire. These LNG hazards are caused by failures of LNG carrier operations. In view of that, all relevant hazards that might affect the proper functions of LNG carriers and their systems and subsystems are identified using a brainstorming technique. Brainstorming is a technique for tapping the creative thinking of a team to generate and clarify a list of ideas, problems and issues (Wang and Trbojevic, 2007).

The above process is proactive and not confined only to the hazards that materialised in the past. Previous experience is properly taken into account and background information such as applicable regulations and codes, list of hazards of LNG carriers, hazardous substances and ignition sources are used. The failure rate values of the generic LNG carrier systems may be difficult to achieve because of the high level of uncertainties associated with the historical data. Therefore, use of expert judgment and a risk matrix technique can provide an alternative solution of prioritising high risk hazards of LNG carriers.

3.2. Background Analysis

The relevance of qualitative risk analysis using a risk matrix technique has been proved in many industries. Qualitative risk analysis is used in the fishing industry to prioritize issues across the seven most valuable Western Australian commercial fisheries (Fletcher, 2005). The brainstorming technique is used by stakeholders to identify issues across three ecological areas such as retained species, non-retained species and the broader ecosystem for each fishery. The risk associated with each issue is assessed using one of the five sets of consequence criteria specifically developed to cover fishery-related impacts. The risk score for each issue is identified using a risk matrix technique. Identification of the group of worst issues in 115 issues across the three ecological areas, improved their entire fish management processes.

The risk matrix technique is used in the defence industry to estimate the risks of hazards associated with military defence systems (Military Standard, 1993). Their experts carried out the HAZID using the brainstorming technique. The experts applied the risk matrix technique to the hazards of the defence systems by using four categories of occurrence likelihood of hazards and four consequence levels on the systems.

In the process industry, the risk matrix technique has also been used in the selection of accident scenarios of an ethylene oxide storage system which needed to be modelled in the calculation of the severity of hazards (Delvosalle, 2006). The usefulness of the risk matrix technique has been proven in management science (Haifang, et al., 2009). In their work, a risk matrix technique is used to identify the key risk factors of the use of private capital in a government project. The work of Zhu et al. (2003) demonstrated the effectiveness of risk matrix technique in technical project risk management.

In the maritime industry, the risk matrix technique has been extensively used in the risk estimation of hazards of shipping activities (Eleye-Datubo, 2006; Loughran et al., 2002; Pillay and Wang, 2003). The technique is applied to a list of hazards of a fishing vessel. The HAZID of the fishing vessel is carried out via the opinion of highly experienced personnel, which is detailed in Loughran et al. (2002) and Pillay and Wang (2003), using case studies.

A similar step by step process of HAZID and risk estimation using a risk matrix technique is applied to a bulk carrier (Eleye-Datubo, 2006). The application of the risk matrix technique to a bulk carrier, proved to be a contribution to knowledge of qualitative risk analysis of vessels. Since the IMO recommended the risk matrix technique in their rule making process (IMO, 2002), it is applied in this research.

3.3. Risk Matrix Methodology

A risk matrix technique (Eleye-Datubo, 2006; Helebsky, 1989; Pillay and Wang, 2003; Tummala and Leung, 1995) is a qualitative risk analysis method used to estimate the risks of hazards in the engineering industries. Expert judgement is used to estimate the risks of hazards of marine and offshore facilities, including LNG carriers for effective hazard ranking. The risk matrix technique serves as a tool for pre-comprehensive risk analysis of a generic LNG carrier shown in Figure 3.1. This can be achieved by using Tables 3.1 and 3.2 to develop a risk matrix table, illustrated in Table 3.3. The description of the risk levels and risk scores of the risk matrix table is shown in Table 3.4. The flow chart of the risk matrix methodology of a generic LNG carrier is shown in Figure 3.2. In Figure 3.2, the information flow starts from the description of a generic LNG carrier, followed by identification of hazards of LNG carrier operations using a brainstorming technique and development of a risk matrix table. The risk matrix table is made up of the consequence and occurrence likelihood, which are used to calculate the risk scores of the hazards. Then, the hazards are prioritized using their risk scores in order to categorise them. Hazards associated with high risks are represented with Fault Tree (FT) diagrams, while the ones associated other risk categories may not be investigated further.

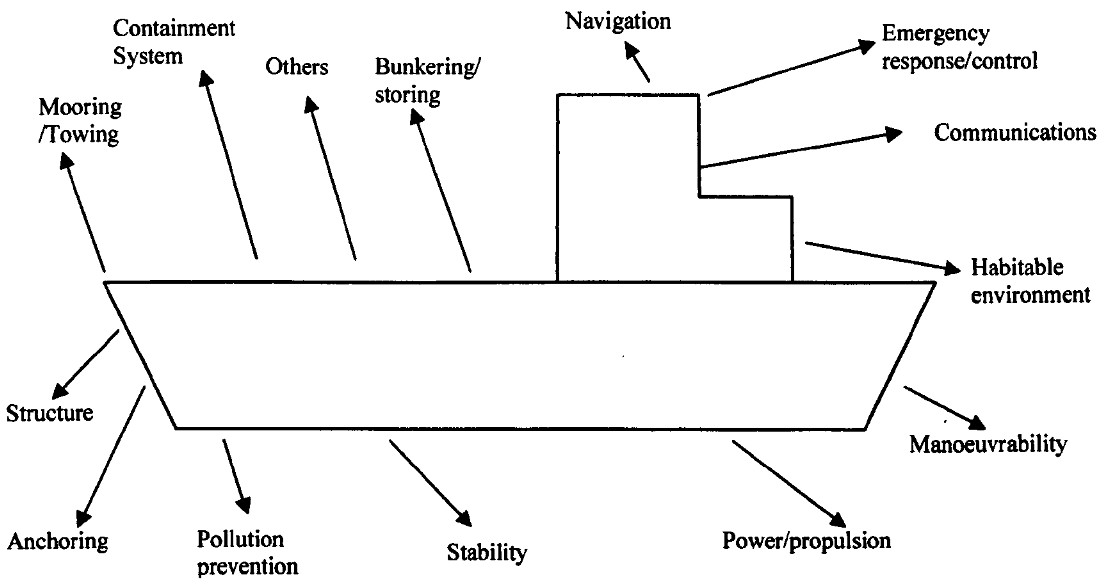

Figure 3.1: A Generic LNG Carrier

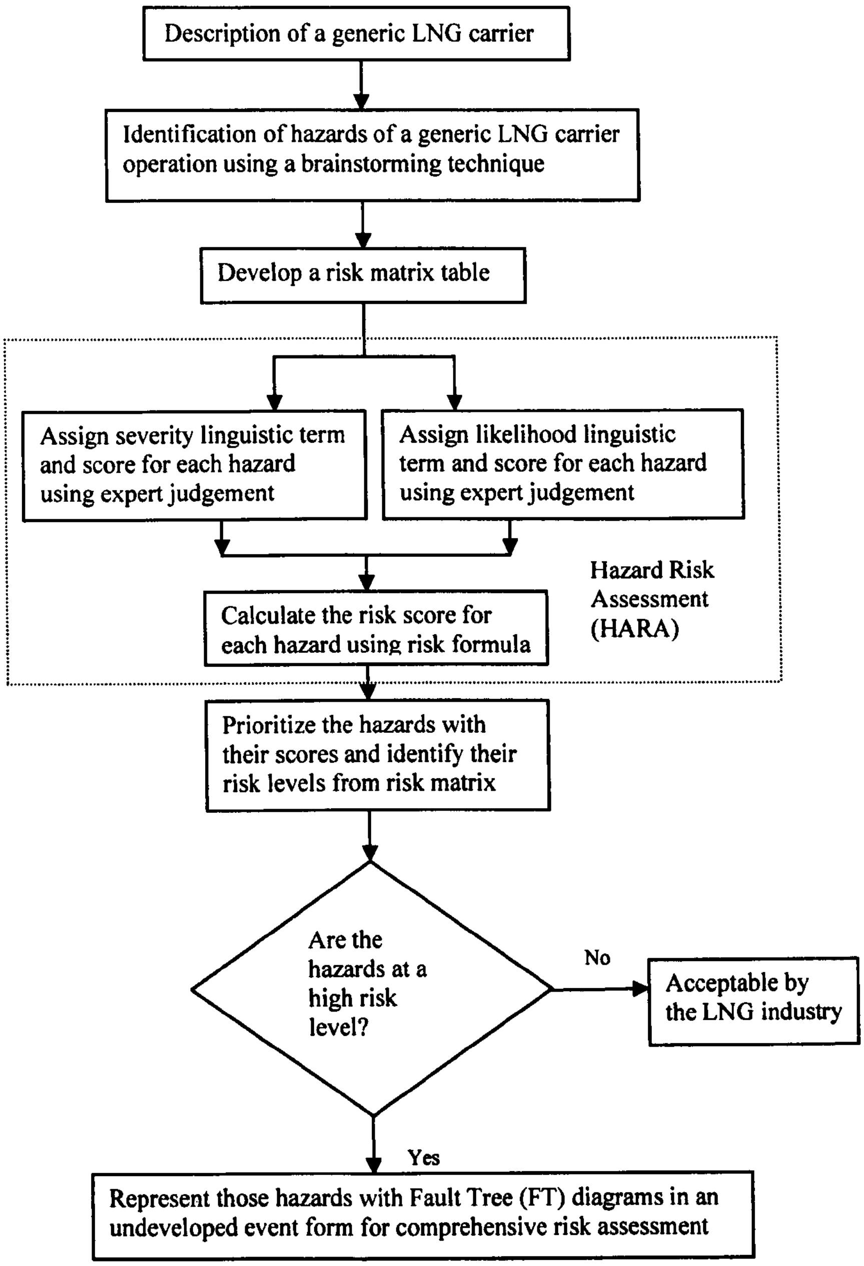

Figure 3.2: A Flow Chart of Risk Matrix Methodology of a Generic LNG Carrier

Table 3.1: Description of Consequence of a Hazard

Linguistic term for consequence of a hazard	Description
Negligible	Less than minor system damage, less than minor injury/illness of personnel or negligible environmental damage.
Marginal	Minor system damage, minor injury/illness of personnel or minor environmental damage
Critical	Major system damage, severe injury/illness of personnel or major environmental damage
Catastrophic	System loss, death of personnel or severe environmental damage.

Table 3.2: Description of Occurrence Likelihood of a Hazard

Linguistic term for occurrence likelihood of a hazard	Description
Less possible	The hazard is unlikely to occur compared to other hazards.
Possible	The hazard is likely to occur compared to other hazards.
More possible	The hazard is reasonably likely to occur compared to other hazards.
Most possible	The hazard is highly likely to occur compared to other hazards.

Table 3.3: Risk Matrix Table

Consequences of hazards with scores that are expressed in $\log_{10} 10$	Occurrence likelihoods of hazards with scores that are expressed in $\log_{10} 10$			
	1. Less possible	2. Possible	3.More possible	4.Most possible
1. Negligible	2	3	4	5
2. Marginal	3	4	5	6
3. Critical	4	5	6	7
4. Catastrophic	5	6	7	8

Each of the scores of the occurrence likelihood and consequence of the hazards in Table 3.3, are expressed in a logarithmic scale. For example, a score of 2 is equivalent to $\log_{10} 10^2$. In Row 1 of Table 3.3, the occurrence likelihood of a hazard can be described using linguistic terms such as less possible, possible, more possible and most possible with their scores of 1, 2, 3 and 4 respectively. In Column 1 of the same table, the consequence of the hazard can be described using linguistic terms such as negligible, marginal, critical and catastrophic with their scores of 1, 2, 3 and 4 respectively. The areas of intersections of the rows and the columns of Table 3.3 are the risks associated with the hazards. Therefore, 2 to 8 are the scores of the risks associated with the hazards. Risk is expressed as follows:

$$\text{Risk (R)} = \text{Occurrence likelihood of a Hazard} \times \text{Consequence of the Hazard} \quad (3.1)$$

$$\text{Log (Risk)} = \text{Log (Occurrence likelihood of a Hazard)} + \text{Log (Consequence of the Hazard)} \quad (3.2)$$

There are four risk levels in Table 3.4 defined by expert judgement using risk scores. These are high, moderate, low and very low risks with their respective risk scores. 6, 7 and 8 are high risk scores in the high risk area of Table 3.4. 5 is a moderate risk score in the moderate risk area of Table 3.4. 3 and 4 are low risk scores in the low risk area of Table 3.4. 2 is a very low risk score in the very low risk area of Table 3.4.

Table 3.4: Description of Risk Levels and Risk Scores of the Risk Matrix Table

Risk levels	Risk scores	Description of risk Levels
High	6, 7, 8	Vessel operations have to be prohibited until the risk is reduced to an acceptable level.
Moderate	5	Vessel operations can continue while risk reduction measures are being applied at an acceptable cost.
Low	3, 4	Vessel operations continue while efforts are being made to reduce the risk, but the cost of prevention should be carefully measured and limited. Risk reduction methods should be implemented within a defined time period.
Very Low	2	Actions are required on the vessel while in operation, if there is no additional cost burden.

3.4. Safety of LNG Carriers

The LNG shipping industry has an exemplary safety record in terms of cargo loss compared to other areas of the shipping industry. Few accidents have occurred since the first converted freighter delivered a Lake Charles, Louisiana cargo of LNG to the United Kingdom in January 1959, none involved a major release of LNG (CLNG, 2008). The safety record of the LNG shipping industry is attributed to safety design of LNG carriers and their effectiveness in handling accidents that happened in the industry using four levels of awareness. These are (Chauvel, 1997):

- Discovering. Associated with curiosity on what went wrong, which results in development of better ideas for improvement.
- Learning. Once new and better ways of doing things have been discovered, this knowledge has to be accepted and passed to future generations and other colleagues in the LNG shipping industry.
- Understanding. Once new ways of working have been established, research and reflection facilitate the level of understanding of the principles based on scientific methods.
- Developing. This is the final stage of the cycle based on the understanding. A new system can be developed with confidence because the outcome can be safely controlled.

The containment tank of a LNG carrier stores LNG at a temperature of about -256^0F (-160^0C) (California Energy Commission, 2003). All LNG carriers are constructed with double hulls (Sandia National Laboratory, 2005). This construction method improves the integrity of the hull system and provides protection for the cargo containment tanks in the event of an accidental collision (Sandia National Laboratory, 2005). The LNG carrier has cargo handling, ship handling and safeguard systems that have the ability to ensure safe delivery of LNG from source to the destination (Foss, 2003). LNG carriers are built with three major cargo containment tanks such as (Foss, 2003):

- Membrane tank design.
- Spherical (moss) tank design.
- Structural prismatic tank design.

3.4.1. Membrane Tank Design

Most LNG carriers are built with membrane tanks that have double containment. The double containment is made up of primary and secondary containment. The primary containment holds LNG while the secondary containment secures the LNG whenever there is leakage. The inner shell consists of thin stainless steel called a membrane that is about 0.7-1.2millimeters (mm) thick (Pitblado, et al., 2004). It is capable of containing the hydrostatic load of LNG, though relies on the vessel for structural support (Pitblado, et al., 2004). Plywood and thick perlite or polyurethane insulation separates the membranes and the space between them is filled up with nitrogen. The membrane tank design has almost zero stress and its structure is below the main deck of the LNG carriers. Such features protect the carriers from external/terrorist attacks (Foss, 2003). A large cofferdam separates each membrane tank so as to reduce the potential of an event in one tank affecting the other (Pitblado, et al., 2004).

3.4.2. Spherical (Moss) Tank Design

Some of the LNG carriers have spherical (moss) containment tanks. Spherical (moss) tank design has double containment as membrane tank, but with different tank shape. The LNG carrier containment tank has a spherical shape and maintains its own structural integrity, without depending on the vessel for support. The LNG carrier containment tank is exposed to external/terrorist attack because the covers of spherical tanks are above the carrier deck, though the tanks are separated with barriers. Aluminium with thickness of 29 to 57mm is used to construct the spherical tanks (Pitblado, et al., 2004). The secondary barrier of a spherical (moss) tank is a splash barrier with a drip pan at the bottom from which accumulated liquid evaporates, because the tank does not depend on the vessel for support (Foss, 2003). The holds collect spilled LNG and the vessels contain equipment capable of recovering LNG (Sandia National Laboratory, 2005). The tanker uses nitrogen to purge some below decks spaces to aid in preventing fires (Sandia National Laboratory, 2005).

3.4.3. Structural Prismatic Tank

The structural prismatic tank design is similar to a membrane tank. The tank has the same application of secondary containment and primary containment safety systems. The tank is also similar to the spherical (moss) tank because it is a self-supported tank that does not rely on the vessel for support (Sandia National Laboratory, 2005). Prismatic tanks are designed to conform to the shape of the LNG carrier's hull, thereby occupying much of the internal area of the carrier. It minimizes the areas in which LNG from a tank rupture or spills can be diverted (Sandia National Laboratory, 2005).

3.5. Hazards of LNG Carriers

Despite all the safety features of LNG carrier systems and subsystems, there are still potential hazards that might impair the proper functioning of LNG carrier operations. Most of these hazards seem to be unavoidable during the operational mode of the LNG carrier systems and subsystems. These hazards are identified and screened using a brainstorming technique by experienced marine professionals. The four experts are considered to have equal experience of the LNG carrier operations and include:

- Professor Jin Wang (Expert #1): A professor of marine technology at Liverpool John Moores University, United Kingdom with more than 10 years experience in field of marine engineering.
- Dr. Stephen Bonsall (Expert #2): A senior lecturer at Liverpool John Moores University, United Kingdom with more than 10 years experience in field of marine operations.
- Dr. Ramin Riahi (Expert #3): A researcher at Liverpool John Moores University, United Kingdom with more than 10 years experience in field of marine engineering.
- Captain Kambiz Mokhtari (Expert #4): A researcher at Liverpool John Moores University, United Kingdom with more than 10 years experience in field of marine operations.

The identified hazards of the LNG carriers are the ones associated with their operations and external events, such as:

- Structural damage due to incorrect loading.
- Overfilling of tanks.

- Overpressure of tanks.
- Unignited leak in the cargo system.
- Fire in cargo handling.
- Fire in forward storage area.
- Explosion in engine room due to crank house failure.
- Explosion in cargo handling.
- Earthquake.
- Lightning.
- Sabotage.
- War action.
- Collision.
- Workplace accident.
- Crane operations.
- Working in tanks/enclosed spaces.
- Operating error.
- Leak from loading arm.
- Loss of instrumentation during loading operations.
- Unignited leak from tank.
- Ignited leak from tank.
- Gas freezing.
- Waves.

The identified hazards are ranked and screened based on their risk level using expert judgement and the risk matrix technique explained in Section 3.3. The high risk hazards are represented with a FT diagram for detailed risk analysis in Chapters 4, 5 and 6. There are other safety analysis techniques that can be used to identify LNG carrier hazards, which depend on the choice of experts and available data. The acceptable safety analysis techniques in the LNG industry have been discussed in Section 2.5.2 of Chapter 2.

3.6. A Test Case of Application of the Risk Matrix Technique to Hazards of a Generic LNG Carrier

The qualitative risk assessment of the hazards of generic LNG carrier operations using a risk matrix technique will be carried out as follows:

- Develop a table containing hazard no., name of hazard, occurrence likelihood of hazard, consequence of hazard, risk score and risk level.
- List the hazards of a generic LNG carrier that are identified in Section 3.5 in the column for name of hazard.
- Estimate the occurrence likelihoods of hazards of a generic LNG carrier using expert judgement with the information provided in the risk matrix table illustrated in Table 3.3.
- Estimate the consequences of hazards of a generic LNG carrier using expert jugdement and a risk matrix table illustrated in Table 3.3.
- Calculate the risk score of the hazards of a generic LNG carrier using Equation (3.2), and a risk matrix table illustrated in Table 3.3.
- Estimate the risk levels of the hazards of a generic LNG carrier using their risk scores in Table 3.3.
- Prioritize the hazards of a generic LNG carrier based on their risk scores and risk levels.
- Represent the high risk hazards with FT diagrams for comprehensive risk analysis.

The risks of hazards of a generic LNG carrier are estimated by expert judgement using the risk matrix table, Table 3.3. The experts involved have equal experience of the subject under investigation and are described as marine risk analyst, marine safety engineer, marine chief engineer and ship captain. The results of the expert judgment are illustrated in Table 3.5. In Table 3.5, risk estimation of hazard no. 1 is calculated using the information in Table 3.3 and Equation (3.2) as follows:

Log (Risk) = Log (Occurrence likelihood of Hazard) + Log (Consequence of the Hazard)

Therefore, risk score of hazard no. 1 (Structural damage due to incorrect loading) = Score of "possible" + Score of "critical" = 5

where the score of "possible" is 2 and score of "critical" is 3 in Table 3.3. Such a risk score is classified as a moderate risk level as shown in Table 3.4. In a similar way, hazard no. 2 to 23 occurrence likelihoods, consequences, risk scores and risk levels are found, as illustrated in Table 3.5.

Table 3.5: Hazards of a Generic LNG Carrier and their Risk Levels

Hazard no.	Name of a hazard	Occurrence likelihood of a hazard	Consequence of a hazard	Risk score	Risk level
1	Structural damage due to incorrect loading	Possible	Critical	5	Moderate
2	Overfilling of tanks	More possible	Marginal	5	Moderate
3	Overpressure of tanks	Less possible	Catastrophic	5	Moderate
4	Unignited leak in the cargo system	Less possible	Critical	4	Low
5	Fire in cargo handling module	Possible	Critical	5	Moderate
6	Fire in forward storage area	Possible	Critical	5	Moderate
7	Explosion in engine room due to crank house failure.	Less possible	Marginal	3	Low

8	Explosion in cargo handling	Less possible	Critical	4	Low
9	Earthquake	Less possible	Catastrophic	5	Moderate
10	Lightning	Less possible	Marginal	3	Low
11	Sabotage	Less possible	Critical	4	Low
12	War action	Less possible	Catastrophic	5	Moderate
13	Collision	Possible	Critical	5	Moderate
14	Workplace accident	Less possible	Marginal	3	Low
15	Crane operations	Less possible	Critical	4	Low
16	Working in tanks/enclosed spaces	Less possible	Catastrophic	5	Moderate
17	Operating error	More possible	Marginal	5	Moderate
18	Leak from loading arm	Most possible	Catastrophic	8	High
19	Loss of instrumentation during loading operations	Less possible	Marginal	3	Low
20	Unignited leak from tank	Possible	Critical	5	Moderate
21	Ignited leak from tank	Most possible	Catastrophic	8	High
22	Gas freezing	More possible	Marginal	5	Moderate
23	Waves	Possible	Critical	5	Moderate

Prioritization of hazards of a generic LNG carrier is very important in the LNG industry. From Table 3.5, hazard no. 18 and 21 have the highest risk scores and classified as high risk hazards by expert judgement using Tables 3.3 and 3.4. Attention is focused on the high risk hazards such as "ignited leak from tank" and "leak from loading arm". FTA is the proposed safety analysis technique for comprehensive risk analysis of "ignited leak from tank" and "leak from loading arm". Therefore, the top events of the high risk hazards of a generic LNG carrier are represented using FT diagrams with undeveloped events in Figures 3.3 and 3.4.

In Figure 3.3, a LNG containment system fails when structural defect, corrosion, fire and explosion, structural potential pressure difference (PD) or failure of supporting structure happens. In Figure 3.4, a LNG spill from transfer arm occurs when transfer arm failure, material defect or failure of piping happens.

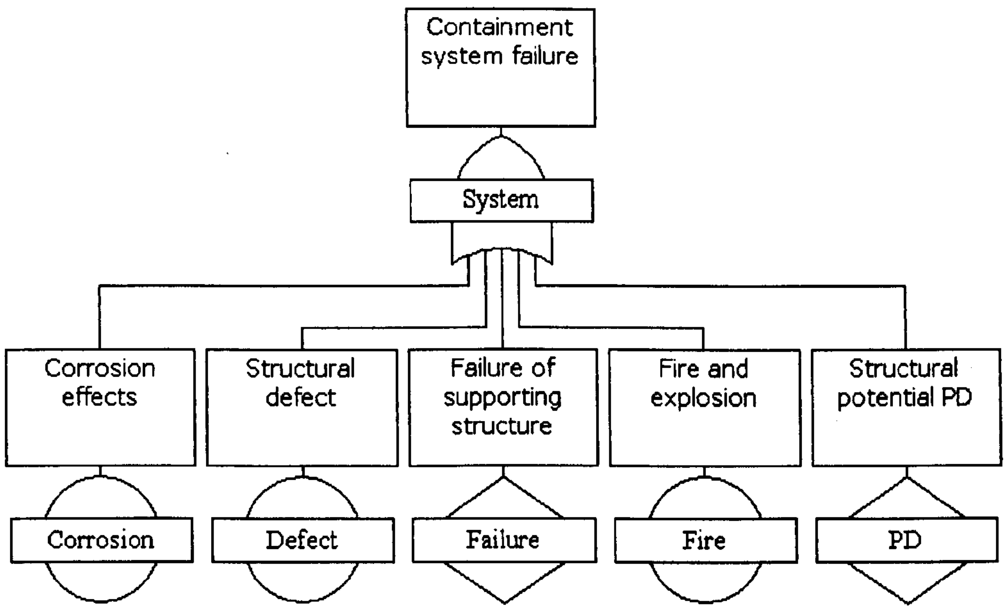

Figure 3.3: Fault Tree of a LNG Containment System Failure

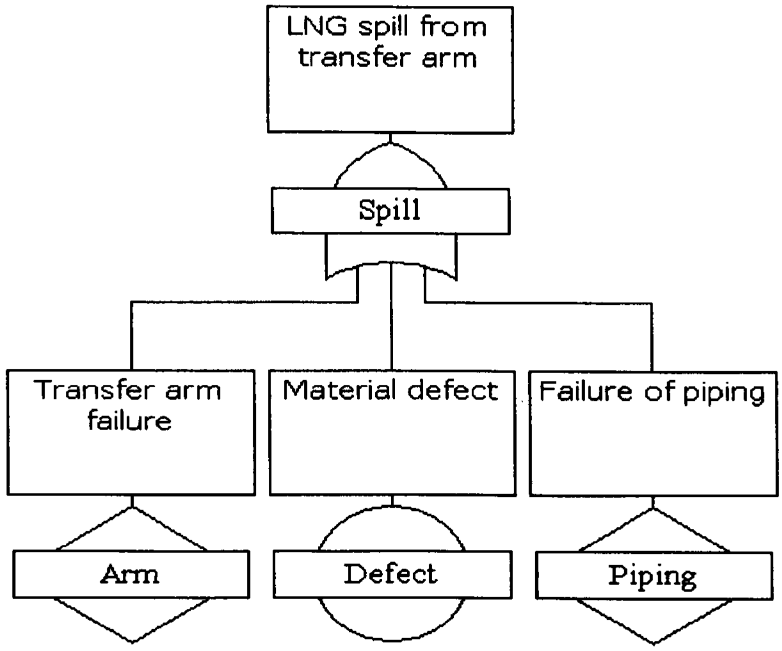

Figure 3.4: Fault Tree of a LNG Spill from Transfer Arm

3.7. Conclusion

HAZID of LNG carriers and prioritization of their associated risks have been successful with the use of the brainstorming technique and risk matrix approach. The risk levels of hazards of a LNG carrier are calculated using expert judgement and the mechanism of a risk matrix table. The mechanism is the categorised occurrence likelihood and consequences of hazards, coupled with risk formula, which facilitated the estimation of the risk scores. The hazards of a generic LNG carrier are prioritized using their risk scores. High risk is associated with high scores as defined in the risk matrix table. Two out of twenty-three of the hazards of a generic LNG carrier are found in a high risk area of the risk matrix table. Other hazards of a generic LNG carrier are in moderate, low and very low risk areas of the risk matrix table. High risk hazards are the major concern in the LNG industry. Therefore, high risk hazards of a generic LNG carrier such as "ignited leak from tank" and "leak from loading arm" pose threats to proper functioning of the LNG carrier systems and subsystems. Finally, FT diagrams with undeveloped events are used to represent the two high risk LNG carrier hazards for comprehensive risk analysis using advance techniques later.

Chapter 4 - Application of Genetic Algorithm to Risk-Based Maintenance Operations of Liquefied Natural Gas Carrier Systems

Summary

The concept of GA is used to model the cost of maintenance of a LNG containment system and its transfer arm, after assessing the total risk of the systems using the PRA technique. The failure frequency data of the basic events of the FT developed to model the LNG containment system and transfer arm, is derived from a careful literature search. A total risk formula is developed, which is dependent on hazard severity weight, failure frequencies, time and cost of maintenance of the LNG carrier systems. The formula serves as the objective function while new total cost allocated for maintenance of the LNG carrier systems as a whole is the constraint with boundaries of presenting initial/unit cost of maintenance of each of the containment system and transfer arm. Optimization is carried out on the objective function and its constraint for identification of new cost of maintaining the containment system and transfer arm independently with the powerful tool of GA using Matlab version 7.7 software for improvement of the system's safety level.

4.1. Introduction

The consumption rate of LNG has increased drastically in recent years, which is supplied using LNG carriers. This has led to public concern about the safety of the carriers and environment. The need for a higher number of LNG carriers is evident; indeed, over the last 10 years, LNG carriers have increased annually, while more new carriers are predicted in the years ahead. LNG carriers have been the most successful in the marine industry in terms of safety and reliability, which is achieved by close attention to detail in the development of new ideas, concepts and procedures used in the LNG industry. In April 2001 (Lloyd's, 2001), the general manager of the SIGTTO stated in an interview with Lloyd's List that the challenges of maintaining the LNG industry's strong safety record would increase in the future. In particular, it is noted that LNG shipping patterns are changing. Traditionally, LNG carriers were dedicated to serve specific terminals. In the future, carriers would be on changing routes more frequently due to "cross-trades" and "gas swaps" (Lloyd's, 2001). Risk assessment produces a comprehensive estimation of the possible consequences in a hazardous situation in order to select appropriate safety measures. It is believed to be useful for the LNG industry in identifying hazards and protecting against them, improving operations, efficiently using resources, and developing or complying with rules and regulations (ABS, 2000). This has subjected the maritime LNG carrier systems to regular/advance checks to ensure that a high level of safety maintained in the LNG industry is still standardised by increasing the systems' level of maintenance.

Cost effectiveness of the maintenance of LNG carrier systems obviously remains a challenge to the industry. Due to complexity of LNG carrier systems and the challenges ahead, a powerful engineering tool of GA that can solve multi-objective and complex problems is usefully adopted to tackle cost effectiveness of the maintenance of the LNG carrier systems. GA application needs procedures to be set up starting from the fitness function to the number of generations for an optimal solution. Detailed breakdown of the genetic operators modelling cost effectiveness analysis of LNG carriers will be addressed for understanding and easy application of simulation processes of the optimal safety solution to control total risk of the systems. The method of GA needed to solve engineering problems depends on the problem formulation and choice of its designer. In this chapter, a single objective GA is used to tackle cost of maintenance of LNG carrier systems.

4.2. Background Analysis

Since the invention of GA in USA in the mid 70s, it has been effectively applied in civil engineering, protein structure, nuclear engineering (Marseguerra et al., 2004), design engineering (Andrew and Bartlett, 2003), water networks, jobshop scheduling, facial recognition, control system, aeronautics engineering, robotics, liquid crystals, image processing and very large scale integration electronic chip layouts (Colley, 1999).

In civil engineering, the cost-effective risk based in situ bioremediation design is determined using GA. This optimises the management/mathematic model which can simultaneously predict risk and propose cost-effective options for reducing risk to acceptable levels. The model combines a GA with a numerical fate and transport model, an analytical fate and transport model, and an exposure and risk assessment model to identify cost-effective combinations of monitoring an active pumping to reduce risks (Minster et al., 1999).

FTA has been combined with the algorithm to accelerate its process, which has been applied in nuclear engineering to find the Optimal Surveillance Test Interval (STI) of Residual Heat Removal (RHR) safety system of a Boiling Water Reactor (BWR) (Marseguerra et al., 2004). In their work, multi-objective GA and FTA are used to achieve the aim after developing a mathematical model.

The usefulness of the combination of GA and FTA is extended to selection of the best design of a safety system such as a Fire Deluge System (FDS) that has 4.4×10^{10} design variations (Andrew and Bartlett, 2003). It tackled the problem of the traditional engineering design process that uses trial and error method in design of a system, whereupon a design is created, analysed and compared with predetermined criteria of acceptability. The FTA with Binary Decision Diagram (BDD) reduction was used to determine the availability performance of the system, i.e. the probability that it will not function on demand (Andrew and Bartlett, 2003). Similar design was carried out on a High-Integrity Protection (HIP) System with 10 design variables using a combination of GA and FTA (Pattison and Andrew, 1999).

It is obvious that GA is very useful to the industries today especially when it is combined with FTA. In this chapter, a combination of FTA and GA is applied to maritime risk assessment of LNG carrier systems, so as to identify the cost of maintenance of each system with assigned budgetary money for the whole system.

4.3. Genetic Algorithm

GA is an optimization and search technique based on the principle of genetics and natural selection (Haupt and Haupt, 2004). In other words, the GA iterates toward a global solution through a process that in many ways is analogous to the Darwinian process of natural selection (Venkatesan and Kumar, 2002). John Holland developed GA in the 1970s at the University of Michigan (Andrew and Bartlett, 2003) and the method was finally popularized by one of his students, David Goldberg, who was able to solve a difficult problem involving the control of gas-pipeline transmission in his dissertation (Haupt and Haupt, 2004). The goal of John Holland's research has been to abstract and rigorously explain the adaptive processes of natural systems, and to design artificial systems software that retains the important mechanisms of natural systems (Goldberg, 1989). A GA allows a population composed of many individuals to evolve under specified selection rules to a state that maximizes the "fitness" (i.e., minimize the objective function) (Haupt and Haupt, 2004). A typical algorithm might consist of the following elements (Colley, 1999):

- A number or population of guesses of the solutions to a problem.
- A way of calculating how good or bad the individual solutions within the population are.
- A method for mixing fragments of the better solutions to form new, on average even better solutions.
- A mutation operator to avoid permanent loss of diversity within the solutions.

Prior to the application of a GA, it is necessary to demonstrate a representation scheme, define the fitness function measure, define the parameters and variables for controlling the algorithm and designate a performance measure and a criterion for terminating a run (Andrew and Bartlett, 2003). The flow chart in Figure 4.1 illustrates a simple GA methodology for better and easy understanding of the process; an example is included in Appendix C1.1. The selection of GA methods needed to solve engineering problems depends on the problem formulation and choice of the designer. Binary (Andrew and Bartlett, 2003; Haupt and Haupt, 2004; Colley, 1999; Harikumar et al., 2004), continuous, steady state (Colley, 1999; Mitchell, 1996; Podofillini et al., 2006) and multiobjective (Torres-Echeverria and Thompson, 2007) GAs are the methods of GA, which have been discussed in Chapter 2.

In this research, a continuous GA is used because it gives an exact or approximate optimal solution as it uses internal precision of the computer and round off to define the precision of the chromosomes (values) during the computational processes. A continuous GA uses real numbers to encode the variables. The difference in the continuous parameter GA occurs in the computation of the fitness function and the crossover and mutation operators (Harikumar et al., 2004).

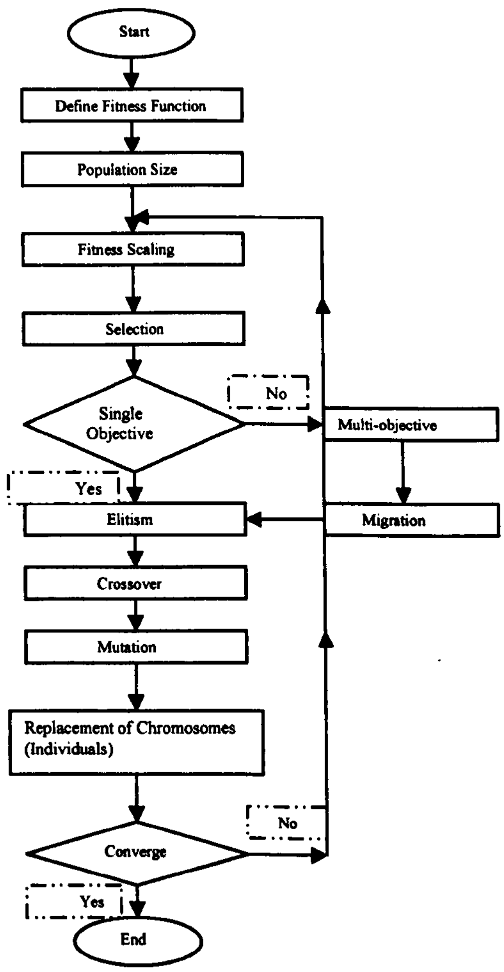

Figure 4.1: Flow Chart of Genetic Algorithm Methodology

In this method, an initial population was formulated using chromosomes (real numbers) and evaluation and selection of the chromosomes will be carried out using the defined fitness function. Elitism is introduced as an operator that ensures that the GA retains the best chromosomes (individuals) at each generation because sometimes a selection operator does not guarantee that the fittest chromosomes are selected for the next generation. Prior to mutation of the chromosomes (parents and offspring), the selected ones (parents) will reproduce offspring by using a genetic operator called crossover. Selection operator could be a roulette wheel selection (Haupt and Haupt, 2004; Colley, 1999; Mitchell, 1996; Man et al., 1999), stochastic universal sampling selection (Colley, 1999; Mitchell, 1996; Man et al., 1999), or tournament selection (Haupt and Haupt, 2004; Mitchell, 1996; Man et al., 1999) while the crossover operators could be a single point crossover (Haupt and Haupt, 2004; Colley, 1999; Mitchell, 1996), two point crossover (Haupt and Haupt, 2004; Colley, 1999; Mitchell, 1996; Sakawa, 2002) and multipoint crossover (Colley, 1999; Man et al., 1999; Sakawa, 2002). The mutation of the offspring reproduced by randomly altering the values of genes in the chromosomes, ensures that there will be no premature convergence during the process of GA to achieve an acceptable optimum solution. Mutation is applied with a lower probability than the crossover probability (Alim, 2007). The offspring formed will replace the weak chromosomes that were not selected during evaluation of the fittest chromosomes as defined by the objective (fitness) function, which leads to the form of a new population. This process of selection, elitism, crossover, and mutation continues until a fixed number of generations have elapsed or some forms of convergence criterion have been met (Colley, 1999).

4.4. Fault Tree Analysis

FTA is a productive hazard analysis technique widely used in the LNG industry. It was invented in 1961 by H. A. Watson of Bell laboratories during the execution of a U.S. Air force contract to study the Minuteman Launch Control System and was developed by Dave Haasl of the Boeing company who applied FTA to the whole Minuteman Missile System with his team in 1964, after recognising FTA as a major system safety analysis tool in 1963. The FTA concept is the translation of the failure behaviour of a physical system into a visual model that portrays system relationships, root cause fault paths, and a logic model, providing the mechanism for qualitative and quantitative evaluation (Ericson II, 1999). FTA is carried out using a deductive analysis from the top event, which is the undesired event followed by causal relationships of the failures leading to that event identified by experience from previous accident and incident/accident reports of the event in question. FTA can be evaluated using two major techniques such as:

- FTA reduction by BDD.
- FTA reduction by Boolean algebra.

The steps for performing FTA using BDD are (Bartlett, 2000, Bartlett and Andrews, 2002):

- Identification of top event.
- Development of the top event through a top down process by determining the intermediate failures and combinations of failures or events that are the minimum to cause the next higher level event to occur as the logic being represented with the example FT in Figure 4.2.
- Continuation of the top down process until further decomposition is not necessary.
- Determination of probabilities of failure assigned to the events at the lowest level.
- Pre-processing of the FT using two techniques such as faunet reduction and modularisation, so that the smallest possible subtrees will be obtained for easy and efficient construction of BDD.
- Faunet reduction reduces the fault tree to its minimal logic form using three stages such as contraction, factorisation and extraction (Karen and Andrews, 2002).
- Modularisation identifies independent subtrees (modules) existing within the tree that can be analysed separately.
- Selection of most appropriate ordering scheme for each independent module of the FT based upon individual characteristics using neural network.
- Conversion of each module to BDD in separate computations using Shannon decomposition theorem, which represents the Boolean equation for the top event.
- Finally the set of BDDs can be quantitatively analysed simultaneously for the

occurrence probability of the top event and the criticality of basic events.

The procedural steps of performing a FTA using Boolean algebra are (Wang and Trbojevic, 2007):

- Identification of top event.
- Development of the top event through a top down process by determining the intermediate failures and combinations of failures or events that are the minimum to cause the next higher level event to occur as the logic being represented in Figure 4.2.
- Continuation of the top down process until further decomposition is not necessary.
- Determination of occurrence probabilities of the lowest level events.
- Using Boolean logic to establish a Boolean equation for the tree and evaluate the occurrence probability of the undesired top event.
- Determination of minimum cut sets.
- Compare to the system level requirement and if met, determine critical failure modes.

It is important to understand that a FT is not a model dealing with all possible systems failures and it covers the most credible faults as assessed by the analyst (Wang and Trbojevic, 2007). FTA uses different types of gates for its construction, which makes it a coherent FT (Amari, et al., 2003, Wang and Trbojevic, 2007) or non-coherent (Takehis, 2006). A coherent FT uses OR and AND gates to construct its tree as illustrated in Figure 4.2 and is mostly used in risk assessment in the LNG industry. OR and AND gates symbolize the relationship of events needed for high level events to happen/occur. The event at the higher level is the output of the gate while the events at the lower level are the inputs to the gate (Wang and Trbojevic, 2007). AND gate denotes that output occurs if all input faults occur. OR gate shows that output occurs if any one of the input faults occurs. FTA can be evaluated using both the qualitative evaluation and quantitative evaluation.

4.4.1. Qualitative Evaluation

Qualitative evaluation is the first phase of fault tree analysis before quantitative evaluation. FTA is a qualitative model that can be evaluated quantitatively (Norman, 1987). The tree is constructed starting with its top event and then with associated gates and events that lead to the occurrence of top event successively. The pathways, known as "cut sets" or "implicant sets", represent the entire events which give rise to the top event. A cut set is described as a collection of basic events; if all these basic events occur, the top event is guaranteed to occur (Wang and Trbojevic, 2007). In this evaluation technique, the minimum cut set is obtained using the Boolean algebra, which will be used in quantitative evaluation. Minimal cut sets are defined as an irreducible pathways leading to the occurrence of the top event (Wang and Trbojevic, 2007). The relevance of these sets must be carefully weighted and major emphasis placed on those of greatest significance (Pillay and Wang, 2003).

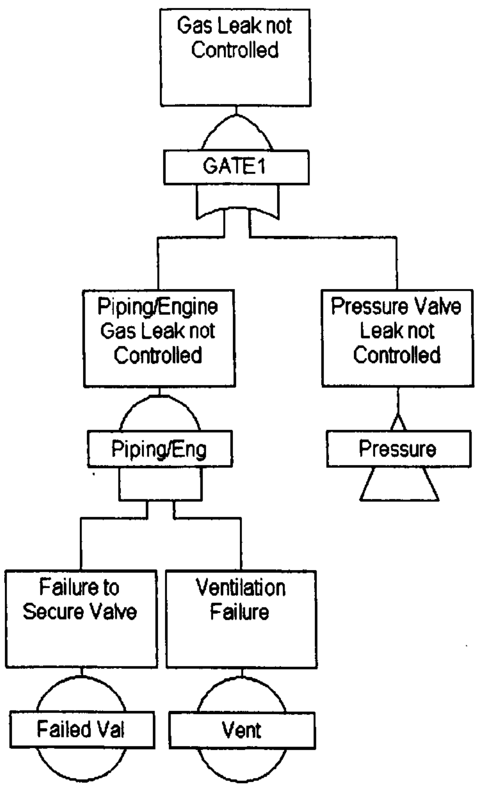

Figure 4.2: FTA of "Gas Leak not Controlled"

4.4.2. Quantitative Evaluation

Although a FT is primarily a qualitative method, it is also suited to quantify the occurrence probability of the undesired event and to determine the relative importance of events in the occurrence of the undesired event (Desmond and Gregory, 2004). Quantitative evaluation multiplies the usefulness of the FTA in the LNG industry. Once the minimal cut sets are defined, if quantitative results are desired, probability evaluations can be performed (Norman, 1987). The quantitative evaluation is most easily performed in a sequential manner, first by determining the component failure probabilities, then the minimal cut set probabilities and finally the top event (system) probability (Norman, 1987). The method used to achieve minimal cut sets is the Boolean algebra and set theory (see Appendix C1.2 for more details).

