Onshore Cross Country Pipelines Risk Assessment and Decision Making Under Uncertainty

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Abstract

Onshore cross-country pipelines are a critical component of refined product transportation in the oil and gas industry. The integrity of those pipelines is key to maintaining supply security, protecting the environment and human life. However, due to incessant pipeline damages and resultant consequences of fires, explosion and environmental pollution because of third-party events in Nigeria, stakeholders are looking at solutions to reduce the human, environmental and the financial losses.

The main objective of this research is to develop risk-based models for identifying and assessing the oil and gas pipelines failures, including risk reduction decision-making framework and cost-benefit estimates. One of the major challenges of carrying out a pipeline risk assessment in some regions is the lack of reliable and objective data for data-driven analysis. The models developed in this thesis addressed this shortcoming and allowed the subjective data to be incorporated into the analysis.

Hazards identification and ranking of the failure modes have been carried out using a modified FMEA based Fuzzy Rules Base (FRB) and Grey Relations Theory (GRT) to accommodate the uncertainty in terms of inadequate data. The results of modified approach serve as an input to developing the failure likelihood and this involves a Bayesian Network (BN) model of the identified failure mode. The BN model has been developed using Hugin software. The results of the BN feeds into the Evidential Reasoning (ER) model to aid risk management decision-making. Also, cost benefit estimates have been carried out to assess the cost benefit of implementing any risk reduction options.

All the objectives set out in the thesis have been achieved. The research has contributed to the stated challenges by identifying the parameters for high failure incidences and develop various models and assess contributing failure factors and the risk control options to reducing the likelihood of the failure including cost benefit estimates.

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Table of Contents

List of Figures

List of Tables

Abbreviations

AGO	Automotive Gas & Oils
AHP	Analytical Hierarchy Process
ANN	Artificial Neural Networks-based
ANP	Analytic Network Process
API	Applicable Programmer's Interface
ATK	Aviation Turbine Kerosene
AV	Average
BBC	British Broadcasting Corporation
BD	Burial Depth
BN	Bayesian Network
BP	British Petroleum
BSI	British Standards Institution
CA	Catastrophic
CBA	Cost Benefit Analysis
CCTV	Close Circuit Television
CF	Construction Factor
CI	Consistency Index
CONCAWE	Conservation of Clean Air and Water in Europe
CPD	Conditional (or Node) Probability Distribution
CPT	Conditional Probability Table
CR	Consistency Ratio
CSX	Cost of Saving Lives
DAG	Directed Acyclic Graph
DF	Design Factor
DFMEA	Development Failure Mode and Effects Analysis
DNV	Der Norske Veritas
DOT	US Department of Transportation
DPK	Dual Purpose Kerosene
DPR	Department of Petroleum Resources
EC	External Corrosion
EGIG	European Gas Pipeline Incident Data Group
ELECTRE	Elimination and Choice Expressing Reality
ER	Evidential Reasoning
EU	European Union
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FPSO	Floating Production Storage and Offloading
FRB	Fuzzy Rule Base
FRN	Federal Republic of Nigeria
FST	Fuzzy Set Theory

GNI	Gross National Income
GRT	Grey Relation Theory
GUI	Graphical User Interface
HAZOP	Hazard and Operability Study
HI	High
HL	Highly Likely
HSE	Health and Safety Executive
IC	Internal Corrosion
ID	Identification
IMO	International Maritime Organisation
IOPCF	International Oil Pollution Compensation Fund
JPD	Joint Probability Distribution
LDS	Leak Detection System
LFN	Laws of the Federation of Nigeria
LI	Likely
LO	Low
LQI	Life-Quality Index
MA	Marginal
MCDM	Multiple Criteria Decision Methods
MD	Material Defect
MIL	Military
MO	Moderate
MOLP	Multi-Objective Linear Problems
MQ	Material Quality
NNPC	Nigerian National Petroleum Corporation
NOSDRA	National Oil Spill Detection and Response Agency
OPOL	Offshore Pollution Liability Association
OSLTF	US Oil Spill Liability Trust Fund
PE	Public Education
PFMEA	Process Failure Mode and Effects Analysis
PHMSA	Pipeline and Hazardous Materials Safety Administration
PMS	Premium Motor Spirit
PPMC	Pipelines and Products Marketing Company
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PV	Present Value
QA	Quality Assurance
QRA	Quantitative Risk Assessment
RCO	Risk Control Options
RI	Random Index
RL	Reasonably Likely
ROW	Right of Way
RPN	Risk Priority Number

SCADA	Supervisory Control and Data Acquisition
SCC	Stress Corrosion Cracking
SF	Security Forces
SFMEA	System Failure Mode and Effects Analysis
SPM	Single Point Mooring
SR	Spill Response
UKOPA	United Kingdom Onshore Pipeline Operators' Association
USA	United States of America
USDT	US Department of Transportation
VSL	Value of Statistical Life
WTP	Willingness to Pay

Chapter 1. Introduction

1.1 Research Background

Pipelines have been the cost effective way of products transportation in large volumes, including oil and gas (BP, 2009; Dawotola *et al.*, 2011). In Nigeria, this has resulted in an exponential increase in the total length of the laid downstream pipeline for cross country products distribution, from 1978 to 1995, of more than 5,000km (Ambisisi, 2016).