4.5. Risk Modelling of LNG Carrier Operations

Risk modelling can be carried out in LNG carrier systems using various safety analysis techniques. In this chapter, FTA explained in Section 4.4 will be used as the safety analysis technique to model the risk of LNG carrier systems because of its compatible advantage for cost effective modelling using the powerful tool of GA. Natural gas production, liquefaction of natural gas, transportation of LNG, re-gasification, and distribution to end users are the five main components of LNG value chains (Sophia and Anne, 2006; Foss, 2003). LNG carrier is used to transport the LNG and it is made of different systems and subsystems. The wide spread of the hazards in the distributed chains indicates the possible high risks of LNG carrier systems. Attention is focused on the systems through increasing the level of maintenance. Risk assessment is believed to be useful for the LNG industry to identify areas that need regular maintenance. Mathematically, risk can be expressed as follows:

$$\text{Risk} = \text{Consequences} \times \text{Likelihood} \tag{4.1}$$

$$= \text{Hazard Severity} \times \text{Failure Probability} \tag{4.2}$$

$= \text{Hazard Severity's Weight } (S_w) \times \text{Failure Probability } (P)$ (4.3)

In risk modelling/assessment of any LNG carrier system, failure probability intends to follow an exponential distribution. The exponential distribution is adopted because it is straightforward, computational effective, and can be used to demonstrate the useful life period of a system. At such period, failure rate is constant. Due to the constant failure rate, the exponential distribution is often regarded as the random failure distribution because it is independent of previous successful operating time (Andrew and Moss, 2002). The failure rate is the inverse of Mean Time Between Failure (MTBF). Therefore,

Risk (R) = $S_w \times P$

$$P = 1 - e^{-\lambda t} \tag{4.4}$$

$$\lambda = \frac{-\ln(1-P)}{t} \tag{4.5}$$

Therefore, R = $S_w^{'} \times (1 - e^{-\lambda t})$ (4.6)

where $1 - e^{-\lambda t}$ = Exponential distribution formula

P = Failure probability

λ = Failure rate/frequency

t = Time of interest

The risk level of the whole system is determined by the ones of its subsystems.

$$R_T = R_{SYSTEM(1)} + R_{SYSTEM(2)} + \dots\dots + R_{SYSTEM(n)} \tag{4.7}$$

where R_T = Total risk of the LNG carrier systems

$R_{SYSTEM(i)}$ = Risk of the LNG carrier subsystem i

$i = 1,2....n$ or $(i \in n)$

Consequently, Equation (4.8) is obtained by substituting Equation (4.6) in Equation (4.7) as follows:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1 t_1}) + S_{W(2)} \times (1 - e^{-\lambda_2 t_2}) + ... + S_{W(n)} \times (1 - e^{-\lambda_n t_n}) \qquad (4.8)$$

where $S_{W(i)}$ = Hazard Severity's Weight of the LNG carrier subsystem i

λ_i = Failure rate of the LNG carrier subsystem i

t_i = Time of interest of the LNG carrier subsystem i

$i = 1,2....n$ or $(i \in n)$

The risk associated with the top event (hazard) of a FTA modelling a LNG carrier system is evaluated in terms of its level. Risk assessment can be carried out at different phases of a LNG carrier and other facilities used in the LNG industry by extending FTA to include ETA for constructing a diagram called the "Risk Contribution Tree (RCT)" based on accident data and expert judgement to display the cause-effect. Risk assessment provides qualitative and/or quantitative information to decision makers (Wilcox, et al., 2000). This is illustrated in Figure 4.3. Qualitative and quantitative risk analyses are explained as follows (Eleye-Datubo, 2006):

- Qualitative risk analysis. It is associated with the identification of the hazards that are catastrophic, critical, marginal or negligible as categorised in Table 4.1. The occurrence probability of the hazards is expressed as frequent, probable, occasional or remote, as illustrated in Table 4.2. This analysis will lead to the knowledge of the level/consequence of risk, in the early design stage when data is not available for quantitative risk analysis.
- Quantitative risk analysis. It is associated with the use of characteristics of each individual component like failure rate, repair rate, system logic, maintenance schedule, mission time and human error to formulate a mathematical model that will help to identify high risk areas that need to be controlled.

Figure 4.3: A Diagram of Risk Assessment Technique (Pillay and Wang, 2003)

Hazards of LNG carrier systems identified based on probability of occurrence can be dealt with using the basis of design actions in Table 4.3, which is a combination of hazard consequence and hazard probability illustrated in Tables 4.1 and 4.2. These can be explained as follows:

- Design action is required to eliminate or control hazards classified as A-1, A-2, A-3, B-1, B-2 and C-1.
- Hazard consequences must be controlled or hazard probability reduced for hazards classified as B-3, C-2 and D-1.
- Hazard control is desirable if cost effective for hazards classified as C-3 and D-2.
- Hazard control is not cost effective for hazards classified as D-3.

Table 4.1: Hazard Consequence

Category	Weight	Description	Equipment	Personnel
1	1000	Catastrophic	System Loss	Death
2	100	Critical	Major System Damage	Severe Injury/Illness
3	10	Marginal	Minor System Damage	Minor Injury/Illness
4	1	Negligible	< Minor System Damage	<Minor Injury/Illness

Table 4.2: Hazard Probability

Level	Description	Frequency
A	Frequent	Likely to happen
B	Probable	Several times during lifetime
C	Occasional	Likely to happen once
D	Remote	Unlikely but possible during life time

Table 4.3: Risk Assessment Matrix

Hazard Severity	Weight	A (Frequent)	B (Probable)	C (Occasional)	D (remote)
1. Catastrophic	1000	A-1	B-1	C-1	D-1
2. Critical	100	A-2	B-2	C-2	D-2
3. Marginal	10	A-3	B-3	C-3	D-3
4. Negligible	1	Negligible hazards ←→ No action required			

4.6. Cost Modelling of LNG Carrier Operations

Cost modelling is carried out on the LNG carrier systems using information provided by risk modelling that identifies the system that needs more attention than others in the LNG industry, so as to reduce the frequency of failures and/or mitigate their possible consequence through improving their maintenance. To maintain and improve the level of safety in the LNG industry, the identified high risk systems of a LNG carrier need particular attention in terms of the level of maintenance carried out on them. To identify/forecast the even distribution of the cost of carrying out maintenance of the high risk LNG carrier systems per year (s) as a result of its operations remains a challenge to the industry because the risk of LNG carrier systems is taken into account in the cost distribution phase. Therefore, a mathematical formula relating to the risk of the LNG carrier systems and cost of their maintenance per year(s) will be developed.

From Equation (4.8), the total risk of the LNG carrier systems is expressed as follows:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1 t_1}) + S_{W(2)} \times (1 - e^{-\lambda_2 t_2}) + \ldots\ldots + S_{W(n)} \times (1 - e^{-\lambda_n t_n})$$

$$C_T = C_{SYSTEM(1)} + C_{SYSTEM(2)} + \ldots\ldots\ldots + C_{SYSTEM(n)} \tag{4.9}$$

where C_T = Total cost of maintenance of the LNG carrier systems

$C_{SYSTEM(i)}$ = Cost of maintenance of the LNG carrier system i

$i = 1,2 \ldots n$ or $(i \in n)$

To combine Equation (4.9) with Equation (4.8), t and C inverse relationship will be used as follows:

For LNG carrier system 1,

$$t_1 = \frac{1}{C_{SYSTEM(1u)}} \tag{4.10}$$

$$t_{11} = \frac{1}{C_{SYSTEM(1)}} \tag{4.11}$$

Equations (4.10) and (4.11) can be used to estimate the times at which a system will be maintained when there is less money for maintenance and more money for maintenance respectively. Therefore, Equations (4.10) and (4.11) can be combined to form Equation (4.12) as follows:

$$\frac{t_1}{t_{11}} = \frac{C_{SYSTEM(1)}}{C_{SYSTEM(1u)}}$$

Thus, $t_{11} = t_1 \frac{C_{SYSTEM(1u)}}{C_{SYSTEM(1)}}$ (4.12)

where t_1 = Initial maintenance time of the LNG carrier system 1

t_{11} = New maintenance time of the LNG carrier system 1

$C_{SYSTEM(1u)}$ = Unit (initial or minimum) cost of maintenance of the LNG carrier system 1

$C_{SYSTEM(1)}$ = New cost of maintenance of the LNG carrier system 1

In a similar way, $C_{SYSTEM(i)}$ $(i = 2,\dots\dots\dots n)$ can be represented respectively as follows:

$$t_{ii} = t_i \frac{C_{SYSTEM(iu)}}{C_{SYSTEM(i)}} \tag{4.13}$$

Substitute Equation (4.12) and (4.13) in Equation (4.8) as expressed below:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1 \left(\frac{t_1 C_{SYSTEM(1u)}}{C_{SYSTEM(1)}}\right)}) + S_{W(2)} \times (1 - e^{-\lambda_2 \left(\frac{t_2 C_{SYSTEM(2u)}}{C_{SYSTEM(2)}}\right)}) + .. S_{W(n)} \times (1 - e^{-\lambda_n \left(\frac{t_n C_{SYSTEM(nu)}}{C_{SYSTEM(n)}}\right)}) \tag{4.14}$$

The values of $S_{W(i)}$, λ_i, t_i, $C_{SYSTEM(i\max)}$ and $C_{SYSTEM(iu)}$ $(i = 1,\dots\dots\dots n)$ are always known, while the values of $C_{SYSTEM(i)}$ $(i = 1,\dots\dots\dots n)$ are unknown. However, the sum of them will be known as the maintenance budget in the real world, while $C_{SYSTEM(i\max)}$ is described as the maximum maintenance cost of system i. To obtain the value of $C_{SYSTEM(i)}$ $(i = 1,\dots\dots\dots n)$, an optimisation technique needs to be used to minimise the total risk of the LNG carrier system (R_T), given that the total cost (C_T) assigned for maintenance of the

LNG carrier system is summation of $C_{SYSTEM(i)}$ $(i = 1, \ldots\ldots\ldots n)$. GA is an optimisation technique that will be used to solve Equation (4.14). Therefore, the objective function will be expressed as follows:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1\left(\frac{t_1 C_{SYSTEM(1u)}}{C_{SYSTEM(1)}}\right)}) + S_{W(2)} \times (1 - e^{-\lambda_2\left(\frac{t_1 C_{SYSTEM(2u)}}{C_{SYSTEM(2)}}\right)}) + \ldots\ldots S_{W(n)} \times (1 - e^{-\lambda_n\left(\frac{t_1 C_{SYSTEM(nu)}}{C_{SYSTEM(n)}}\right)})$$

Subject to: (4.15)

$$C_T = C_{SYSTEM(1)} + C_{SYSTEM(2)} + \ldots\ldots\ldots C_{SYSTEM(n)}$$

$$C_{SYSTEM(iu)} \leq C_{SYSTEM(i)} \leq C_{SYSTEM(i\max)}$$

$$i = 1,2 \ldots n \text{ or } (i \in n)$$

4.7. Test Case of Genetic Algorithm to Cost Analysis of LNG Carrier Maintenance Operations

LNG operations involve exploration, extraction, production, transportation, storage and distribution via interstate or intrastate pipelines to the consumers. Safety is applied to the different components of the gas supply chain to ensure that there are no environmental pollution and Potential Loss of Life (PLL). Regular risk assessment is carried out on all the LNG systems and subsystems to maintain a high level of safety by appropriately improving their maintenance policy. GA is applied to a unit of cargo handling (LNG transfer arm) and storage system/tank (LNG membrane tank) to ascertain the feasibility of the aforementioned GA methodology for cost effectiveness of maintenance of LNG carriers.

4.7.1. LNG Storage System

The proper selection of LNG storage tank type is made according to location to be sited, safety, reliability, environmental considerations and economic efficiency (Hyo et al., 2005). Full containment tanks are used onshore and on LNG ships because of the operational safety of the tanks and their associated equipment as well as the ease of maintenance. The storage tank and the associated pipes can be affected by the following six major accident scenarios which may cause a LNG spill (Hyo et al., 2005):

- Overfilling of storage tank.
- Over pressurization of storage tank.
- Under pressurization of storage tank.
- Failure of inlet lines.
- Failure of outlet lines.
- Loss of mechanical integrity of tank.

4.7.2. Cargo Handling/Transfer

Cargo handling/transfer is operated with a high level of safety in order to reduce the occurrence of environmental pollution. The cargo transfer connections are designed to the standards laid down by the Oil Companies International Marine Forum (OCIMF) and the SIGTTO. The standards ensure that similar arrangements are defined for jetty loading arms and pipe-work, together with defined limits on the allowable cargo flow rates and pressures, as well as the provision of defined and proven arrangements of communications systems, function monitoring requirements, alarm and emergency shut down arrangement (Newell, 2003). These standards ensure that LNG and natural gas vapour transfer between ship and shore can be performed easily and safely. LNG transfer normally takes place through a set of articulated loading arms mounted on a jetty or a process and storage ship connected to a shuttle ship. Despite the fact that the OCIMF and SIGTTO set the standards for design and operation of LNG transfer arms, certain hazards still exist. Some of the hazards are identified as:

- Bad weather condition. This affects the ship while discharging or loading thereby causing LNG transfer to cease due to the inability of most loading arms to cope with ship movement.
- Overloading of the arms. It causes the breakaway coupling to operate automatically, system valves to close and loading arms to withdraw, thereby causing LNG spillage from pipe-work.

4.7.3. Hazard Identification in LNG Carrier Operations

Potential hazards associated with LNG operations can be identified with the help of LNG experts in the industry. A hazard is defined as a physical situation with a potential to cause injury, damage to environment or some combination of these (Wang and Trbojevic, 2007). HAZID team members can be made up of marine engineers, naval architects, structural specialists, marine officers, risk analysts, and process, mechanical and safety engineers. The team works with the theme of believability/credibility, which is that there must be potential for an initiating event to be technically feasible (even if highly unlikely) within the expected lifetime of the activity (Pitblado et al., 2004). HAZID is carried out from systematic reviews of all operational modes modelling the different sections of the LNG industry. The team involved in this research, carried out HAZID using brainstorming and FTA methods. The team also ensures that the process is proactive and not confined only to hazards that have materialised in the past. The hazards identified by the team are detailed in Section 3.5 of Chapter 3.

These identified hazards in Section 3.5 of Chapter 3 cause LNG spill, thereby resulting in more serious consequences, including (CLNG, 2008):

- Rapid phase transition.
- Vapour clouds.
- Rollover.
- Freezing liquids.
- Pool fire.

An accident can be defined as an unintended event involving fatality, injury, property loss or damage, and/or environmental damage (Wang and Trbojevic, 2007). "LNG containment system failure" and "LNG spill from transfer arm" accident scenarios are identified using FTA as illustrated in Figures 4.4 and 4.5. In Figure 4.4, LNG containment system fails when structural defect, corrosion, fire and explosion, structural pressure difference or failure of supporting structure happens. Structural pressure difference (PD) occurs when excessive positive pressure difference (PPD) and corrosion happen simultaneously. Excessive PPD occurs when pressure relief systems fail and containment pressure occur simultaneously. Failure of the supporting structure occurs when chock failure or plastic collapse of supports occurs. Chock failure occurs when excess load, structural defect and installation defect happen simultaneously. Excess load occurs when corrosion or fire and explosion happens. Plastic collapse of supports occurs when structural defects, and fire and explosion happen. Structural defect, corrosion, fire and explosion, installation defect, pressure relief system failure and containment pressure are basic events. In Figure 4.5, a LNG spill from the transfer arm occurs when transfer arm failure, material defect or failure of piping happens. Transfer arm failure occurs when the arm design limit is exceeded, fire and explosion or mechanical failure within design envelope happens. When manual release, fire and explosion and auto release failure happen, exceeding of arm design limit occurs. Mechanical failure within the design envelope occurs when application of ship motion, fire and explosion, and failure of motion and controls happen simultaneously. Failure of piping occurs when pipe rupture, pipe coupling sleeve failure and structural defect occur. Pipe coupling sleeve failure occurs when overpressure and material defect happen simultaneously. Manual release failure, auto release failure, fire and explosion, application of ship motion, failure of motion and controls, pipe rupture, overpressure and material defect are basic events.

4.7.4. Risk Modelling of the LNG Carrier System

Information produced from the HAZID phase will be processed to estimate risk (Pillay, 2001). In "Containment system failure" and "LNG spill from the transfer arm" accident scenarios, risks are assessed by the quantitative analysis of FTs illustrated in Figures 4.4

and 4.5. The probabilities of failure of the LNG carrier systems at a particular/specified time will be calculated using the failure frequencies/rates of "Containment system failure" and "LNG spill from transfer arm". It will be further used in cost modelling for improvement of maintenance of the systems. PRA is applied to the top event and the accident scenarios of Figure 4.4 and 4.5, given the availability of their basic events' data.

4.7.4.1. Risk Modelling of the LNG Containment System and the LNG Transfer Arm

For quantification of the top event, LNG containment system's basic events in Figure 4.4 and their failure frequencies/rates are listed as follows:

- Fire and explosion with failure frequency of 1.78E-006/hour (SINTEF, 2002) and failure probability of P(A).
- Structural defects with failure frequency of 2.31e-006/hour (SINTEF, 2002) and failure probability of P(B).
- Corrosion effects with failure frequency of 1.115E-006/hour (SINTEF, 2002) and failure probability of P(C).
- Containment pressure with failure frequency of 0.01/hour (Hyo et. al, 2005) and failure probability of P(D).
- Pressure relief system failure with failure frequency of 2.12e-005/hour (SINTEF, 2002) and failure probability of P(E).
- Installation defect with failure frequency of 1.382e-005/hour (SINTEF, 2002) and failure probability of P(F).

$$\text{Top Event} = A + B + C + C \bullet D \bullet E + A + B + B \bullet C \bullet F + A \bullet B \bullet F$$

$$= A + B + C(1 + D \bullet E) + A + B(1 + C \bullet F + A \bullet F)$$

$$= A + B + C$$

P(LNG Containment System) = P($A + B + C$)

$$\rightarrow P(A) + P(B) + P(C) - P(A) \bullet P(B) - P(A) \bullet P(C) - P(B) \bullet P(C) +$$

$$P(A) \bullet P(B) \bullet P(C)$$

At t = 43,800 hours (5 years)

$P(A) = 1 - e^{-\lambda t}$

$\lambda = 1.78e\text{-}006$

$$P(A) = 1 - e^{-1.78e-006 \times 43800}$$

$$= 1\text{-}0.925$$

$$= 0.075$$

Similarly, the failures probabilities, P(B) and P(C) can be calculated as 0.0962 and 0.0477 at t = 43,800 hours and λ = 2.31e-006 and 1.115e-006 respectively.

P(LNG Containment System) = 0.075 + 0.0962 + 0.0477– (0.075×0.0962) - (0.075×0.0477) - (0.09623×0.0477) + $(0.09623 \times 0.0477 \times 0.075)$ = 0.2038

P(LNG Containment System) = $1 - e^{-\lambda_1 \times 43800}$

$$0.2038 = 1 - e^{-\lambda_1 \times 43800}$$

$$e^{-\lambda_1 \times 43800} = 1 - 0.2038 = 0.7962$$

$$-\lambda_1 \times 43800 \times \ln e = \ln 0.7962$$

$$-\lambda_1 = -5.203e\text{-}006$$

$$\lambda_1 = 5.203e\text{-}006$$

The probability of failure of an LNG containment system is 0.2038 at 43,800 hours (5 years) with hazard severity weight $S_{W(1)}$ of 1000 from Table 4.1, which is catatrosphic if it occurs. The associated failure frequency λ_1 is 5.203e-006/hour. In a similar way, the failure frequency of the LNG transfer arm can be calculated as 1.293e-005, given that the minimum cut sets of the top event are $I + N + L$, and t = 43,800 hours. The basic events with their failure frequencies that lead to LNG spill from transfer arm in Figure 4.5 are:

- Manual release failure frequency of 0.024/hour (Risknology, 2006) and failure probability of P(G).
- Auto release failure frequency of 0.03/hour (Risknology, 2006) and failure probability of P(H).
- Fire and explosion of failure frequency of 1.78e-06/hour (SINTEF, 2002) and failure probability of P(I).
- Application of ship motion of failure frequency of 0.00066/hour (Risknology, 2006) and failure probability of P(J).
- Failure of motion and controls of failure frequency of 1.382e-005/hour (Risknology, 2006) and failure probability of P(K).
- Pipe rupture of failure frequency of 2.96e-010/hour (Hyo et. al, 2005) and failure probability of P(L).
- Overpressure of failure frequency of 0.01/hour (Hyo et. al, 2005) and failure probability of P(M).
- Material defect of failure frequency of 11.15e-06/hour (SINTEF, 2002) and failure probability of P(N).

4.7.5. Cost Modelling of the LNG Carrier Systems

The cost associated with maintenance of the LNG carrier systems is identified by using GA on the objective function and constraints of the systems in Equation (4.15). Therefore the objective function and constraints are expressed as follows:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1 \left(\frac{t_1 C_{SYSTEM(1u)}}{C_{SYSTEM(1)}} \right)}) + S_{W(2)} \times (1 - e^{-\lambda_2 \left(\frac{t_1 C_{SYSTEM(2u)}}{C_{SYSTEM(2)}} \right)})$$

Subject to:

$$C_T = C_{SYSTEM(1)} + C_{SYSTEM(2)}$$

$$C_{SYSTEM(1u)} \leq C_{SYSTEM(1)} \leq C_{SYSTEM(1\max)}$$

$$C_{SYSTEM(2u)} \leq C_{SYSTEM(2)} \leq C_{SYSTEM(1\max)}$$

4.7.5.1. Cost Modelling of the LNG Containment System and the LNG Transfer Arm

The hazard severity weight illustrated in Table 4.1, failure frequency and time of maintenance associated with the LNG containment system (LNG carrier system 1) in Section 4.7.4.1 are:

Hazard Severity's Weight of the LNG carrier system 1 ($S_{W(1)}$) = 1000

Failure frequency of the LNG carrier system 1 (λ_1) = 5.203e-006/hour

Time of interest (maintenance) of the LNG carrier system 1 (t_1) = 43800 hours

The cost of the LNG membrane containment system that can contain 155,000 m^3 of LNG is \$2.16m (Chu, 2007). The unit and maximum costs of maintenance of the LNG membrane containment system in 43,800 hours time are:

$C_{SYSTEM(1u)}$ = \$550,000 and $C_{SYSTEM(1\max)}$ = \$1,170,000

Substituting the values in the objective function in Section 4.7.5 implies:

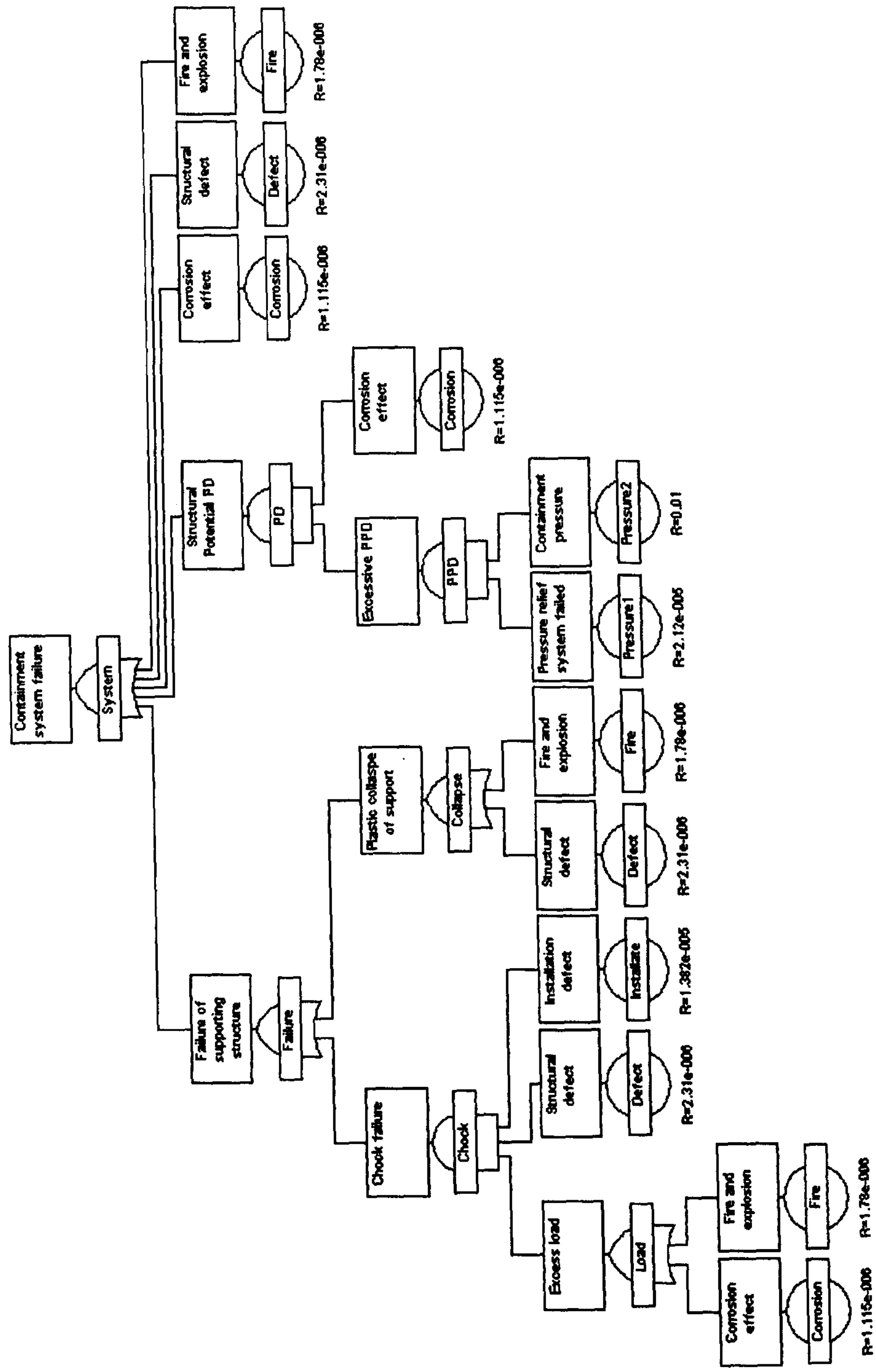

Figure 4.4: Fault Tree of LNG Containment System Failure

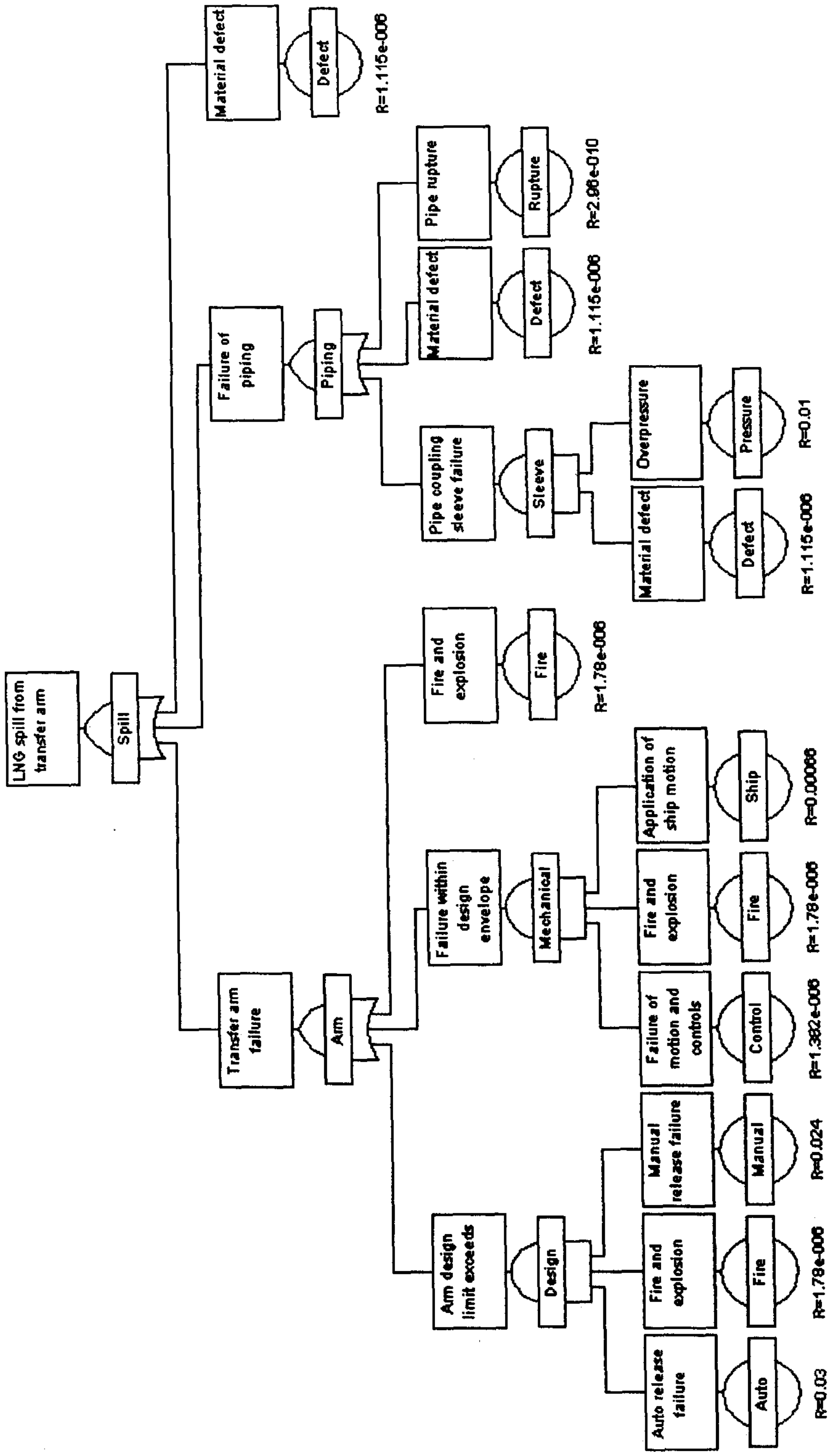

Figure 4.5: Fault Tree of LNG Spill from Transfer Arm

$$R_T = 1000 \times (1 - e^{-5.203e-006\left(\frac{43800 \times 550000}{C_{SYSTEM(1)}}\right)}) + S_{W(2)} \times (1 - e^{-\lambda_2\left(\frac{t_2 C_{SYSTEM(2u)}}{C_{SYSTEM(2)}}\right)})$$

Subject to:

$$C_T = C_{SYSTEM(1)} + C_{SYSTEM(2)}$$

$$550000 \leq C_{SYSTEM(1)} \leq C_{SYSTEM(1\max)}$$

$$C_{SYSTEM(2u)} \leq C_{SYSTEM(2)} \leq C_{SYSTEM(2\max)}$$

The LNG transfer arm (LNG carrier system 2) has the hazard severity weight illustrated in Table 4.1, failure frequency (rate), time of maintenance in Section 4.7.4.1 as follows:

Hazard Severity's Weight of the LNG carrier system 2 ($S_{W(2)}$) = 1000

Failure frequency (rate) of the LNG carrier system 2 (λ_2) = 1.293e-05

Time of maintenance of the LNG carrier system 2 (t_2) = 43800 hours

The unit and maximum costs for maintenance of the LNG transfer arm in 43800 hours time are:

$C_{SYSTEM(2u)}$ = \$130,000 and $C_{SYSTEM(1\max)}$ = \$750,000

To improve the level of safety of the LNG carrier systems, suppose the new cost allocated for maintenance of the LNG carrier systems is:

C_T = \$1,300,000

Substituting the values in the objective function in Section 4.7.5 yields:

$$R_T = 1000\times(1-e^{-5.203e-06\left(\frac{43800\times 550000}{C_{SYSTEM(1)}}\right)}) + 1000\times(1-e^{-1.293e-05\left(\frac{43800\times 130000}{C_{SYSTEM(2)}}\right)})$$

Subject to:

$$1300000 = C_{SYSTEM(1)} + C_{SYSTEM(2)}$$

$$550000 \le C_{SYSTEM(1)} \le 1170000$$

$$130000 \le C_{SYSTEM(2)} \le 750000$$

4.7.5.2. Simulation Result/Analysis of Cost of the LNG Carrier Systems: Containment System and Transfer Arm

The values of the objective function and its constraint parameters defined in Section 4.7.5.1 are used in the Matlab environment for a simulation exercise, using GA to identify $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$ for improvement of level of safety. The objective function and its constraint in question are expressed as follows:

$$R_T = 2000 - 1000e^{-125340.3/C_{SYSTEM(1)}} - 1000e^{-73623.42/C_{SYSTEM(2)}}$$

Subject to:

$$1300000 = C_{SYSTEM(1)} + C_{SYSTEM(2)}$$

$$550000 \le C_{SYSTEM(1)} \le 1170000$$

$$130000 \le C_{SYSTEM(2)} \le 750000$$

The GA Matlab 7.7 platform provides the designer/researcher with different GA operators and parameters that will be selected for identification of $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$, at which the point of convergence is achieved. The useful operators and parameters are assigned values in the GA Matlab 7.7 platform (software), which enables the development of a Matlab file for the objective function. The operators and parameter values are:

1. Population size = 80
2. Fitness Scaling = Rank
3. Selection = Stochastic
4. Crossover = Two point
5. Elite = 2
6. Mutation = Adaptive feasible or constraint dependent default
7. Generation = 51

These operators and parameter values are recommended as the best for a constrained optimization problem according to Matlab Version 7.7 (R2008b). The next step is to run the simulation to produce the final result shown in Figure 4.6. In Figure 4.6, the fitness is plotted against the generation and the optimal solution is found at the point where $C_{SYSTEM(1)}$ = \$729,087 and $C_{SYSTEM(2)}$ = \$570,913 with fitness value of 278.94 (i.e. R_T), after 10th generation at time limit of 10 minutes and simulation stopped at 51st generation, which can be illustrated in GA Matlab 7.7 platform. These values of the cost of maintenance of the LNG containment system and transfer arm are the best for improvement of levels of safety of the LNG carrier systems.

4.7.5.3. Verification of the Model

The model of an engineering problem needs to be verified. This can be conducted by carrying out a sensitivity analysis on the model to ascertain the usefulness of the model. In this research, the model with its simulation illustrated in Figure 4.6 would be verified with the aim of satisfying the following three axioms:

- Axiom 1. An increase of the value of C_T (total budgeted maintenance cost of the LNG carrier systems) should result in a decrease of the value of R_T (total risk of the LNG carrier systems) in the model.
- Axiom 2. An increase of the value of $C_{SYSTEM(1u)}$ (unit cost of maintenance of the LNG containment system) should result in an increase of the value of R_T in the model.
- Axiom 3. An increase of the value of $C_{SYSTEM(2u)}$ (unit cost of maintenance of the LNG transfer arm) should result in an increase of R_T in the model.

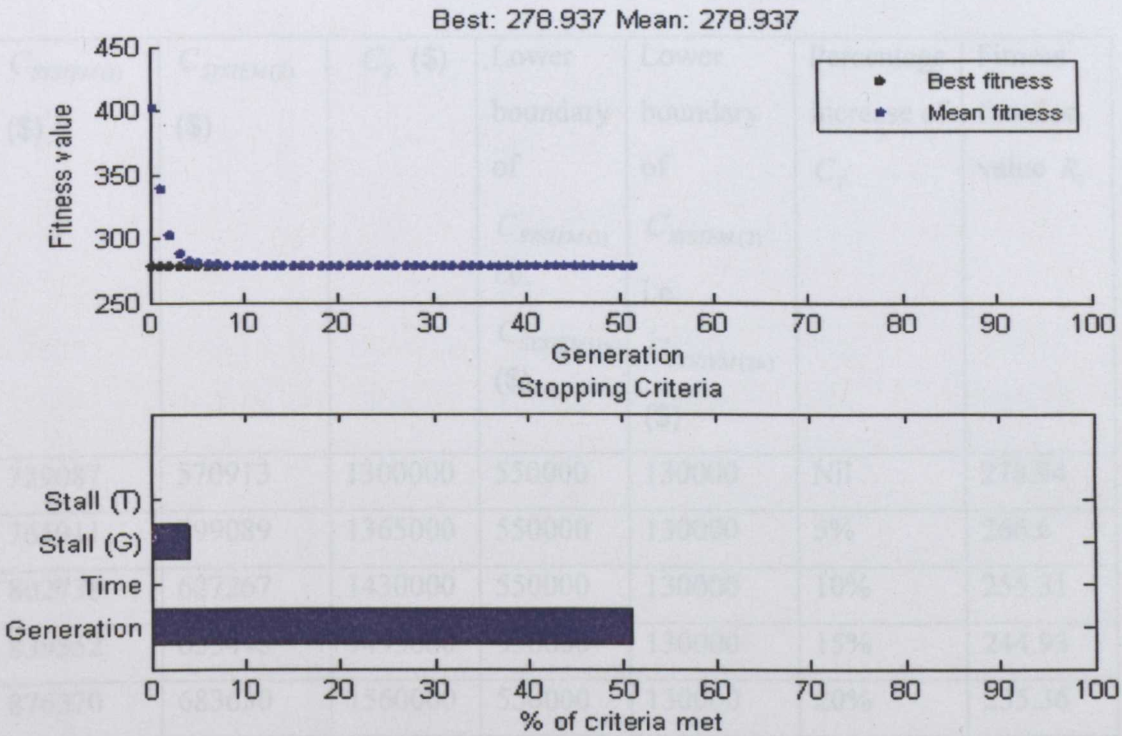

Figure 4.6: Graph of Fitness against Generation

Tables 4.4, 4.5 and 4.6 have been produced after carrying out simulation exercises on the model with increase of 5%, 10%, 15% and 20% of C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$ values from their original values of \$1300000, \$550000 and \$130000 respectively. Table 4.4 shows a resultant decrease of R_T value in one direction from its initial/original value of 278.94 because of the 5%, 10%, 15% and 20% increase of the values of C_T.

In Row 2 of Table 4.4, $C_{SYSTEM(1)}$ has a value of \$765911 with lower boundary value ($C_{SYSTEM(1u)}$) of \$550000 and 5% increased C_T value of \$1365000. While $C_{SYSTEM(2)}$ has a value of \$599089 with lower boundary value ($C_{SYSTEM(2u)}$) and C_T value of \$130000 and \$1365000 respectively. Their fitness function value R_T is 266.6. Other rows in Table 4.4 follow a similar pattern and have R_T values of 255.31, 244.93 and 235.36 with respect to 10%, 15% and 20% increase of C_T value. This is in line with Axiom 1.

Table 4.4: Model Verification by Increase of C_T Value

$C_{SYSTEM(1)}$ (\$)	$C_{SYSTEM(2)}$ (\$)	C_T (\$)	Lower boundary of $C_{SYSTEM(1)}$ i.e. $C_{SYSTEM(1u)}$ (\$)	Lower boundary of $C_{SYSTEM(2)}$ i.e. $C_{SYSTEM(2u)}$ (\$)	Percentage increase of C_T	Fitness function value R_T
729087	570913	1300000	550000	130000	Nil	278.94
765911	599089	1365000	550000	130000	5%	266.6
802733	627267	1430000	550000	130000	10%	255.31
839552	655448	1495000	550000	130000	15%	244.93
876370	683630	1560000	550000	130000	20%	235.36

In a similar way, Table 4.5 is described. In Table 4.5, there is an increase of the R_T value from its original value of 278.94 as a result of 5%, 10%, 15% and 20% increase of the $C_{SYSTEM(1u)}$ value in the model. The resultant R_T values are 286.12, 293.31, 300.14 and 306.99 respectively. This is in line with Axiom 2.

Similar to Table 4.5, the value of R_T increases from its original value of 278.94 as a result of 5%, 10%, 15% and 20% increase of the $C_{SYSTEM(2u)}$ value in Table 4.6. The resultant values of R_T are 284.56, 290.08, 295.51 and 300.86 respectively. This is in harmony with Axiom 3. The increase and decrease of R_T values as a result of the increase of C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$ values are illustrated graphically in Figure 4.7.

Table 4.5: Model Verification by Increase of the $C_{SYSTEM(1u)}$ Value

$C_{SYSTEM(1)}$ ($)	$C_{SYSTEM(2)}$ ($)	C_T ($)	Lower boundary of $C_{SYSTEM(1)}$ i.e. $C_{SYSTEM(1u)}$ ($)	Lower boundary of $C_{SYSTEM(2)}$ i.e. $C_{SYSTEM(2u)}$ ($)	Percentage increase of $C_{SYSTEM(1u)}$ ($)	Fitness function value R_T ($)
729087	570913	1300000	550000	130000	Nil	278.94
736041	563959	1300000	577500	130000	5%	286.12
742725	557275	1300000	605500	130000	10%	293.31
748828	551172	1300000	632500	130000	15%	300.14
754725	545275	1300000	660000	130000	20%	306.99

4.7.5.4. Functions and Effects of Genetic Algorithm Operators on the Simulation Exercise

The GA operator is the prime determinate of the optimal solution. For the objective function and constraint in this research, it is recommended (Haupt and Haupt 2004; and Colley, 1999) to choose a population size of 50-100 in order to obtain the best result. Fitness scaling has to be ranked because it ensures that the fitness values are ranked from the lowest to the highest for identification of the best cost (individual or chromosome).

Though other fitness scaling does exist, this may suit different scenarios or objective functions and their respective constraints. Stochastic uniform selection method selects the best cost from the ranked cost for the next generations while the two point crossover operator, reproduce new cost that will replace the costs that were not selected. Elitism guarantees that the two best costs always survive in the next generation until convergence is met before the 51st generation, after introduction of adaptive feasible mutation to ensure genetic diversity within the constraint of the objective function.

Table 4.6: Model Verification by Increase of the $C_{SYSTEM(2u)}$ Value

$C_{SYSTEM(1)}$ ($)	$C_{SYSTEM(2)}$ ($)	C_T ($)	Lower boundary of $C_{SYSTEM(1)}$ i.e. $C_{SYSTEM(1u)}$ ($)	Lower boundary of $C_{SYSTEM(2)}$ i.e. $C_{SYSTEM(2u)}$ ($)	Percentage increase of $C_{SYSTEM(2u)}$	Fitness function value R_T
729087	570913	1300000	550000	130000	Nil	278.94
721743	578257	1300000	550000	136500	5%	284.56
714748	585252	1300000	550000	143000	10%	290.08
708073	591927	1300000	550000	149500	15%	295.51
701693	598307	1300000	550000	156000	20%	300.86

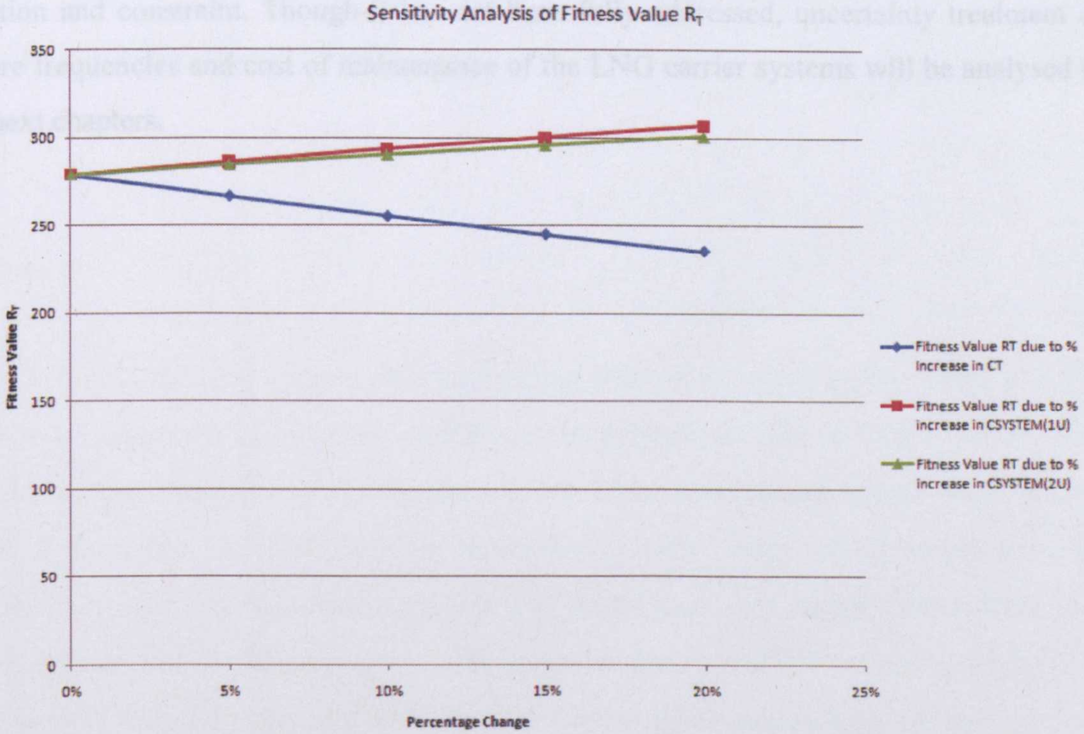

Figure 4.7: Graph of R_T Against Percentage Change of C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$

4.8. Conclusion

The cost effectiveness of improving the level of safety (reduction of risk) is identified as a method of ensuring that a high level of safety of LNG carrier systems is maintained. Attention is focused on areas of high risk in the LNG industry such as containment system and transfer arm in this research, which could cause LNG spill, in case of system failure. The total risk of the LNG containment system and transfer is developed mathematically from first principles which serve as an objective function to be minimised for cost effectiveness of the systems maintenance, while the initial cost of maintenance and an allocated cost for improvement of the LNG containment system and transfer arm safety from its former safety/risk level serve as constraints and boundaries where the optimisation processes could be practiced. A powerful tool of GA that can search the optimal solution globally is employed for this service. GA is attached with Matlab 7.7 software in optimization of the mathematical model. GA successfully identified the cost of maintaining the LNG containment system and transfer arm by applying its mechanism on the objective function and constraint. Though it has not been fully addressed, uncertainty treatment of failure frequencies and cost of maintenance of the LNG carrier systems will be analysed in the next chapters.

Chapter 5 – A Fuzzy Genetic Algorithm Approach to Analyse Maintenance Cost of High Risk Liquefied Natural Gas Carrier Systems under Uncertainty

Summary

A FGA is used to treat uncertainties associated with unit costs of maintenance of LNG carrier systems such as a containment system and a transfer arm. A FRB is established to identify the unit costs of maintenance of the LNG containment system and transfer arm. It includes 125 LNG carrier maintenance cost rules, which used technical consultancy cost, maintenance duration, and spare part cost as the antecedents and maintenance cost as the consequent. The outcome from the FRB is used to optimise a risk model using GA principles to find the new/optimal maintenance cost of each system with provided information on their respective time of interest, failure probability, failure rate and maintenance cost of the whole LNG carrier systems.

5.1. Introduction

In the maritime industry, LNG carriers are among the vessels in which safety is incorporated in their design stage. A proactive approach has been used to tackle the potential hazards and threats associated with the LNG carrier operations. Risk mitigation measures of failure frequencies and their possible consequences of the hazards and threats have always been put in place. These have led to the introduction of regulations by appropriate authorities to check the operations of LNG carriers and maintain their safety record.

Several guidelines, rules and regulations are currently in place to avoid and respond to the release of LNG (Aspen Environment Group, 2005; Nova Scotia Department of Energy, 2005; SIGTTO, 1997). LNG carriers have been designed with a double hull, which ensures safe transportation of LNG by provision of optimum protection for the integrity of the cargo in the event of collision or grounding as well as separate ballast (Foss, 2003). Various organisations such as the SIGTTO, the IMO and the IACS have contributed immensely in prevention and mitigation of potential risks associated with LNG carriers and their systems and subsystems. The maritime industry classifies LNG carriers using members of the IACS. They have been proactive in enhancing the safety of the LNG carriers through emphasizing the need for incorporation of risk analysis in ships. Their recommendations for maintenance of any LNG carrier system and subsystem that did not meet the IMO safety standard are always implemented. Maintenance is defined as the combination of all technical and administrative actions, including supervision actions, intended to retain an entity in, or restore it to a state in which it can perform a required function (Pillay and Wang, 2003). It could be preventive, reactive, predictive or proactive maintenance (Pillay and Wang, 2003; Ben-Daya and Hariga, 1998; Crocker, 1999; Lofsten, 1999) as described in Chapter 2.

The existence of uncertainties associated with the unit cost of maintenance of LNG carrier systems, makes this work very important in the determination of the maintenance cost of the LNG carrier systems using a risk model. A combination of algorithms such as FGA facilitates the process. Therefore, the FGA approach is used to address the high level of uncertainties associated with the unit cost of maintenance of the LNG carrier systems and optimisation of the risk model. The step by step FGA approach is applied. The unit cost of maintenance of each LNG carrier system is treated with a suitable uncertainty technique such as a FRB for combination with a continuous steady-state GA, because its operations can be easily computed.

The FRB is used to provide a reasonable interpretation of linguistic variables. Membership values are assigned between 0 and 1 in the FRB. There is a definition of the fitness function of the risk model and parameters of GA before simulation is carried out with MATLAB 7.7 until a fixed number of generations have elapsed or some forms of convergence criteria have been met, producing an optimal risk solution. The objective of this work is to explore the application of FGA to the determination of maintenance cost of the LNG carrier systems considering uncertainties of their unit cost of maintenance.

5.2. Background Analysis

The welcome development of the fuzzy logic and its combination with other algorithms, including the GA has been effectively applied to the industrial challenges such as uncertainty of data. Notable professionals like Zadeh (Zadeh, 1965) and Holland (Colley, 1999; Golberg, 1989; Haupt and Haupt, 2004) invented the fuzzy logic in the mid 60s and GA in mid 70s respectively. The FRB method is developed using IF-THEN rules. The usefulness of the FRB has attracted experts to employ the service for decision making in engineering, technology, science and management.

In the field of maritime safety, applications of the FRB have been carried out on the marine and offshore systems and their environments (Yang, 2007; Ung, 2007; Eleye-Datubo, 2006; Pillay, 2001; Sii et al., 2001). A Fuzzy Rule Base-Evidential Reasoning (FRB-ER) algorithm is used to conduct threat and hazard based risk assessment in container supply chain systems (Yang, 2007). The FRB inference system estimates the safety level of each basic event while the ER is used to synthesise all the basic events for each RCO. Similarly, a safety assessment is carried out on the risks introduced by collision of a Floating Production, Storage and Offloading (FPSO) unit and a shuttle tanker using the FRB-ER (Eleye-Datubo, 2006). In this evaluation, 32 rules are fired for actual safety assessment.

The usefulness of a FRB is also proved in risk assessment of port security with the adoption of FMECA (Ung, 2007). The concept of FMECA is used in the development of the "IF" and "THEN" part of the 625 rules of a FRB. The FRB-FMECA processes identified the risk ranking of the port security. Similarly, a combination of FRB and FMEA is used to assess safety of the structure, propulsion, electrical and auxiliary systems of a fishing vessel (Pillay and Wang, 2003). A FRB that is made up of 125 rules is developed using probability of occurrence, severity and detectability as the antecedents and priority for attention as the consequent for effective safety assessment of the systems of a fishing vessel.

A FRB has solved manufacturing problems in delay time analysis of an environmental model (Jones, 2009). The uncertainties surrounding the parameters of the delay time analysis of an environmental model are solved by firing the relevant rules of the 25 rules of a FRB in the model. The model is used to find the optimal inspection period based on minimal cost to the environment.

In nuclear engineering, the FGA approach is used to find test interval optimization of safety systems of a nuclear power plant (Durga Rao et al., 2007). A fuzzy logic based on an alpha cut method (Soman and Misra, 1993), also known as resolution identity is used to treat uncertainties in the parameters of the developed mathematical model. The civil engineering experts also used the FGA approach in solving structural engineering optimization problems (Yang and Soh, 2000; Soh and Yang, 1996).

There is no doubt that the FGA is useful to the LNG industry using a FRB method. Expert judgement is used to develop a FRB that has 125 rules for treatment of uncertainties associated with the unit costs of maintenance of the LNG carrier systems. The rules have LNG Carrier System Technical Consultancy Cost (LTCC), LNG Carrier System Maintenance Duration (LMD), and LNG Carrier System Spare Part Cost (LSPC) as the antecedents, and LNG Carrier System Maintenance Cost (LMC) as the consequent. The unit costs of maintenance of the LNG carrier systems are parameters in the risk model that is optimised using a continuous steady-state GA in this work.

5.3. Genetic Algorithm

The GA and its methodology have been discussed in Section 4.3 of Chapter 4. In this work, a continuous steady state GA is used in optimisation of a risk model because the algorithm uses real numbers in encoding the parameters of the risk model, thereby avoiding data loss during computational processes. The GA can be easily combined with other algorithms such as fuzzy logic as illustrated in Figure 5.1, which is used to solve the uncertainties of the unit costs of maintenance of LNG carrier systems.

The information flow in Figure 5.1 started from problem formulation and gathering of data for a solution, which is referred to the risk model that needed to be optimised using the GA methodology, after treatment of uncertainties of unit costs of maintenance of LNG carrier systems.

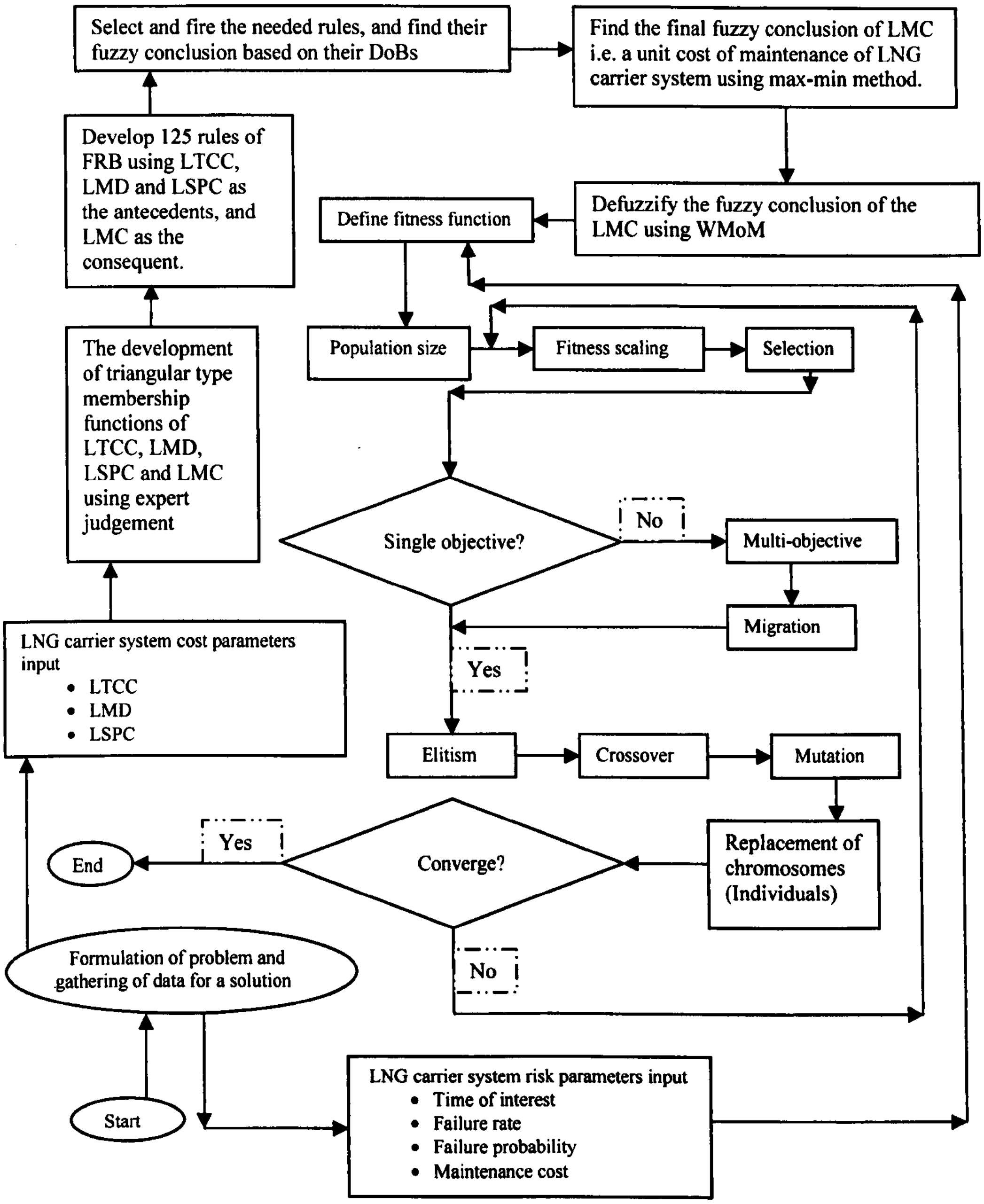

Figure 5.1: A Flow Chart of Fuzzy Genetic Algorithm Methodology

The risk model has parameters such as time of interest, failure rate, failure probability and maintenance cost as illustrated in Figure 5.1. A FRB methodology is used in the treatment of uncertainties of unit costs of maintenance of the LNG carrier systems. The first step of establishing the FRB is use of LNG carrier system cost parameters such as LTCC, LMD and LSPC as components of the antecedent part of IF-THEN rules, which used triangular membership functions in estimation of LMC, guided by the 125 fuzzy rules of the LNG carrier system maintenance cost as illustrated in Figure 5.1. The resultant fuzzy values of the LMC are defuzzified to crisp values using a WMoM method before being used in the risk model for the definition of the fitness function. The definition of fitness function is the first step of the GA methodology, followed by population size, fitness scaling and selection of fittest/best individuals (chromosomes). The type of objective function of the risk model is chosen, followed by an elitism operator that ensures the best individuals are retained in the population as illustrated in Figure 5.1. The individuals undergo crossover and mutation processes accordingly, and the ones reproduced via these processes, replaced the ones that are not selected after the fitness scaling. The FGA process ends, if the risk model has converged, otherwise, the iteration continues from the fitness scaling until an optimal risk solution is found as illustrated in Figure 5.1.

5.4. Risk and Cost Modelling of the LNG Carrier Systems

The risk and cost model are developed in Sections 4.5 and 4.6 of Chapter 4 with parameters such as time of interest, failure rate, failure probability, unit cost of maintenance of each LNG carrier system and budgeted maintenance cost of the whole LNG carrier systems. Therefore, the objective function that will be optimised using GA is expressed as follows:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1 \left(\frac{t_1 C_{SYSTEM(1u)}}{C_{SYSTEM(1)}} \right)}) + S_{W(2)} \times (1 - e^{-\lambda_2 \left(\frac{t_2 C_{SYSTEM(2u)}}{C_{SYSTEM(2)}} \right)}) + \ldots . S_{W(n)} \times (1 - e^{-\lambda_n \left(\frac{t_n C_{SYSTEM(nu)}}{C_{SYSTEM(n)}} \right)})$$

Subject to:

$$C_T = C_{SYSTEM(1)} + C_{SYSTEM(2)} + \ldots\ldots . C_{SYSTEM(n)} \tag{5.1}$$

$$C_{SYSTEM(iu)} \leq C_{SYSTEM(i)} \leq C_{SYSTEM(i\max)}$$

$$i = 1,2 \ldots . n \text{ or } (i \in n)$$

where, R_T = Total risk of the LNG carrier systems

$S_{W(i)}$ = Hazard severity's weight of the LNG carrier system i

λ_i = Failure rate of the LNG carrier system i

t_i = Time of interest of the LNG carrier system i

C_T = Total cost of maintenance of the LNG carrier systems

$C_{SYSTEM(i)}$ = New cost of maintenance of the LNG carrier system i

$C_{SYSTEM(iu)}$ = Unit cost of maintenance of the LNG carrier system i

$C_{SYSTEM(i\max)}$ = Maximum cost of maintenance of the LNG carrier system i

5.5. Fuzzy Logic

The fuzzy logic is a logic developed from FST, which uses a range from 0 to 1 to express the degree of truth of a sentence. Since 1965, Zadeh and various experts such as E. H. Mamdani (Mamdani, 1974), T. Takagi and Professor M. Sugeno (Sugeno and Kang, 1988; Sugeno and Yasukawa 1993) and B. Kosko (Kosko, 1994; Kosko, 1997) have improved the strength of the algorithm by development of a FRB method. Fuzzy logic systems are knowledge/rule based systems constructed from human knowledge in form of Fuzzy IF-THEN rules (Wang, 1997). The IF-THEN rules of FRB are fuzzified using membership functions.

5.5.1. Fuzzy Membership Functions

There are many fuzzy membership functions used to solve challenging problems in different fields. The trapezoidal and triangular membership functions are often used in the maritime industry (Yang, 2007; Ung, 2007; Eleye-Datubo, 2006; Pillay and Wang, 2003; Sii et al., 2001). A particular fuzzy membership function chosen for solving engineering problems depends on the choice of the experts involved and the problem formulated. In this work, a triangular membership function is used because of its computational simplicity.

5.5.1.1. Triangular Membership Function

Three parameters are used to specify a triangular membership function. The parameters are a, b and c, as expressed below:

$$triangle\,(x : a, b, c) = \begin{cases} 0 & x < a \\ (x-a)/(b-a) & a \le x \le b \\ (c-x)/(c-b) & b \le x \le c \\ 0 & x > c \end{cases} \tag{5.2}$$

The appearance of the function is determined by the choice of the parameters a, b and c (Yen and Langari, 1999). A triangular membership function is defined using the three parameters a, b, and c with values of 1, 5 and 9 as the points that formed the triangle shown in Figure 5.2.

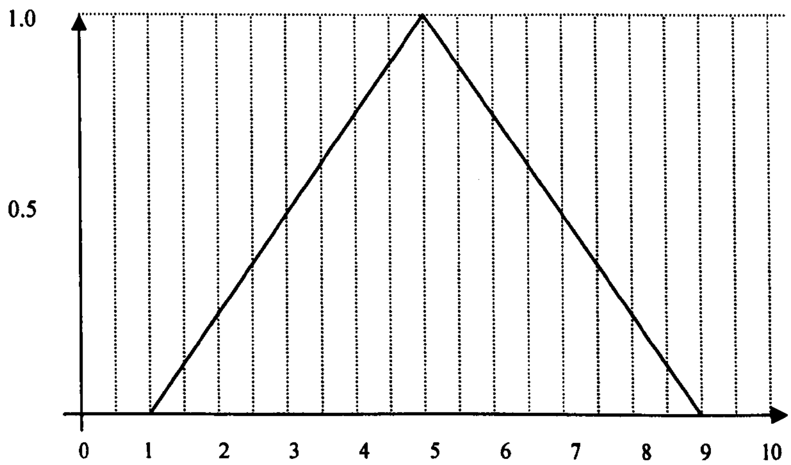

Figure 5.2: A Triangular Membership Function

5.5.2. Fuzzy Rule Base

A fuzzy IF-THEN rule is a knowledge representation scheme for capturing human knowledge that is imprecise by nature (Yen and Langari, 1999). This is achieved by using linguistic variables to describe conditions that can be satisfied to a degree in the "IF" part of the fuzzy rules (Yen and Langari, 1999). A fuzzy rule has two main parts such as an "IF" and a "THEN" part. The "IF" part is called "antecedent" while the "THEN" part is called "consequent". The fuzzy rule sentence is expressed as follows:

IF<antecedent>THEN<consequent>

In most cases, the "antecedent" uses logic connectors such as AND, OR and NOT. This depends on the number of inputs and nature of the engineering problem. In this work, AND is used to develop fuzzy IF-THEN rules for uncertainty treatment of the unit cost of maintenance of LNG carrier systems. The components of the LNG carrier systems maintenance cost framework are illustrated in Figure 5.3, which are used to develop the FRB methodology shown in Figure 5.4. The descriptions of the linguistic variables of the "IF" and "THEN" parts are illustrated in Tables 5.1, 5.2, 5.3 and 5.4, and their respective membership functions shown in Figures 5.5, 5.6, 5.7 and 5.8. The 125 rules of FRB of the LNG carrier system maintenance cost are outlined in Appendix D1.1. The rules are 125 because there are 3 antecedents each of which is described with 5 linguistic terms (i.e. $5\times5\times5$). The triangular shapes of Figures 5.5, 5.6, 5.7 and 5.8 are independent from one another. Figure 5.8 has a monetary scale value that can be used to describe the maximum possible values of the linguistic terms ("very cheap", "cheap", "normal", "expensive" and "very expensive"), to facilitate defuzzification process. At the maximum possible value (i.e. membership function value of 1), "very cheap", "cheap", "normal", "expensive" and "very expensive" linguistic terms have scale values of \$125000, \$250000, \$937500, \$2187500 and \$2500000 respectively.

Experts used the methodology of the FRB in Figure 5.4 for decision making on the unit cost of maintenance of the LNG carrier systems. The fuzzy conclusion is achieved using a max-min method (Pillay and Wang, 2003; Sii et al., 2001; Yen and Langari, 1999). The crisp value of a membership function is produced using a defuzzification method such as WMoM (Andrew and Moss, 2002; Pillay and Wang, 2003). The max-min method for any category (linguistic term) of the consequent part (LMC) of fired fuzzy rules can be expressed as follows:

$$\mu_{LMC}^{j} = \max\left(\min\left(\mu_{LTCC}^{i}, \mu_{LMD}^{i}, \mu_{LSPC}^{i}\right)\right) \quad i = 1 \ldots\ldots\ldots n; \; j = 1 \ldots\ldots\ldots 5 \tag{5.3}$$

where, μ_{LMC}^{j} = Maximum fuzzy membership function value of a category (linguistic term) of the consequent part of the fired fuzzy rules.

μ_{LTCC}^{i} = Fuzzy membership function value of the LTCC for fired fuzzy rule i.

μ_{LMD}^{i} = Fuzzy membership function value of the LMD for fired fuzzy rule i.

μ_{LSPC}^{i} = Fuzzy membership function value of the LPSC for fired fuzzy rule i.

j = 5 linguistic variables/terms of consequent part (Table 5.4).

n = Number of the rules of having the same jth linguistic variable of the consequent.

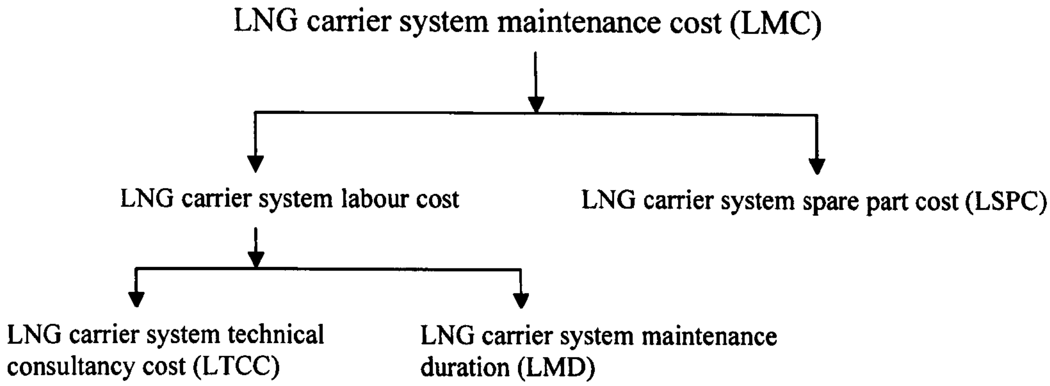

Figure 5.3: LNG Carrier System Maintenance Cost Framework

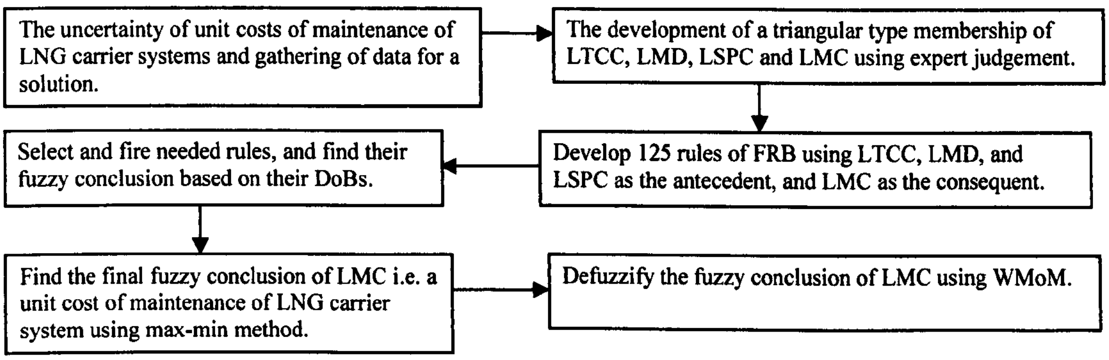

Figure 5.4: A Fuzzy Rule Base Methodology for LNG Carrier System Maintenance Cost.

The judgement of two or more experts with equal experience of LNG carrier systems maintenance cost can be combined using the mathematical expressions as follows (Klir and Yaun, 1995):

$$A(x) = \frac{\sum_{i=1}^{n} a_i(x)}{n} \tag{5.4}$$

where $A(x)$, the final fuzzy value is produced as a result of expert judgements made by n experts with equal LNG carrier systems maintenance cost experience and $a_i(x)$ is the fuzzy value of each expert's judgement, i.e. $i \in n$.

Table 5.1: Categories of LTCC

Category	Description of LTCC (Linguistic Terms)	Level of Damage on LNG Carrier Systems	Level of Injury/Illness on LNG Carrier Personnel
1	Very Low	< Minor System Damage	<Minor Injury/Illness
2	Low	Minor System Damage	Minor Injury/Illness
3	Moderate	Multiple System Damage	Multiple Injury/Illness
4	High	Major System Damage	Severe Injury/Illness
5	Very High	System Loss	Death

Table 5.2: Categories of LMD

Category	Description of LMD (Linguistic Terms)	Level of Damage on LNG Carrier System	Level of Injury/Illness on LNG Carrier Personnel
1	Very Short	< Minor System Damage	<Minor Injury/Illness
2	Short	Minor System Damage	Minor Injury/Illness
3	Medium	Multiple System Damage	Multiple Injury/Illness
4	Long	Major System Damage	Severe Injury/Illness
5	Very Long	System Loss	Death

Table 5.3: Categories of LSPC

Category	Description of LSPC (Linguistic Terms)	Level of Damage on LNG Carrier System	Level of Injury/Illness on LNG Carrier Personnel
1	Very Cheap	< Minor System Damage	<Minor Injury/Illness
2	Cheap	Minor System Damage	Minor Injury/Illness
3	Average	Multiple System Damage	Multiple Injury/Illness
4	Costly	Major System Damage	Severe Injury/Illness
5	Very Costly	System Loss	Death

Table 5.4: Categories of LMC

Category	Description of LMC (Linguistic Terms)	Level of Damage on LNG Carrier System	Level of Injury/Illness on LNG Carrier Personnel
1	Very Cheap	< Minor System Damage	<Minor Injury/Illness
2	Cheap	Minor System Damage	Minor Injury/Illness
3	Normal	Multiple System Damage	Multiple Injury/Illness
4	Expensive	Major System Damage	Severe Injury/Illness
5	Very Expensive	System Loss	Death

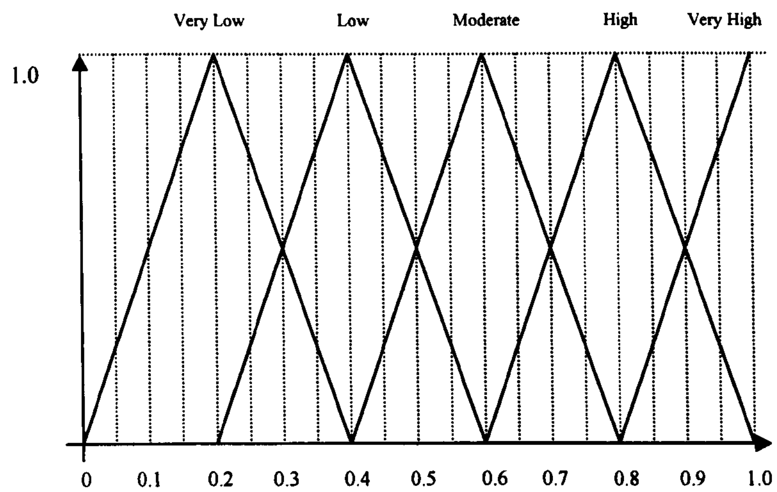

Figure 5.5: A Membership Function for Linguistic Terms of LTCC

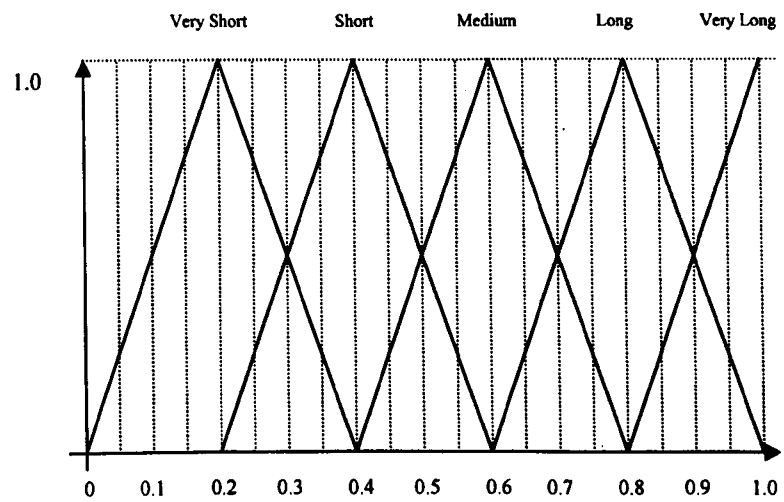

Figure 5.6: A Membership for Linguistic Terms of LMD

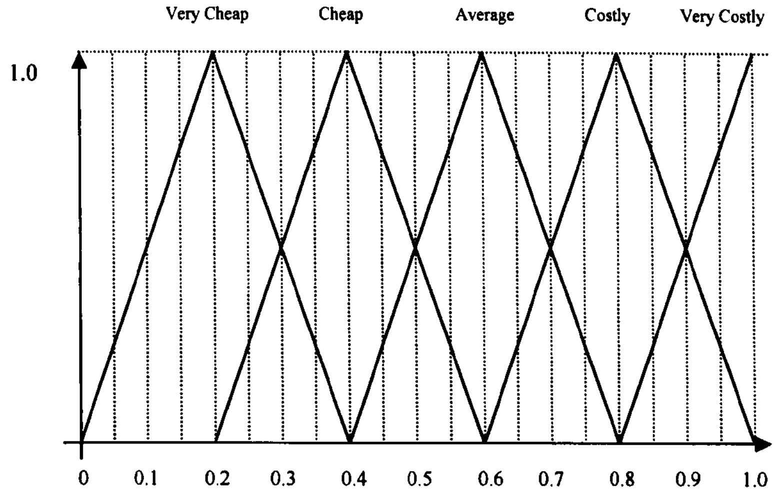

Figure 5.7: A Membership for Linguistic Terms of LSPC

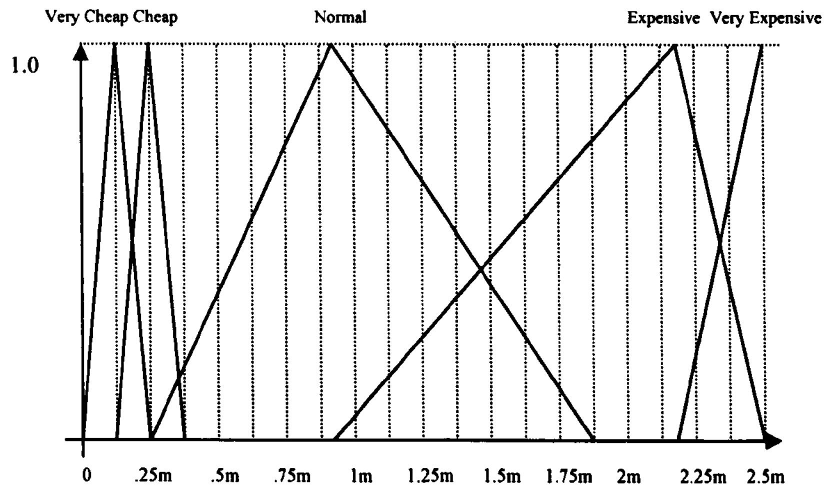

Figure 5.8: A Membership Function for Linguistic Terms of LMC

5.5.3. Defuzzification

Defuzzification is the process of transformation of a fuzzy conclusion set to a crisp number. It creates a single assessment from the fuzzy conclusion set, expressing the exact unit cost of maintenance of the LNG carrier system defined by the experts. It is applied in situations where the fuzzy membership output needs to be a single scalar quantity as opposed to a fuzzy set. The output of a fuzzy process can be the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variable (Ross, 2004). The two main defuzzification methods that are commonly used are a WMoM method (Andrew and Moss, 2002; Pillay and Wang, 2003;

Ung, 2007) and a centroid method (Jiang and Li, 1999; Sii et al., 2001; Wang et al., 2009). In this work, the WMoM is used because it can be easily computed.

5.5.3.1. Weighted Mean of Maximum

The WMoM defuzzification method averages the points of maximum possibility of each fuzzy conclusion, weighted by their degrees of truth (Pillay and Wang, 2003). This defuzzication method can be expressed as follows:

$$WMoM(Z) = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{5.5}$$

where x_i is the point of maximum possibility of each fuzzy conclusion while w_i is the degree of beliefs (DoBs) to which the conclusion belongs to the *ith* linguistic term in the consequent.

5.6. A Test Case of Application of Fuzzy Genetic Algorithm to the Determination of Maintenance Cost of the LNG Carrier Systems

The two main systems of a LNG carrier such as the containment system and transfer arm are identified as areas of high risk in Chapter 3. The uncertainties associated with their unit costs of maintenance hinder the exact minimisation of the total risk of the LNG carrier systems using GA, thus, making it difficult to find the exact new maintenance cost of the LNG carrier systems based on budgeted maintenance cost. In this study, four experts with equal experience of the maintenance of the LNG carrier systems used an engineering judgement in a fuzzy environment to tackle the uncertainties associated with the unit costs of maintenance of the LNG carrier systems. The four experts and their levels of experience in marine technology have been described in Chapter 3.

5.6.1. Risk and Cost Modelling of LNG Carrier Systems Using Fuzzy Genetic Algorithm

The risk model is optimised using GA for the identification of maintenance cost of the LNG containment system and transfer arm based on budgeted maintenance cost. The uncertainties associated with the unit cost of maintenance of the LNG containment system and transfer arm are treated using the FRB methodology in Figure 5.4, before the optimisation of the risk model. Therefore, the objective function is expressed as follows:

$$R_T = S_{W(1)} \times (1 - e^{-\lambda_1\left(\frac{t_1 C_{SYSTEM(1u)}}{C_{SYSTEM(1)}}\right)}) + S_{W(2)} \times (1 - e^{-\lambda_2\left(\frac{t_2 C_{SYSTEM(2u)}}{C_{SYSTEM(2)}}\right)})$$

Subject to:

$$C_T = C_{SYSTEM(1)} + C_{SYSTEM(2)} \quad (5.6)$$

$$C_{SYSTEM('1u)} \leq C_{SYSTEM(1)} \leq C_{SYSTEM(1\max)}$$

$$C_{SYSTEM('2u)} \leq C_{SYSTEM(2)} \leq C_{SYSTEM(2\max)}$$

where, $S_{W(1)}$ = Hazard severity's weight of the LNG containment system.

$S_{W(2)}$ = Hazard severity's weight of the LNG transfer arm.

λ_1 = Failure rate of the LNG containment system.

λ_2 = Failure rate of the LNG transfer arm.

t_1 = Time of interest of the LNG containment system.

t_2 = Time of interest of the LNG transfer arm.

C_T = Total/budgeted cost of maintenance of the LNG containment system and transfer arm.

$C_{SYSTEM(1)}$ = New cost of maintenance of the LNG containment system.

$C_{SYSTEM(2)}$ = New cost of maintenance of the LNG transfer arm.

$C_{SYSTEM(1u)}$ = Unit cost of maintenance of the LNG containment system.

$C_{SYSTEM(2u)}$ = Unit cost of maintenance of the LNG transfer arm.

$C_{SYSTEM(1\max)}$ = Maximum cost of maintenance of the LNG containment system.

$C_{SYSTEM(2\max)}$ = Maximum cost of maintenance of the LNG transfer arm.

From Section 4.7.5 of Chapter 4, $S_{W(1)}$, $S_{W(2)}$, λ_1, λ_2, t_1, t_2, $C_{SYSTEM(1\max)}$, $C_{SYSTEM(2\max)}$ and C_T are given as 1000, 1000, 5.203e-06/hour, 1.293e-05/hour, 43800 hours, 43800 hours, \$1,170,000, \$750,000 and \$1,300,000 respectively. Since the unit costs of maintenance of the LNG containment system $(C_{SYSTEM(1u)})$ and transfer arm $(C_{SYSTEM(2u)})$ are associated with uncertainties, the uncertainties must be treated for more reasonable minimisation of the model, thus producing the new maintenance costs of the LNG containment system and transfer arm.

5.6.2. Uncertainty Treatment of the Unit Cost of Maintenance of the LNG Containment System

The LNG containment system has been described in Section 4.7.1 of Chapter 4. The uncertainty associated with the unit cost of maintenance of the LNG containment system is tackled using the FRB methodology in Figure 5.4. Five linguistic terms are used to describe each of the antecedents (LTCC, LMD and LSPC), and the consequent (LMC), for effective treatment of the uncertainty associated with the unit cost of maintenance of the LNG containment system.

5.6.2.1. Expert #1 Opinion

Expert #1 estimates the values of LTCC, LMD, and LSPC to be 0.27, 0.45, and 0.68 on the scale of [0, 1] as illustrated in Figures 5.9, 5.10 and 5.11 respectively. In the fuzzification processes, LTCC, LMD and LSPC can be described as (0.65, low; 0.35, very low), (0.75, short; 0.25, medium) and (0.6, average; 0.4, costly) respectively. In doing so, there are 8 fired fuzzy rules of the LNG carrier system maintenance cost out of the 125 rules. These are:

Rule #3: IF LTCC is very low, LMD is medium AND LSPC is average, THEN LMC is normal.

Rule #8: IF LTCC is low, LMD is medium AND LSPC is average, THEN LMC is normal.

Rule #79: IF LTCC is very low, LMD is short AND LSPC is costly, THEN LMC is normal.

Rule #84: IF LTCC is low, LMD is short AND LSPC is costly, THEN LMC is normal.

Rule #103: IF LTCC is very low, LMD is short AND LSPC is average, THEN LMC is cheap.

Rule #104: IF LTCC is very low, LMD is medium AND LSPC is costly, THEN LMC is normal.

Rule #108: IF LTCC is low, LMD is short AND LSPC is average, THEN LMC is normal.

Rule #109: IF LTCC is low, LMD is medium AND LSPC is costly, THEN LMC is normal.

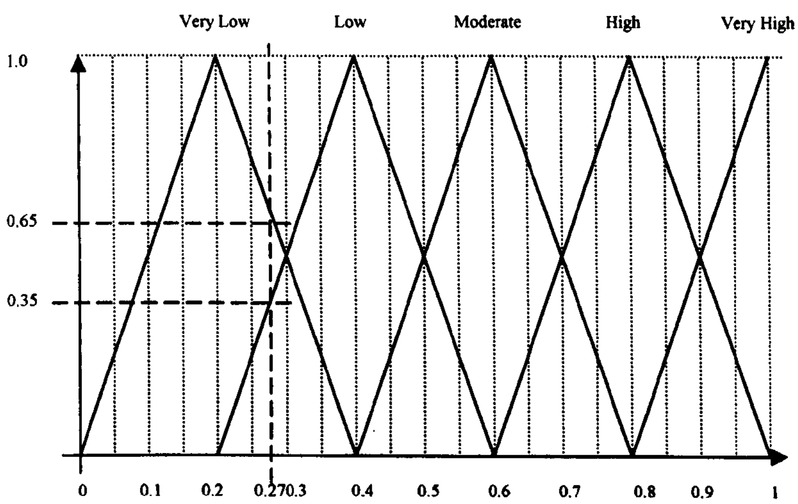

Figure 5.9: A Membership Function for LTCC

The membership function values are assigned to the selected fuzzy rules using the information provided in their respective membership functions in Figures 5.9, 5.10, and 5.11. A max-min method is applied using Equation (5.3), on the membership function values of the LTCC, LMD, and LSPC to produce the membership values of the LMC. The fired fuzzy rules and their membership values are illustrated in Table 5.5.

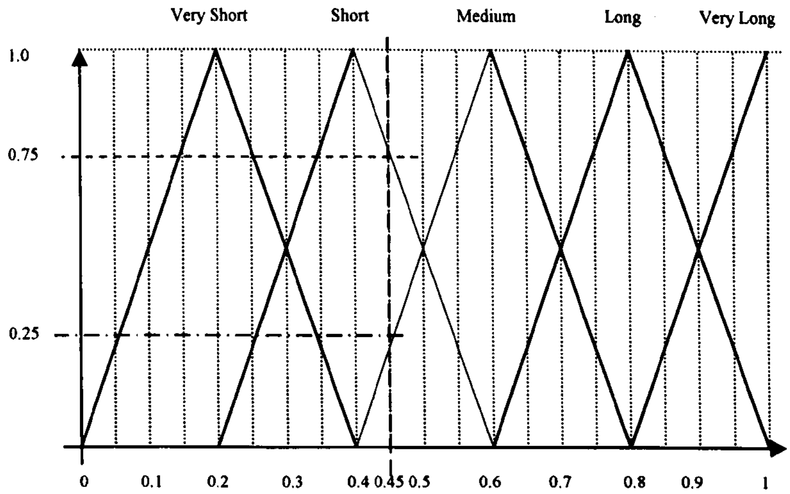

Figure 5.10: A Membership Function for LMD

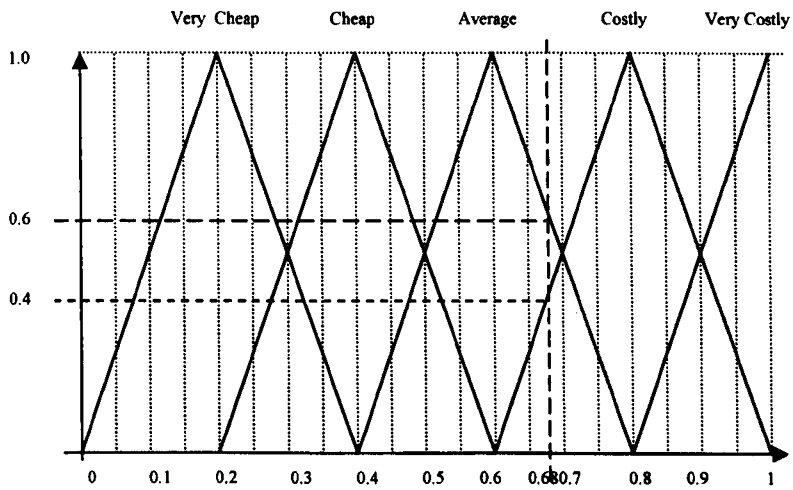

Figure 5.11: A Membership Function for LSPC

In Table 5.5, the third row has a fuzzy rule number 3 and the membership function values of 0.65, 0.25, 0.6 and 0.25 of LTCC, LMD, LSPC and LMC respectively. The value of LMC, 0.25 is calculated by min (0.65, 0.25, 0.6). In the same row, the LTCC, LMD, LSPC and LMC are respectively described with "very low", "medium", "average", and "normal" linguistic terms. In a similar way, the other rows of Table 5.5 are interpreted.

Table 5.5: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of the LNG Containment System

Rules	Fuzzy membership function value (μ)				Linguistic terms			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#3	0.65	0.25	0.6	0.25	Very Low	Medium	Average	Normal
#8	0.35	0.25	0.6	0.25	Low	Medium	Average	Normal
#79	0.65	0.75	0.4	0.4	Very Low	Low	Costly	Normal
#84	0.35	0.75	0.4	0.35	Low	Low	Costly	Normal
#103	0.65	0.75	0.6	0.6	Very Low	Low	Average	Cheap
#104	0.65	0.25	0.4	0.25	Very Low	Medium	Costly	Normal
#108	0.35	0.75	0.6	0.35	Low	Low	Average	Normal
#109	0.35	0.25	0.4	0.25	Low	Medium	Costly	Normal

5.6.2.2. Fuzzy Conclusion

The second step of the max-min method is selection of the maximum values of the same linguistic term of the LMC i.e. unit cost of maintenance of the LNG containment system, in the fired fuzzy rules in Table 5.5. Expert #1's fuzzy conclusion is:

From Rule #103, the LMC has a μ_{LMC} value of 0.6 associated with "cheap" linguistics term, where 0.6 = max (0.6).

From other fuzzy rule numbers in Table 5.5, the LMC has a μ_{LMC} value of 0.4 associated with "normal" linguistics term, where 0.4 = max (0.25, 0.25, 0.4, 0.35, 0.25, 0.35, 0.25).

In a similar way, the fuzzy conclusions of Experts #2, #3 and #4 are produced (see Appendix D1.2 for details). The fuzzy conclusion of Expert #2 is:

- The LMC has a μ_{LMC} value of 0.55 associated with "cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.45 associated with "normal" linguistics term.

The fuzzy conclusion of Expert #3 is:

- The LMC has a μ_{LMC} value of 0.5 associated with "cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.5 associated with "normal" linguistics term.

The fuzzy conclusion of the Expert #4 is:

- The LMC has a μ_{LMC} value of 0.65 associated with "cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.35 associated with "normal" linguistics term.

The fuzzy conclusions of Experts #1, #2, #3 and #4 can be combined using Equation (5.4) as follows:

For "cheap" linguistic term, the $A(\mu_{LMC})$ value of LMC is:

$$(0.6+0.55+0.5+0.65)/4=0.575$$

For "normal" linguistic term, the $A(\mu_{LMC})$ value of LMC is:

$$(0.4+0.45+0.5+0.35)/4=0.425$$

5.6.2.3. Defuzzification of the Fuzzy Conclusion

The defuzzification of the fuzzy conclusion is carried out using the WMoM because of its computational effectiveness. Using Equation (5.4), the WMoM can be calculated as follows:

$$\text{Crisp value, Z} = \frac{w_1x_1 + w_2x_2}{w_1 + w_2} = \frac{0.575\times 250000 + 0.425\times 937500}{0.575+0.425} = \$542188$$

Therefore, $C_{SYSTEM(1u)} = \$542188$

5.6.3. Uncertainty Treatment of the Unit Cost of Maintenance of the LNG Transfer Arm

The LNG transfer arm is one of the LNG carrier systems discussed in Section 4.7.2 of Chapter 4. The four experts used in Section 5.6.2 are involved in the decision making process of the unit cost of maintenance of the LNG transfer arm $\left(C_{SYSTEM(2u)}\right)$. The application of the FRB methodology in the determination of the $C_{SYSTEM(2u)}$ of the LNG transfer arm is detailed in Appendix D1.3. The fuzzy conclusions of the four experts are aggregated to a single fuzzy conclusion which is then defuzzified. The crisp value produced is \$162500 for $C_{SYSTEM(2u)}$ (see Appendix D1.4 for details).