Pipelines are designed to contain the products they carry and convey them from one point to the other without loss of integrity of the pipeline. However even with the best of engineering designs, sometimes failure do occur. The risk assessment often relies on the records and lessons learnt from such failure to help in the design and construction improvements which reduce future failures. Pipeline managers are experiencing a challenging environment on failures, ranging from material quality, in-service defects and the need to extend the life of ageing infrastructure. A stricter safety regulatory regime in most countries is being enforced due to the much wider impact of pipeline failure and the recent escalation of deliberate sabotage (Hopkins, 2008). Although material quality was a concern in developed countries some 30 years ago, this is still a concern in developing countries where cost often results in procuring and installing pipes of low quality that would not have been allowed in developed countries. Defects detection technology has advanced and is routinely employed in developed economies. However, such sophisticated technologies are not usually utilised in developing countries, again due to cost concerns. These, together with the ageing of the infrastructure and the recent criminal sabotage, provide a conducive environment for catastrophic failures.

Risk assessment, including Quantitative Risk Assessment (QRA), is regularly used for safety evaluation and land use planning (Haswell *et al.*, 2009; Hopkins *et al.*, 2009; Pasman & Reniers, 2014) or when bringing pipelines back to service. The same risk assessment principle applies to the wider oil and gas industry and other high-risk industries such as nuclear (Apostolakis, 1981). However, the practice has never been uniform, resulting in different and often conflicting conclusions, depending on the data available, practitioner experience and the company practice (Muhlbauer, 2004). Regulators and trade bodies in Europe, America and other parts of the world with historical data, aware of the subjectivity of the practice, provide guidance to ensure a uniform approach to the process (Haswell *et al.*, 2009; Goodfellow *et al.*, 2014). However, this has resulted in industrial and academic researchers adopting a historical data based QRA approach, as it is likely to be less scrutinised, to satisfy the authorities having jurisdiction. This approach, though widely accepted, has the unintended consequence of limiting the value that can be gained from the process and reduces the research effort that had been ongoing to improve the QRA process. It also results in a poor safety assessment for the geographies with either limited historical data or unreliable data (Eze, 2017).

1.2 Problem Statement and Research Motivation

Even though pipelines are the safest and most cost-effective mode of transporting oil and gas for long distances (Furchtgoth-Roth, 2013), when a failure occurs, the resulting consequence in terms of safety, economic loss and environmental pollution could be devastating. Available data from literature (Onuoha, 2009; Rowland, 2010; Ekwo, 2011; Fadeyibi *et al.*, 2011; Omodanisi *et al.*, 2014) indicates that since the late 1980s thousands of fatalities, economic losses and environmental damage have occurred, linked to pipeline incidents in Nigeria. Incidents like Jesse in 1998, with more than 1,000 fatalities and Abule Egba in 2006, with circa 500 fatalities are among the worst globally. The direct product loss for the cross-country pipeline system in the country run into hundreds of million dollars per annum. One pipeline system alone – system 2B - is estimated to be losing about fifty million dollars per annum due to direct product loss (Ekwo, 2011). When payments due to compensation, fines, and environmental clean-up are included, the annual loss to the economy is significantly higher.

The failure of oil and gas pipelines in developed economies have been extensively studied and addressed. The data required for analysing and assessing the risks is available and reliable, e.g., EGIG (2018) and Concawe (2019) in Europe. This data-driven assessment results in a consistent downward trend in terms of pipeline failure since the 1970s in Europe (EGIG, 2015; Haswell & McConnell, 2015; Cech *et al.*, 2018) and a flat-lining of the number of failures in the US in the past 20 years (PHMSA, 2017).

In Nigeria and other developing countries, the absence of reliable failure data and effective maintenance and management procedure, amongst other factors, make it difficult to conduct an effective assessment of pipeline risks. Such absence also makes it difficult to put in place measures to reduce, control or mitigate the identified risks. This lack of data makes the application of appropriate risk assessment tools ineffective and results in a high pipeline loss incidents with devastating consequences. It could be argued that this has led to the gradual abandonment of the pipeline system for other modes of refined product transport in the country. This further exacerbates the situation, as the pipelines fall into further disrepair. Additionally, in the last decade, World Bank (2017) data indicates that Nigeria's population has increased by more than 60 million. The population increase is shown to be directly connected with the uncontrolled development around the pipeline corridors, leading to increased pipeline accident rate.