5.6.4. Simulation of the Result

A simulation exercise is carried out on the risk model using GA in Matlab 7.7 environment to find $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$. The substitution of the values of the parameters in the risk model produces the objective function expressed as follows:

$$R_T = 1000 \times (1 - e^{-5.203e-06\left(\frac{43800 \times 542188}{C_{SYSTEM(1)}}\right)}) + 1000 \times (1 - e^{-1.293e-05\left(\frac{43800 \times 162500}{C_{SYSTEM(2)}}\right)})$$

Subject to:

$$1300000 = C_{SYSTEM(1)} + C_{SYSTEM(2)}$$

$$542188 \leq C_{SYSTEM(1)} \leq 1117000$$

$$162500 \leq C_{SYSTEM(2)} \leq 750000$$

The GA operators and their values for the simulation, and the resultant R_T, $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$ as illustrated in Figure 5.12 are:

1. Population Size = 80
2. Fitness Scaling = Rank
3. Selection = Stochastic
4. Crossover = Two point
5. Elite = 2
6. Mutation = Adaptive feasible or constraint dependent default
7. Generation = 51
8. $R_T = 303.99$
9. $C_{SYSTEM\,(1)} = \$693517$
10. $C_{SYSTEM\,(2)} = \$606483$

Figure 5.12 is a graph of fitness value against generation used to demonstrate how the model converged. The fitness value and generation are at the vertical axis and horizontal axis of the graph respectively. The dotted line is used to show when the model converged. The model converged at fitness value of 303.99 after 10th generation. The simulation stopped at 51th generation as shown on the horizontal axis of the graph and the plane of stopping criteria. The stall (G) can be used to stop the simulation at any time if need be.

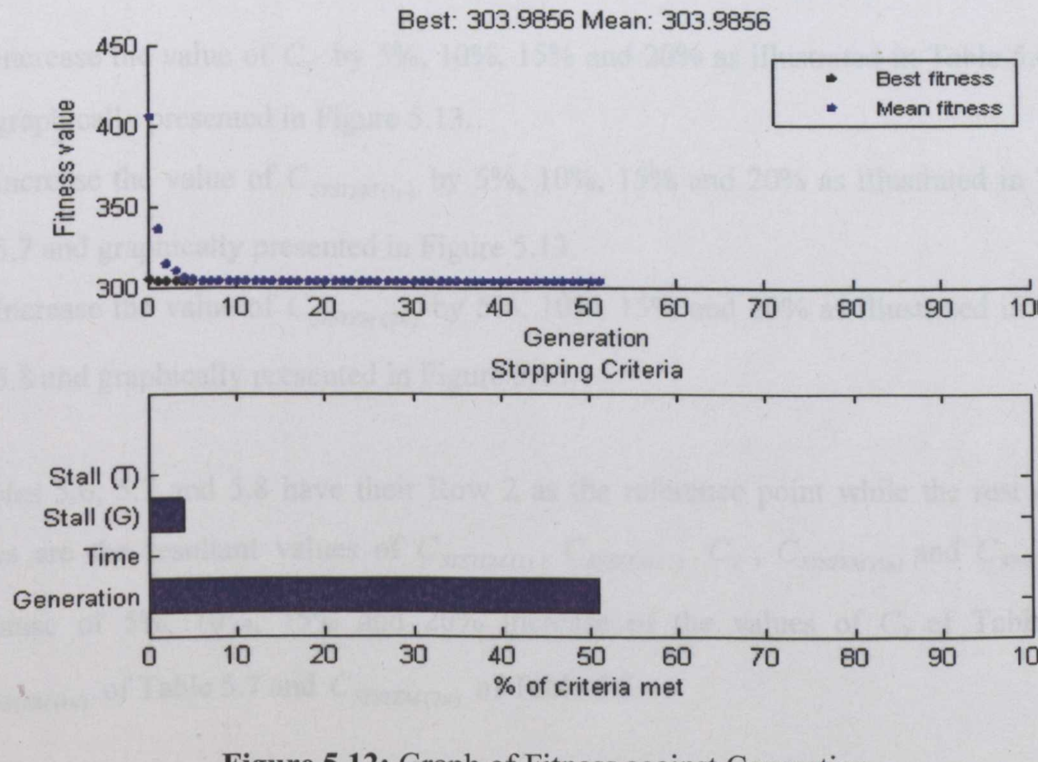

Figure 5.12: Graph of Fitness against Generation

5.6.5. Result Verification

The identified new maintenance costs of the LNG containment system and transfer arm are verified via sensitivity analysis of the model. The values of their new maintenance costs are considered to be acceptable if three axioms are satisfied as follows:

- Axiom 1. The value of R_T (total risk of the LNG carrier systems) should decrease whenever there is a slight increase of the value of C_T (total budgeted maintenance cost of the LNG carrier systems) in the model.
- Axiom 2. The value of R_T should increase whenever there is a slight increase of the value of $C_{SYSTEM(1u)}$ (unit cost of maintenance of the LNG containment system) in the model.
- Axiom 3. The value of R_T should increase whenever there is a slight increase of the value of $C_{SYSTEM(2u)}$ (unit cost of maintenance of the LNG transfer arm) in the model.

The model is verified by increasing the values of C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$ as follows:

- Increase the value of C_T by 5%, 10%, 15% and 20% as illustrated in Table 5.6 and graphically presented in Figure 5.13.
- Increase the value of $C_{SYSTEM(1u)}$ by 5%, 10%, 15% and 20% as illustrated in Table 5.7 and graphically presented in Figure 5.13.
- Increase the value of $C_{SYSTEM(2u)}$ by 5%, 10%, 15% and 20% as illustrated in Table 5.8 and graphically presented in Figure 5.13.

Tables 5.6, 5.7 and 5.8 have their Row 2 as the reference point while the rest of the rows are the resultant values of $C_{SYSTEM(1)}$, $C_{SYSTEM(2)}$, C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$ because of 5%, 10%, 15% and 20% increase of the values of C_T of Table 5.6, $C_{SYSTEM(1u)}$ of Table 5.7 and $C_{SYSTEM(2u)}$ of Table 5.8.

Table 5.6: Model Verification by Increase of C_T Value

$C_{SYSTEM(1)}$ ($)	$C_{SYSTEM(2)}$ ($)	C_T ($)	Lower boundary of $C_{SYSTEM(1)}$ i.e. $C_{SYSTEM(1u)}$ ($)	Lower boundary of $C_{SYSTEM(2)}$ i.e. $C_{SYSTEM(2u)}$ ($)	Percentage increase of C_T	Fitness function value R_T
693517	606483	1300000	542188	162500	Nil	303.99
728425	636575	1365000	542188	162500	5%	290.62
763331	666669	1430000	542188	162500	10%	278.39
798235	696765	1495000	542188	162500	15%	267.14
833138	726862	1560000	542188	162500	20%	256.76

Table 5.7: Model Verification by Increase of the $C_{SYSTEM(1u)}$ Value

$C_{SYSTEM(1)}$ ($)	$C_{SYSTEM(2)}$ ($)	C_T ($)	Lower boundary of $C_{SYSTEM(1)}$ i.e. $C_{SYSTEM(1u)}$ ($)	Lower boundary of $C_{SYSTEM(2)}$ i.e. $C_{SYSTEM(2u)}$ ($)	Percentage increase of C_T	Fitness function value R_T
693517	606483	1300000	542188	162500	Nil	303.99
700556	599444	1300000	569297	162500	5%	311.38
707213	592787	1300000	596407	162500	10%	318.64
713522	586478	1300000	623516	162500	15%	325.79
719512	580488	1300000	650626	162500	20%	332.84

Table 5.8: Model Verification by Increase of the $C_{SYSTEM(2u)}$ Value

$C_{SYSTEM(1)}$ (\$)	$C_{SYSTEM(2)}$ (\$)	C_T (\$)	Lower boundary of $C_{SYSTEM(1)}$ i.e. $C_{SYSTEM(1u)}$ (\$)	Lower boundary of $C_{SYSTEM(2)}$ i.e. $C_{SYSTEM(2u)}$ (\$)	Percentage increase of C_T	Fitness function value R_T
693517	606483	1300000	542188	162500	Nil	303.99
686235	613235	1300000	542188	170625	5%	310.45
679314	620686	1300000	542188	178750	10%	316.80
672726	627274	1300000	542188	186875	15%	323.04
666442	633558	1300000	542188	195000	20%	329.19

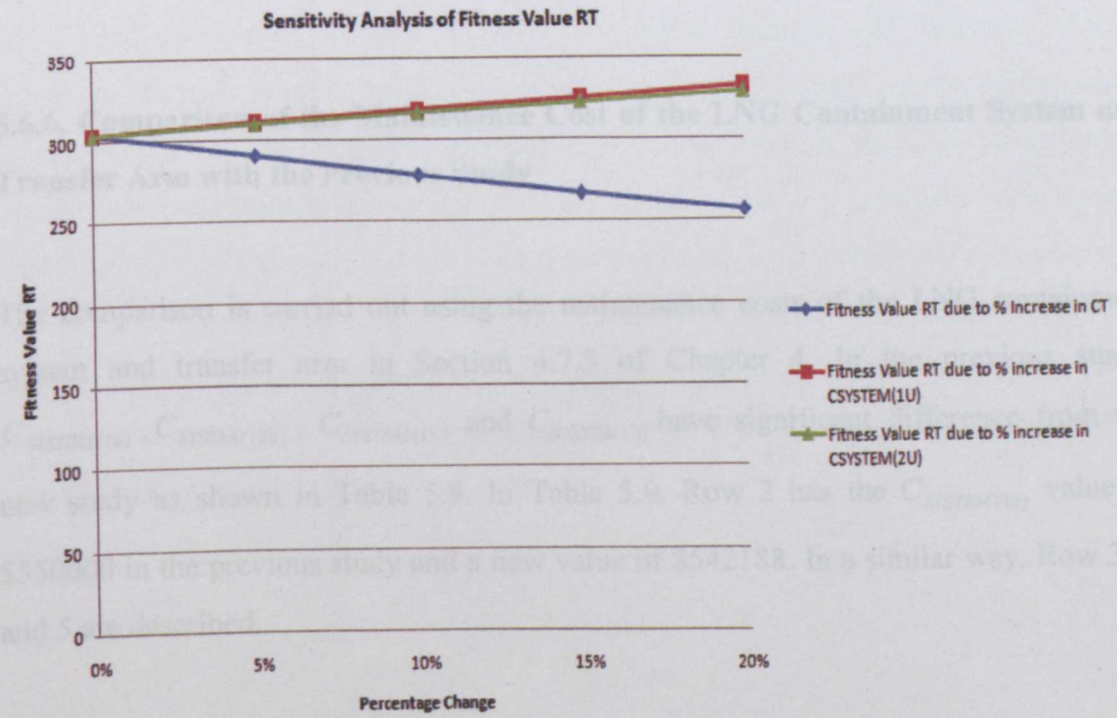

Figure 5.13: Graph of R_T Against Percentage Change of C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$ Values

In Row 3 of Table 5.6, $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$ have values of \$728425 and \$636575 respectively, where C_T, $C_{SYSTEM(1u)}$ and $C_{SYSTEM(2u)}$ have values of \$1365000, \$542188 and \$162500 respectively, because of 5% increase of the C_T value of the model. The fitness function value R_T decreased from 303.99 to 290.62. Other rows in Table 5.6 are described in a similar way and have decreased values of R_T (278.39, 267.14 and 256.76). This is in consistence with Axiom 1.

In a similar way, Table 5.7 is described. Table 5.7 has R_T values of 311.38, 318.64, 325.79 and 332.84 in Rows 3, 4, 5 and 6 respectively, as a result of 5%, 10%, 15% and 20% increase of the $C_{SYSTEM(1u)}$ value of the model. Therefore, Axiom 2 has been satisfied.

Table 5.8 is explained in a similar way to Table 5.7, with 5%, 10%, 15% and 20% increase of the $C_{SYSTEM(2u)}$ value. The resultant R_T values of 310.45, 316.8, 323.04 and 329.19 are in Rows 3, 4, 5 and 6 of Table 5.8 respectively. The increase in the values of R_T is in harmony with Axiom 3.

5.6.6. Comparison of the Maintenance Cost of the LNG Containment System and Transfer Arm with the Previous Study

The comparison is carried out using the maintenance costs of the LNG containment system and transfer arm in Section 4.7.5 of Chapter 4. In the previous study, $C_{SYSTEM(1u)}$, $C_{SYSTEM(2u)}$, $C_{SYSTEM(1)}$, and $C_{SYSTEM(2)}$ have significant difference from the new study as shown in Table 5.9. In Table 5.9, Row 2 has the $C_{SYSTEM(1u)}$ value of \$550000 in the previous study and a new value of \$542188. In a similar way, Row 3, 4 and 5 are described.

Table 5.9: Comparison of Previous and New Maintenance Cost

Parameter	Previous study	New study
$C_{SYSTEM(1u)}$	\$550000	\$542188
$C_{SYSTEM(2u)}$	\$130000	\$162500
$C_{SYSTEM(1)}$	\$729087	\$693517
$C_{SYSTEM(2)}$	\$570913	\$606483

5.7. Conclusion

The uncertainties associated with the unit costs of maintenance of the LNG containment system and transfer arm have been treated and optimal risk solutions found successfully using FGA, which produced the new maintenance costs of the systems. The mechanism of the algorithm tackled the problem by firing the relevant rules in the LNG carrier maintenance cost FRB for the identification of the unit cost of maintenance of the LNG containment system, which is described with five linguistics terms ("very cheap", "cheap", "normal", "expensive" and "very expensive"), and the fuzzy conclusion is defuzzified using the WMoM method. The LNG transfer arm followed similar processes but with firing of another set of relevant rules in the LNG carrier maintenance cost fuzzy rules. The identified unit costs of maintenance of the LNG containment system and transfer arm are used to find the more reasonably estimated maintenance cost of these LNG carrier systems, based on their budgeted maintenance cost using a GA in a Matlab environment. A comparison of maintenance costs with the previous study is carried out and the differences are noted. The ability of the fuzzy logic in the treatment of uncertainty will be extended in risk analysis of the LNG carrier systems using a FER approach in the next chapter.

Chapter 6 - A New Fuzzy Evidential Reasoning Method for Risk Analysis and Control of Liquefied Natural Gas Carrier Systems

Summary

In this chapter, safety/risk levels of LNG carrier systems are investigated through the application of a FER method to uncertainty treatment of their failure modes (basic events). A fuzzy set manipulation formula that has parameters such as consequence severity, failure consequence probability and failure likelihood is used to assess the safety/risk levels of failure modes of the systems (LNG containment system and transfer arm). Such failure estimations are synthesised to evaluate the systems' safety/risk levels using an ER approach. RCOs are developed for the reduction/control of safety/risk levels of the systems. The best RCO, which is the one with the highest preference degree, is used to control the high level risks of the systems.

6.1. Introduction

LNG carriers are quite important and necessary for transportation of LNG in the marine and offshore industries. Although they are reliable in their in-service operation, they can still be prone to accidents. The IMO adopted the FSA concept to proactively ensure the safety of shipping vessels, including LNG carriers and their systems/subsystems as well as their pollution prevention to the maritime environment. However, the evaluation of safety/risk level of LNG carrier systems may be difficult, given the high level of uncertainties in the historical failure data associated with LNG carrier operations.

The inherent uncertainty can be caused by imperfect understanding of the domain, incomplete knowledge of the state of the domain at the time where a given task is to be performed, randomness in the mechanisms governing the behaviour of the domain, or a combination of these (Eleye-Datubo, 2006). The current and future development of the FSA methodology and its various applications to marine and offshore facilities has been discussed in many publications (Fang et al., 2005; Hu et al., 2007; Lee et al., 2001;

IACS, 2004; IMO, 2002a; Rosqvist and Tuominen, 2004; Soares and Teixeira, 2001; Vanem et al., 2008; Wang, 2001; Wang and Foinikis, 2001). This can support the argument of this study that the safety of LNG carriers needs to be appropriately addressed by carrying out comprehensive risk assessment and particularly applying the FSA in an uncertainty environment, given the recent rapid enlargement of the LNG carrier fleet.

In this chapter, FSA will be applied to LNG carrier systems such as a containment system and a transfer arm as these are areas of high risk that can lead to LNG spills. FSA is feasible on LNG carrier operations using advanced computational techniques. A FST coupled with an ER approach can be used to address the uncertainty problem in the LNG industry. FST will ascertain safety levels of the failure modes (basic events) while the ER tool will use its mechanism for hierarchical propagation of various failure modes' safety levels that lead to the top event (LNG containment system failure and LNG spill from the transfer arm).

The modelling of the failure modes of the LNG containment system and the LNG transfer arm includes parameters such as failure likelihood, consequence severity, failure consequence probability, cost expression and safety expression. The parameters are described by linguistic terms, which are characterised by membership functions to the defined categories. The best RCO is based on the option with the highest preference degree.

6.2. Background Analysis

A practical solution is by far the most desired output when making decisions under the realm of uncertainty on a LNG carrier and its systems/subsystems. The FER deals with those uncertainties while following the FSA procedure. Researchers have tapped the uncertainty treatment capability of the FER as a stand alone method or in combination with the FSA methodology and other reliable and meaningful techniques (Yang et al., 2005; Yang and Singh, 1994; Wang, 1997; Liu et al., 1994; Godaliyadde et al., 2009).

According to Yang et al. (2005)'s work, after the 9/11 terrorism attacks, the lock-out of the American West Ports in 2002 and the breakout of SARS disease in 2003 have further focused the mind of both the public and industrialists to take effective and timely measures for assessing and controlling the risks related to container supply chains. A FER method was used to deal with those threat-based risks, which were more ubiquitous and uncertain than the hazard-based ones in the chains. Its feasibility was validated by a case study associated with a threat of terrorists attacking ports (Yang et al., 2005).

In another study, the advantage of the feasibility of a combination of FER and FSA was used (Wang, 2000). A FER method for analysing subjective safety and cost was illustrated based on a proposed formal ship safety assessment in situations where a high level of uncertainty was involved. A similar approach of the FER algorithm has been used in several other risk and safety assessment studies (Godaliyadde et al., 2009; Wang et al., 1995; Wang et al., 1996; Wang, 1997).

FSA has been applied to a LNG carrier using a quantitative risk analysis method with safety analysis technique such as ETA (Vanem et al., 2008). In their work, they used the FSA methodology to tackle total risk of a LNG carrier that is made up of collision, grounding, contact, fire/explosion and loading/unloading risks.

The relevant combination of FER and FSA with the adoption of FTA is extended to LNG carrier systems. In this work, the uncertainties surrounding failure modes (basic events) of FTA of the LNG containment system and the LNG transfer arm are tackled using the aforementioned FER and FSA.

6.3. Formal Safety Assessment

FSA is the process of identifying hazards, evaluating risks and deciding on an appropriate course of action to manage these risks in a cost-effective manner (Trbojevic and Carr, 2000). Marine and offshore accidents that happened in the past made the United Kingdom Maritime and Coastguard Agency (UK MCA) propose to the IMO in 1993 that FSA should be applied to ships (Wang, 2001). The application to ships will improve the safety of ships and drastically reduce the rate of negative effect to the environment, systems and personnel onboard vessels. The UK MCA recommended that the application of FSA should be from the design of ship to its operation (Wang, 2001). The IMO adopted this process as interim guidelines for their rule making process after studying notable incident/accident investigation reports (IMO, 2002a; IMO, 1997a). These include:

- Lord Carver's report on the investigation of the capsize of the Herald of Free Enterprise (House of Lords, 1992).
- Lord Cullen's report on the Piper Alpha accident (Department of Energy, 1990).

These reports and other incidents/accidents (Wang and Trbojevic, 2007) that happened in the maritime and offshore industry made the IMO attempt application of FSA on various vessels and systems so as to ensure the best safety practice. This includes:

- Application to the transportation of dangerous goods on passenger ships (IMO, 1998a).
- Application on high speed catamaran passenger vessels (IMO, 1997b).
- Application to novel emergency propulsion and steering devices for oil tankers (IMO, 1998d).
- Trial application on bulk carriers (MCA, 1998).

A company such as P & O Cruises Ltd has proved the benefits of FSA by application of the methodology to their carriers. The various steps helped to solve challenging problems of hazards, risks, RCOs and their costs and benefits in a rational, structured and auditable manner that improved the safety of their fleet of carriers. Adopting this process as a regulatory tool is of great benefit. These benefits are (MSA, 1993):

- A consistent regulatory regime that addresses all aspects of safety in an integrated way.
- Cost effectiveness, whereby the safety investment is targeted where it will achieve the greatest benefit.

- A proactive approach, enabling hazards that have not yet given rise to accidents to be properly considered.
- Confidence that regulatory requirements are in proportion to the severity of the risks.
- A rational basis for addressing new risks posed by the ever-changing marine technology.

The five steps of the aforementioned FSA methodology are (IMO, 2002a; IMO, 1997a; Pillay and Wang, 2003; Wang, 2001):

1. Hazard Identification (HAZID).
2. Risk Assessment.
3. Risk Control Options (RCOs).
4. Cost Benefit Assessment (CBA).
5. Decision Making.

The FSA methodology is illustrated in Figure 6.1, which shows the relationship of the steps with the aim of reducing the risk associated with hazards to an ALARP level, using the best RCO, considering the cost of controlling the risk and benefit of such risk control with respect to the cost. The FSA methodology is further broken down in Figure 6.2 to accommodate uncertainties in risk analysis of the LNG carrier systems, using the powerful tool of FER.

The information flow in Figure 6.2 starts from the description of a LNG carrier system. The next step is development of the system's FTA diagram for identification of its failure modes. Once all the failure modes have been identified, their safety levels are estimated using a fuzzy manipulation formula. Otherwise, the system's FTA diagram is re-examined before safety assessment of its failure modes. In a situation where there are two or more failure modes, ER is used to combine them in order to estimate the safety level of a top event. If the safety level of the top event is not acceptable, RCOs are identified. The cost and benefit of each RCO are investigated using cost and utility expression as illustrated in Figure 6.2. The RCO that has highest preference degree is the best one for safety improvement of the LNG carrier system.

Figure 6.1: A Flow Chart of the FSA Methodology (Pillay and Wang, 2003)

6.3.1. Hazard Identification

The first step and foundation of FSA is HAZID. Hazard is a physical situation or condition with a potential for human injury, damage to property, damage to the environment or a combination of them (Wang and Trbojevic, 2007). The objective of this step is to identify all relevant hazards that might affect the proper functions of LNG carriers. A technique used for identifying relevant hazards in LNG carriers is called brainstorming, which is a technique for tapping the creative thinking of a team to generate and clarify a list of ideas, problems and issues. The team involved in HAZID consists of experts from various aspects of the shipping industry such as ship design, operations and management, and specialists in the HAZID process. The team ensures that previous experience is properly taken into account, and typically makes use of background information such as applicable regulations and codes, available statistical data on accident categories and list of hazards to personnel, hazardous substances and ignition sources. The brainstorming technique is used to recommend safety analysis techniques that can be used to know hazards and possible causes and outcomes of each accident category, outlined in Chapter 3. An accident is an unintended event involving fatality, injury, property loss or damage and/or environmental damage (Wang and Trbojevic, 2007).

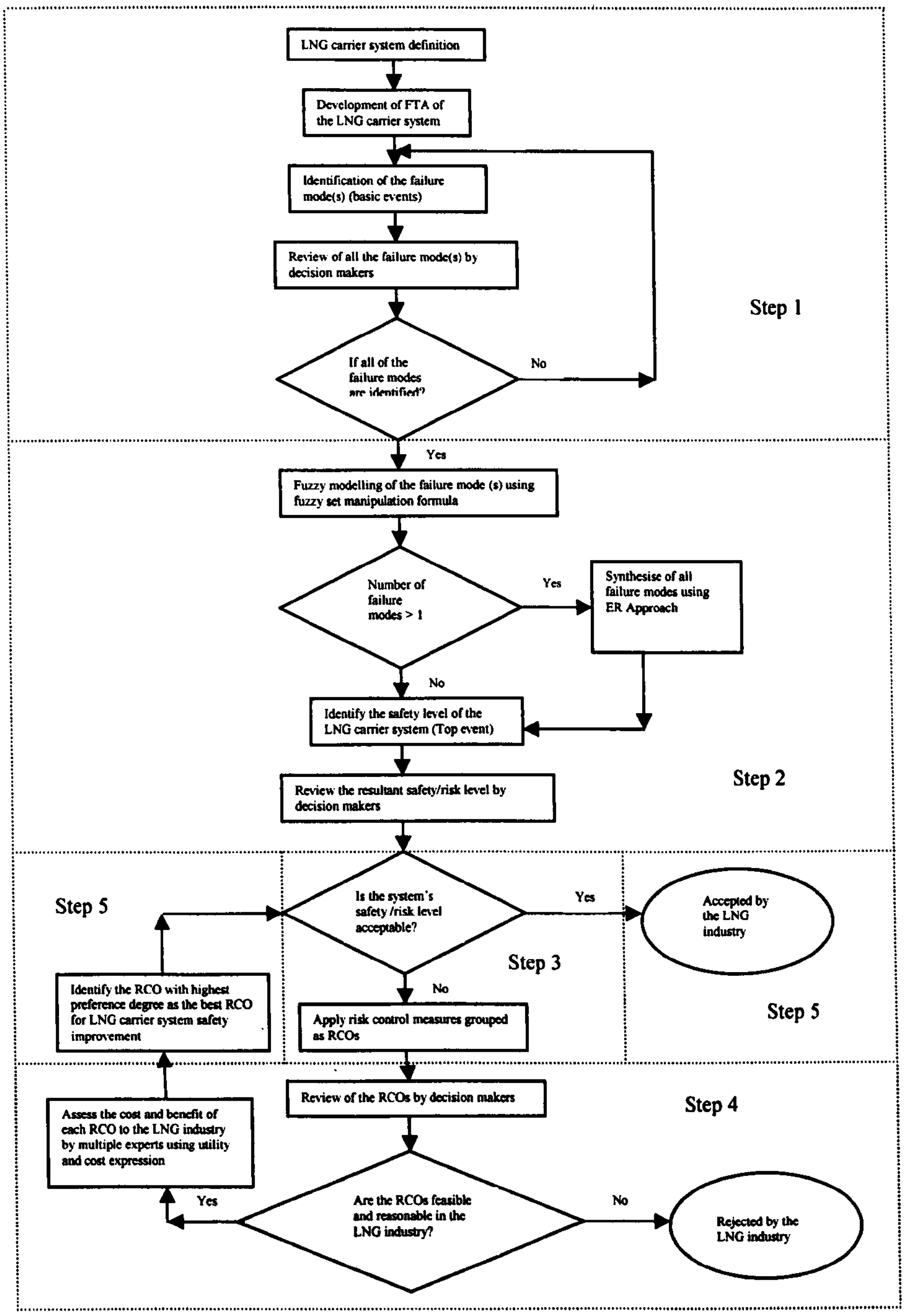

Figure 6.2: A Flow Chart of the FSA Methodology Based on a FER Method in Uncertainty Environment.

6.3.2. Risk Assessment

The purpose of Step 2 of FSA in the LNG industry, which is risk assessment, is to identify the distribution of risk, thereby focusing on high risk areas that will be evaluated and controlled. Risk is defined as a combination of the probability of occurrence of an undesired event and the degree of its possible consequences (Wang and Trbojevic, 2007). Risk assessment is a comprehensive estimation of the probability and the degree of the possible consequences in a hazardous situation in order to select appropriate safety measures (Wang and Trbojevic, 2007). In this step, risks associated with the identified hazards of the LNG carrier in Step 1, are evaluated to know if they are significant.

Risk assessment can be carried out on various areas of a LNG carrier and other facilities used in the LNG industry by using a diagram called "Risk Contribution Tree (RCT)". An RCT is a combination of FT and ET, showing causes and consequences of an accident. Risk assessment provides qualitative and/or quantitative information to decision makers (Pillay, 2001). RCT can be used to calculate the Frequency versus No of fatalities (F-N) and Potential Loss for Life (PLL). Qualitative and quantitative risk analyses are explained in Section 4.5 of Chapter 4. If there is no availability of data or existence of uncertainty for quantification of the FTA or ETA, a special technique such as the FER method can be used to access the risk of the LNG carrier as illustrated in Figure 6.2.

6.3.2.1. Risk Assessment Using Fuzzy Evidential Reasoning Method

Unavailability of data and uncertainty of a LNG component often makes PRA impossible, thereby giving room for application of FST coupled with ER. This is capable of combining uncertain evaluations at a single level and implementing hierarchical propagation of such evaluations between different levels in risk assessment of a LNG carrier system.

6.3.2.1.1. Fuzzy Set Modelling

To assess the fuzzy safety associated with an event or element, it is required to synthesize the associated occurrence likelihood, consequence severity and failure consequence probability (Wang et al., 2004). The fuzzy set manipulation used in risk assessment is (Wang and Trbojevic, 2007):

$$S_i = C_i \, o \, E_i \times L_i \qquad (6.1)$$

This can be represented in terms of membership functions as follows:

$$\mu_{S_i} = \mu_{C_i \; o E_i \times L_i} = \left(\mu^1{}_{S_i} \,......., \mu^j{}_{S_i}\right) \qquad (6.2)$$

where, S_i means risk/safety score.

C_i means fuzzy set of consequence severity of a failure mode i.

o means Composition operation.

× means Cartesian product operation.

E_i means fuzzy set of failure consequence probability of a failure mode i.

L_i means fuzzy set of failure likelihood of a failure mode i.

μ_{S_i} means description function of S_i in terms of membership degrees $\mu^j_{S_i}$ $(j = 1,2,3.......7)$ associated with the defined categories.

μ_{E_i} means description function of E_i in terms of membership degree $\mu^j_{E_i}$ $(j = 1,2,3........7)$ associated with the defined categories.

μ_{C_i} means description function of C_i in terms of membership degree $\mu^j_{C_i}$ $(j = 1,2,3.........7)$ associated with the defined categories.

μ_{L_i} means description function of L_i in terms of membership degree $\mu^j_{L_i}$ $(j = 1,2,3.........7)$ associated with the defined categories.

μ_{S_i} is obtained using a max-min method that is illustrated in Example 1 of Appendix E1.1.

The membership values, categories and linguistic variables/terms of L, E, C and S are shown in Tables 6.1, 6.2, 6.3 and 6.4 (Wang and Trbojevic, 2007, Wang et al., 1995). The choice/estimation of membership values of L, E, C and S depends on the experience of the safety analysts.

Table 6.1: Failure Likelihood (L)

Linguistic variables μ_L	Categories						
	1	2	3	4	5	6	7
Highly frequent	0	0	0	0	0	0.75	1
Frequent	0	0	0	0	0.75	1	0.25
Reasonably frequent	0	0	0	0.75	1	0.25	0
Average	0	0	0.5	1	0.5	0	0
Reasonably low	0	0.25	1	0.75	0	0	0
Low	0.25	1	0.75	0	0	0	0
Very low	1	0.75	0	0	0	0	0

Table 6.2: Failure Consequence Probability (E)

Linguistic variables μ_E	Categories						
	1	2	3	4	5	6	7
Definite	0	0	0	0	0	0.75	1
Highly likely	0	0	0	0	0.75	1	0.25
Reasonably likely	0	0	0	0.75	1	0.25	0
Likely	0	0	0.5	1	0.5	0	0
Reasonably Unlikely	0	0.25	1	0.75	0	0	0
Unlikely	0.25	1	0.75	0	0	0	0
Highly Unlikely	1	0.75	0	0	0	0	0

From the information provided in Tables 6.1-6.4, failure mode modelling can be carried out. For instance, the linguistic variables "negligible", "highly unlikely", "very low", and "excellent" can be modelled by:

Negligible = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

Highly unlikely = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

Very low = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

Excellent = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

Table 6.3: Consequence Severity (C)

Linguistic variables μ_C	Categories						
	1	2	3	4	5	6	7
Catastrophic	0	0	0	0	0	0.75	1
Critical	0	0	0	0.75	1	0.25	0
Marginal	0	0.25	1	0.75	0	0	0
Negligible	1	0.75	0	0	0	0	0

Table 6.4: Safety Expressions (S)

Linguistic variables μ_S	Categories						
	1	2	3	4	5	6	7
1. Poor	0	0	0	0	0	0.75	1
2. Average	0	0	0	0.5	1	0.25	0
3. Good	0	0.25	1	0.5	0	0	0
4. Excellent	1	0.75	0	0	0	0	0

Where the integers in the numerator of each term within the brackets represent the categories, and the real values in the denominator stand for the membership degrees (Wang et al., 1995). In Tables 6.1-6.4, the first row represents the categories (1-7) while the other rows represent the membership degrees. Thus,

$\mu_{negligible} \quad = \{1, 0.75, 0.... 0\}$

$\mu_{highly\ unlikely} \quad = \{1, 0.75, 0...0\}$

$\mu_{very\ low} \quad = \{1, 0.75, 0.... 0\}$

$\mu_{excellent} \quad = \{1, 0.75, 0.... 0\}$

The safety expressions "poor", "average", "good" and "excellent" are incorporated into safety score as follows (Wang et al., 1995):

$$
\begin{aligned}
&1.\ S_{poor} = C_{catastrophic}\ o\ E_{definite} \times L_{high\ frequent}\\
&2.\ S_{average} = C_{critical}\ o\ E_{reasonable\ likely} \times L_{reasonably\ frequent}\\
&3.\ S_{good} = C_{marginal}\ o\ E_{reasonable\ unlikely} \times L_{reasonably\ low}\\
&4.\ S_{excellent} = C_{negligible}\ o\ E_{highly\ unlikely} \times L_{very\ low}
\end{aligned}
\tag{6.3}
$$

Using the Best-Fit method, the obtained fuzzy safety/risk score description S_i of failure mode i of a component can be mapped back to one (or all) of the defined safety expressions (i.e. "excellent", "good", "average" and "poor") (Wang and Trbojevic, 2007; Wang et al., 1995). The method uses the distance between S_i and each of the safety expressions to represent the degree to which S_i is confirmed to each of them (Wang and Trbojevic, 2007; Wang et al., 1995). An illustration is given below using the safety expressions "poor", "average", "good" and "excellent".

$$
\begin{aligned}
d_{i1}(S_i, poor) &= \left[\sum_{j=1}^{7}\left(\mu_{S_i}^{j} - \mu_{poor}^{j}\right)^2\right]^{1/2}\\
d_{i2}(S_i, average) &= \left[\sum_{j=1}^{7}\left(\mu_{S_i}^{j} - \mu_{average}^{j}\right)^2\right]^{1/2}\\
d_{i3}(S_i, good) &= \left[\sum_{j=1}^{7}\left(\mu_{S_i}^{j} - \mu_{good}^{j}\right)^2\right]^{1/2}
\end{aligned}
\tag{6.4}
$$

$$d_{i4}(S_i, excellent) = \left[\sum_{j=1}^{7}\left(\mu_{Si}^{j} - \mu_{excellent}^{j}\right)^2\right]^{1/2}$$

When the unscaled distance $d_{ij}(j = 1,2,3,4)$ is equal to zero, S_i is just the same as the jth safety expression in terms of membership functions. In such a condition, S_i should not be evaluated to other expressions at all due to exclusiveness of these expressions (Wang et al., 1995). Therefore, $d_{iJ}(1 \le J \le 4)$ is introduced and defined based on $d_{ij}(j = 1,2,3,4)$, to embody such feature. The smallest value of d_{iJ} for any given distances for S_i is used to find α_{ij} . α_{ij} is reciprocals of the relative distances between S_i and each safety expression with reference to d_{iJ}^{l} . α_{ij} is normalised into new index $\beta_{ij}(j = 1,2,3,4)$ in order to more clearly express the safety level of S_i. α_{ij} can be defined mathematically as:

$$\alpha_{ij} = 1 \Big/ \left(d_{ij} / d_{iJ} \right) \qquad j = 1,2,3,4 \tag{6.5}$$

If d_{ij} is equal to zero, it follows that β_{ij} is equal to 1 and the others are equal to 0. In other situations, β_{ij} can be expressed as:

$$\beta_{ij} = \alpha_{ij} \Big/ \sum_{m=1}^{4} \alpha_{im} \qquad j = 1,2,3,4 \tag{6.6}$$

where each $\beta_{ij}(j = 1,2,3,4)$ represents the extent to which S_i belongs to the jth defined safety expression. Mapping it back to safety expressions implies:

$$S(S_i) = \{(\beta_{i1}, "poor"), (\beta_{i2}, "average"), (\beta_{i3}, "good"), (\beta_{i4}, "excellent")\}. \tag{6.7}$$

6.3.2.1.2. Evidential Reasoning

If there is more than one component that make up a system, the ER approach can be used to synthesise the multiple $S(S_i)$ with the help of the Intelligent Decision System (IDS) software (Yang and Xu, 2000). The mechanism of ER can be explained using the aggregation of two safety assessments. The two assessments are:

$$S(S_{i1}) = \{(\beta^1_{S_{i1}}, \text{"Poor"}), (\beta^2_{S_{i1}}, \text{"Average"}), (\beta^3_{S_{i1}}, \text{"Good"}), (\beta^4_{S_{i1}}, \text{"Excellent"})\}$$

$$S(S_{i2}) = \{(\beta^1_{S_{i2}}, \text{"Poor"}), (\beta^2_{S_{i2}}, \text{"Average"}), (\beta^3_{S_{i2}}, \text{"Good"}), (\beta^4_{S_{i2}}, \text{"Excellent"})\} \quad (6.8)$$

where each $\beta^j_{S_{i1}}$ and $\beta^j_{S_{i2}}$ $(j = 1,2,3,4)$ represent the extent to which S_{i1} and S_{i2} are confirmed to jth safety expression. Suppose the relative weights for $S(S_{i1})$ and $S(S_{i2})$ are w_1 and w_2. The relative weights of $S(S_{i1})$ and $S(S_{i2})$ are normalised using the expression as follows.

$$\sum_{i=1}^{2} w_i = 1 \; ; \; 0 \le w_i \le 1 \quad (6.9)$$

For $S(S_{i1})$ and $S(S_{i2})$, the probability masses are expressed as follows:

$$S_{i1m} = w_1 \beta^m_{S_{i1}} \; , \; m = 1,2,3,4 \quad (6.10)$$

Similarly,

$$S_{i2m} = w_2 \beta^m_{S_{i2}} \; , \; m = 1,2,3,4 \quad (6.11)$$

$$\bar{S}_{i1H} = 1 - w_1 = w_2 \quad (6.12)$$

Similarly,

$$\bar{S}_{i2H} = 1 - w_2 = w_1 \quad (6.13)$$

where $\bar{S}_{i1H}$ and $\bar{S}_{i2H}$ represent the degree to which other assessors or failure modes can play a role in the assessment.

$$\tilde{S}_{i1H} = w_1\left(1 - \sum_{j=1}^{4} \beta_{S_{i1}}^{j}\right) = w_1\left[1 - \left(\beta_{S_{i1}}^{1} + \beta_{S_{i1}}^{2} + \beta_{S_{i1}}^{3} + \beta_{S_{i1}}^{4}\right)\right] \quad (6.14)$$

Similarly,

$$\tilde{S}_{i2H} = w_2\left(1 - \sum_{j=1}^{4} \beta_{S_{i2}}^{j}\right) = w_2\left[1 - \left(\beta_{S_{i2}}^{1} + \beta_{S_{i2}}^{2} + \beta_{S_{i2}}^{3} + \beta_{S_{i2}}^{4}\right)\right] \quad (6.15)$$

where $\tilde{S}_{i1H}$ and $\tilde{S}_{i2H}$ are the individual remaining belief values unassigned for $S(S_{i1})$ and $S(S_{i2})$ respectively.

$$S_{i1H} = \bar{S}_{i1H} + \tilde{S}_{i1H} \quad (6.16)$$

$$S_{i2H} = \bar{S}_{i2H} + \tilde{S}_{i2H} \quad (6.17)$$

where, S_{i1H} and S_{i2H} represent possible incompleteness in the subsets $S(S_{i1})$ and $S(S_{i2})$. The combined probability masses, S_{im} and S_{iH} are generated using basic probability masses, S_{i1m} and S_{i2m}, and S_{i1H} and S_{i2H} as follows:

$$S_{im} = K\left(S_{i1m}S_{i2m} + S_{i1m}S_{i2H} + S_{i2m}S_{i1H}\right),\ m = 1,2,3,4 \quad (6.18)$$

$$S_{iH} = K(S_{i1H}S_{i2H}) \quad (6.19)$$

$$\text{where, } K = \left[1 - \sum_{T=1}^{4} \sum_{\substack{R=1 \\ R \neq T}}^{4} S_{i1T} S_{i2R} \right]^{-1} \tag{6.20}$$

The combined DoBs can be calculated as follows:

$$\beta_i^m = \frac{S_{im}}{1 - S_{iH}}, \quad m = 1,2,3,4 \tag{6.21}$$

where β_i^m $(m = 1,2,3,4)$ are the resultant DoBs of the synthesised two fuzzy sets, $S(S_{i1})$ and $S(S_{i2})$. Three or more fuzzy sets can also be synthesised in a similar way, in which the obtained β_i^m can be combined with the third or more subset(s).

To rank the risk levels of the failure modes, the crisp values of their fuzzy safety estimates can be calculated using preference degree formula as follows:

$$Q_i = \sum_{m=1}^{4} \beta_i^m \times V_m + \left(1 - \sum_{m=1}^{4} \beta_i^m \right) \times \frac{1}{4} \times \sum_{m=1}^{4} V_m \tag{6.22}$$

$$\text{where, } V_1 = \frac{V_4'}{V_1'},\ V_2 = \frac{V_3'}{V_1'},\ V_3 = \frac{V_2'}{V_1'},\ V_4 = 1$$

V_1', V_2', V_3', and V_4' represent the unscaled numerical values associated with the linguistic terms (i.e. "poor", "average", "good" and "excellent") of the safety expression shown in Table 6.4. V_1', V_2', V_3', and V_4' can be calculated while normalization of β_i^m of each linguistic term in Table 6.4 as follows:

$$V_1' = [0.75/(0.75+1)] \times 6 + [1/(0.75+1)] \times 7 = 6.571$$

$$V_2' = [0.5/(0.5+1+0.25)] \times 4 + [1/(0.5+1+0.25)] \times 5 + [0.25/(0.5+1+0.25)] \times 6 = 4.854$$

$$V_3' = [0.25/(0.25+1+0.5)] \times 2 + [1/(0.25+1+0.5)] \times 3 + [0.5/(0.25+1+0.5)] \times 4 = 3.141$$

$$V_4' = [1/(1+0.75)]\times 1 + [0.75/(1+0.75)]\times 2 = 1.428$$

Substituting the values of V_1, V_2, V_3 and V_4 in Equation (6.22) yields:

$$Q_i = 0.217 \times \beta_i^1 + 0.478 \times \beta_i^2 + 0.739 \times \beta_i^3 + 1 \times \beta_i^4 + \left(\frac{0.217 + 0.478 + 0.739 + 1}{4}\right) \times \left(1 - \left(\beta_i^1 + \beta_i^2 + \beta_i^3 + \beta_i^4\right)\right) \quad (6.23)$$

where $Q_i(i = 1,2,3...n)$ is the preference degree of the *i*th failure mode. Each $Q_i(i = 1,2,3...n)$ is used to represents the risk rank of the *i*th failure mode. A low risk failure mode is associated with larger preference degree and vice versa.

6.3.3. Risk Control Option

In this step, effective Risk Control Measures (RCMs) are developed based on the risk assessment (Step 2) of the hazards (Step 1) and cost benefit assessment (Step 4). The RCM that are not identified by existing measure can be known with the use of casual chains. Casual chain can be used to develop appropriate measures at a selected control point in sequence of "Cause ⟶ Incident ⟶ Accident ⟶ Consequence" (Lois et al., 2004; PVA, 1997). However, the RCMs developed must have the following attributes (MSA, 1993):

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

The produced RCOs are finally reviewed by assessing their effectiveness in Step 4. FST can be used to investigate the effectiveness of the RCOs if there is existence of uncertainties.

6.3.4. Cost Benefit Assessment

The basis for decision-making about the RCOs is provided by CBA. This step shows whether the benefits of a measure outweigh its costs. To conduct CBA, it is required to set a base case that can be used as a reference for comparison (Wang, 2001). A base case reflects the existing levels of risk associated with the shipping activity before the implementation of risk control (Wang, 2001). It should be initially carried out for the overall situation and then for those interested entities influenced by the consideration of the problem (Pillay and Wang, 2003). The costs should include the following:

- Cost of training, regulations, documentation, equipment, redesign and construction, inspection and maintenance.
- Reduced commercial use (e.g. reduced deck space with commercial use).
- Operational limitation such as reduced loads and speed.

The benefits are:

- Reduction of costs for injuries and fatalities.
- Reduction of costs for clean up, environmental damage, liability claims and ship deterioration.

The cost and benefit for each RCO are calculated in terms of its Net Present Value (NPV) expressed as follows:

$$NPV = \sum_{t=1}^{n} \left[(C_t - B_t)(1-r)^{-t} \right] \qquad (6.24)$$

where, t = Time horizon for the assessment, starting in year 1.

B_t = Sum of benefits in year t.

C_t = Sum of costs in year t.

r = Annual discount rate.

n = Number of years in the vessel's lifetime.

The safety level of a system/component and cost of application of the RCOs can be modelled using the FST because of the existence of uncertainties. This can be achieved using Tables 6.4 - 6.6 (Wang and Trbojevic, 2007; Wang et al., 1995). The safety estimate is mapped onto an utility space to know the utility estimate of the RCO with respect to safety. The safety estimate obtained in Section 6.3.2 is expressed as follows:

$$S(S_i) = \{(\mu_{S_i}^1, \text{"}poor\text{"}), (\mu_{S_i}^2, \text{"}average\text{"}), (\mu_{S_i}^3, \text{"}good\text{"}), (\mu_{S_i}^4\ \text{"}excellent\text{"})\}$$

The $S(S_i)$ is mapped onto the utility space and expressed in terms of the utility expressions in Table 6.6 as follows:

$$U(S_i) = \{(\mu_{S_i}^1, \text{“}slightly\ preferred\text{”}), (\mu_{S_i}^2, \text{“}moderately\ preferred\text{”}), (\mu_{S_i}^3, \text{“}preferred\text{”}), (\mu_{S_i}^4, \text{“}greatly\ preferred\text{”})\}$$

(6.25)

Each $\mu_{S_i}^j\ (j = 1,2,3,4)$ represents a degree of confidence that S_i belongs to the *jth* utility expression. The safety/risk analyst l can estimate the cost C_i^l for RCO i to eliminate the failure mode in terms of the cost expressions in Table 6.5. The cost C_i^l is expressed in terms of membership functions as follows:

$$C_i^l = (\mu_{C_i^l}^1/1,\ \mu_{C_i^l}^2/2,\ \mu_{C_i^l}^3/3,\ \mu_{C_i^l}^4/4,\ \mu_{C_i^l}^5/5,\ \mu_{C_i^l}^6/6,\ \mu_{C_i^l}^7/7) \qquad (6.26)$$

The Best–Fit method is used to map the fuzzy cost description onto the defined utility expressions in a similar way to Section 6.3.2.1.1. The method makes use of the distance between C_i^l and each of the utility expressions to represent the degree to which C_i^l is confirmed to each of the defined utility expressions. The distance between the obtained cost description C_i^l and the expressions are defined as follows:

Table 6.5: Cost Expression

Linguistic variables μ_L	Categories						
	1	2	3	4	5	6	7
Very high	0	0	0	0	0	0.75	1
High	0	0	0	0	0.75	1	0.25
Moderately high	0	0	0	0.5	1	0.25	0
Average	0	0	0.5	1	0.5	0	0
Moderately low	0	0.25	1	0.5	0	0	0
Low	0.25	1	0.75	0	0	0	0
Very low	1	0.75	0	0	0	0	0

Table 6.6: Utility Expression

Linguistic variables μ_S	Categories						
	1	2	3	4	5	6	7
1. Slightly preferred	0	0	0	0	0	0.75	1
2. Moderately preferred	0	0	0	0.5	1	0.25	0
3. Preferred	0	0.25	1	0.5	0	0	0
4. Greatly preferred	1	0.75	0	0	0	0	0

$$d_{i1}^{l}\left(C_i^l, slightly\ preferred\right) = \left[\sum_{j=1}^{7}\left(\mu_{C_i^l}^{j} - \mu_{slightly\ preferred}^{j}\right)^2\right]^{1/2}$$

$$d_{i2}^{l}\left(C_i^l, moderately\ preferred\right) = \left[\sum_{j=1}^{7}\left(\mu_{C_i^l}^{j} - \mu_{moderately\ preferred}^{j}\right)^2\right]^{1/2} \quad (6.27)$$

$$d_{i3}^{l}\left(C_i^l,\ preferred\right)=\left[\sum_{j=1}^{7}\left(\mu_{C_i^l}^{j}-\mu_{preferred}^{j}\right)^2\right]^{1/2}$$

$$d_{i4}^{l}\left(C_i^l,\ greatly\ preferred\right)=\left[\sum_{j=1}^{7}\left(\mu_{C_i^l}^{j}-\mu_{greatly\ preferred}^{j}\right)^2\right]^{1/2}$$

where each $d_{ij}^{l}\left(j=1,2,3,4\right)$ is an unscaled distance. If d_{ij}^{l} is equal to zero, C_i^l has the same values with the jth utility expressions in terms of membership functions.

$$\alpha_{ij}^{l}=\frac{1}{d_{ij}^{l}/d_{iJ}^{l}} \quad j=1,2,3,4 \tag{6.28}$$

where $\alpha_{ij}^{l}\left(j=1,2,3,4\right)$ are the reciprocals of the relative distance d_{ij}^{l} between the identified fuzzy cost description C_i^l and each of the defined utility expressions with reference to d_{iJ}^{l}. $d_{iJ}^{l}\left(1 \leq J \geq 4\right)$ is the smallest of the obtained distances for C_i^l. When the value of d_{ij}^{l} is zero, α_{ij}^{l} is assumed to be 1, while others are assumed to be zero. $\mu_{C_i^l}^{j}$ can be the normalisation of α_{ij}^{l} as follows (Wang et al., 1996):

$$\mu_{C_i^l}^{j}=\frac{\alpha_{ij}^{l}}{\sum_{n=1}^{4}\alpha_{in}^{l}} \quad j=1,2,3,4. \tag{6.29}$$

where each $\mu_{C_i^l}^{j}\left(j=1,2,3,4\right)$ represents the extent to which C_i^l is confirmed to the jth defined utility expression.

$$\sum_{n=1}^{4}\alpha_{in}^{l}=1\text{, is the summation of } \alpha_{ij}^{l}\left(j=1,2,3,4\right) \tag{6.30}$$

$\mu_{C_i^l}^{j}\left(j=1,2,3,4\right)$ is mapped onto the utility space as follows:

$$U(C_i^l)=\begin{Bmatrix}\left(\mu_{C_i^l}^1, \text{"}slightly\,preferred\text{"}\right),\left(\mu_{C_i^l}^2, \text{"moderately preferred"}\right),\left(\mu_{C_i^l}^3, \text{"}preferred\text{"}\right),\\ \left(\mu_{C_i^l}^4, \text{"}greatly\,preferred\text{"}\right)\end{Bmatrix}$$

(6.31)

The ER approach can be used to synthesise various $U(C_i^l)$ $(i = 1......n)$ and combine the result with $U(S_i)$ to obtain utility description $U(U_i)$ as follows:

$U(U_i)$ = {(μ_i^1, "*slightly preferred*"), (μ_i^2, "*moderately preferred*"), (μ_i^3, "*preferred*"), (μ_i^4, "*greatly preferred*")}

(6.32)

The weights of $U(C_i^l)$ and $U(S_i)$ play an important role in determination of $U(U_i)$. When cost is more important than safety, the weight of $U(C_i^l)$ will be larger than the one of safety and vice versa.

$U(U_i)$ is used for the analysis of RCO i, which states that (Wang et al., 1996):

$$P_i = \sum_{j=1}^{4} \mu_i^j \times K_j + \left(1 - \sum_{j=1}^{4} \mu_i^j\right) \times \frac{1}{4} \times \sum_{j=1}^{4} K_j \qquad (6.33)$$

where, $K_1 = \frac{K_4^{'}}{K_1^{'}}$, $K_2 = \frac{K_3^{'}}{K_1^{'}}$, $K_3 = \frac{K_2^{'}}{K_1^{'}}$, $K_4 = 1$

where, $\left(1 - \sum_{j=1}^{4} \mu_i^j\right)$ = Unassigned degrees of belief.

$K_1^{'}$, $K_2^{'}$, $K_3^{'}$, and $K_4^{'}$ represent the unscaled numerical values associated with the utility expression (i.e. "slightly preferred", "moderately preferred", "preferred" and "greatly preferred") illustrated in Table 6.6. $K_1^{'}$, $K_2^{'}$, $K_3^{'}$, and $K_4^{'}$ can be calculated while normalization of μ_i^j of each linguistic term in Table 6.6 as follows (Yang, 2006):

$$K_1^{'} = [0.75/(0.75+1)]\times 6 + [1/(0.75+1)]\times 7 = 6.571$$

$$K_2^{'} = [0.5/(0.5+1+0.25)]\times 4 + [1/(0.5+1+0.25)]\times 5 + [0.25/(0.5+1+0.25)]\times 6 = 4.854$$

$$K_3^{'} = [0.25/(0.25+1+0.5)]\times 2 + [1/(0.25+1+0.5)]\times 3 + [0.5/(0.25+1+0.5)]\times 4 = 3.141$$

$$K_4^{'} = [1/(1+0.75)]\times 1 + [0.75/(1+0.75)]\times 2 = 1.428$$

Substituting the values of K_1, K_2, K_3 and K_4 in Equation (6.33) yields:

$$P_i = 0.217 \times \mu_i^1 + 0.478 \times \mu_i^2 + 0.739 \times \mu_i^3 + 1 \times \mu_i^4 + \left(\frac{0.217 + 0.478 + 0.739 + 1}{4}\right) \times \left(1 - \left(\mu_i^1 + \mu_i^2 + \mu_i^3 + \mu_i^4\right)\right) \qquad (6.34)$$

where $P_i(i = 1,2,3...n)$ is the preference degree of RCO i. Each $P_i(i = 1,2,3...n)$ represents the extent to which RCO i is preferred in comparison with the others. A larger P_i means that RCO i is more desirable. The RCO i with the highest preference degree will be recommended in the decision making phase.

6.3.5. Decision Making

In this step, decision and recommendation is made for safety improvement of the LNG carrier operations. The information gathered from Steps 1 to 4 is reiterated for effective selection of a RCO. The RCOs are compared and ranked using their CBA for selection of most cost effective one based on the principle of ALARP illustrated in Figure 6.3. The ALARP diagram illustrates that if a risk lies within the ALARP or intolerable region, the risk must be reduced using the most cost effective RCO. Conversely, no RCO is needed if the risk lies at the broadly acceptable region. In event of lack of data for the costs of the RCOs, FST can be used to estimate costs incurred for the reduction of risks, as described in Section 6.3.4.

6.4. A Test Case of Fuzzy Evidential Reasoning Method to Failure Modes Modelling of LNG Carrier Systems

A combination of the FSA methodology and a FER method is used for uncertainty treatment of failure modes of the LNG carrier systems such as a LNG containment system and a LNG transfer arm. The LNG containment system and transfer arm have been described in Chapter 4, including identification of the respective failure modes for the top events (a LNG containment system failure and a LNG spill from transfer arm) using a FTA technique.

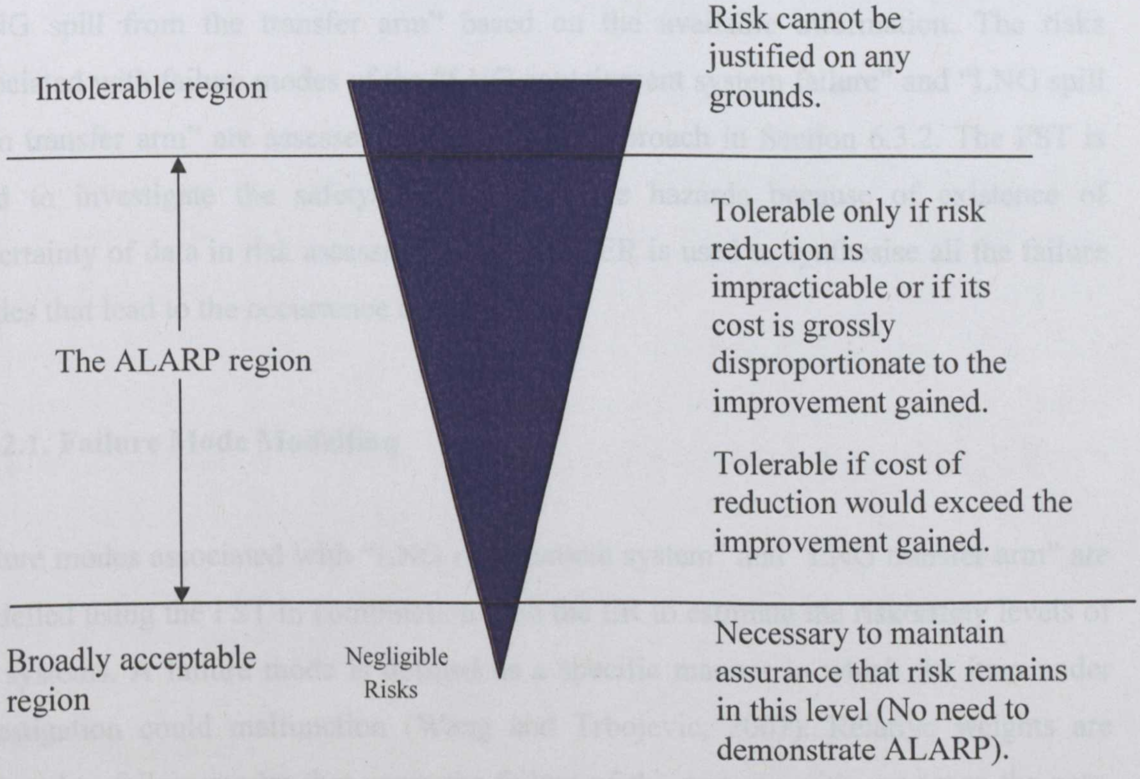

Figure 6.3: Principle of ALARP

6.4.1. Hazard Identification

The hazards of LNG carrier operations such as "LNG containment system failure" and "LNG spill from the transfer arm" are the estimated high risk ones in Chapter 3. The failure modes of the LNG containment system identified in the FTA diagram in Chapter 4 are fire and explosion, structural defects, corrosion effects, containment pressure, pressure relief system failure and installation defect. Manual release failure, auto release failure, fire and explosion, application of ship motion, failure of motion and controls, pipe rupture, overpressure and material defect are the failure modes associated with the LNG transfer arm, according to its FTA diagram in Chapter 4.

6.4.2. Risk Assessment

Risk assessment is carried out on two hazards, "LNG containment system failure" and "LNG spill from the transfer arm" based on the available information. The risks associated with failure modes of the "LNG containment system failure" and "LNG spill from transfer arm" are assessed using the FER approach in Section 6.3.2. The FST is used to investigate the safety/risk levels of the hazards because of existence of uncertainty of data in risk assessment, while the ER is used to synthesise all the failure modes that lead to the occurrence of the hazards.

6.4.2.1. Failure Mode Modelling

Failure modes associated with "LNG containment system" and "LNG transfer arm" are modelled using the FST in combination with the ER to estimate the risk/safety levels of the systems. A failure mode is defined as a specific manner in which the item under investigation could malfunction (Wang and Trbojevic, 2007). Relative weights are assigned to failure modes that cause the failure of the systems with respect to the gate, in which the failure modes are the input events, for facilitation of the application of ER. In an OR gate, all input events of the gate are given the same equal relative weight to that of the output event of the gate. In an AND gate, the relative weight of all input events of the gate are assigned through dividing the relative weight of the output event of the gate by the number of the input events.

6.4.2.1.1. Failure Mode Modelling of the "LNG Containment System"

The LNG containment system has failure modes of fire and explosion that directly causes the system failure (fire and explosion 1), fire and explosion that causes plastic collapse of support (fire and explosion 2), fire and explosion that results in excess load (fire and explosion 3), structural defect that directly causes the containment system failure (structural defect 1), structural defect that causes plastic collapse of support (structural defect 2), structural defect that contributes to chock failure (structural defect 3), corrosion effect that directly causes the containment system failure (corrosion effect 1), corrosion effect that is part of the causes of structural pressure difference (corrosion effect 2), corrosion effect that caused excess load (corrosion effect 3), containment pressure, pressure relief system failure and installation defect that lead to the top event (LNG containment system failure) as illustrated in its FTA diagram in Chapter 4. Their corresponding relative weights (w) are 1, 1, 0.33, 1, 1, 0.33, 1, 0.5, 0.33, 0.25, 0.25 and 0.33 respectively. The gates of their FTA diagram are used to assign their relative weights.

For the purpose of combination of all the failure modes using the ER approach, their relative weight (w) need to be normalised using Equation (6.9). Therefore, the normalised relative weight (w) of fire and explosion 1, fire and explosion 2, fire and explosion 3, structural defect 1, structural defect 2, structural defect 3, corrosion effect 1, corrosion effect 2, corrosion effect 3, containment pressure, pressure relief system failure and installation defect are 0.137, 0.137, 0.045, 0.137, 0.137, 0.045, 0.137, 0.067, 0.045, 0.034, 0.034 and 0.045 respectively.

The failure modes are modelled as follows:

1. Fire and explosion 1

The parameters of the fuzzy set manipulation formula are estimated as follows:

$$L_{11} = \{1/1.0, 2/0.9, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$$
$$C_{11} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$$
$$E_{11} = \{1/0, 2/0.1, 3/0.75, 4/.01, 5/0.75, 6/0, 7/0\}$$

$S_{11} = C_{11} \, o \, E_{11} \times L_{11} = \{1/0.1, 2/0.1, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$

The Best-Fit method (detailed in Example 1 of Appendix E1.1) is applied on the above expression to obtain the safety level description of fire and explosion 1 as follows:

$$S(S_{11}) = \{(0.2258, \text{"}poor\text{"}), (0.2459, \text{"}average\text{"}), (0.2726, \text{"}good\text{"}), (0.2557, \text{"}excellent\text{"})\}$$

where $w_{11} = 0.137$

The risk rank of "fire and explosion 1" can be identified and calculated using Equation (6.23) as follows:

$$Q_{11} = 0.217 \times 0.2258 + 0.478 \times 0.2459 + 0.739 \times 0.2726 + 1 \times 0.2557 = 0.624$$

In a similar way, the safety/risk levels of the other failure modes of the LNG containment system are calculated as follows (see Appendix E1.2 for details):

2. Fire and explosion 2

$$S(S_{12}) = \{(0.2258, \text{"}poor\text{"}), (0.2459, \text{"}average\text{"}), (0.2726, \text{"}good\text{"}), (0.2557, \text{"}excellent\text{"})\}$$

where $w_{12} = 0.137$; $Q_{12} = 0.624$

3. Fire and explosion 3

$$S(S_{13}) = \{(0.2258, \text{"}poor\text{"}), (0.2459, \text{"}average\text{"}), (0.2726, \text{"}good\text{"}), (0.2557, \text{"}excellent\text{"})\}$$

where $w_{13} = 0.045$; $Q_{13} = 0.624$

4. Structural defect 1

$$S(S_{14}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{14} = 0.137$; $Q_{14} = 0.674$

5. Structural defect 2

$$S(S_{15}) = \{(0.1695, "poor"), (0.1806, "average"), (0.3778, "good"), (0.2721, "excellent")\}$$

where $w_{15} = 0.137$; $Q_{15} = 0.674$

6. Structural defect 3

$$S(S_{16}) = \{(0.1695, "poor"), (0.1806, "average"), (0.3778, "good"), (0.2721, "excellent")\}$$

where $w_{16} = 0.045$; $Q_{16} = 0.674$

7. Corrosion effect 1

$$S(S_{17}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{17} = 0.137$, $Q_{17} = 0.551$

8. Corrosion effect 2

$$S(S_{18}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{18} = 0.067$; $Q_{18} = 0.551$

9. Corrosion effect 3

$$S(S_{19}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{19} = 0.045$; $Q_{19} = 0.551$

10. Containment pressure

$$S(S_{110}) = \{(0.2271, "poor"), (0.2730, "average"), (0.2729, "good"), (0.2270, "excellent")\}$$

where $w_{110} = 0.034$; $Q_{110} = 0.608$

11. Pressure relief system failure

$$S(S_{111}) = \{(0.1649, "poor"), (0.1793, "average"), (0.4103, "good"), (0.2455, "excellent")\}$$

where $w_{111} = 0.034$; $Q_{111} = 0.670$

12. Installation defect

$$S(S_{112}) = \{(0.1379, "poor"), (0.5685, "average"), (0.1673, "good"), (0.1263, "excellent")\}$$

where $w_{112} = 0.045$; $Q_{112} = 0.552$

Safety/risk level, $S(S_1)$of "LNG containment system failure" is then obtained using the ER approach attached with IDS software as follows:

$$S(S_1) = \{(0.1776, "poor"), (0.3182, "average"), (0.2847, "good"), (0.2195, "excellent")\}$$

This implies that safety/risk level of the LNG containment system belongs to "poor" with DoB of 17.76%, "average" with DoB of 31.82%, "good" with DoB of 28.47% and "excellent" with DoB of 21.95%.

6.4.2.1.2. Failure Mode Modelling of the "LNG Transfer Arm"

The failure modes that lead to the LNG spill from the transfer arm developed from the FTA of the LNG transfer arm in Chapter 4 are manual release failure, auto release failure, fire and explosion that causes transfer arm failure (fire and explosion 1), fire and explosion that contributes to mechanical failure within design envelope (fire and explosion 2), fire and explosion that contributes to the exceed of arm design limit (fire and explosion 3), application of ship motion, failure of motion and controls, pipe rupture, overpressure, material defect that directly causes a LNG spill from the transfer arm (material defect 1), material defect that causes failure of piping (material defect 2) and material defect that contributes to pipe coupling sleeve failure (material defect 3). Their respective relative weights (w) are 0.33, 0.33, 1, 0.33, 0.33, 0.33, 0.33, 1, 0.5, 1, 1 and 0.5 respectively. The relative weights (w) are assigned using the gates of their FTA diagram. In a similar way to Section 6.4.2.1.1, the safety/risk levels of the failure modes of the LNG transfer arm and their normalised relative weights (w) and preference degree values can be obtained as follows (see Appendix E1.3 for details):

1. Manual release failure

$$S(S_{21}) = \{(0.2258, \text{"}poor\text{"}), (0.2459, \text{"}average\text{"}), (0.2726, \text{"}good\text{"}), (0.2557, \text{"}excellent\text{"})\}$$

where $w_{21} = 0.047$; $Q_{21} = 0.6236$

2. Auto release failure

$$S(s_{22}) = \{(0.1544, \text{"}poor\text{"}), (0.5425, \text{"}average\text{"}), (0.1719, \text{"}good\text{"}), (0.1312, \text{"}excellent\text{"})\}$$

where $w_{22} = 0.047$; $Q_{22} = 0.5511$

3. Fire and explosion 1

$$S(S_{23}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{23} = 0.143$; $Q_{23} = 0.6744$

4. Fire and explosion 2

$S(S_{24}) = \{(0.1695, "poor"), (0.1806, "average"), (0.3778, "good"), (0.2721, "excellent")\}$

where $w_{24} = 0.047$; $Q_{24} = 0.6744$

5. Fire and explosion 3

$S(S_{25}) = \{(0.1695, "poor"), (0.1806, "average"), (0.3778, "good"), (0.2721, "excellent")\}$

where $w_{25} = 0.047$; $Q_{25} = 0.6744$

6. Application of ship motion

$S(S_{26}) = \{(0.1605, "poor"), (0.3218, "average"), (0.3478, "good"), (0.1699, "excellent")\}$

where $w_{26} = 0.047$; $Q_{26} = 0.6156$

7. Failure of motion and controls

$S(S_{27}) = \{(0.1863, "poor"), (0.2414, "average"), (0.3411, "good"), (0.2312, "excellent")\}$

where $w_{27} = 0.047$; $Q_{27} = 0.6391$

8. Pipe rupture

$S(S_{28}) = \{(0.2499, "poor"), (0.2729, "average"), (0.2499, "good"), (0.2273, "excellent")\}$

where $w_{28} = 0.143$; $Q_{28} = 0.5967$

9. Overpressure

$S(S_{29}) = \{(0.1699, "poor"), (0.1811, "average"), (0.3859, "good"), (0.2631, "excellent")\}$

where $w_{29} = 0.071$; $Q_{29} = 0.6717$

10. Material defects 1

$S(S_{210}) = \{(0.2112, "poor"), (0.2289, "average"), (0.2837, "good"), (0.2762, "excellent")\}$

where $w_{210} = 0.143$; $Q_{210} = 0.6411$

11. Material defects 2

$S(S_{211}) = \{(0.2112, "poor"), (0.2289, "average"), (0.2837, "good"), (0.2762, "excellent")\}$

where $w_{211} = 0.14$; $Q_{211} = 0.6411$

12. Material defects 3

$S(S_{212}) = \{(0.2112, "poor"), (0.2289, "average"), (0.2837, "good"), (0.2762, "excellent")\}$

where $w_{212} = 0.071$; $Q_{212} = 0.6411$

$S(S_2)$ which is the safety/risk level of the "LNG spill from transfer arm" is obtained using the IDS software as follows:

$S(S_2) = \{(0.1932, "poor"), (0.2381, "average"), (0.3162, "good"), (0.2525, "excellent")\}$

This implies that the safety/risk level of the LNG transfer arm belongs to "poor" with DoB of 19.32%, "average" with DoB of 23.81%, "good" with DoB of 31.62% and "excellent" with DoB of 25.25%.

6.4.3. Risk Control Option

The main objective of the RCO is to reduce the frequency of failures and/or mitigate their possible consequences (Pillay, 2001). The RCOs that can be used to control the hazards of the LNG containment system and transfer arm depend on their CBA and interest of stakeholders. In this study, the safety levels of the LNG containment system and transfer arm are improved via selection of RCOs. In view of that, Marine Risk Analyst (Expert #1), Marine Safety Engineer (Expert #2), Chief Marine Engineer (Expert #3) and Ship Captain (Expert #4) chose three RCOs for the LNG containment system and LNG transfer arm, respectively, as possible risk control solutions. The RCOs for the LNG containment system are:

- RCO1A: Regular inspection of the system per voyage.
- RCO2A: Training of crew members on new technology and change of operating procedures in loading of LNG to the system.
- RCO3A: Effective maintenance of the system.

The RCOs for the LNG transfer arm are:

- RCO1B: Use of well experienced personnel in loading/unloading of LNG.
- RCO2B: Redesign of the system.
- RCO3B: Effective maintenance of the system.

6.4.4. Cost Benefit Assessment

The cost benefit assessments of the RCOs of the LNG containment system and transfer arm are investigated using Tables 6.5 – 6.6 and the Best-Fit method. Expert #1, Expert #2, Expert #3 and Expert #4 with equal experience, estimated the fuzziness of the costs (C_1, C_2, C_3 and C_4) of all the RCOs of each of the systems using Table 6.5 as a reference point. The utility descriptions of the costs are identified using the Best-Fit method. The application of the Best-Fit method to the costs followed similar procedures in Section 6.3.4, and the resultant utility descriptions of the costs are synthesised with those of safety levels to facilitate the determination of the preference degrees of the RCOs.

6.4.4.1. Cost Benefit Assessment of the LNG Containment System

RCO1A, RCO2A and RCO3A can be used to improve the safety/risk level of a LNG containment system. The cost incurred for using the RCOs is very important in decision making on the best RCO. The safety/risk level associated with the LNG containment system is illustrated in Section 6.4.2.1.1.

Using RCO1A, the safety levels of failure modes such as corrosion effect 1, corrosion effect 2, and corrosion effect 3 are improved to "excellent" with DoB of 100%. Their new safety levels are combined with the one of other failure modes using the IDS to obtain an improved safety level of a LNG containment system estimated as:

$$S(S_{1A}) = \{(0.1354, \text{"}poor\text{"}), (0.1659, \text{"}average\text{"}), (0.2316, \text{"}good\text{"}), (0.4671, \text{"}excellent\text{"})\}$$

The safety description is mapped onto the utility space as follows:

$U(S_{1A})$ = {(0.1354, "*slightly preferred*"), (0.1659, "*moderately preferred*"), (0.2316, "*preferred*"), (0.4671, "*greatly preferred*")}

The cost incurred for using RCO1A is considered as "Moderately low" with reference to Table 6.5, and can vary about the "Moderately low". Therefore, Experts #1, #2, #3 and #4 estimated the cost as follows:

$$C_{1A}^{1} = \{1/0, 2/0.2, 3/1.0, 4/0.5, 0/5, 0/6, 7/0\}$$

$$C_{1A}^{2} = \{1/0, 2/0.1, 3/1.0, 4/0.6, 5/0.2, 6/0, 7/0\}$$

$$C_{1A}^{3} = \{1/0, 2/0.25, 3/1.0, 4/0.5, 5/0, 6/0, 7/0\}$$

$$C_{1A}^{4} = \{1/0, 2/0.3, 3/1.0, 4/0.6, 5/0.1, 6/0, 7/0\}$$

The Best-Fit method is applied to the estimated costs of RCO1A for the LNG containment system and the utility descriptions of the costs by Experts #1, #2, #3 and #4 are expressed as follows:

$U(C_{1A}^{1})$ = {(0.0543, "*slightly preferred*"), (0.0664, "*moderately preferred*"), (0.8218, "*preferred*"), (0.0575, "*greatly preferred*")}

$U(C_{1A}^{2})$ = {(0.1026, "*slightly preferred*"), (0.1348, "*moderately preferred*"), (0.6572, "*preferred*"), (0.1054, "*greatly preferred*")}

$U(C_{1A}^{3})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (1, "*preferred*"), (0, "*greatly preferred*")}

$U(C_{1A}^{4})$ = {(0.0671, "*slightly preferred*"), (0.083, "*moderately preferred*"), (0.7772, "*preferred*"), (0.0727, "*greatly preferred*")}

The combination of the above four judgements resulted to the following:

$U(C_{1A})$ = {(0.0411, "*slightly preferred*"), (0.0524, "*moderately preferred*"), (0.8632, "*preferred*"), (0.0433, "*greatly preferred*")}

Suppose the cost is of equal importance to safety and the weights of both the attributes are 0.5 and 0.5 respectively, as shown in Table 6.7. $U(C_{1A})$ and $U(S_{1A})$ can be synthesised to obtain the utility description as follows:

$U(U_{1A})$ = {(0.0815, "*slightly preferred*"), (0.1016, "*moderately preferred*"), (0.5794, "*preferred*"), (0.2375, "*greatly preferred*")}

The preference degree for RCO1A by Experts #1, #2, #3 and #4 can be calculated using Equation (6.34) as follows:

$$P_{1A} = 0.217 \times 0.0815 + 0.478 \times 0.1016 + 0.739 \times 0.5794. + 1 \times 0.2375$$

$P_{1A} = 0.7319$

Similarly, the preference degree for RCO2A by Experts #1, #2, #3 and #4 is (see Appendix E1.4 for details):

$P_{2A} = 0.745$

In a similar way, the preference degree for RCO3A by Experts #1, #2, #3 and #4 is (see Appendix E1.5 for details):

$P_{3A} = 0.6983$

Other relative weights of safety and cost (i.e. weight rate between safety and cost) and the produced preference degree values of RCO1A, RCO2A and RCO3A are shown in Table 6.7. In Row 7 of Table 6.7, the values of relative weights of safety and cost are 0.5 and 0.5 respectively, followed by a value of 1, which is the weight rate of safety to cost. The next values are the preference degree values of 0.7319, 0.745 and 0.6983 for RCO1A, RCO2A and RCO3A respectively. Subsequent rows of Table 6.7 can be explained in a similar way.

Table 6.7: Preference Degree of RCOs of the LNG Containment System

Relative weights (w)		Weight rates between safety and cost	Preference degree of RCOs		
Safety	Cost		RCO1A	RCO2A	RCO3A
0.167	0.833	0.2	0.7173	0.7097	0.5084
0.286	0.714	0.4	0.7210	0.7182	0.5505
0.375	0.625	0.6	0.7251	0.7279	0.6026
0.444	0.556	0.8	0.7287	0.7370	0.6534
0.5	0.5	1	0.7319	0.7450	0.6983
0.75	0.25	3	0.7435	0.7742	0.8640
0.833	0.167	5	0.7454	0.7794	0.8911
0.875	0.125	7	0.7461	0.7812	0.8999
0.9	0.1	9	0.7440	0.7820	0.9037

The influence of relative weights of safety and cost in ranking of the RCOs is shown in Table 6.8 and graphically illustrated in Figure 6.4. It can be observed in Table 6.8 that when the relative weights of safety and cost are 0.5 and 0.5 respectively, the RCO1A is ranked as 2 and RCO2A is ranked as 1, while RCO3A is ranked as 3. This is as a result of the preference degree values of 0.7319 for RCO1A, 0.7450 for RCO2A and 0.6983 for RCO3A in Table 6.7. The ranking of the RCOs in other rows of Table 6.8 is also influenced by the relative weight of safety and cost. The best RCO for the LNG containment system and the associated relative weights of cost and safety will be discussed in decision-making of Section 6.4.5.

Table 6.8: Ranking of RCOs of the LNG Containment System

Relative weights (w)		Weight rates between safety and cost	Ranking of RCOs based on their preference degrees		
Safety	Cost		RCO1A	RCO2A	RCO3A
0.167	0.833	0.2	1	2	3
0.286	0.714	0.4	1	2	3
0.375	0.625	0.6	2	1	3
0.444	0.556	0.8	2	1	3
0.5	0.5	1	2	1	3
0.75	0.25	3	3	2	1
0.833	0.167	5	3	2	1
0.875	0.125	7	3	2	1
0.9	0.1	9	3	2	1

6.4.4.2. Cost Benefit Assessment of the LNG Transfer Arm

The safety/risk level of the LNG transfer arm has been described in Section 6.4.2.1.2. Three RCOs such as RCO1B, RCO2B and RCO3B are identified in Section 6.4.3, as the possible RCOs that can be used to improve the safety level of the LNG transfer arm. The cost of each RCO is estimated using expert judgement. When RCO1B is applied to the LNG transfer arm, the safety estimates of the system can be described as follows:

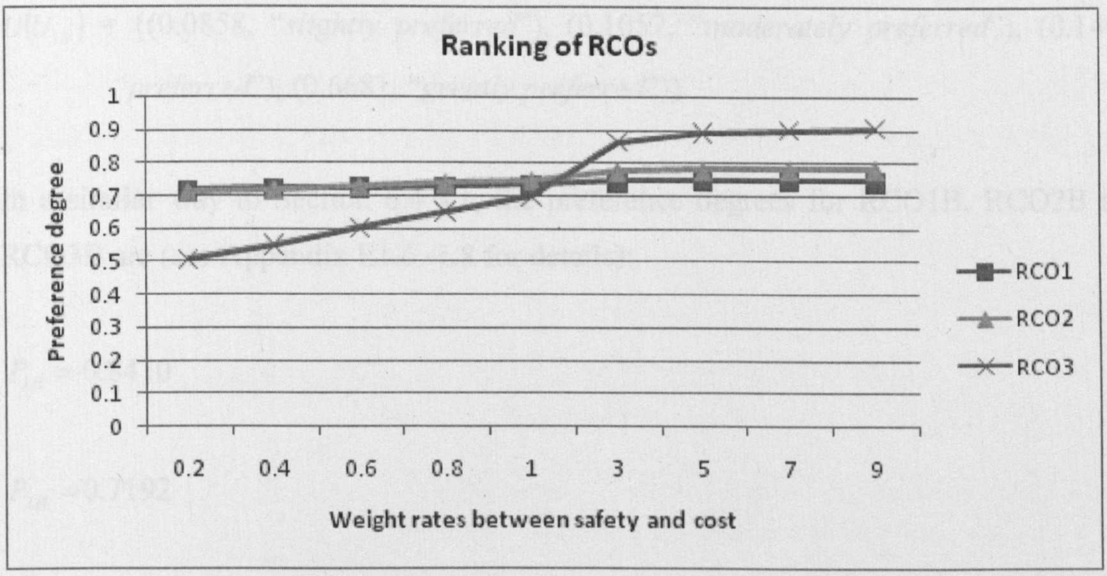

Figure 6.4: Ranking of Preference Degrees of RCOs of the LNG Containment System

$$S(S_{1B}) = \{(0.1932, \text{"}poor\text{"}), (0.2381, \text{"}average\text{"}), (0.3162, \text{"}good\text{"}), (0.2525, \text{"}excellent\text{"})\}$$

$S(S_{1B})$ is mapped onto the utility space for utility description of the safety/risk level of the LNG transfer arm as follows:

$U(S_{1B})$ = {(0.1932, "*slightly preferred*"), (0.2381, "*moderately preferred*"), (0.3162, "*preferred*"), (0.2525, "*greatly preferred*")}

The cost of RCO1B are estimated by Experts #1, #2, #3 and #4, and mapped onto the utility space (see Appendix E1.6 for details). The synthesised utility descriptions of the cost of RCO1B are given as follows:

$U(C_{1B})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (0, "*preferred*"), (1, "*greatly preferred*")}

Suppose $U(C_{1B})$ and $U(S_{1B})$ are synthesised with safety and cost weights of 0.5 and 0.5 respectively. The following utility description can be obtained:

$U(U_{1B})$ = {(0.0858, "*slightly preferred*"), (0.1057, "*moderately preferred*"), (0.1404, "*preferred*"), (0.6681, "*greatly preferred*")}

In a similar way to Section 6.4.4.1, the preference degrees for RCO1B, RCO2B and RCO3B are (see Appendix E1.6 -1.8 for details):

$P_{1B} = 0.8410$

$P_{2B} = 0.7192$

$P_{3B} = 0.6776$

Other preference degree values for RCOs of the LNG transfer arm and the associated relative weights of safety and cost are shown in Table 6.9. Table 6.9 is described in a similar way to Table 6.7.

Table 6.9: Preference Degree of RCOs of the LNG Transfer Arm

Relative weights (w)		Weight rates between safety and cost	Preference degree of RCOs		
Safety	Cost		RCO1B	RCO2B	RCO3B
0.167	0.833	0.2	0.9869	0.7070	0.5067
0.286	0.714	0.4	0.9544	0.7102	0.5447
0.375	0.625	0.6	0.9147	0.7137	0.5915
0.444	0.556	0.8	0.8758	0.7167	0.6372
0.5	0.5	1	0.8410	0.7192	0.6776
0.75	0.25	3	0.7004	0.7281	0.8295
0.833	0.167	5	0.6717	0.7294	0.8558
0.875	0.125	7	0.6611	0.7298	0.8644
0.9	0.1	9	0.6558	0.7299	0.8684

The tabular and graphical representations of the influence of relative weights of safety and cost in ranking of the RCOs of the LNG transfer arm are shown in Table 6.10 and Figure 6.5 respectively. Table 6.10 is explained in a similar way to Table 6.8. The relative weights of 0.5 for safety and 0.5 for cost, together with the rank of 1 for

RCO1B, rank of 2 for RCO2B and rank of 3 for RCO3B, can be found in Row 7 of Table 6.10. In the same way, other relative weights of safety and cost, and ranks of RCOs are identified in Table 6.10. The best RCO for safety improvement of the LNG transfer arm and the associated weights of safety and cost will be recommended in decision-making of Section 6.4.5.

Table 6.10: Ranking of RCOs of the LNG Transfer Arm

Relative weights (w)		Weight rates between safety and cost	Ranking of RCOs based on their preference degrees		
Safety	Cost		RCO1B	RCO2B	RCO3B
0.167	0.833	0.2	1	2	3
0.286	0.714	0.4	1	2	3
0.375	0.625	0.6	1	2	3
0.444	0.556	0.8	1	2	3
0.5	0.5	1	1	2	3
0.75	0.25	3	3	2	1
0.833	0.167	5	3	2	1
0.875	0.125	7	3	2	1
0.9	0.1	9	3	2	1

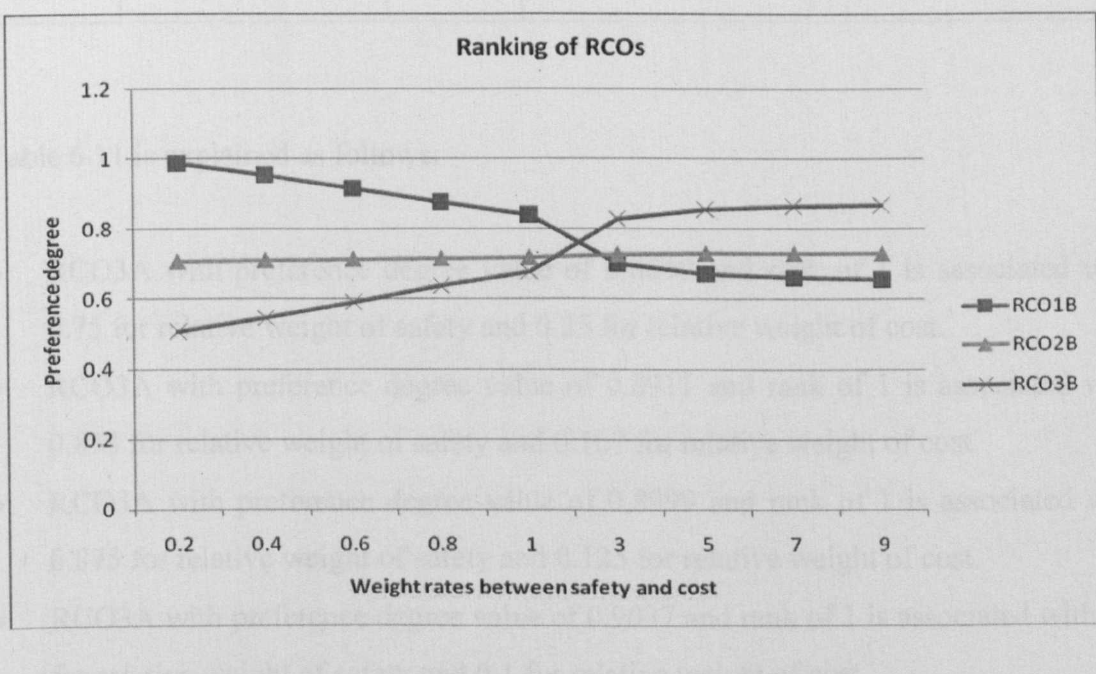

Figure 6.5: Ranking of Preference Degrees of RCOs of the LNG Transfer Arm

6.4.5. Decision Making

The selection of a RCO can be carried out on the basis of the preference degrees associated with the RCOs with regard to the particular considerations of cost and safety. The RCOs identified by Experts #1, #2, #3 and #4 with the highest preference degree will be chosen as the best RCOs for the LNG containment system and transfer arm. In this study, safety should be more important than cost because of the catastrophic consequences of the two hazards of the LNG carrier operations under investigation. Tables 6.7 – 6.10 can be used to make such a decision. The information provided in Tables 6.7 and 6.8 is used to develop Table 6.11.

Table 6.11: Preference Degree of the best RCO of the LNG Containment System

RCO	Preference degree of the RCO	Rank of RCO	Relative weight (w) of safety	Relative weight (w) of cost
RCO3A	0.8640	1	0.75	0.25
RCO3A	0.8911	1	0.833	0.167
RCO3A	0.8999	1	0.875	0.125
RCO3A	0.9037	1	0.9	0.1

Table 6.11 is explained as follows:

- RCO3A with preference degree value of 0.8640 and rank of 1 is associated with 0.75 for relative weight of safety and 0.25 for relative weight of cost.
- RCO3A with preference degree value of 0.8911 and rank of 1 is associated with 0.833 for relative weight of safety and 0.167 for relative weight of cost.
- RCO3A with preference degree value of 0.8999 and rank of 1 is associated with 0.875 for relative weight of safety and 0.125 for relative weight of cost.
- RCO3A with preference degree value of 0.9037 and rank of 1 is associated with 0.9 for relative weight of safety and 0.1 for relative weight of cost.

RCO3A has been identified as the best RCO that will control/prevent LNG containment system failure because it has the highest preference degree value and rank of 1 in situations where safety is more important than cost as shown in Table 6.11.

Table 6.12: Preference Degree of the best RCO of the LNG Transfer Arm

RCO	Preference degree of the RCO	Rank of RCO	Relative weight (w) of safety	Relative weight (w) of cost
RCO3B	0.8295	1	0.75	0.25
RCO3B	0.8558	1	0.833	0.167
RCO3B	0.8644	1	0.875	0.125
RCO3B	0.8684	1	0.9	0.1

In a similar way to Table 6.11, Table 6.12 is developed using the information in Tables 6.9 and 6.10, and described as follows:

- RCO3B with preference degree value of 0.8295 and rank of 1 is associated with 0.75 for relative weight of safety and 0.25 for relative weight of cost.
- RCO3B with preference degree value of 0.8558 and rank of 1 is associated with 0.833 for relative weight of safety and 0.167 for relative weight of cost.
- RCO3B with preference degree value of 0.8644 and rank of 1 is associated with 0.875 for relative weight of safety and 0.125 for relative weight of cost.
- RCO3B with preference degree value of 0.8684 and rank of 1 is associated with 0.9 for relative weight of safety and 0.1 for relative weight of cost.

In situations where safety is more important than cost as shown in Table 6.12, RCO3B is the best RCO that will control/prevent LNG spill from the transfer arm.

6.4.6. Verification of the Results

A partial verification of the safety/risk levels of the LNG containment system and transfer arm is conducted to ensure that the safety/risk levels of the LNG carrier systems estimated using ER are appropriate. The safety/risk levels of the LNG containment system and transfer arm are determined by the ones of their failure modes. Their failure modes' safety/risk levels belong to "poor", "average", "good" and "excellent". In this study, the safety/risk levels of the LNG containment system and transfer arm are validated by satisfying the following axioms.

- Axiom 1. The safety/risk levels of most of the failure modes of the LNG containment system belong to "average" and "good" to a large extent in Section 6.4.2.1.1. Therefore, the safety/risk level of the top event (LNG containment system failure) should belong to either "average" or "good" to a large extent.
- Axiom 2. The safety/risk levels of most of the failure modes of the LNG transfer arm belong to "good" to a large extent in Section 6.4.2.1.2. Therefore, the safety/risk level of the top event (LNG spill from the transfer arm) should belong to "good" to a large extent.

The safety/risk levels of the failure modes of the LNG containment system are synthesised using IDS in order to estimate the top event's (LNG containment system failure) safety/risk level. The resultant safety/risk level of the top event's (LNG containment system failure) belongs to "average" to a large extent. This result satisfies the Axiom 1.

In a similar way, the safety/risk levels of the failure modes of the LNG transfer arm are combined using IDS so as to estimate the safety/risk level of the top event (LNG spill from the transfer arm). The IDS produced a safety/risk level that belongs to "good" to a large extent. This result satisfies the Axiom 2.

Another partial verification can be conducted to investigate the ranking of the RCOs. The rank of a RCO is correct if the following axioms are satisfied:

- Axiom 1. When safety is more important than cost (i.e. the weight of safety is greater than the one of cost), the RCO with rank of 1 should improve the safety level of a LNG carrier system more than others via elimination of failure modes.

- Axiom 2. When cost is more important than safety (i.e. the weight of cost is greater than the one of safety), the RCO with rank of 1 needed to improve the safety level of a LNG carrier system should not be the most expensive one.

In situations where safety is more important than cost, RCO3A of the LNG containment system and RCO3B of the LNG transfer arm are ranked first in their respective Tables 6.8 and 6.10. The preference degree values of RCO3A and RCO3B are graphically represented in Figures 6.4 and 6.5 respectively. RCO3A can improve the safety level of the LNG containment system more than the other RCOs via elimination of failure modes and the preference degree value is the highest in Table 6.7 and Figure 6.4. Similarly, RCO3B can improve the safety level of the LNG transfer arm more than the other RCOs via elimination of failure modes and has the highest preference degree value in Table 6.9 and Figure 6.11. This satisfies Axiom 1 for ranking of the RCOs of the LNG containment system and transfer arm in situations where safety is more important than cost.

In this research, when cost is more important than safety, RCO1A or RCO2A of the LNG containment system has a rank of 1 as shown in Table 6.8 and graphically represented with a highest preference degree value in Figure 6.4. The cost incurred for carrying out either RCO1A or RCO2A is less expensive compared to RCO3A. This result is in harmony with Axioms 2. RCO1B of the LNG transfer arm is ranked as 1 in Table 6.10 because it has the highest preference degree value among the RCOs, as illustrated in Figure 6.5. The cost incurred for RCO1B is less expensive compared to RCO2B and RCO3B. This is in line with the Axioms 2.

6.5. Conclusion

A FER method has been applied in this chapter incorporating the FSA methodology. The safety/risk levels of the failure modes of the LNG containment system and transfer arm are known using a fuzzy set manipulation formula that includes three parameters of failure likelihood, failure consequence probability and consequence severity. The parameters are represented by their respective fuzzy values. Each of the parameters is characterised with seven linguistic terms and assigned fuzzy values for each linguistic term with categories ranging from 1-7. The fuzzy values served as a reference/base for estimation of new ones for the three parameters of each failure mode of the LNG containment system and transfer arm. The new fuzzy values are developed by varying the reference/base ones using expert judgement.

Best-Fit method is applied on the safety fuzzy values of each failure mode of the LNG containment system and transfer arm. The resultant safety/risk levels of each failure mode of the LNG containment system and transfer arm are synthesised using the ER mechanism attached with IDS in order to estimate their top events' safety levels. Three RCOs are chosen and the best one is identified and analysed by four experts using both cost and safety estimates based on defined utility expression characterised as "slightly preferred", "moderately preferred", "preferred", and "greatly preferred".

The fuzzy values of the cost expression are used as a base that guided the estimation of new ones by the experts. The fuzzy cost values estimated by the experts for each RCO of the "LNG containment system failure" and "LNG spill from the transfer arm" are evaluated using the Best-Fit method and mapped onto their utility space. Each of their utility descriptions of cost is aggregated at a single level using the IDS. A further aggregation is carried out with the safety estimates of the "LNG containment system failure" and "LNG spill from the transfer arm" respectively with each of their utility description of cost for the calculation of preference degrees of their RCOs.

The preference degree formula gave room for the utility estimates of the "LNG containment system failure" and "LNG spill from the transfer arm" to be used in facilitation of its values. The values of preference degrees of their RCOs are identified. Finally, RCOs with the highest preference degrees such as RCO3A and RCO3B are the best RCOs for safety improvement of the LNG containment system and transfer arm respectively.

Chapter 7 – Discussion

Summary

In this chapter, the results produced in Chapters 3, 4, 5 and 6 are described. The models used in this research are outlined, followed by the discussion of how the model tests are carried out. The strengths and weaknesses of the models are analysed through the test cases. The industries that will benefit from the research are identified and indicated.

7.1. Discussion of the Results of Chapter 3

The estimation of risks associated with the hazards of LNG carrier operations are conducted by four experts. It is successful by carrying out a brainstorming session. Scores of consequence and likelihood of the hazards are described and assigned with respect to LNG carrier operations. The risk score of a hazard is the summation of its consequence and occurrence likelihood scores. These scores are expressed in logarithmic scale. Each of the categories of the consequence of the hazards such as negligible, marginal, critical and catastrophic is described with a numerical score. The less possible, possible, more possible and most possible categories of the occurrence likelihood of the hazards are also described with numerical scores. The categories of the risks of the hazards are described with range of scores.

In the above analysis, the two high risk hazards such as "a LNG spill from the transfer arm" and "a LNG containment system failure" have received a risk score of 8. In the risk matrix approach used in this study, the high risk scores are defined 6 to 8, while the moderate risk score is 5. Any hazard with a risk score of 3 or 4 is categorised as a low risk hazard, while the ones with a risk score of 2 is categorised as very low risk hazard. Risk estimations of the hazards of LNG carrier operations depend on the competency of the experts involved. If experts involved in this study are not experienced, high risk hazards might be estimated as low risk ones or other categories. In such a situation, oil and gas companies that adopt this methodology in risk management of their LNG carrier operations will be misled.

Only experienced experts that well understand the hazards of the LNG carrier operations and their associated risks are used in this study. In the proposed methodology, not all the causes of the hazards of LNG carrier operations are needed, which helps save time in this investigation. The methodology is used to prioritise the hazards of LNG carrier operations. It reveals the hazards associated with catastrophic consequences and high risks, which need to be further investigated to identify their causes. Although the methodology has shown some attractiveness, it still exposes some application problems. For example, hazards such as "a LNG spill from the transfer arm" and "a LNG containment system failure" that have the same risk score, may have different risk implications in the real world. Therefore, different causes of the hazards are also analysed in this study.

7.2. Discussion of the Results of Chapter 4

The results of the maintenance cost of a LNG containment system and a LNG transfer arm have been verified in order to ascertain the purpose of the model. The purpose of the model is to identify the maintenance cost of the LNG containment system and the LNG transfer arm so as to reduce the risks associated with their operations. The verification of the model reveals that its constraint cannot be violated. In LNG maintenance practice, the budget is always limited, which further indicates the necessity of study of optimising the use of the limited budget to achieve the highest possible safety level. The model reveals that the maintenance cost of a system can increase whenever there is an increase in the system risk and vice versa.

In the relevant test case (i.e. Table 4.4), the developed model is tested by increasing the values of C_T by 5%, 10%, 15% and 20%. Such increase in the value of C_T reveals that the value of R_T is decreasing. It means that whenever total maintenance cost is increased, the total risk of the LNG containment system and the LNG transfer arm decreased. This is as a result of more money spent on maintenance of the LNG containment system and the LNG transfer arm by using more experienced experts and better quality spare parts. Another model test is also carried out to analyse the value of $C_{SYSTEM(1u)}$ by increasing its value by 5%, 10%, 15% and 20%. This results in an increase of the value of R_T. It means that the unit (minimum) cost of maintenance of a LNG containment system can help to reveal the risk of the system. When the unit cost of maintenance of the LNG containment system is increased, the total risk of the LNG carrier systems will be increased. The results in Table 4.6 are used to demonstrate the behaviour of the model when the value of $C_{SYSTEM(2u)}$ is increased. In Table 4.6, the value of $C_{SYSTEM(2u)}$ is increased by 5%, 10%, 15% and 20% to analyse its effect on the model. It can be found in Figure 4.7 and Table 4.6 that the value of R_T is increased whenever the value of $C_{SYSTEM(2u)}$ is increased. It means that the minimum amount of money needed to maintain the LNG transfer arm depends on the risk associated with its operations. The verification of all the results carried out in this chapter shows that the model can function well to reflect the reality and the values of $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$ are reasonable. This methodology can be adopted by ship design companies in decision making on maintenance cost of the LNG carrier systems.

7.3. Discussion of the Results of Chapter 5

The exact unit costs of maintenance of the LNG containment system and the LNG transfer arm are identified through the use of the FRB method, including the establishment of 125 fuzzy rules, the definition of triangular membership function, the use of WMoM defuzzification method and four experts with equal experience of LNG carrier maintenance cost. Change of any of the above elements will affect the exact maintenance cost values of the LNG containment system and the LNG transfer arm. Therefore, experience of the experts in the FRB method and maintenance cost of the LNG carrier system is crucial in this study.

A sensitivity analysis is conducted to verify the new costs of maintenance of the LNG containment system and the LNG transfer arm, with reference to the optimization of the model using GA approach. In the optimization of the model, the values of unit costs of maintenance of the LNG containment system and the LNG transfer arm that have been treated from uncertainties are used. Firstly, the value of C_T is increased by 5%, 10%, 15% and 20% to check its effect on the model. Such increment of the value of C_T, leads to the decrease of the value of R_T in Table 5.6 and Figure 5.13. This is in line with reality. This helps achieve the purpose of the model that is to distribute the budgeted maintenance cost to the high risk LNG carrier systems in order to minimise the total risk of the systems. The second test of the model is carried out via the increment of the value of $C_{SYSTEM(1u)}$. The increment of the value of $C_{SYSTEM(1u)}$ leads to an increment of the value of R_T, as shown in Table 5.7 and Figure 5.13. It keeps consistency with the fact that the model can be used to reduce the risk of LNG carrier systems by distribution of maintenance cost as safety improvement measure. Further investigation of the results produced by the model is conducted through increasing the values of $C_{SYSTEM(2u)}$ by 5%, 10%, 15% and 20%. The increment of the value of $C_{SYSTEM(2u)}$ by 5%, 10%, 15% and 20% shows that the value of R_T gradually increased up to four times in Table 5.8 and Figure 5.13. This validates the feasibility of the model and the rationality of the new values of $C_{SYSTEM(1)}$ and $C_{SYSTEM(2)}$.

Though the strengths of the combination of the FRB and GA methods in optimization of the model have been revealed, there are still some weaknesses. The antecedent part of the FRB method used in this research has 3 components such as LTCC, LMD and LSPC. More components could be identified and used to evaluate the LNG carrier system maintenance cost. However, it could be prone to error due to involvement of a larger number of fuzzy rules. Due to the strength of this methodology, ship construction companies can use it in uncertainty treatment of the cost of maintenance of the LNG carrier systems. The maintenance department of oil and gas companies can also use the methodology of Chapter 5 in development of planned maintenance strategy of the LNG carrier systems.

7.4. Discussion of the Results of Chapter 6

The validity of the results produced in Chapter 6 is investigated by carrying out a partial verification. In the case study, it is found that when the safety/risk levels of failure modes of a LNG containment system are aggregated using the ER method attached with IDS software, the top event (LNG containment system failure)'s safety/risk level belongs to "average" to a large extent. Since the safety/risk levels of the failure modes of the LNG containment system mainly belong to "average" and "good" to a large extent, it shows that the top event (LNG containment system failure)'s safety/risk level is rational. The safety/risk level of top event (LNG spill from the transfer arm) belongs to "good" to a large extent. Such safety descriptions of the "LNG spill from the transfer arm" is verified because most of the safety/risk levels of the failure modes of the LNG transfer arm belong to "good" to a large extent.

The safety descriptions of the "LNG spill from the transfer arm" and the "LNG containment system failure" show that the model is feasible and reliable. Another result verification is conducted to confirm the importance of safety over cost and vice versa. Three RCOs are identified for safety improvement of the LNG containment system and the LNG transfer arm. RCO3A can be used to improve the safety level of the LNG containment system, which is better than RCO1A and RCO2A. The cost of implementation of the RCOs (RCO1A, RCO2A and RCO3A) differs. The RCO3A that can maximally improve the safety level of the LNG containment system is expected to have the highest preference degree value, if safety carries more weight than cost. The result shows the RCO3A has the highest preference degree value as can be seen in Table 6.7 and Figure 6.4. Furthermore, the cost of implementation of the RCO3A is the most expensive among the RCOs of the LNG containment system and is proven to have the lowest preference degree value when cost is more important than safety.

In control of the risk of "LNG spill from the transfer arm", three RCOs (RCO1B, RCO2B and RCO3B) are identified. The RCO that can produce optimal safety level of the LNG transfer arm should be associated with highest preference degree value. Such safety level of the LNG transfer arm can be achieved using the RCO3B, proved by its preference degree value of 0.8684. The preference degree value of the RCO3B is the highest as shown in Table 6.9 and Figure 6.5 in the situation where safety is more important than cost. Table 6.9 and Figure 6.5 also reveal that the preference degree value of the RCO3B becomes the lowest value when cost is more important than safety. This is because it is more costly to implement RCO3B compared to RCO1B or RCO2B. This partially verifies the model.

In Tables 6.8 and 6.10, it can be found that different weights are used to investigate how the RCOs are ranked with respect to safety and cost. Such illustrations can be used to know the implications of preferring safety over cost and vice versa. Oil and gas companies can use the tables in making decision on the best RCOs of the LNG carrier operations, considering the cost and benefit of each RCO. The methodology of this research can be adopted by regulatory authorities and oil and gas companies for risk management of their LNG facilities associated with uncertainties.

Chapter 8 – Conclusion

Summary

In this chapter, the conclusion of the research is described. The summary of how the aim and objectives of this research are achieved is outlined. The limitation of the research is discussed and the need for further application of the methodologies used in this research to other areas in the LNG and maritime industries are recommended.

8.1. Introduction

It is obvious that there has been a significant enlargement of the LNG carrier fleet in recent times, which has raised doubts over maintaining the outstanding safety record of the LNG carrier operations. Therefore, it is necessary to apply a proactive risk-based approach to ensure that such safety records of the LNG carrier operations are maintained.

The LNG industry has evolved technically and operationally so as to ensure safe and secure operations as described in Chapter 2 (Literature Review). Technical and operational advances include everything from the engineering domain that underlies LNG facilities from operational procedures to technical competency of personnel. Secondly, the physical and chemical properties of LNG, which are analyzed in Chapter 2, require risks of hazards of LNG to be well understood and incorporated into the technology and operations for prevention and mitigation purposes. Furthermore, the standards, codes and regulations that apply to the LNG industry ensure safety (Foss, 2003). The double hull construction of LNG carriers and standards set by the United States Coast Guard Agency (USCGA) contributed to the safety of LNG during transportation.

The LNG shipping safety becomes solidified after application of FSA to all ships (including LNG carriers), so as to ensure oversight of safety and environmental pollution prevention. In this research, the FSA methodology is applied to the LNG containment system and transfer arm using a new approach in Chapter 6, after comprehensive study of Chapters 2 to 5. LNG carrier operations that could cause severe hazards such as explosion, vapour clouds, rollover, freezing liquid, rapid phase transition, and pool fire were investigated and addressed using a proactive risk-based maintenance approach and subjective (possibilistic) risk assessment based on FSA methodology.

8.2. Main Conclusion of the Research

In this research, a proactive risk-based maintenance approach and a subjective risk assessment based on FSA have been developed to improve the operations of the LNG carriers. Uncertainty treatments of the unit costs of maintenance of the LNG carrier systems were incorporated in the research. In view of these, the research findings are summarised as follows:

- All relevant hazards of LNG carrier operations have been identified using brainstorming and risk matrix techniques. The risks of the hazards were prioritized to know the high risk ones. The risk matrix technique has been proved as an effective method for qualitative risk assessment of a high number of hazards of LNG carrier operations.
- The occurrence probabilities and frequencies of top events ("LNG containment system failure" and "LNG spill from the transfer arm") were estimated using a FTA method. The FTA method demonstrated that the failure logic of the failure modes of the top events determine their failure probabilities. The mechanism of Boolean algebra was used to produce reasonable results of top event's probabilities.
- A maintenance decision making model was developed. GA has been demonstrated as a backbone of this model via optimization of the model (risk model) to determine the

maintenance cost of high risk LNG carrier systems, needed for the systems' safety improvement. Reasonable results of maintenance costs were obtained.

- A new maintenance decision making model has been developed to enable the treatment of uncertainty of unit costs of maintenance of high risk LNG carrier systems with the use of FRB and GA. A combination of FRB and GA has demonstrated that uncertainty of maintenance costs can be subdued. Acceptable results of maintenance costs were produced.
- A FER algorithm has been used to demonstrate how uncertainties of failure modes of top events ("LNG containment system failure" and "LNG spill from the transfer arm") can be subdued in the FSA framework. Acceptable results of safety levels and the best RCOs for addressing the top events were identified.

8.3. Research Contributions

The novel contribution of this research is important and its aim has been achieved. The aim was to carry out a proactive risk assessment and maintenance modelling using the FSA methodology on high risk LNG carrier systems. This was achieved in a structured manner as follows:

- A methodology of identifying hazards of LNG carrier operations and prioritizing their associated risks was developed using the risk matrix technique in Chapter 3. This methodology was generic and can be used by other industries.
- A methodology of risk-based maintenance of high risk LNG carrier systems was developed in Chapter 4. A PRA was carried out using the FTA method on high risk LNG carrier systems and their maintenance modelling implemented using GA, so as to investigate the maintenance cost. An optimal risk solution was found, including the maintenance cost.
- An advanced methodology of risk-based maintenance was developed in Chapter 5. The methodology was similar to the former, but a difference was the introduction of the

FRB method for uncertainty treatment of unit costs of maintenance of the high risk LNG carrier systems in the optimization of the risk model using GA.

- A subjective risk assessment of high risk LNG carrier systems based on FSA methodology using the FER algorithm was developed in Chapter 6. The FER algorithm was used for estimation of safety levels and RCOs of these systems to facilitate safety-based design decisions due to incomplete safety and cost data.

8.4. Research Limitations

Risk estimation has been conducted using the risk matrix technique in Chapter 3, for investigating areas of high risk on the LNG carrier operations. The LNG containment system and transfer arm were the areas of LNG carrier operations where the methodologies of a risk-based maintenance and subjective risk assessment based on FSA principles were demonstrated. FTA was adopted as quantitative and qualitative techniques that can be used in PRA of the LNG containment system and transfer, followed by their maintenance modelling using GA, as the optimization technique in this research. The optimization process was limited to identification of maintenance cost based on the research framework. The risk model was developed using an exponential distribution in representation of probability of failure of a system, therefore other distributions were not considered in the research framework. The uncertainty treatments of unit costs of maintenance of the LNG containment system and transfer arm were conducted using the FRB method. The antecedent part of this method has components such as technical consultancy cost, maintenance duration and spare parts cost. Therefore, the research was limited to these components in the uncertainty treatments of the unit costs of maintenance of the systems. Any unforeseen component was not accommodated in this research framework.

8.5. Recommendation for Future Research

There is need to recommend some areas for further research. Such areas are outlined as follows:

- It will be appropriate that the FSA methodology is developed and applied to all the aspects of LNG operations. This will ensure uniformity and confirmation of safety levels in the LNG industry. The application of FSA should focus on components of gas chain and the environment, in which the onshore tank is sited.
- The author also suggests that risk assessment should need more failure rate data in the LNG carrier so that a comprehensive assessment of safety level can be carried out on any LNG carrier systems for effective maintenance modelling. The failure rate data is a prime factor that determines risk assessment levels. The industries in question should have an open policy on failure rate data issues so that researchers can have access to them. This will enable the successful application of risk-based maintenance to various areas of the LNG carrier operations.
- The FER algorithm can be used for subjective risk assessment of various systems of the LNG carriers. This research is limited to the LNG containment system and transfer arm. A comprehensive FTA will be needed for other systems of the LNG carrier, so that there will be an appropriate consideration of failure modes that lead to their top events using the FER approach.
- Risk assessment should be extended to the loading and unloading lines of LNG. These lines are pipes mounted on the top of the LNG tank for loading and unloading of LNG. The lines are not always under operation, hence there will be some zones where LNG is locked out and isolated from the main stock in the tank. Once the lines are isolated, LNG will evaporate due to heat input from the surroundings and result in high pressure in this section. This situation has potential to cause damage to pipes. The damages can be identified using HAZOP studies and FTA.
- It will be useful if adequate maintenance strategies are carried out in the LNG industry. A hazard such as overfilling of the LNG storage tank is caused as a result of the level indicator failure to indicate the true level of LNG in the tank to the operator. Also, over pressurization of the LNG storage tank occurs due to blockage of discharge lines by valve failure, or a sudden drop in barometric pressure. Another hazard such as under pressurization of the LNG storage tank normally happens as a result of control valve failure or barometric pressure increases abruptly. At this time, if the gas make-up

system fails to actuate after recognising the low-pressure alarm, the pressure in the tank continuously decreases before the vacuum breaker opens, thereby causing tank damage. Further research in this aspect is highly necessary.

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Appendices

Appendix A - Published Paper

Nwaoha, T. C., Yang, Z. and Wang, J. (2011), "Application of Genetic Algorithm to Risk-Based Maintenance Operations of Liquefied Natural Gas Carrier Systems", Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Vol. 225, No. 1 , pp. 40-52.

Abstract: *The concept of genetic algorithm (GA) is used to model the cost of maintenance and repairs of a liquefied natural gas (LNG) containment system and its transfer arm, after assessing the total risk of the systems using the probabilistic risk assessment (PRA) technique. The failure frequency data of the basic events of the fault tree developed to model the LNG containment system and transfer arm, which is implemented and evaluated to estimate the failure frequencies of the systems, is derived from a careful literature search. A total risk formula is developed, which is dependent on hazard severity weight, failure frequencies, time and cost of maintenance and repairs of the LNG carrier systems. The formula serves as the objective function while new total cost allocated for maintenance and repairs of the LNG carrier systems as a whole is the constraint with boundaries of presenting initial/unit cost of maintenance and repairs of each containment system and transfer arm. Optimization is carried out on the objective function and its constraint for identification of new cost of maintaining and repairing the containment system and transfer arm independently with the powerful tool of GA using Matlab version 7.7 software for improvement of the system's safety level.*

Appendix B – An Appendix of Chapter 2

Appendix B1 – LNG Carriers Accidents/Incidents

Various accidents have happened in the LNG industry. Some of the accidents that involved LNG carriers, which did not result to LNG spills are listed in Table B1.

Table B1: Incidents/Accidents of LNG Carriers (Østvik, et al., 2005)

Date of Accident	Ship Name	Description of Accident
1974	Methane Progress	While in port, the vessel touched bottom. There was no LNG spillage or injury/fatality recorded.
1979	El Paso Paul Kayser	The vessel was stranded at sea. There was severe damage to the bottom, ballast tanks, motors water and bottom of containment system set up. No casualty or LNG spillage was recorded.
1980	LNG Libra	While at sea, the shaft moved against rudder. Tailshaft fractured. There was no spillage of LNG or injuries/fatalities.
1980	LNG Taurus	The vessel was stranded at port and ballast tanks all flooded thus leading to listing the vessel. There was extensive bottom damage, but no spillage of LNG or injury/fatality was experienced.
1984	Melrose	There was fire in engine room at sea and no structural damage sustained. No LNG spill or fatality/injury was recorded.
1985	Gadinia (Bebatik)	Steering gear failure at the port. No LNG spill or injury/fatality was experienced.
1985	Isabella	There were cargo valve failure and the cargo overflows during unloading of LNG. There were also deck fractures, though no LNG spillage or

		injury/fatality was experienced.
1990	Bachir Chihani	While at sea, the vessel sustained structural cracks allegedly caused by stressing and fatigue in the inner hull. There was no LNG spillage or fatality/injury.
1995	Mourad Didouche	Lifting cable broke while the turbine was lifted out of engine room, causing turbine to fall from great height at the shipyard.
1996	LNG Finima	The vessel was boarded by pirates while anchored. The pirates stole paint and broached a lifeboat. There was no spillage or casualty.
1996	Mostefa Ben Boulaid	There was electrical fire in the main engine room, while at quay discharging. This caused power lost and there was no spillage.
1996	LNG Portovenere	Fire broke out in the engine room, when the empty vessel was at sea, which killed 6 people. There was no spillage of LNG.
1997	LNG Capricorn	Sustained damage to shell plating on contact with mooring dolphin, while in port. No spillage or damage to cargo system.
1997	Northwest Swift	Had a collision with fishing vessel. The port side and bulkward were damaged. No water ingress and LNG spillage.
1998	Mostefa Ben Boulaid	Had generator problems in port, though there was no spillage or casualty.
1998	LNG Bonny	Had complete power failure while at sea. There was no spillage or injuries/fatalities.
1999	Methane Polar	Had engine breakdown and struck the Petrotrin jetty at Point Fortin, while being brought in empty for loading. There was no casualty or damage experienced.
1999	Matthew	Had tailshaft problem and overheated bearing

		while at sea. There was no casualty or spillage experienced.
2000	Hanjin Pyeong Taek	Had collision with bulk carrier at sea and damage occurred to shell plating. No spillage reported.
2000	LNG Jamal	Insulating materials & vinyl sheeting burnt out during welding operations on No. 3 tank cover at wharf. There was no spillage or casualty experienced.
2000	Hoegh Galleon (Pollenger)	An outbreak of fire in the yard caused damage to part of the tank insulation, which caused the death of 1 ship builder.
2001	Ramdane Abane	There was engine break down at sea and no casualty or spillage was experienced.
2001	Methane Polar	Had collision with bulk carrier at sea (in ballast), which caused minor hull damage and sustained holing to bow. There were three injuries and one fatality of the bulk carrier crew, though no spillage was recorded.
2002	Norman Lady	The LNG vessel collided with a U.S. Navy submarine, while at sea (in ballast condition). The LNG vessel suffered a leakage of seawater into the double bottom of the dry tank area. There was no LNG spillage or injuries/fatalities.
2003	Methane Princess	Had fire on board while under construction. Fire burnt part of the cargo tanks, though the damage was minor. There was no injury/fatality.
2003	Century	Sustained main engine damage offshore. There was no LNG spillage or injury/fatality of personnel.
2003	Hoegh Galleon (Pollenger)	Developed gearbox problems at sea. There was no LNG spillage or casualty.

2003	Hilli	Had a boiler tube failure at anchorage. The failure did not result to any spillage or casualty.
2003	Gimi	Softly touched bottom when approaching pier. It did not result in injuries or spillage.
2003	Fuwairit	Grounded during passage of typhoon "Maemi" while under construction. There was no casualty experienced.
2003	Galicia Spirit	Grounded after mooring ropes released during typhoon "Maemi" while under construction. The vessel sustained damage to bottom and starboard shell plating, but there was no casualty.
2003	LNG Berge Arzew	While under construction, mooring ropes broke due to typhoon "Maemi" and drifted away from berth, touching bottom. The bottom plating was damaged, but there was no casualty.
2004	British Trader	There was minor electrical fire onboard, which damaged one transformer while the vessel was at sea. No spillage or casualty reported.
2004	Methane Arctic	The vessel had minor fire breakout after being struck by lightning during discharge. There was slight damage on the vessel, but no casualty or LNG spillage.
2004	Tenage Lima	Made contact with a submerged rock due to a strong southerly current. The starboard side shell plating in way of No. 1 membrane tank was heavily damaged, though, no spillage or casualties were experienced.
2005	Hispania Spirit	The hull was damaged via contact during berthing operations, which resulted in oil spill. There was no LNG spill or casualty.
2005	Laieta	Engine breakdown while in ballast. LNG spill or casualty was not experienced.

2005	Methane Kari Elin	Suffered damaged insulation and had nitrogen leak (Gasbridge, 2010). No LNG spillage or casualty reported.
2006	Catalunya Spirit	The vessel had damaged insulation (Gasbridge, 2010). No LNG spillage or casualty reported.
2008	Catalunya Spirit	The vessel went adrift for hours off Cape Cod because a computer glitch caused the vessel to lose power (TimeLeyLaw, 2010). No spillage or casualty was experienced.
2009	Matthew	Grounded on coral reef habitat off the south coast of Puerto Rico near Guayanilla (DARRP, 2010). No spillage or casualty reported.
2010	Umm Al Amad	The vessel was boarded by six pirates while sailing. The pirates stole cash from the ship and crew members (ReCAAP, 2010). There was no spillage or casualty.

Appendix C - Appendices of Chapter 4

Appendix C1.1 – Example of how a Simple Genetic Algorithm Works

Example 1

Suppose the objective function of an LNG engineering product to be "minimise" is symbolised as $f(x, y) = x\sin(5x) + 1.2y\sin(3y)$, such that $0 \leq x \leq 12$ and $0 \leq y \leq 12$. Find the following:

i. The steps of genetic algorithm before convergence.
ii. The first iteration by manual calculation.

Solution

The steps of finding the genetic algorithm are:

1. Randomly pick four numbers from the variable bounds as population size.
2. Convert the selected numbers to binary.
3. Assign fitness values to these numbers, using the objective function.
4. Rank the fitness values from lowest to highest.
5. Select the first half of the population for the next generation.
6. Select pairs of parents from half of the population chosen for next generation.
7. Apply crossover on the parents to produce individuals that will produce discarded ones, maintaining the same population size.
8. Apply mutation to the formed individual (children) by flipping a 0 to 1 and vice versa.
9. Arrange the parents and formed individual (children) as the new population with size of four.
10. Check for convergence, and go back to step 2 if it has not been achieved.

ii. The objective function which is also called fitness function in GA, to be minimised is:

$f(x,y) = x\sin(5x) + 1.2y\sin(3y)$

Subject to:

$0 \le x \le 12$

$0 \le y \le 12$

The variables (x and y) values picked randomly for population size of four are:

1. 3.0 and 7.0
2. 9.0 and 2.0
3. 4.0 and 5.0
4. 6.0 and 8.0

Using binary based genetic algorithm called steady state or single objective genetic algorithm, the real numbers of x and y variables, which are in base ten (denary number) are converted to binary numbers, where bits of the binary represents the genes of the chromosomes. The binary numbers and fitness values of population member 1 (3.0 and 7.0), population member 2 (9.0 and 2.0), population member 3 (4.0 and 5.0), and population member 4 (6.0 and 8.0) will be represented respectively as follows:

1. 0011 and 0111 with fitness value of 3.7867

2 | 3
2 | 1 - 1
2 | 0 - 1

Then $3_{10} = 0011_2$

2 | 7 ↑
2 | 3 - 1
2 | 1 - 1
| 0 - 1

Then $7_{10} = 0111_2$

$f(x,y) = x\sin(5x) + 1.2y\sin(3y)$

$f(3.0,7.0) = 3.0\sin(5 \times 3.0) + 1.2 \times 7.0 \times \sin(3 \times 7.0)$

$= 3.7867$

Therefore fitness value = 3.7867

In a similar way, binary and fitness values of population member 2, 3 and 4 are found.

2. 1001 and 0010 with fitness value of 6.6148

3. 0100 and 0101 with fitness value of 2.9210
4. 0110 and 1000 with fitness value of 6.9047

The fitness values, population member, binary numbers of the variables, and chromosomes (individuals) are presented in Table C1.1 and C1.2 which are explained as follows:

- Population member 1 with fitness value 3.7867 and chromosome 00110111 has x and y values as 3 and 7 with string of 0011 and 0111.
- Population member 2 with fitness value 6.6148 and chromosome 10010010 has x and y values as 9 and 2 with string of 1001 and 0010.
- Population member 3 with fitness value 2.9210 and chromosome 01000101 has x and y values as 4 and 5 with string of 0100 and 0101.
- Population member 4 with fitness value 6.9047 and chromosome 01101000 has x and y values as 6 and 8 with string of 0110 and 1000.

Rank the fitness value in Table C1.1 from lowest to highest in Table C1.2 with their corresponding population number, variables value and their string (binary) representation, and individual/chromosomes. The first half of the population member will be selected for next generation. From Table C1.2, the population member 3 and 1 will be selected for next generation while the population member 2 and 4 will be discarded. Population member 2 and 4 positions will be replaced after reproduction (crossover and mutation).

Table C1.1: Unranked First/Initial Population Fitness Value

Population member	x	y	String x	String y	String x ⊕ String y = chromosome(individual)	Fitness value
1	3	7	0011	0111	00110111	3.7867
2	9	2	1001	0010	10010010	6.6148
3	4	5	0100	0101	01000101	2.9210
4	6	8	0110	1000	01101000	6.9047

Table C1.2: Ranked First/Initial Population Fitness Value

Population member	x	y	String x	String y	String x ⊕ String y = chromosome(individual)	Fitness value
3	4	5	0100	0101	01000101	2.9210
1	3	7	0011	0111	00110111	3.7867
2	9	2	1001	0010	10010010	6.6148
4	6	8	0110	1000	01101000	6.9047

The chromosomes of population member 3 and 1 are selected as the chromosomes (parents) in the population that will mate to reproduce new chromosomes/individuals (offspring or children) by crossover and mutation of their bits (genes). The chromosomes (parents) which will be part of the new population are:

- 01000101
- 00110111

Applying single point crossover on the parents by exchange of the first four bits from the right, two new chromosomes (offspring or children) will be reproduced. The reproduced chromosomes are:

- 01000111
- 00110101

The next step is to mutate the reproduced chromosomes by randomly flipping the fifth bit (0) of the first string from the right to that of second string and vice versa. Thus the mutation operator is not necessary inventing new information but simply working as an insurance policy against premature loss of genetic information (Colley, 1999). It allows for various attributes of the candidate solutions to be occasionally altered (Charles and Freeman, 1999). The reproduced chromosomes (offspring) will replace the chromosomes of population member 2 and 4 in Table C1.2, maintaining the same population size. The new offspring (children) that is produced after mutation are:

- 01010111
- 00100101

The new population formed will be made up of population member 3 and 1 in Table C1.2 and the mutated chromosomes produced after crossover. The four new population chromosomes are:

1. 01000101
2. 00110111
3. 01010111
4. 00100101

Convert the binary string of the chromosomes to their real values and corresponding fitness values and check if the population have converged. The values are:

1. 4 and 5 with fitness value of 2.9210 as illustrated in Table C1.1, C1.2 and C1.3.

$01000101 = 0100 \oplus 0101$

$0100 \Rightarrow 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0$

$= 0 + 4 + 0 + 0$

$= 4$

Then $0100_2 = 4_{10}$

$0101 \Rightarrow 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$

$= 0 + 4 + 0 + 1$

$= 5$

Then $0101_2 = 5_{10}$

$f(x,y) = x\sin(5x) + 1.2y\sin(3y)$

$f(4.0, 5.0) = 4.0\sin(5.0 \times 4.0) + 1.2 \times 5.0 \times \sin(3.0 \times 5.0)$

$= 2.92$

Therefore, fitness value = 2.9210

Using the same method, the real and fitness values of population member 2, 3 and 4 are identified.

2. 3 and 7 with fitness value of 3.7867 as illustrated in Table C1.1, C1.2 and C1.3.
3. 5 and 7 with fitness value of 5.189 as illustrated in Table C1.3.
4. 2 and 5 with fitness value of 1.9 as illustrated in Table C1.3.

Table C1.3: Unranked Second Generation Fitness Value

Population member	x	y	String x	String y	String x ⊕ String y = chromosome (individual)	Fitness value
1	4	5	0100	0101	01000101	2.9210
2	3	7	0011	0111	00110111	3.7867
3	5	7	0101	0111	01010111	5.1890
4	2	5	0010	0101	00100101	1.9000

Table C1.4: Ranked Second Generation Fitness Value

Population member	x	y	String x	String y	String x ⊕ String y = chromosome (individual)	Fitness value
4	2	5	0010	0101	00100101	1.9000
1	4	5	0100	0101	01000101	2.9210
2	3	7	0011	0111	00110111	3.7867
3	5	7	0101	0111	01010111	5.1890

In a similar way to Table C1.1 and C1.2, Table C1.3 and C1.4 are described as follows:

- Population member 1 with fitness value 2.9210 and chromosome 01000101 has x and y values as 4 and 5 with string of 0100 and 0101.
- Population member 2 with fitness value 3.7867 and chromosome 00110111 has x and y values as 3 and 7 with string of 0011 and 0111.
- Population member 3 with fitness value 5.1890 and chromosome 01010111 has x and y values as 5 and 7 with string of 0101 and 0111.
- Population member 4 with fitness value 1.9000 and chromosome 00100101 has x and y values as 2 and 5 with string of 0010 and 0101.

From Table C1.3, fitness value of the population members is not the same. Therefore, the new population formed did not converge at first iteration/generation. The population will continue to be ranked as in Table C1.4, selected, crossover and mutated using the same procedures from generation to generation until the population start to converge at fitness value of -25.279 as illustrated in Figure C1.2, x and y values of 10.99 and 12 using Matlab version 7.7 GA and direct search toolbox.

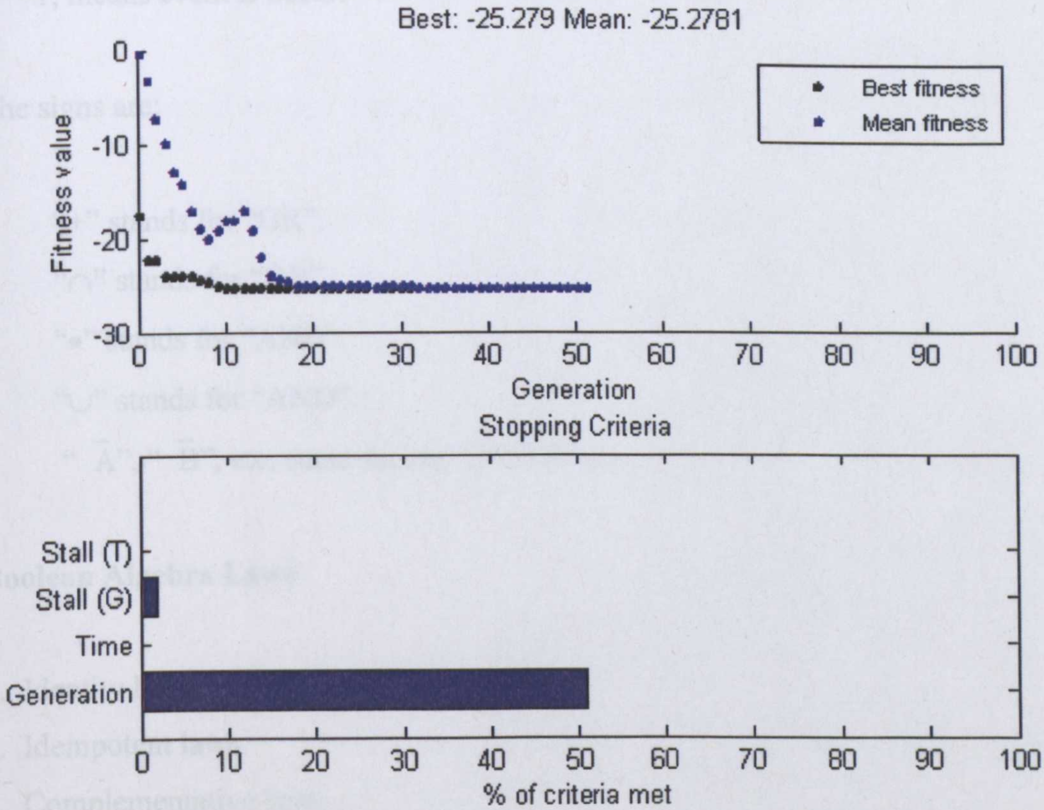

Figure C1.1. Graph of Fitness against Generation of Example 1

Appendix C1.2 - Boolean Algebra Rules

Representation of State of an Event

1 and 0 are used to represent two states of an event in Boolean algebra. There meanings are as follows:

- 1 means occurrence, true or on.
- 0 means non-occurrence, false or off.

Applying these two states to events, for example, event A and B.

A = 0; means event A does not occur.

A = 1; means event A occur.

B = 0; means event B does not occur.

B = 1; means event B occur.

The signs are:

- "+" stands for "OR".
- "$\cap$" stands for "OR".
- "•" stands for "AND".
- "$\cup$" stands for "AND".
- "$\bar{A}$", "$\bar{B}$", etc. stand for not "A", "B" etc.

Boolean Algebra Laws

1. Identity laws.
2. Idempotent laws.
3. Complementative laws.
4. Commutative laws.
5. Associative laws.
6. Distributive laws.
7. Absorption laws.
8. De Morgan's laws.

Identity Laws

Identity law states the following:

1. Addition of an event and zero is equal to that event. For examples,

$$A + 0 = A$$
$$B + 0 = B$$

2. Addition of an event and one is equal to one. For examples,

$$A + 1 = 1$$

$B + 1 = 1$

3. Multiplication of an event and zero is equal to zero. For examples,

$A \bullet 0 = 0$

$B \bullet 0 = 0$

4. Multiplication of an event and one is equal to that event. For examples,

$A \bullet 1 = A$

$B \bullet 1 = B$

Idempotent Laws

Idempotent laws state its laws as follows:

1. Addition of an event and the same event is equal to that event. For examples,

$A + A = A$

$B + B = B$

2. Multiplication of an event and the same event is equal that event. For examples,

$A \bullet A = A$

$B \bullet B = B$

Complementative Laws

Complementative laws states that:

1. Multiplication of an event and "not an event" is equal to zero. For example,

$A \bullet \bar{A} = 0$

$$B \bullet \bar{B} = 0$$

2. Addition of an event and "not an event" is equal to one.

$$A + \bar{A} = 1$$

$$B + \bar{B} = 1$$

3. Not "not an event" is equal to an event. For example,

$$\bar{\bar{A}} = A$$

$$\bar{\bar{B}} = B$$

Commutative Laws

Commutative laws states that:

1. Addition of an event and another different event is the same. For example,

$$A + B = B + A$$

2. Multiplication of an event and another event is the same. For example,

$$A \bullet B = B \bullet A$$

Associate Laws

Associative laws state the following:

1. Addition of an event (A) and another event (B) in bracket, added to third event (C) is equal to the first event (A) added to second and third event added in bracket. For example,

$$(A + B) + C = A + (B + C)$$

2. Multiplication of an event (A) and another event (B) in bracket, multiplied with third event (C) is equal to the first event (A) multiplied to the second (B) and third (C) event multiplied in bracket. For example,

$$(A \bullet B) \bullet C = A \bullet (B \bullet C)$$

Distributive Laws

Distributive laws state the following:

1. An event (A) multiplied with the second (B) and third (C) event added in bracket, is equal to the event (A) multiplied by the second event (B) and added to event (A) multiplied to the third event (C). For example,

$$A \bullet (B + C) = A \bullet B + A \bullet C$$

2. An event (A) added to two different events (B and C) that is multiplied to each, other in a bracket, is equal to an event (A) added to the first event (B) in bracket, multiplied by an event (A) added to the second event (C) in bracket. For example,

$$A + (B \bullet C) = (A + B) \bullet (A + C)$$

Absorption Laws

Absorption laws states as follows:

1. An event (A) multiplied by another event (B), added to event (A) is equal to the event (A). For example,

$$A + A \bullet B = A$$

2. An event (A) multiplied by two events (A and B) added together in bracket is equal to an event (A). For example,

$$A \bullet (A + B) = A$$

De Morgan's Laws

De Morgan's laws states as follows:

1. Not "an event (A) multiplied by another event (B)" is equal to not an event (A) added to not an event (B). For example,

$$\overline{A \bullet B} = \bar{A} + \bar{B}$$

2. Not "an event (A) added to another event (B)" is equal to not an event (A) multiplied by not an event (B). For example,

$$\overline{A + B} = \bar{A} \bullet \bar{B}$$

Minimal cut sets can be obtained using Boolean algebra laws and FT shown in Figure C1.2 and C1.3. It helps to determine the occurrence probability of top event (hazardous event) in the LNG industry.

In Figure C1.2 if event A is independent of event B, the occurrence probability (P) of A is P(A) and the occurrence probability of B is P(B), the probability of occurrence of the top event K becomes:

$$P(K) = P(A \bullet B) = P(A) \times P(B)$$

In Figure C1.3, if one event is independent of the other and the occurrence probability of event A and B are P(A) and P(B). The top event K becomes:

$$\begin{aligned} P(K) &= P(A + B) \\ &= P(A) + P(B) - P(A \bullet B) \\ &= P(A) + P(B) - P(A) \times P(B) \end{aligned}$$

The application of theorem above and Boolean algebra are shown in example 2, below.

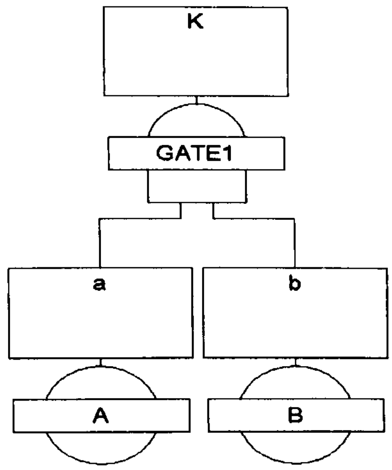

Figure C1.2: AND Gate Fault Tree

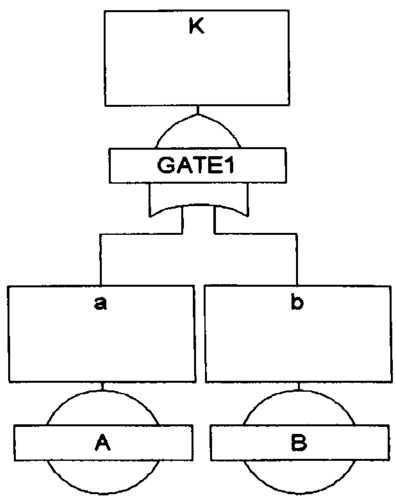

Figure C1.3: OR Gate Fault Tree

Example 2

A sprinkler system in an LNG ship accommodation region is being assessed. It is considered that a hazardous situation arises if there is a fire (event X1) and the sprinkler system fails (event X2). A fire (event X1) starts if there is a source of ignition (event X3) and some combustible material is available (basic event A). Event X2 can occur either due to electrical failure (basic event B) or due to pump failure (basic event D).

Event X3 can occur either because of event B above or due to another source of ignition being present (basic event C). It is assumed that event A, B, C and D follow an exponential distribution. The failure rate (1/hour) of event A, B, C and D are 0.0001, 0.0002, 0.0003 and 0.0004, respectively.

i. Draw the fault tree for the above problem.
ii. Find the minimum cut sets.
iii. Discuss how the likelihood occurrence of top event can be reduced/eliminated.
iv. Calculate the occurrence likelihood of the top event at time t = 10,000 hours, assumming events A, B, C and D are independent of each other.

Solution

i. The fault tree is illustrated in Figure C1.4.

ii.

$$
\begin{aligned}
& X_1 \bullet X_2 \\
&= (A \bullet X_3) \bullet (B + D) \\
&= A \bullet (B + C) \bullet (B + D) \\
&= (A \bullet B + A \bullet C) \bullet (B + D) \\
&= A \bullet B \bullet (B + D) + A \bullet C\,(B + D) \\
&= A \bullet B \bullet B + A \bullet B \bullet D + A \bullet C \bullet B + A \bullet C \bullet D \\
&= A \bullet B\,(1 + D) + A \bullet C\,(B + D) \\
&= A \bullet B + A \bullet C\,(B + D) \\
&= A \bullet B + A \bullet B \bullet C + A \bullet C \bullet D \\
&= A \bullet B\,(1 + C) + A \bullet C \bullet D \\
&= A \bullet B + A \bullet C \bullet D
\end{aligned}
$$

iii. Ensure that A and B do not happen simultaneously or A, C and D do not happen simultaneously.

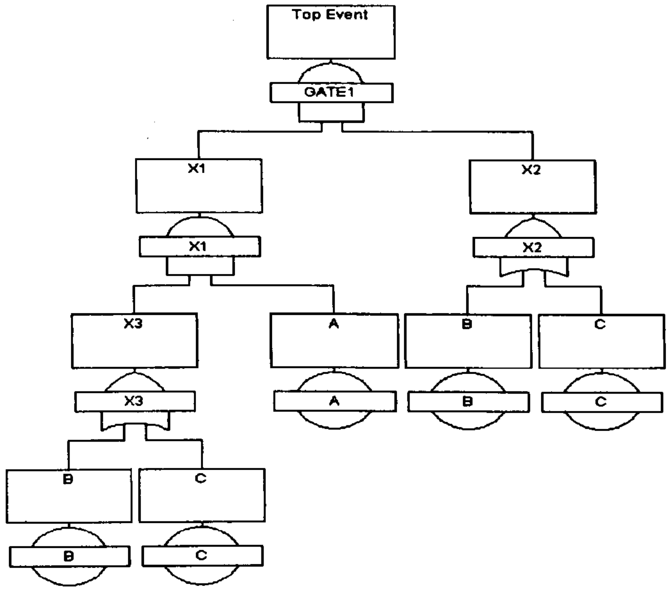

Figure C1.4: Fault Tree Analysis of Sprinkler System

iv. At t = 10,000 hours

$P(\text{Event}) = 1 - e^{-\lambda t}$

$\lambda = 0.0001$

$P(A) = 1 - e^{-0.0001 \times 10{,}000} = 0.632$

$\lambda = 0.0002$

$P(B) = 1 - e^{-0.0002 \times 10{,}000} = 0.865$

$\lambda = 0.0003$

$P(C) = 1 - e^{-0.0003 \times 10{,}000} = 0.95$

$\lambda = 0.0004$

$P(D) = 1 - e^{-0.0004 \times 10{,}000} = 0.982$

$P(\text{Sprinkler system failure}) = P(A \bullet B + A \bullet C \bullet D)$

$= P(A \bullet B) + P(A \bullet C \bullet D) - P(A \bullet B \bullet A \bullet C \bullet D)$

$= P(A) \times P(B) + P(A) \times P(C) \times P(D) - P(A \bullet B \bullet C \bullet D)$

$= P(A) \times P(B) + P(A) \times P(C) \times P(D) - P(A) \times P(B) \times P(C) \times P(D)$

$= 0.632 \times 0.865 + 0.632 \times 0.95 \times 0.982 - 0.632 \times 0.865 \times 0.95 \times 0.982$

$= 0.627$

At t = 10,000 hours, 0.627 is the occurrence likelihood of top event (sprinkler failure).

Appendix D - Appendices of Chapter 5

Appendix D1.1 - The 125 Fuzzy Rules of the LNG Carrier System Maintenance Cost

Rule #1: IF LTCC is very low, LMD is very short AND LSPC is very cheap, THEN LMC is very cheap.
Rule #2: IF LTCC is very low, LMD is short AND LSPC is cheap, THEN LMC is cheap.
Rule #3: IF LTCC is very low, LMD is medium AND LSPC is average, THEN LMC is normal.
Rule #4: IF LTCC is very low, LMD is long AND LSPC is costly, THEN LMC is normal.
Rule #5: IF LTCC is very low, LMD is very long AND LSPC is very costly, THEN LMC is expensive.
Rule #6: IF LTCC is low, LMD is very low AND LSPC is very cheap, THEN LMC is cheap.
Rule #7: IF LTCC is low, LMD is short AND LSPC is cheap, THEN LMC is cheap.
Rule #8: IF LTCC is low, LMD is medium AND LSPC is average, THEN LMC is normal.
Rule #9: IF LTCC is low, LMD is long AND LSPC is costly, THEN LMC is normal.
Rule #10: IF LTCC is low, LMD is very long AND LSPC is very costly, THEN LMC is expensive.
Rule #11: IF LTCC is moderate, LMD is very short AND LSPC is very cheap, THEN LMC is cheap.
Rule #12: IF LTCC is moderate, LMD is short AND LSPC is cheap, THEN LMC is normal.
Rule #13: IF LTCC is moderate, LMD is medium AND LSPC is average, THEN LMC is normal.
Rule #14: IF LTCC is moderate, LMD is long AND LSPC is costly, THEN LMC is expensive.
Rule #15: IF LTCC is moderate, LMD is very long AND LSPC is very costly, THEN LMC is very expensive.

Rule #16: IF LTCC is high, LMD is very short AND LSPC is very cheap, THEN LMC is cheap.

Rule #17: IF LTCC is high, LMD is short AND LSPC is cheap, THEN LMC is normal.

Rule #18: IF LTCC is high, LMD is medium AND LSPC is average, THEN LMC is expensive.

Rule #19: IF LTCC is high, LMD is long AND LSPC is costly, THEN LMC is expensive.

Rule #20: IF LTCC is high, LMD is very long AND LSPC is very costly, THEN LMC is very expensive.

Rule #21: IF LTCC is very high, LMD is very short AND LSPC is very cheap, THEN LMC is normal.

Rule #22: IF LTCC is very high, LMD is short AND LSPC is cheap, THEN LMC is normal.

Rule #23: IF LTCC is very high, LMD is medium AND LSPC is average, THEN LMC is expensive.

Rule #24: IF LTCC is very high, LMD is long AND LSPC is costly, THEN LMC is very expensive.

Rule #25: IF LTCC is very high, LMD is very long AND LSPC is very costly, THEN LMC is very expensive.

Rule #26: IF LTCC is very low, LMD is short AND LSPC is very cheap, THEN LMC is cheap.

Rule #27: IF LTCC is very low, LMD is medium AND LSPC is cheap, THEN LMC is cheap.

Rule #28: IF LTCC is very low, LMD is long AND LSPC is average, THEN LMC is normal.

Rule #29: IF LTCC is very low, LMD is very long AND LSPC is costly, THEN LMC is expensive.

Rule #30: IF LTCC is very low, LMD is very short AND LSPC is very costly, THEN LMC is normal.

Rule #31: IF LTCC is low, LMD is short AND LSPC is very cheap, THEN LMC is cheap.

Rule #32: IF LTCC is low, LMD is medium AND LSPC is cheap, THEN LMC is normal.

Rule #33: IF LTCC is low, LMD is long AND LSPC is average, THEN LMC is normal.

Rule #34: IF LTCC is low, LMD is very long AND LSPC is costly, THEN LMC is expensive.

Rule #35: IF LTCC is low, LMD is very short AND LSPC is very costly, THEN LMC is normal.

Rule #36: IF LTCC is moderate, LMD is short AND LSPC is very cheap, THEN LMC is cheap.

Rule #37: IF LTCC is moderate, LMD is medium AND LSPC is cheap, THEN LMC is normal.

Rule #38: IF LTCC is moderate, LMD is long AND LSPC is average, THEN LMC is expensive.

Rule #39: IF LTCC is moderate, LMD is very long AND LSPC is costly, THEN LMC is expensive.

Rule #40: IF LTCC is moderate, LMD is very short AND LSPC is very costly, THEN LMC is normal.

Rule #41: IF LTCC is high, LMD is short AND LSPC is very cheap, THEN LMC is normal.

Rule #42: IF LTCC is high, LMD is medium AND LSPC is cheap, THEN LMC is normal.

Rule #43: IF LTCC is high, LMD is long AND LSPC is average, THEN LMC is expensive.

Rule #44: IF LTCC is high, LMD is very long AND LSPC is costly, THEN LMC is very expensive.

Rule #45: IF LTCC is high, LMD is very short AND LSPC is very costly, THEN LMC is expensive.

Rule #46: IF LTCC is very high, LMD is short AND LSPC is very cheap, THEN LMC is normal.

Rule #47: IF LTCC is very high, LMD is medium AND LSPC is cheap, THEN LMC is expensive.

Rule #48: IF LTCC is very high, LMD is long AND LSPC is average, THEN LMC is expensive.

Rule #49: IF LTCC is very high, LMD is very long AND LSPC is costly, THEN LMC is very expensive.

Rule #50: IF LTCC is very high, LMD is very short AND LSPC is very costly, THEN LMC is expensive.

Rule #51: IF LTCC is very low, LMD is medium AND LSPC is very cheap, THEN LMC is cheap.

Rule #52: IF LTCC is very low, LMD is long AND LSPC is cheap, THEN LMC is normal.

Rule #53: IF LTCC is very low, LMD is very long AND LSPC is average, THEN LMC is normal.

Rule #54: IF LTCC is very low, LMD is very short AND LSPC is costly, THEN LMC is cheap.

Rule #55: IF LTCC is very low, LMD is short AND LSPC is very costly, THEN LMC is normal.

Rule #56: IF LTCC is low, LMD is medium AND LSPC is very cheap, THEN LMC is cheap.

Rule #57: IF LTCC is low, LMD is long AND LSPC is cheap, THEN LMC is normal.

Rule #58: IF LTCC is low, LMD is very long AND LSPC is average, THEN LMC is expensive.

Rule #59: IF LTCC is low, LMD is very short AND LSPC is costly, THEN LMC is normal.

Rule #60: IF LTCC is low, LMD is short AND LSPC is very costly, THEN LMC is normal.

Rule #61: IF LTCC is moderate, LMD is medium AND LSPC is very cheap, THEN LMC is cheap.

Rule #62: IF LTCC is moderate, LMD is high AND LSPC is cheap, THEN LMC is normal.

Rule #63: IF LTCC is moderate, LMD is very long AND LSPC is average, THEN LMC is expensive.

Rule #64: IF LTCC is moderate, LMD is very short AND LSPC is costly, THEN LMC is normal.

Rule #65: IF LTCC is moderate, LMD is short AND LSPC is very costly, THEN LMC is expensive.

Rule #66: IF LTCC is high, LMD is medium AND LSPC is very cheap, THEN LMC is normal.

Rule #67: IF LTCC is high, LMD is high AND LSPC is cheap, THEN LMC is expensive.

Rule #68: IF LTCC is high, LMD is very long AND LSPC is average, THEN LMC is expensive.

Rule #69: IF LTCC is high, LMD is very short AND LSPC is costly, THEN LMC is normal.

Rule #70: IF LTCC is high, LMD is short AND LSPC is very costly, THEN LMC is expensive.

Rule #71: IF LTCC is very high, LMD is medium AND LSPC is very cheap, THEN LMC is normal.

Rule #72: IF the LTCC is very high, LMD is long AND LSPC is cheap, THEN LMC is expensive.

Rule #73: IF LTCC is very high, LMD is very long AND LSPC is average, THEN LMC is very expensive.

Rule #74: IF LTCC is very high, LMD is very short AND LSPC is costly, THEN LMC is expensive.

Rule #75: IF LTCC is very high, LMD is short AND LSPC is very costly, THEN LMC is very expensive.

Rule #76: IF LTCC is very low, LMD is long AND LSPC is very cheap, THEN LMC is cheap.

Rule #77: IF LTCC is very low, LMD is very long AND LSPC is cheap, THEN LMC is normal.

Rule #78: IF LTCC is very low, LMD is very short AND LSPC is average, THEN LMC is cheap.

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Rule #82: IF LTCC is low, LMD is very long AND LSPC is cheap, THEN LMC is normal.

Rule #83: IF LTCC is low, LMD is very low AND LSPC is average, THEN LMC is cheap.

Rule #84: IF LTCC is low, LMD is short AND LSPC is costly, THEN LMC is normal.

Rule #85: IF LTCC is low, LMD is medium AND LSPC is very costly, THEN LMC is expensive.

Rule #86: IF LTCC is moderate, LMD is long AND LSPC is very cheap, THEN LMC is normal.

Rule #87: IF LTCC is moderate, LMD is very long AND LSPC is cheap, THEN LMC is expensive.

Rule #88: IF LTCC is moderate, LMD is very short AND LSPC is average, THEN LMC is normal.

Rule #89: IF LTCC is moderate, LMD is short AND LSPC is costly, THEN LMC is normal.

Rule #90: IF LTCC is moderate, LMD is medium AND LSPC is very costly, THEN LMC is expensive.

Rule #91: IF LTCC is high, LMD is long AND LSPC is very cheap, THEN LMC is normal.

Rule #92: IF LTCC is high, LMD is very long AND LSPC is cheap, THEN LMC is expensive.

Rule #93: IF LTCC is high, LMD is very short AND LSPC is average, THEN LMC is normal.

Rule #94: IF LTCC is high, LMD is short AND LSPC is costly, THEN LMC is expensive.

Rule #95: IF LTCC is high, LMD is medium AND LSPC is very costly, THEN LMC is expensive.

Rule #96: IF LTCC is very high, LMD is long AND LSPC is very cheap, THEN LMC is expensive.

Rule #97: IF LTCC is very high, LMD is very long AND LSPC is cheap, THEN LMC is expensive

Rule #98: IF LTCC is very high, LMD is very short AND LSPC is average, THEN LMC is normal.

Rule #99: IF LTCC is very high, LMD is short AND LSPC is costly, THEN LMC is expensive.

Rule #100: IF LTCC is very high, LMD is medium AND LSPC is very costly, THEN LMC is very expensive.

Rule #101: IF LTCC is very low, LMD is very long AND LSPC is very cheap, THEN LMC is cheap.

Rule #102: IF LTCC is very low, LMD is very short AND LSPC is cheap, THEN LMC is cheap.

Rule #103: IF LTCC is very low, LMD is short AND LSPC is average, THEN LMC is cheap.

Rule #104: IF LTCC is very low, LMD is medium AND LSPC is costly, THEN LMC is normal.

Rule #105: IF LTCC is very low, LMD is long AND LSPC is very costly, THEN LMC is expensive.

Rule #106: IF LTCC is low, LMD is very long AND LSPC is very cheap, THEN LMC is normal.

Rule #107: IF LTCC is low, LMD is very short AND LSPC is cheap, THEN LMC is cheap.

Rule #108: IF LTCC is low, LMD is short AND LSPC is average, THEN LMC is normal.

Rule #109: IF LTCC is low, LMD is medium AND LSPC is costly, THEN LMC is normal.

Rule #110: IF LTCC is low, LMD is long AND LSPC is very costly, THEN LMC is expensive.

Rule #111: IF LTCC is moderate, LMD is very long AND LSPC is very cheap, THEN LMC is normal.

Rule #112: IF LTCC is moderate, LMD is very short AND LSPC is cheap, THEN LMC is cheap.

Rule #113: IF LTCC is moderate, LMD is short AND LSPC is average, THEN LMC is normal.

Rule #114: IF LTCC is moderate, LMD is medium AND LSPC is costly, THEN LMC is expensive.

Rule #115: IF LTCC is moderate, LMD is long AND LSPC is very costly, THEN LMC is expensive.

Rule #116: IF LTCC is high, LMD is very long AND LSPC is very cheap, THEN LMC is expensive.

Rule #117: IF LTCC is high, LMD is very short AND LSPC is cheap, THEN LMC is normal.

Rule #118: IF LTCC is high, LMD is short AND LSPC is average, THEN LMC is normal.

Rule #119: IF LTCC is high, LMD is medium AND LSPC is costly, THEN LMC is expensive.

Rule #120: IF LTCC is high, LMD is long AND LSPC is very costly, THEN LMC is very expensive.

Rule #121: IF LTCC is very high, LMD is very long AND LSPC is very cheap, THEN LMC is expensive.

Rule #122: IF LTCC is very high, LMD is very short AND LSPC is cheap, THEN LMC is normal.

Rule #123: IF LTCC is very high, LMD is short AND LSPC is average, THEN LMC is expensive.

Rule #124: IF LTCC is very high, LMD is medium AND LSPC is costly, THEN LMC is expensive.

Rule #125: IF LTCC is very high, LMD is long AND LSPC is very costly, THEN LMC is very expensive.

Appendix D1.2 - The Results of Expert #2, #3, and #4 Fuzzy Conclusions for the Determination of the Unit Cost of Maintenance of the LNG Containment System

Result of Expert #2 Fuzzy Conclusion

Expert #2 estimates the values of LTCC, LMD, and LSPC to be 0.29, 0.47 and 0.69 on the scale of [0, 1] as illustrated in Figures D1.1, D1.2 and D1.3 respectively. The sets of the fired fuzzy rules are illustrated in Table D1.1.

Expert #2 Fuzzy Conclusion

The fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.55 associated with "cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.45 associated with "normal" linguistics term.

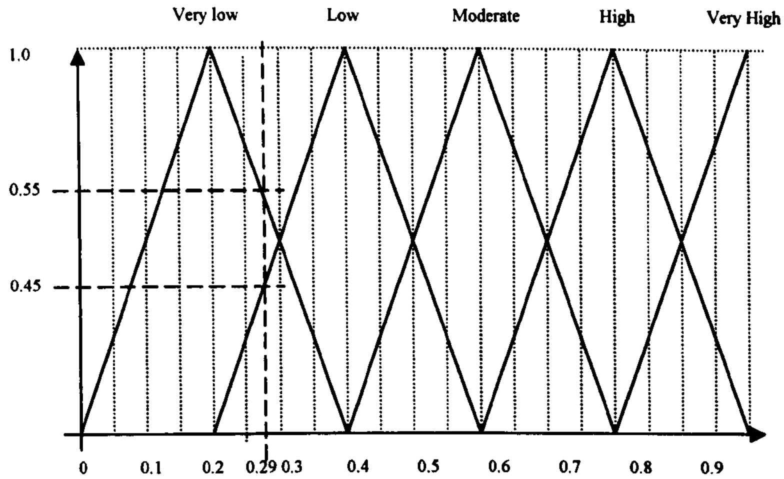

Figure D1.1: Membership Function for LTCC of LNG Containment System (Expert #2)

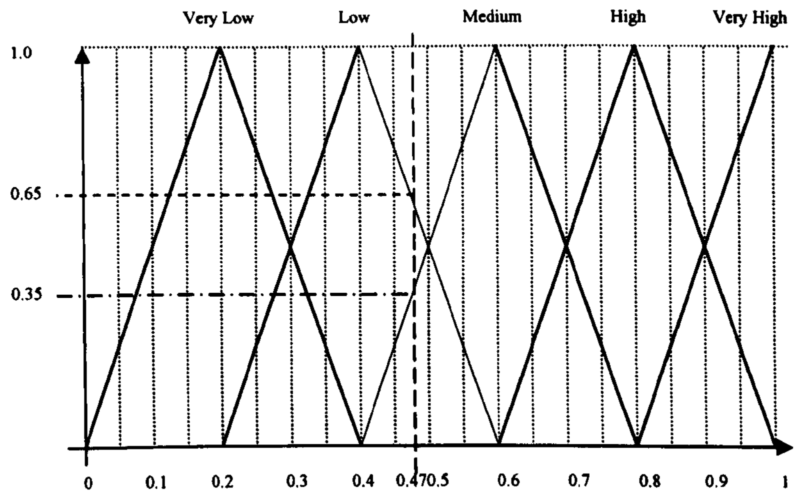

Figure D1.2: Membership Function for LMD of LNG Containment System (Expert #2)

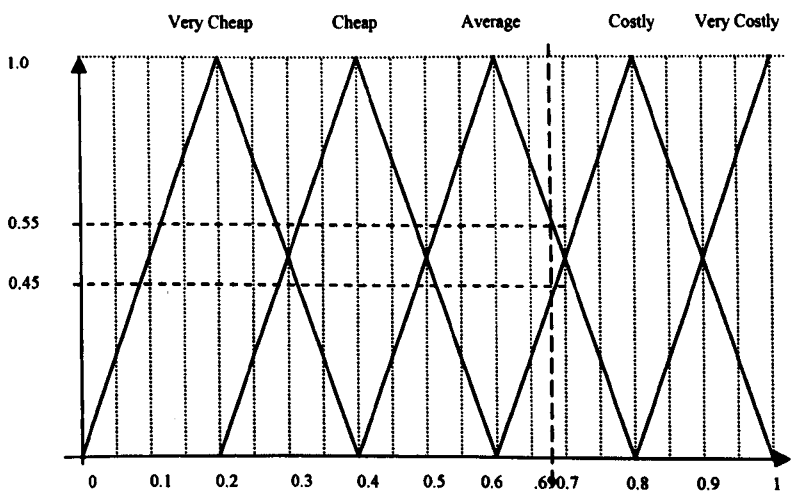

Figure D1.3: Membership Function for LSPC of LNG Containment System (Expert #2)

Table D1.1: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of LNG Containment System (Expert #2)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#3	0.55	0.35	0.55	0.35	Very Low	Medium	Average	Normal
#8	0.45	0.35	0.55	0.35	Low	Medium	Average	Normal
#79	0.55	0.65	0.45	0.45	Very Low	Short	Costly	Normal
#84	0.45	0.65	0.45	0.45	Low	Short	Costly	Normal
#103	0.55	0.65	0.55	0.55	Very Low	Short	Average	Cheap
#104	0.55	0.35	0.45	0.35	Very Low	Medium	Costly	Normal
#108	0.45	0.65	0.55	0.45	Low	Short	Average	Normal
#109	0.45	0.35	0.45	0.35	Low	Medium	Costly	Normal

Result of Expert #3 Fuzzy Conclusion

Expert #3 estimates the values of LTCC, LMD, and LSPC to be 0.28, 0.48 and 0.7 on scale of [0, 1] as illustrated in Figures D1.4, D1.5, and D1.6 respectively. The sets of the fired fuzzy rules are illustrated in Table D1.2.

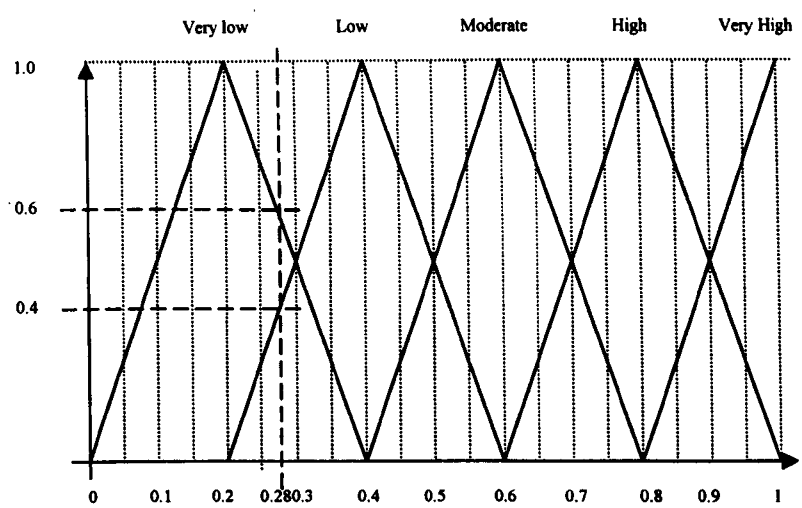

Figure D1.4: Membership Function for LTCC of LNG Containment System (Expert #3)

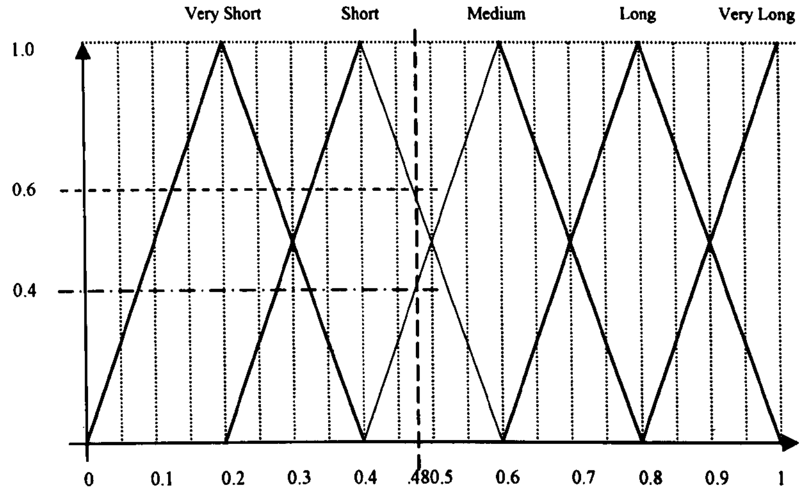

Figure D1.5: Membership Function for LMD of LNG Containment System (Expert #3)

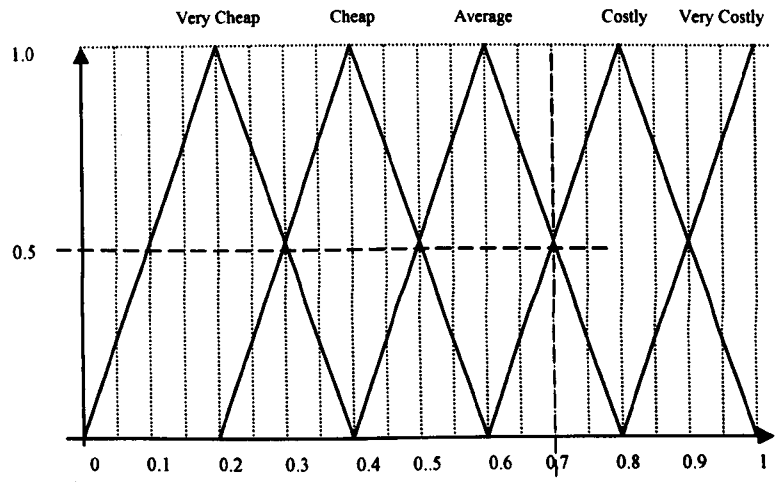

Figure D1.6: Membership Function for LSPC of LNG Containment System (Expert #3)

Table D1.2: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of LNG Containment System (Expert #3)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#3	0.6	0.4	0.5	0.4	Very Low	Medium	Average	Normal
#8	0.4	0.4	0.5	0.4	Low	Medium	Average	Normal
#79	0.6	0.6	0.5	0.5	Very Low	Short	Costly	Normal
#84	0.4	0.6	0.5	0.4	Low	Short	Costly	Normal
#103	0.6	0.6	0.5	0.5	Very Low	Short	Average	Cheap

#104	0.6	0.4	0.5	0.4	Very Low	Medium	Costly	Normal
#108	0.4	0.6	0.5	0.4	Low	Short	Average	Normal
#109	0.4	0.4	0.5	0.4	Low	Medium	Costly	Normal

Expert #3 Fuzzy Conclusion

The fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.5 associated with "cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.5 associated with "normal" linguistics term.

Result of Expert #4 Fuzzy Conclusion

Expert #4 estimates the values of LTCC, LMD, and LSPC to be 0.25, 0.46, and 0.67 on scale of [0, 1] as illustrated in Figures D1.7, D1.8, and D1.9 respectively. The sets of the fired fuzzy rules are illustrated in Table D1.3.

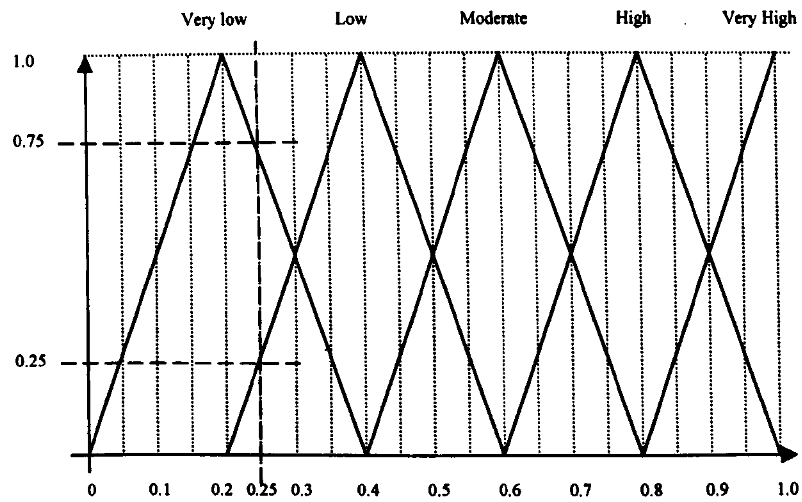

Figure D1.7: Membership Function for LTCC of LNG Containment System (Expert #4)

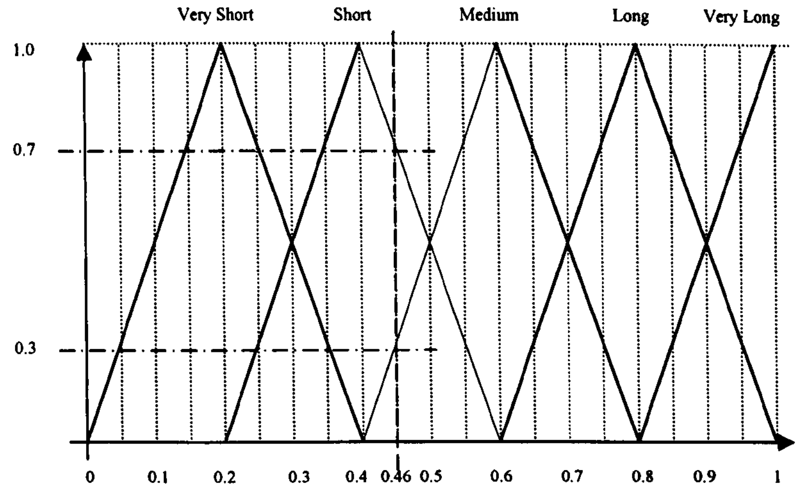

Figure D1.8: Membership Function for LMD of LNG Containment System (Expert #4)

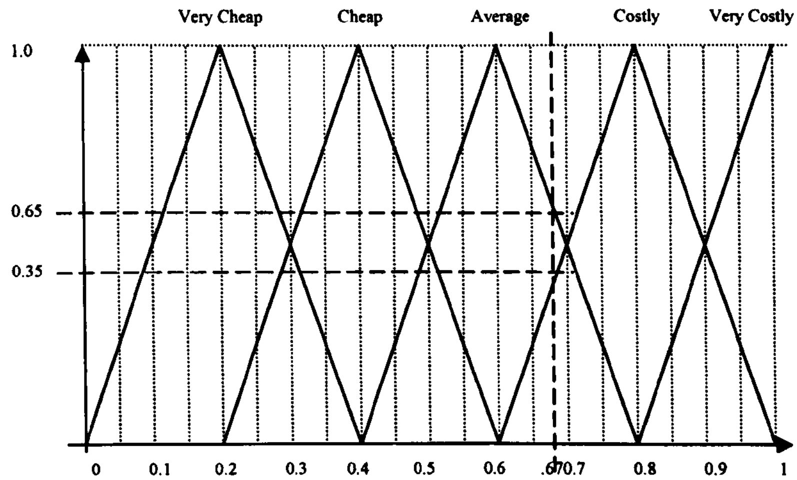

Figure D1.9: Membership Function for LSPC of LNG Containment System (Expert #4)

Table D1.3: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of LNG Containment System (Expert #4)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#3	0.75	0.3	0.65	0.3	Very Low	Medium	Average	Normal
#8	0.25	0.3	0.65	0.25	Low	Medium	Average	Normal
#79	0.75	0.7	0.35	0.35	Very Low	Short	Costly	Normal
#84	0.25	0.7	0.35	0.25	Low	Short	Costly	Normal
#103	0.75	0.7	0.65	0.65	Very Low	Short	Average	Cheap

#104	0.75	0.3	0.35	0.3	Very Low	Medium	Costly	Normal
#108	0.25	0.7	0.65	0.25	Low	Short	Average	Normal
#109	0.25	0.3	0.35	0.25	Low	Medium	Costly	Normal

Expert #4 Fuzzy Conclusion

The fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.65 associated with "cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.35 associated with "normal" linguistics term.

Appendix D1.3 - The Experts #1, #2, #3 and #4 Uncertainty Treatments of the Unit Cost of Maintenance of the LNG Transfer Arm

Expert #1 Opinion

Expert #1 estimates the values of LTCC, LMD, and LSPC to be 0.22, 0.25 and 0.24 on scale of [0, 1] as illustrated in Figures D1.10, D1.11 and D1.12 respectively. The 8 fired fuzzy rules are:

Rule #1: IF LTCC is very low, LMD is very short AND LSPC is very cheap, THEN LMC is very cheap.
Rule #2: IF LTCC is very low, LMD is short AND LSPC is cheap, THEN LMC is cheap.
Rule #6: IF LTCC is low, LMD is very short AND LSPC is very cheap, THEN LMC is cheap.
Rule #7: IF LTCC is low, LMD is short AND LSPC is cheap, THEN LMC is cheap.

Rule #26: IF LTCC is very low, LMD is short AND LSPC is very cheap, THEN LMC is cheap.
Rule #31: IF LTCC is low, LMD is short AND LSPC is very cheap, THEN LMC is cheap.

Rule #102: IF LTCC is very low, LMD is very short AND LSPC is cheap, THEN LMC is cheap.

Rule #107: IF LTCC is low, LMD is very short AND LSPC is cheap, THEN LMC is cheap.

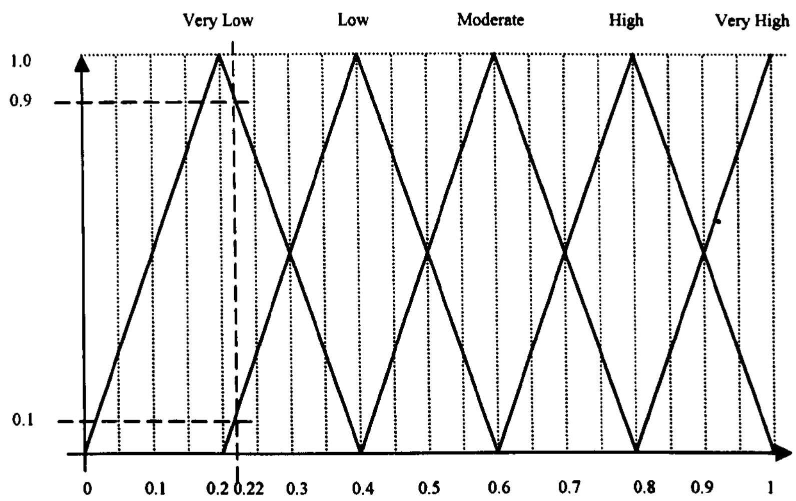

Figure D1.10: Membership Function for LTCC of LNG Transfer Arm (Expert #1)

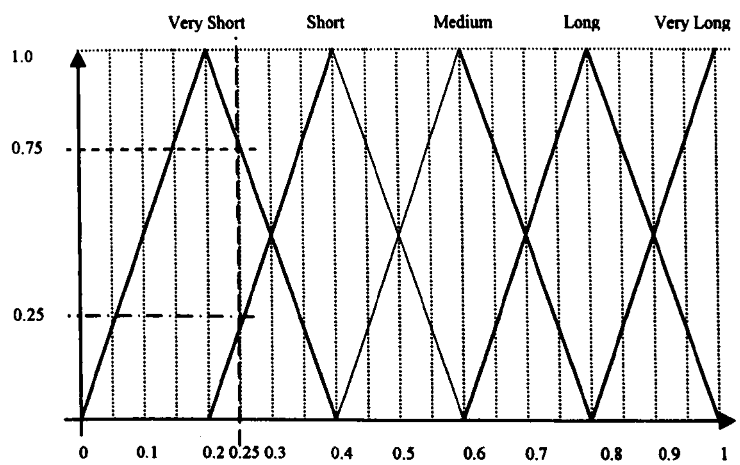

Figure D1.11: Membership Function for LMD of LNG Transfer Arm (Expert #1)

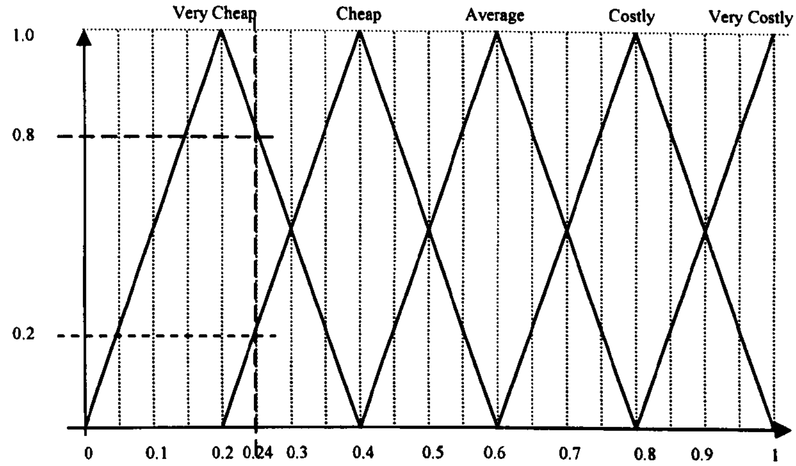

Figure D1.12: Membership Function for LSPC of LNG Transfer Arm (Expert #1)

A max-min method is applied on the membership function values of the LTCC, LMD, and LSPC to produce the membership function value of the LMC of the LNG transfer arm as illustrated in Table C1.4.

Table D1.4: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of LNG Transfer Arm (Expert #1)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#1	0.9	0.75	0.8	0.75	Very Low	Very Short	Very Cheap	Very Cheap
#2	0.9	0.25	0.2	0.2	Very Low	Short	Cheap	Cheap
#6	0.1	0.75	0.8	0.1	Low	Very Short	Very Cheap	Cheap
#7	0.1	0.25	0.2	0.1	Low	Short	Cheap	Cheap
#26	0.9	0.25	0.8	0.25	Very Low	Short	Very Cheap	Cheap
#31	0.1	0.25	0.8	0.1	Low	Short	Very Cheap	Cheap
#102	0.9	0.75	0.2	0.2	Very Low	Very Short	Cheap	Cheap
#107	0.1	0.25	0.2	0.1	Low	Very Short	Cheap	Cheap

The Fuzzy Conclusion

The Expert #1 fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.75 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.25 associated with "cheap" linguistics term.

In a similar way, the fuzzy conclusions of Expert #2, #3 and #4 are produced. The Expert #2 fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.65 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.35 associated with "cheap" linguistics term.

The Expert #3 fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.8 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.2 associated with "cheap" linguistics term.

The Expert #4 fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.6 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.4 associated with "cheap" linguistics term.

The fuzzy conclusions of Expert #1, #2, #3 and #4 can be aggregated as follows:

For "very cheap" linguistic term, the $A(\mu_{LMC})$ value of LMC for LNG transfer arm is:

$$(0.75 + 0.65 + 0.8 + 0.6)/4 = 0.7$$

For "cheap" linguistic term, the $A(\mu_{LMC})$ value of LMC for LNG transfer arm is:

$$(0.25 + 0.35 + 0.2 + 0.4)/4 = 0.3$$

Defuzzification of Fuzzy Conclusion

$$\text{Crisp value} = \frac{w_1 x_1 + w_2 x_2}{w_1 + w_2} = \frac{0.7 \times 125000 + 0.3 \times 250000}{0.7 + 0.3} = \$162500$$

Therefore, $C_{SYSTEM(2u)} = \$162500$

Appendix D1.4 - The Results of Expert #2, #3, and #4 Fuzzy Conclusions for the Determination of the Unit Cost of Maintenance of LNG Transfer Arm

Result of Expert #2 Fuzzy Conclusion

Expert #2 estimates the values of LTCC, LMD, and LSPC to be 0.24, 0.27 and 0.22 on scale of [0, 1] as illustrated in Figure D1.13, D1.14 and D1.15 respectively.

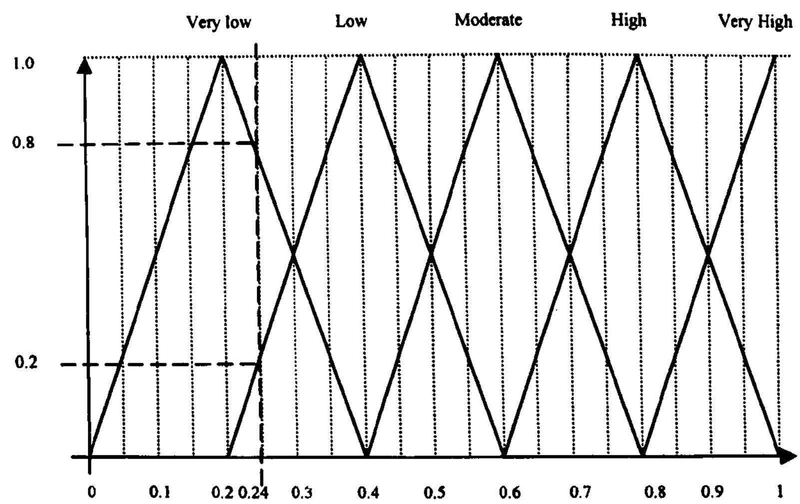

Figure D1.13: Membership Function for LTCC of LNG Transfer Arm (Expert #2)

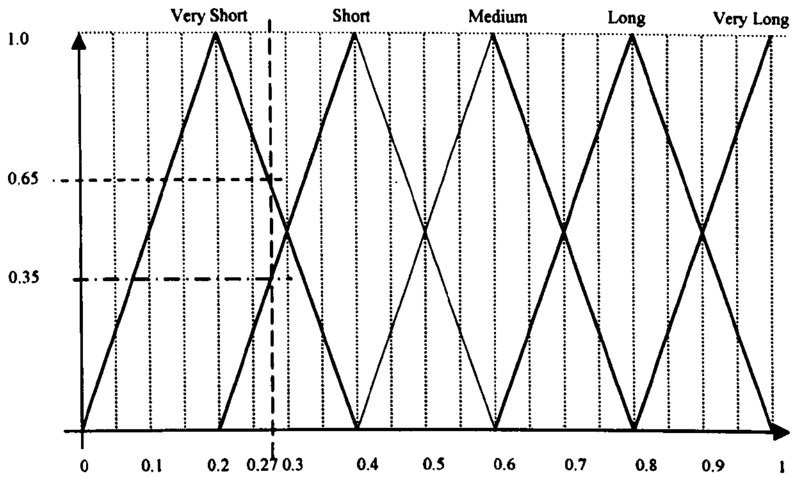

Figure D1.14: Membership Function for LMD of LNG Transfer Arm (Expert #2)

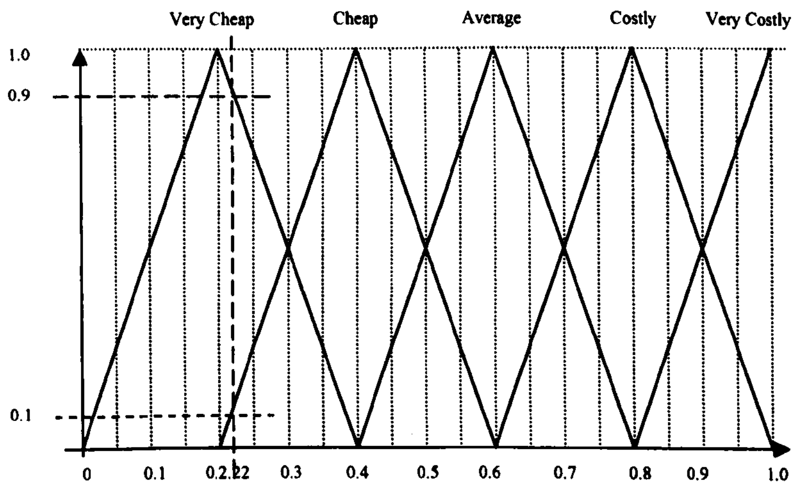

Figure D1.15: Membership Function for LSPC of LNG Transfer Arm (Expert #2)

Table D1.5: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of the LNG Transfer Arm (Expert #2)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#1	0.8	0.65	0.9	0.65	Very Low	Very Short	Very Cheap	Very Cheap
#2	0.8	0.35	0.1	0.1	Very Low	Short	Cheap	Cheap
#6	0.2	0.65	0.9	0.2	Low	Very Short	Very Cheap	Cheap
#7	0.2	0.35	0.1	0.1	Low	Short	Cheap	Cheap

#26	0.8	0.35	0.9	0.35	Very Low	Short	Very Cheap	Cheap
#31	0.2	0.35	0.9	0.2	Low	Short	Very Cheap	Cheap
#102	0.8	0.65	0.1	0.1	Very Low	Very Short	Cheap	Cheap
#107	0.2	0.35	0.1	0.1	Low	Very Short	Cheap	Cheap

Expert #2 Fuzzy Conclusion

The fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.65 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.35 associated with "cheap" linguistics term.

Result of Expert #3 Fuzzy Conclusion

Expert #3 estimates the values of LTCC, LMD, and LSPC to be 0.23, 0.24, and 0.21 on scales of [0, 1] as illustrated in Figure D1.16, D1.17 and D1.18 respectively.

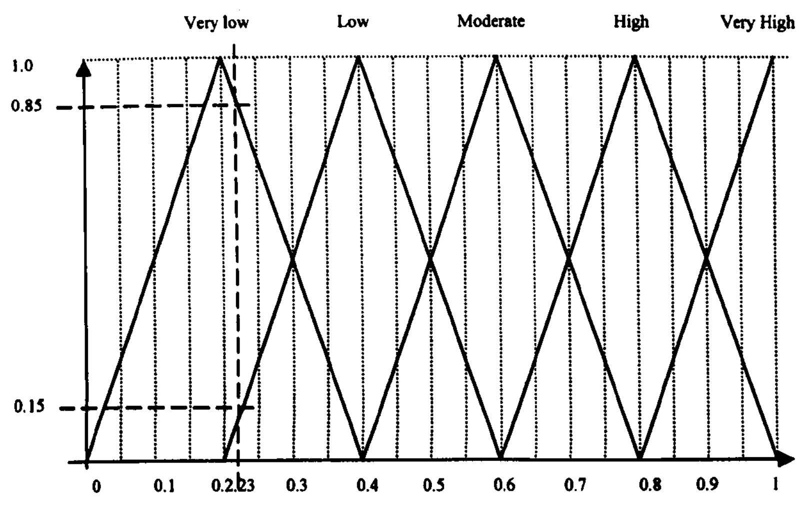

Figure D1.16: Membership Function for LTCC of LNG Transfer Arm (Expert #3)

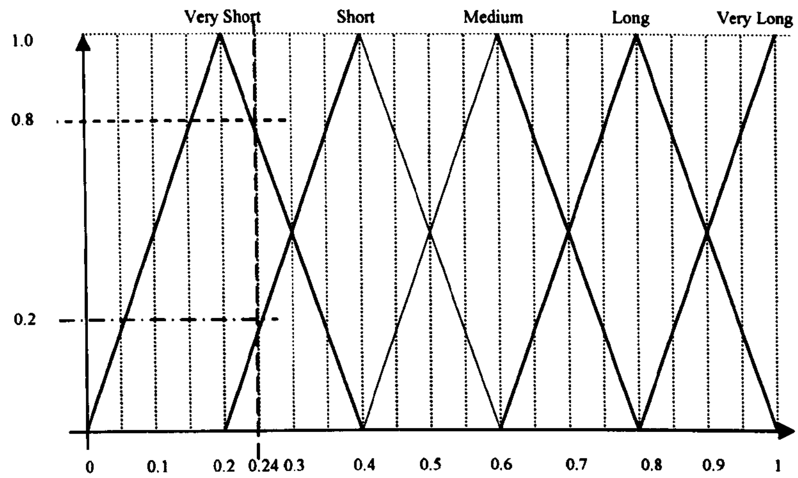

Figure D1.17: Membership Function for LMD of LNG Transfer Arm (Expert #3)

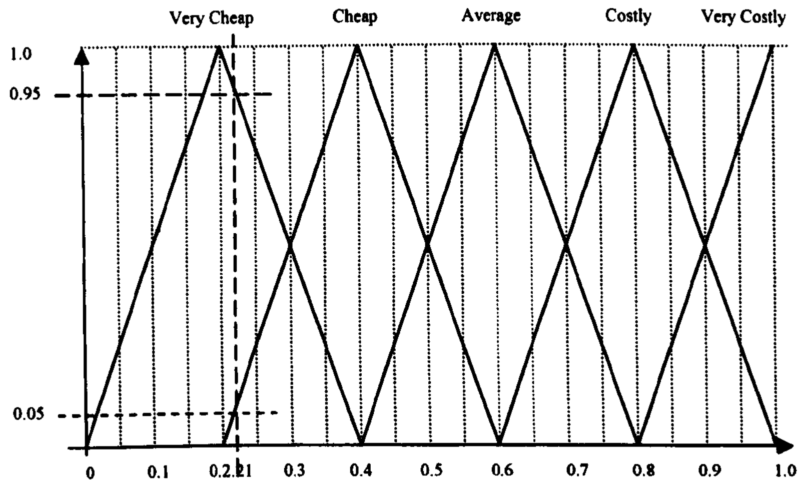

Figure D1.18: Membership Function for LSPC of LNG Transfer Arm (Expert #3)

Table D1.5: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of LNG Transfer Arm (Expert #3)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#1	0.85	0.8	0.95	0.8	Very Low	Very Short	Very Cheap	Very Cheap
#2	0.85	0.2	0.05	0.05	Very Low	Short	Cheap	Cheap
#6	0.15	0.8	0.95	0.15	Low	Very Short	Very Cheap	Cheap
#7	0.15	0.2	0.05	0.15	Low	Short	Cheap	Cheap

#26	0.85	0.2	0.95	0.2	Very Low	Short	Very Cheap	Cheap
#31	0.15	0.2	0.95	0.15	Low	Short	Very Cheap	Cheap
#102	0.85	0.8	0.05	0.05	Very Low	Very Short	Cheap	Cheap
#107	0.15	0.2	0.05	0.05	Low	Very Short	Cheap	Cheap

Expert #3 Fuzzy Conclusion

The fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.8 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.2 associated with "cheap" linguistics term.

Result of Expert #4 Fuzzy Conclusion

Expert #4 estimates the values of LTCC, LMD, and LSPC to be 0.25, 0.28, and 0.26 on scale of [0, 1] as illustrated in Figures D1.19, D1.20 and D1.21 respectively.

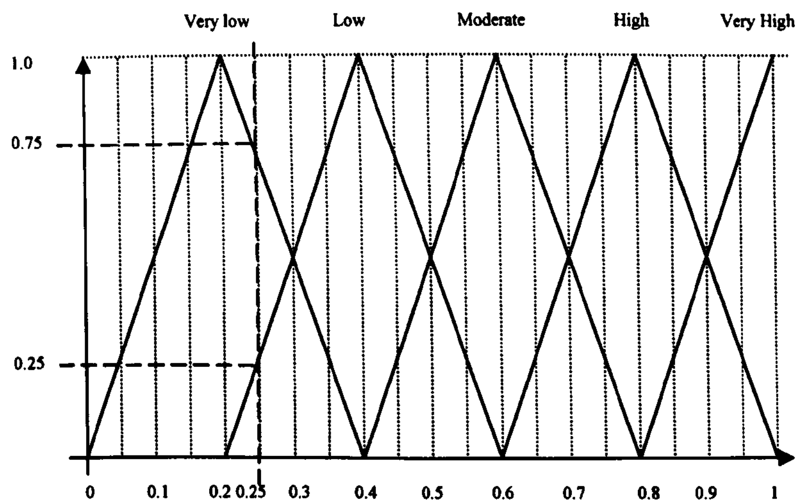

Figure D1.19: Membership Function for LTCC of LNG Transfer Arm (Expert #4)

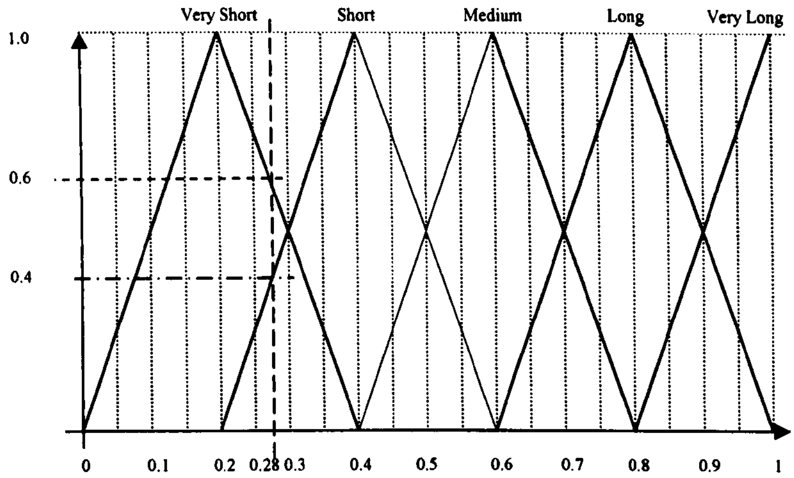

Figure D1.20: Membership Function for LMD of LNG Transfer Arm (Expert #4)

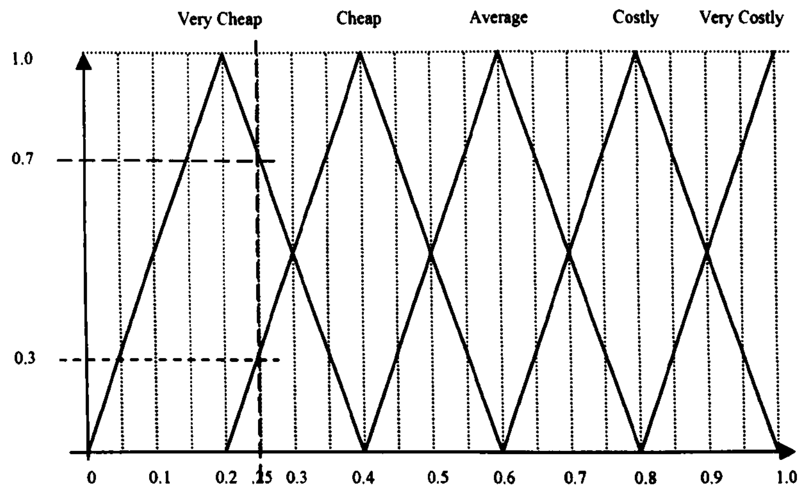

Figure D1.21: Membership Function for LSPC of LNG Transfer Arm (Expert #4)

Table D1.6: Fired Fuzzy Rules for Determination of the Unit Cost of Maintenance of LNG Transfer Arm (Expert #4)

Rules	Fuzzy membership function value (μ)				Linguistic term			
	LTCC	LMD	LSPC	LMC	LTCC	LMD	LSPC	LMC
#1	0.75	0.6	0.7	0.6	Very Low	Very Short	Very Cheap	Very Cheap
#2	0.75	0.4	0.3	0.3	Very Low	Short	Cheap	Cheap
#6	0.25	0.6	0.7	0.25	Low	Very Short	Very Cheap	Cheap
#7	0.25	0.4	0.3	0.25	Low	Short	Cheap	Cheap

#26	0.75	0.4	0.7	0.4	Very Low	Short	Very Cheap	Cheap
#31	0.25	0.4	0.7	0.25	Low	Short	Very Cheap	Cheap
#102	0.75	0.6	0.3	0.3	Very Low	Very Short	Cheap	Cheap
#107	0.25	0.6	0.3	0.25	Low	Very Short	Cheap	Cheap

Expert #4 Fuzzy Conclusion

The fuzzy conclusion includes:

- The LMC has a μ_{LMC} value of 0.6 associated with "very cheap" linguistics term.
- The LMC has a μ_{LMC} value of 0.4 associated with "cheap" linguistics term.

Appendix E - Appendices of Chapter 6

Appendix E1.1 – An Example of Fuzzy Set Manipulation Used in Risk Assessment of LNG Carrier Component

Example 1

Suppose E = (0, 0, 0, 0, 0, 0.75, 1); L = (0, 0, 0, 0, 0, 0.75, 1) and C = (0, 0, 0, 0, 0.75, 1, 0.75) of an LNG carrier component. What is the level of the system safety?

Solution

$$S = C \circ E \times L$$

$$\mu_S = \mu_{C \circ E \times L} = \left(\mu_S^1, \ldots\ldots \mu_S^j \ldots\right)$$

$$\mu_{E \times L} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.75 & 0.75 \\ 0 & 0 & 0 & 0 & 0 & 0.75 & 1 \end{bmatrix}$$

Using max-min method

$$\mu_S^1 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0), \min(0.5,0))$$

$$= \max(0,0,0,0,0,0,0)$$

$$= 0$$

$$\mu_S^2 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0), \min(0.5,0))$$

$$= \max(0,0,0,0,0,0,0)$$

$$= 0$$

$$\mu_S^3 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0), \min(0.5,0))$$
$$= \max(0,0,0,0,0,0,0)$$
$$= 0$$

$$\mu_S^4 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0), \min(0.5,0))$$
$$= \max(0,0,0,0,0,0,0)$$
$$= 0$$

$$\mu_S^5 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0), \min(0.5,0))$$
$$= \max(0,0,0,0,0,0,0)$$
$$= 0$$

$$\mu_S^6 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0.75), \min(0.5,0.75))$$
$$= \max(0,0,0,0,0,0.75,0.5)$$
$$= 0.75$$

$$\mu_S^7 = \max(\min(0,0), \min(0,0), \min(0,0), \min(0,0), \min(0.75,0), \min(1,0.75), \min(0.5,1))$$
$$= \max(0,0,0,0,0,0.75,0.5)$$
$$= 0.75$$

$$\Rightarrow S = (0,\ 0,\ 0,\ 0,\ 0,\ 0.75,\ 0.75)$$
$$\mu_S = (0,\ 0,\ 0,\ 0,\ 0,\ 0.75,\ 0.75)$$

The Best-Fit method is applied as follows:

$$d_{ij}\,(j = 1,2,3,4)$$

$$d_{i1}(S_i,\ poor) = \sqrt{(0-0)^2 + (0-0)^2 + (0-0)^2 + (0-0)^2 + (0-0)^2 + (0.75-0.75)^2 + (0.75-1)^2}$$
$$= 0.25$$

$$d_{i2}(S_i,\ average) = \sqrt{(0-0)^2 + (0-0)^2 + (0-0)^2 + (0-0.5)^2 + (0-1)^2 + (0.75-0.25)^2 + (0.75-0)^2}$$
$$= 1.436$$

$$d_{i3}(S_i,\ good) = \sqrt{(0-0)^2 + (0-0.25)^2 + (0-1)^2 + (0-0.5)^2 + (0-0)^2 + (0.75-0)^2 + (0.75-0)^2}$$

$$= 1.561$$

$$d_{i4}(S_i,\ excellent) = \sqrt{(0-1)^2 + (0-0.75)^2 + (0-0)^2 + (0-0)^2 + (0-0)^2 + (0.75-0)^2 + (0.75-0)^2}$$

$$= 1.639$$

$$\alpha_{ij}(j = 1,2,3,4)$$

$$\alpha_{i1} = \frac{1}{0.25/0.25} = 1$$

$$\alpha_{i2} = 0.25/1.436 = 0.174$$

$$\alpha_{i3} = 0.25/1.561 = 0.160$$

$$\alpha_{i4} = 0.25/1.639 = 0.153$$

$$\beta_{i1} = 1/(1 + 0.174 + 0.160 + 0.153) = 0.672$$

$$\beta_{i2} = 0.174/1.487 = 0.117$$

$$\beta_{i3} = 0.160/1.487 = 0.108$$

$$\beta_{i4} = 0.153/1.487 = 0.103$$

$$\beta_{i1} + \beta_{i2} + \beta_{i3} + \beta_{i4} = 0.672 + 0.117 + 0.108 + 0.103 = 1$$

Mapping $\beta_{i1}, \beta_{i2}, \beta_{i3}$ and β_{i4} back to four safety expression implies:

$$S(S_i) = \{(0.672, "poor"), (0.117, "average"), (0.108, "good"), (0.103, "excellent")\}$$

This means that the safety/risk level of the LNG carrier component belongs to "poor" with a DoB of 67.2%, "average" with a DoB of 11.7%, "good" with a DoB of 10.8% and "excellent" with DoB of 10.3%.

Appendix E1.2 - Failure Modes (Fire and Explosion 2, Fire and Explosion 3, Structural Defect 1, Structural Defect 2, Structural Defect 3, Corrosion Effect 1, Corrosion Effect 2, Corrosion Effect 3, Containment Pressure, Pressure Relief System Failure and Installation Defect) Modelling of "LNG Containment System"

1. Fire and explosion 2

Suppose $L_{12} = \{1/1.0, 2/0.9, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$

$C_{12} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$

$E_{12} = \{1/0, 2/0.1, 3/0.75, 4/0.1, 5/0.75, 6/0, 7/0\}$

$S_{12} = C_{12} \, o \, E_{12} \times L_{12} = \{1/0.1, 2/0.1, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$

$$S(S_{12}) = \{(0.2258, "poor"), (0.2459, "average"), (0.2726, "good"), (0.2557, "excellent")\}$$

where $w_{12} = 0.137$; $Q_{12} = 0.624$

2. Fire and explosion 3

Suppose $L_{13} = \{1/1.0, 2/0.9, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$

$C_{13} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$

$E_{13} = \{1/0, 2/0.1, 3/0.75, 4/1.0, 5/0.75, 6/0, 7/0\}$

$S_{13} = C_{13} \, o \, E_{13} \times L_{13} = \{1/0.1, 2/0.1, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$

$$S(S_{13}) = \{(0.2258, "poor"), (0.2459, "average"), (0.2726, "good"), (0.2557, "excellent")\}$$

where $w_{13} = 0.045$; $Q_{13} = 0.624$

3. Structural defect 1

Suppose $L_{14} = \{1/0.3, 2/1.0, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{14} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1.0\}$$

$$E_{14} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1.0, 6/0.3, 7/0\}$$

$$S_{14} = C_{14}\, o\, E_{14} \times L_{14} = \{1/0.3, 2/0.3, 3/0.3, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{14}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{14} = 0.137$; $Q_{14} = 0.674$

4. Structural defect 2

Suppose $L_{15} = \{1/0.3, 2/1.0, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{15} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1.0\}$$

$$E_{15} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1.0, 6/0.3, 7/0\}$$

$$S_{15} = C_{15}\, o\, E_{15} \times L_{15} = \{1/0.3, 2/0.3, 3/0.3, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{15}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{15} = 0.137$; $Q_{15} = 0.674$

5. Structural defect 3

Suppose $L_{16} = \{1/0.3, 2/1.0, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{16} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1.0\}$$

$$E_{16} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1.0, 6/0.3, 7/0\}$$

$$S_{16} = C_{16}\, o\, E_{16} \times P_{16} = \{1/0.3, 2/0.3, 3/0.3, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{16}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{16} = 0.045$; $Q_{16} = 0.674$

6. Corrosion effect 1

Suppose $L_{17} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1, 6/0.4, 7/0.1\}$

$$C_{17} = \{1/1.0, 2/0.75, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$$

$$E_{17} = \{1/0.25, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$$

$$S_{17} = C_{17} \, o \, E_{17} \times L_{17} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/0.75, 6/0.4, 7/0.1\}$$

$$S(S_{17}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{17} = 0.137$, $Q_{17} = 0.551$

7. Corrosion effect 2

Suppose $L_{18} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1, 6/0.4, 7/0.1\}$

$$C_{18} = \{1/1.0, 2/0.75, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$$

$$E_{18} = \{1/0.25, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$$

$$S_{18} = C_{18} \, o \, E_{18} \times L_{18} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/0.75, 6/0.4, 7/0.1\}$$

$$S(S_{18}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{18} = 0.067$; $Q_{18} = 0.551$

8. Corrosion effect 3

Suppose $L_{19} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1, 6/0.4, 7/0.1\}$

$$C_{19} = \{1/1.0, 2/0.75, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$$

$$E_{19} = \{1/0.25, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$$

$$S_{19} = C_{19} \, o \, E_{19} \times L_{19} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/0.75, 6/0.4, 7/0.1\}$$

$$S(S_{19}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{19} = 0.045$; $Q_{19} = 0.551$

9. Containment pressure

Suppose $L_{110} = \{1/0, 2/0.1, 3/0.7, 4/1.0, 5/0.7, 6/0.1, 7/0\}$

$C_{110} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1.0\}$

$E_{110} = \{1/0, 2/0.1, 3/0.7, 4/1.0, 5/0.7, 6/0.1, 7/0\}$

$S_{110} = C_{110} \, o \, E_{110} \times L_{110} = \{1/0, 2/0.1, 3/0.1, 4/0.1, 5/0.1, 6/0.1, 7/0\}$

$S(S_{110}) = \{(0.2271, \text{"}poor\text{"}), (0.2730, \text{"}average\text{"}), (0.2729, \text{"}good\text{"}), (0.2270, \text{"}excellent\text{"})\}$

where $w_{110} = 0.034$; $Q_{110} = 0.608$

10. Pressure relief system failure

Suppose $L_{111} = \{1/0.2, 2/1.0, 3/0.9, 4/0.2, 5/0, 6/0, 7/0\}$

$C_{111} = \{1/0.1, 2/0.4, 3/1.0, 4/0.8, 5/0.1, 6/0, 7/0\}$

$E_{111} = \{1/0, 2/0.1, 3/0.6, 4/1.0, 5/0.6, 6/0.1, 7/0\}$

$S_{111} = C_{111} \, o \, E_{111} \times L_{111} = \{1/0.2, 2/0.8, 3/0.8, 4/0.2, 5/0, 6/0, 7/0\}$

$S(S_{111}) = \{(0.1649, \text{"}poor\text{"}), (0.1793, \text{"}average\text{"}), (0.4103, \text{"}good\text{"}), (0.2454, \text{"}excellent\text{"})\}$

where $w_{111} = 0.034$; $Q_{111} = 0.670$

11. Installation defect

Suppose $L_{112} = \{1/0, 2/0.1, 3/0.1, 4/0.8, 5/1.0, 6/0.3, 7/0\}$

$C_{112} = \{1/1.0, 2/0.75, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$

$E_{112} = \{1/0.25, 2/1.0, 3/0.75, 4/0.1, 5/0, 6/0, 7/0\}$

$S_{112} = C_{112} \, o \, E_{112} \times L_{112} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/0.75, 6/0.3, 7/0\}$

$S(S_{112}) = \{(0.1379, \text{"}poor\text{"}), (0.5685, \text{"}average\text{"}), (0.1673, \text{"}good\text{"}), (0.1263, \text{"}excellent\text{"})\}$

where $w_{112} = 0.045$; $Q_{112} = 0.552$

Appendix E1.3 - Failure Modes (Manual Release Failure, Auto Release Failure, Fire and Explosion 1, Fire and Explosion 2, Fire and Explosion 3, Application of Ship Motion, Failure of Motion and Controls, Pipe Rupture, Overpressure Material Defect 1, Material Defect 2 and Material Defect 3) Modelling of "LNG Transfer Arm"

1. Manual release failure

Suppose $L_{21} = \{1/0.3, 2/1.0, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$

$$C_{21} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$$

$$E_{21} = \{1/0, 2/0.1, 3/0.75, 4/1.0, 5/0.75, 6/0, 7/0\}$$

$$S_{21} = C_{21}\, o\, E_{21} \times L_{21} = \{1/0.1, 2/0.1, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$$

$$S(S_{21}) = \{(0.2258, "poor"), (0.2459, "average"), (0.2726, "good"), (0.2557, "excellent")\}$$

where $w_{21} = 0.047$; $Q_{21} = 0.6236$

2. Auto release failure

Suppose $L_{22} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/1, 6/0.4, 7/0.1\}$

$$C_{22} = \{1/1.0, 2/0.75, 3/0.1, 4/0, 5/0, 6/0, 7/0\}$$

$$E_{22} = \{1/0.25, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$$

$$S_{22} = C_{22}\, o\, E_{22} \times L_{22} = \{1/0, 2/0, 3/0.1, 4/0.75, 5/0.75, 6/0.4, 7/0.1\}$$

$$S(S_{22}) = \{(0.1544, "poor"), (0.5425, "average"), (0.1719, "good"), (0.1312, "excellent")\}$$

where $w_{22} = 0.047$; $Q_{22} = 0.5511$

3. Fire and explosion 1

Suppose $L_{23} = \{1/0.3, 2/1.0, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{23} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$$

$$E_{23} = \{1/0, 2/0, 3/0.1, 4/0.2, 5/0.75, 6/1.0, 7/0.3\}$$

$$S_{23} = C_{23} \, o \, E_{23} \times L_{23} = \{1/0.3, 2/0.8, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{23}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{23} = 0.143$; $Q_{23} = 0.6744$

4. Fire and explosion 2

Suppose $L_{24} = \{1/0.3, 2/1.0, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{24} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$$

$$E_{24} = \{1/0, 2/0, 3/0.1, 4/0.2, 5/0.75, 6/1.0, 7/0.3\}$$

$$S_{24} = C_{24} \, o \, E_{24} \times L_{24} = \{1/0.3, 2/0.8, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{24}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{24} = 0.047$; $Q_{24} = 0.6744$

5. Fire and explosion 3

Suppose $L_{25} = \{1/0.3, 2/1.0, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{25} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$$

$$E_{25} = \{1/0, 2/0, 3/0.1, 4/0.2, 5/0.75, 6/1.0, 7/0.3\}$$

$$S_{25} = C_{25} \, o \, E_{25} \times L_{25} = \{1/0.3, 2/0.8, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{25}) = \{(0.1695, \text{"}poor\text{"}), (0.1806, \text{"}average\text{"}), (0.3778, \text{"}good\text{"}), (0.2721, \text{"}excellent\text{"})\}$$

where $w_{25} = 0.047$; $Q_{25} = 0.6744$

6. Application of ship motion

Suppose $L_{26} = \{1/0, 2/0.3, 3/0.6, 4/1.0, 5/0.6, 6/0.1, 7/0\}$

$$C_{26} = \{1/0, 2/0.25, 3/1, 4/0.75, 5/0, 6/0, 7/0\}$$

$$E_{26} = \{1/0, 2/0, 3/0.1, 4/0.8, 5/1, 6/0.4, 7/0.1\}$$

$$S_{26} = C_{26} \, o \, E_{26} \times L_{26} = \{1/0, 2/0.3, 3/0.6, 4/0.75, 5/0.6, 6/0.1, 7/0\}$$

$$S(S_{26}) = \{(0.1605, "poor"), (0.3218, "average"), (0.3478, "good"), (0.1699, "excellent")\}$$

where $w_{26} = 0.047$; $Q_{26} = 0.6156$

7. Failure of motion and controls

Suppose $L_{27} = \{1/0.1, 2/0.3, 3/1.0, 4/0.8, 5/0.1, 6/0, 7/0\}$

$$C_{27} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1.0\}$$

$$E_{27} = \{1/0, 2/0, 3/0.1, 4/0.7, 5/1.0, 6/0.3, 7/0\}$$

$$S_{27} = C_{27} \, o \, E_{27} \times L_{27} = \{1/0.1, 2/0.3, 3/0.3, 4/0.3, 5/0.1, 6/0, 7/0\}$$

$$S(S_{27}) = \{(0.1863, "poor"), (0.2414, "average"), (0.3411, "good"), (0.2312, "excellent")\}$$

where $w_{27} = 0.047$; $Q_{27} = 0.6391$

8. Pipe rupture

Suppose $L_{28} = \{1/0, 2/0, 3/0, 4/0.1, 5/0.9, 6/1.0, 7/0.3\}$

$$C_{28} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1.0\}$$

$$E_{28} = \{1/0, 2/0, 3/0.6, 4/1.0, 5/0.6, 6/0, 7/0\}$$

$$S_{28} = C_{28} \, o \, E_{28} \times L_{28} = \{1/0, 2/0, 3/0, 4/0.1, 5/0.1, 6/0.1, 7/0.1\}$$

$$S(S_{28}) = \{(0.2499, "poor"), (0.2729, "average"), (0.2499, "good"), (0.2273, "excellent")\}$$

where $w_{28} = 0.143$; $Q_{28} = 0.5967$

9. Overpressure

Suppose $L_{29} = \{1/0.25, 2/1, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$

$$C_{29} = \{1/0, 2/0, 3/0, 4/0, 5/0.1, 6/0.8, 7/1\}$$

$$E_{29} = \{1/0, 2/0, 3/0, 4/0.1, 5/0.8, 6/1.0, 7/0.3\}$$

$$S_{29} = C_{29} \, o \, E_{29} \times L_{29} = \{1/0.25, 2/0.8, 3/0.8, 4/0.1, 5/0, 6/0, 7/0\}$$

$$S(S_{29}) = \{(0.1699, "poor"), (0.1811, "average"), (0.3859, "good"), (0.2631, "excellent")\}$$

where $w_{29} = 0.071$; $Q_{29} = 0.6717$

10. Material defect 1

Suppose $L_{210} = \{1/0.3, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$

$$C_{210} = \{1/0, 2/0, 3/0, 4/0, 5/0.2, 6/0.9, 7/1\}$$

$$E_{210} = \{1/0, 2/0.1, 3/0.8, 4/1, 5/0.8, 6/0.1, 7/0\}$$

$$S_{210} = C_{210} \, o \, E_{210} \times L_{210} = \{1/0.2, 2/0.2, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$$

$$S(S_{210}) = \{(0.2112, "poor"), (0.2289, "average"), (0.2837, "good"), (0.2762, "excellent")\}$$

where $w_{210} = 0.143$; $Q_{210} = 0.6411$

11. Material defect 2

Suppose $L_{211} = \{1/0.3, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$

$$C_{211} = \{1/0, 2/0, 3/0, 4/0, 5/0.2, 6/0.9, 7/1\}$$

$$E_{211} = \{1/0, 2/0.1, 3/0.8, 4/1, 5/0.8, 6/0.1, 7/0\}$$

$$S_{211} = C_{211} \, o \, E_{211} \times L_{211} = \{1/0.2, 2/0.2, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$$

$$S(S_{211}) = \{(0.2112, "poor"), (0.2289, "average"), (0.2837, "good"), (0.2762, "excellent")\}$$

where $w_{211} == 0.143$; $Q_{211} = 0.6411$

12. Material defect 3

Suppose $L_{212} = \{1/0.3, 2/1, 3/0.75, 4/0, 5/0, 6/0, 7/0\}$

$$C_{212} = \{1/0, 2/0, 3/0, 4/0, 5/0.2, 6/0.9, 7/1\}$$

$$E_{212} = \{1/0, 2/0.1, 3/0.8, 4/1, 5/0.8, 6/0.1, 7/0\}$$

$$S_{212} = C_{212} \, o \, E_{212} \times L_{212} = \{1/0.2, 2/0.2, 3/0.2, 4/0, 5/0, 6/0, 7/0\}$$

$$S(S_{212}) = \{(0.2112, \text{"}poor\text{"}), (0.2289, \text{"}average\text{"}), (0.2837, \text{"}good\text{"}), (0.2762, \text{"}excellent\text{"})\}$$

where $w_{212} = 0.071$; $Q_{212} = 0.6411$

Appendix E1.4 - Cost Benefit Assessment of the LNG Containment System for RCO2A

When RCO2A is used, the safety levels of the failure modes such as corrosion effect 1, corrosion effect 2, corrosion effect 3, containment pressure and installation defect can be improved to "excellent" with DoB of 100%. Their safety levels are synthesised with the ones of other failure modes of the LNG containment system to obtain the safety description as follows:

$$S(S_{2A}) = \{(0.1198, \text{"}poor\text{"}), (0.1298, \text{"}average\text{"}), (0.2096, \text{"}good\text{"}), (0.5408, \text{"}excellent\text{"})\}$$

The safety description is mapped onto the utility space as follows:

$U(S_{2A})$ = {(0.1198, "*slightly preferred*"), (0.1298, "*moderately preferred*"), (0.2096, "*preferred*"), (0.5408, "*greatly preferred*")}

The four experts estimated the cost of RCO2A to be "Moderately high" and vary about "Moderately high". Their cost estimates are expressed as follows:

$$C^1_{2A} = \{1/0, 2/0.2, 3/1, 4/0.6, 5/0.1, 6/0, 7/0\}$$

$$C^2_{2A} = \{1/0, 2/0.1, 3/1.0, 4/0.6, 5/0.2, 6/0.1, 7/0\}$$

$$C^3_{2A} = \{1/0, 2/0.3, 3/1.0, 4/0.4, 5/0, 6/0, 7/0\}$$

$$C^4_{2A} = \{1/0, 2/0.3, 3/1.0, 4/0.4, 5/0, 6/0, 7/0\}$$

The Best-Fit method is applied on the estimated costs, followed by mapping the outcome onto utility spaces to identify the utility descriptions for cost in a similar way to the one of RCO1A. Therefore, the four utility estimates for cost of RCO2A can be expressed as follows:

$U(C_{2A}^{1})$ = {(0.0676, "*slightly preferred*"), (0.0841, "*moderately preferred*"), (0.777, "*preferred*"), (0.0713, "*greatly preferred*")}

$U(C_{2A}^{2})$ = {(0.1026, "*slightly preferred*"), (0.1348, "*moderately preferred*"), (0.6572, "*preferred*"), (0.1054, "*greatly preferred*")}

$U(C_{2A}^{3})$ = {(0.0671, "*slightly preferred*"), (0.083, "*moderately preferred*"), (0.7772, "*preferred*"), (0.0727, "*greatly preferred*")}

$U(C_{2A}^{4})$ = {(0.0671, "*slightly preferred*"), (0.083, "*moderately preferred*"), (0.7772, "*preferred*"), (0.0727, "*greatly preferred*")}

The above four judgements is synthesised and the cost estimate is obtained as follows:

$U(C_{2A})$ = {(0.059, "*slightly preferred*"), (0.0754, "*moderately preferred*"), (0.803, "*preferred*"), (0.0626, "*greatly preferred*")}

$U(C_{2A})$ and $U(S_{2A})$ are synthesised with weights of 0.5 and 0.5 respectively, and the outcome expressed as follows:

$U(U_{2A})$ = {(0.0838, "*slightly preferred*"), (0.0969, "*moderately preferred*"), (0.5322, "*preferred*"), (0.2872, "*greatly preferred*")}

The preference degree for RCO2A can be found in a similar way to the one of RCO1A as:

$$P_{2A} = 0.217 \times 0.0838 + 0.478 \times 0.0969 + 0.739 \times 0.5322 + 1 \times 0.2872$$

$P_{2A} = 0.745$

Appendix E1.5 - Cost Benefit Assessment of the LNG Containment System for RCO3A

Adopting RCO3A, corrosion effect 1, corrosion effect 2, corrosion effect 3, containment pressure, installation defect, fire and explosion 1, fire and explosion 2, and fire and explosion 3 safety levels are improved to "excellent" with DoB of 100%. Their safety levels are combined with the ones of other failure modes of the LNG containment system to obtain the following safety estimate:

$$S(S_{3A}) = \{(0.0458, \text{"}poor\text{"}), (0.049, \text{"}average\text{"}), (0.1062, \text{"}good\text{"}), (0.799 \text{"}excellent\text{"})\}$$

The safety description is mapped onto the utility space as follows:

$U(S_{3A})$ = {(0.0458, "*slightly preferred*"), (0.049, "*moderately preferred*"), (0.1062, "*preferred*"), (0.799, "*greatly preferred*")}

The cost of RCO3A is considered to be "Very high" and varying about "Very high". The four experts estimated the cost as follows:

C_{3A}^{1} = {1/0, 2/0, 3/0, 4/0.4, 5/1.0, 6/0.3, 7/0}

C_{3A}^{2} = {1/0, 2/0, 3/0, 4/0.5, 5/1.0, 6/0.2, 7/0}

C_{3A}^{3} = {1/0, 2/0, 3/0, 4/0.4, 5/1.0, 6/0.2, 7/0}

C_{3A}^{4} = {1/0, 2/0, 3/0, 4/0.5, 5/1.0, 6/0.25, 7/0}

The Best-Fit method is applied to the estimated costs and the outcome is mapped onto utility space in a similar way to the one of RCO1A. The utility descriptions of cost for RCO3A are expressed as follows:

$U(C^1_{3A})$ = {(0.0598, "*slightly preferred*"), (0.8228, "*moderately preferred*"), (0.0626, "*preferred*"), (0.0548, "*greatly preferred*")}

$U(C^2_{3A})$ = {(0.0286, "*slightly preferred*"), (0.9129, "*moderately preferred*"), (0.0315, "*preferred*"), (0.027, "*greatly preferred*")}

$U(C^3_{3A})$ = {(0.0577, "*slightly preferred*"), (0.8263, "*moderately preferred*"), (0.0628, "*preferred*"), (0.0532, "*greatly preferred*")}

$U(C^4_{3A})$ = {(0, "*slightly preferred*"), (1, "*moderately preferred*"), (0, "*preferred*"), (0, "*greatly preferred*")}

The above four judgements are synthesised using the IDS to obtain the following:

$U(C_{3A})$ = {(0.0250, "*slightly preferred*"), (0.9249, "*moderately preferred*"), (0.0269, "*preferred*"), (0.0232, "*greatly preferred*")}

$U(C_{3A})$ and $U(S_{3A})$ are synthesised with weights of 0.5 and 0.5 respectively, to obtain utility estimates expressed below:

$U(U_{3A})$ = {(0.0348, "*slightly preferred*"), (0.4929, "*moderately preferred*"), (0.0657, "*preferred*"), (0.4066, "*greatly preferred*")}

The preference degree value for RCO3A can be found in a similar way to the one of RCO1A as:

$$P_{3A} = 0.217 \times 0.0348 + 0.478 \times 0.4929 + 0.739 \times 0.0657 + 1 \times 0.4066$$

$$P_{3A} = 0.6983$$

Appendix E1.6 - Cost Benefit Assessment of the LNG Transfer Arm for RCO1B

The cost for no particular failure mode targeted for elimination using RCO1B is considered to be "Very low". This implies that Experts #1, #2, #3 and #4 estimated the cost as follows:

C_{1B}^{1} = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

C_{1B}^{2} = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

C_{1B}^{3} = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

C_{1B}^{4} = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

The Best-Fit method is applied to C_{1B}^{1}, C_{1B}^{2}, C_{1B}^{3} and C_{1B}^{4}, and the outcomes are mapped onto utility spaces as follows:

$U(C_{1B}^{1})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (0, "*preferred*"), (1, "*greatly preferred*")}

$U(C_{1B}^{2})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (0, "*preferred*"), (1, "*greatly preferred*")}

$U(C_{1B}^{3})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (0, "*preferred*"), (1, "*greatly preferred*")}

$U(C_{1B}^{4})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (0, "*preferred*"), (1, "*greatly preferred*")}

The above four judgements are synthesised using IDS to obtain the cost estimate as follows:

$U(C_{1B})$ = {(0, "*slightly preferred*"), (0, "*moderately preferred*"), (0, "*preferred*"), (1, "*greatly preferred*")}

Suppose $U(C_{1B})$ and $U(S_{1B})$ are synthesised with safety and cost weights of 0.5 and 0.5 respectively. The following utility description can be obtained:

$U(U_{1B})$ = {(0.0858, "*slightly preferred*"), (0.1057, "*moderately preferred*"), (0.1404, "*preferred*"), (0.6681, "*greatly preferred*")}

The preference degree value for RCO1B can be known using the expression below:

$$P_{1B} = 0.217 \times 0.0858 + 0.478 \times 0.1057 + 0.739 \times 0.1404 + 1 \times 0.6681$$

$$P_{1B} = 0.8410$$

Appendix E1.7 - Cost Benefit Assessment of the LNG Transfer Arm for RCO2B

Fire and explosion 1, fire and explosion 2, and fire and explosion 3 are eliminated using RCO2B. The IDS is used to synthesise their new safety/risk levels with the ones of manual release failure, auto release failure, application of ship motion, failure of motion and controls, pipe rupture, overpressure, material defect 1, material defect 2 and material defect 3 to obtain the safety estimates as follows:

$$S(S_{2B}) = \{(0.1488, \text{"}poor\text{"}), (0.1884, \text{"}average\text{"}), (0.2107, \text{"}good\text{"}), (0.4521, \text{"}excellent\text{"})\}$$

The safety description is mapped onto the utility space as follows:

$U(S_{2B})$ = {(0.1488, "*slightly preferred*"), (0.1884, "*moderately preferred*"), (0.2107, "*preferred*"), (0.4521, "*greatly preferred*")}

The cost for elimination of fire and explosion 1, fire and explosion 2, and fire and explosion 3 are considered to be "Moderately high" and varying about "Moderately high". The Experts #1, #2, #3 and #4 estimated the cost as follows:

C^1_{2B} = {1/1, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0}

C^2_{2B} = {1/0, 2/0.1, 3/1, 4/0.6, 5/0.2, 6/0.1, 7/0}

C^3_{2B} = {1/0, 2/0.3, 3/1, 4/0.4, 5/0, 6/0, 7/0}

C^4_{2B} = {1/0, 2/0.3, 3/1, 4/0.4, 5/0, 6/0, 7/0}

The Best-Fit method is applied to C^1_{2B}, C^2_{2B}, C^3_{2B} and C^4_{2B}, followed by mapping the outcomes onto the utility spaces. The utility descriptions of cost by Experts #1, #2, #3 and #4 are expressed as follows:

$U(C^1_{2B})$ = {(0.0676, "*slightly preferred*"), (0.0841, "*moderately preferred*"), (0.777, "*preferred*"), (0.0712, "*greatly preferred*")}

$U(C^2_{2B})$ = {(0.1026, "*slightly preferred*"), (0.1348, "*moderately preferred*"), (0.6572, "*preferred*"), (0.1053, "*greatly preferred*")}

$U(C^3_{2B})$ = {(0.0671, "*slightly preferred*"), (0.083, "*moderately preferred*"), (0.7772, "*preferred*"), (0.0727, "*greatly preferred*")}

$U(C^4_{2B})$ = {(0.0671, "*slightly preferred*"), (0.083, "*moderately preferred*"), (0.7772, "*preferred*"), (0.0727, "*greatly preferred*")}

The above four judgements are synthesised to obtain the following:

$U(C_{2B})$ = {(0.0590, "*slightly preferred*"), (0.0754, "*moderately preferred*"), (0.8030, "*preferred*"), (0.0626, "*greatly preferred*")}

$U(C_{2B})$ and $U(S_{2B})$ are synthesised with weights of 0.5 and 0.5 respectively, to obtain the following utility estimates:

$U(U_{2B})$ = {(0.0976, "*slightly preferred*"), (0.1252, "*moderately preferred*"), (0.5327, "*preferred*"), (0.2445, "*greatly preferred*")}

The preference degree value for RCO2B can be obtained as follows:

$$P_{2B} = 0.217 \times 0.0976 + 0.478 \times 0.1252 + 0.739 \times 0.5327 + 1 \times 0.2445$$

$$P_{2B} = 0.7192$$

Appendix E1.8 - Cost Benefit Assessment of the LNG Transfer Arm for RCO3B

Fire and explosion 1, fire and explosion 2, fire and explosion 3, material defect 1, material defect 2 and material defect 3 are eliminated using RCO3B. The IDS is used to synthesise their new safety/risk levels with the ones of manual release failure, auto release failure, application of ship motion, failure of motion and controls, pipe rupture and overpressure to obtain the safety estimate as follows:

$$S(S_{3B}) = \{(0.0652, \text{"}poor\text{"}), (0.0921, \text{"}average\text{"}), (0.093, \text{"}good\text{"}), (0.7497, \text{"}excellent\text{"})\}$$

The safety description is mapped onto the utility space as follows:

$U(S_{3B})$ = {(0.0652, "*slightly preferred*"), (0.0921, "*moderately preferred*"), (0.093, "*preferred*"), (0.7497, "*greatly preferred*")}

The cost for RCO3B is considered to be "Very high" and vary about "Very high". The four Experts estimated the cost as follows:

$$C_{3B}^{1} = \{1/0, 2/0, 3/1, 4/0.4, 5/1, 6/0.3, 7/0\}$$

$$C_{3B}^{2} = \{1/0, 2/0, 3/0, 4/0.5, 5/1, 6/0.2, 7/0\}$$

$$C_{3B}^{3} = \{1/0, 2/0, 3/0, 4/0.4, 5/1, 6/0.2, 7/0\}$$

C^4_{3B} = {1/0, 2/0, 3/0, 4/0.5, 5/1, 6/0.25, 7/0}

The Best-Fit method is applied to C^1_{3B}, C^2_{3B}, C^3_{3B}, and C^4_{3B}, followed by mapping the outcomes onto the utility spaces. The utility descriptions of cost are expressed as follows:

$U(C^1_{3B})$ = {(0.0598, "*slightly preferred*"), (0.8228, "*moderately preferred*"), (0.0626, "*preferred*"), (0.0548, "*greatly preferred*")}

$U(C^2_{3B})$ = {(0.0286, "*slightly preferred*"), (0.9129, "*moderately preferred*"), (0.0315, "*preferred*"), (0.027, "*greatly preferred*")}

$U(C^3_{3B})$ = {(0.0577, "*slightly preferred*"), (0.8263, "*moderately preferred*"), (0.0628, "*preferred*"), (0.0532, "*greatly preferred*")}

$U(C^4_{3B})$ = {(0, "*slightly preferred*"), (1, "*moderately preferred*"), (0, "*preferred*"), (0, "*greatly preferred*")}

The above four judgements are synthesised to obtain the following:

$U(C_{3B})$ = {(0.0250, "*slightly preferred*"), (0.9249, "*moderately preferred*"), (0.0269, "*preferred*"), (0.0232, "*greatly preferred*")}

$U(C_{3B})$ and $U(S_{3B})$ are synthesised with weights of 0.5 and 0.5 respectively, to obtain the following utility description:

$U(U_{3B})$ = {(0.0436, "*slightly preferred*"), (0.5232, "*moderately preferred*"), (0.0581, "*preferred*"), (0.3751, "*greatly preferred*")}

The preference degree value for RCO3B can be obtained as follows:

$P_{3B} = 0.217 \times 0.0436 + 0.478 \times 0.5232 + 0.739 \times 0.0581 + 1 \times 0.3751$

$P_{3B} = 0.6776$