The need to bring back the onshore cross-country pipelines in Nigeria to full operation has become the main preoccupation of the stakeholders in the country (Okafor, 2016). The stakeholders also want to reduce the frequency and the consequence of the pipeline failure and extend the asset's life. These stakeholder desires inform the motivation of this research.

The uncertainties in carrying out risk assessments due to lack of data or unreliable data would render the typical frequentist risk assessment tools unsuitable for assessing pipelines risks in Nigeria and similar countries. Typically, where relative frequencies for the identified hazards are limited or uncertain, then subjectivist and other non-probabilistic uncertainty analysis approaches seem more appropriate. Such approaches include Bayesian Theory, Fuzzy Set Theory, Evidence Theory and Plausibility Theory (Aven & Zio, 2011; Aven *et al.*, 2014).

This study aims to develop novel models of pipeline failure assessment for the cross-country petroleum products pipelines under uncertainty. The models would help the decision makers in identifying the hazards and analyse the associated risks, including the cost-benefits for implementing risk reduction measures. The results of this research will help stakeholders in the pipeline industry in their decision-making process for risk management, integrity assessment, inspection and maintenance plans.

To address the above challenges, one overarching research question has been identified, which is: *What are the factors responsible for products pipelines failure and what are the best methodologies to minimise the risk?*

1.3 Aims and Objectives

The overall aim of the research is to develop methodologies and models which provide decision support tools that address onshore oil and gas pipeline failure in Nigeria. The research will develop a framework that decision makers can utilise to assess pipeline failure likelihood for effective risk management. The new methodologies in the research has been developed from the baseline models including Fuzzy Set Theory and Grey Relation Theory, Bayesian Network and Evidential Reasoning.

The objectives of the research are to:

i. Identify the drivers for onshore cross-country pipeline failures in developing countries and particularly in Nigeria.

ii. Develop suitable methodologies that identify, screen and assess the failure modes of the pipelines and the potential consequence resulting from such failure.
iii. Develop a model that assesses the likelihood of the pipeline failures appropriate for countries where data is limited or unreliable.
iv. Provide a risk-based decision-making framework that helps reduce the pipeline's exposure to the identified risks.
v. Provide a cost-benefit model for optimum decision-making.

1.4 Scope

This thesis is based on the research problem that is limited to particular challenges identified with Nigeria's onshore cross-country products pipeline and other similar systems where data is often not available or not reliable and also where strict adherence to risk management practices are not in line with the global best industry practice.

Therefore, it is important to identify the scope of the work in relation to the wider area of pipeline risk management.

- The research is aimed at the countries where lack of failure data or uncertainty in the available data makes data-based risk assessment unreliable or not possible.
- Usually, the risk assessment process involves failure consequence analysis, in addition to the failure likelihood analysis, and these inform the risk-based decision making. However, the scope of this research excludes the detailed failure consequence assessment, as the main aim of the research is to model uncertainty treatment in the risk assessment due to lack of or unreliability of data. The failure likelihood and the decision-making models suffer more from these uncertainty treatments in this research.
- The modified Failure Mode and Effects Analysis (FMEA) based hazards identification model uses the generic failure mode; however, the ranking

relies on site-specific features and the experience of the participating field operatives and domain experts. The results would be influenced by those individual's judgment.

- The failure likelihood model developed is underpinned by the peculiar integrity management approach used by the local pipeline operator as elicited from the operator's personnel and documentation reviewed. The model, therefore, may not be directly portable to other scenarios or systems without a full understanding of the system's approach to pipeline safety and integrity management. .

1.5 Structure of the Thesis

The results of the research in this thesis, developed to include the application of the novel approaches to risk-based pipeline failure assessment under uncertainty, is presented using methodologies and case studies over a number of chapters and covering products pipeline systems in Nigeria. Figure 1-1 shows the outline of the thesis, highlighting the main chapters that encompass the thesis including the risk assessment models and the case studies.

Chapter 1 presents the introduction to the thesis and provides the general background motivation, aims and objectives, scope and limitation and the thesis structure.

In Chapter 2, the review of the related literature to support the research has been carried out. The chapter underpins the research in that it reviewed the body of knowledge to understand the research development in the field to date and ensures that this work builds upon it. Appropriately carried out literature review ensures the work presented in the thesis is original, novel and contributes to the body of knowledge in the area investigated. The literature survey reviewed includes works on pipeline failures in general and cross-country onshore products pipelines in particular. It also reviewed the developments in the area of risk assessment and decision-making techniques with an emphasis on assessment and decision making under uncertainty. The uncertainty could be due to lack of or inadequate data and knowledge as found in Nigeria and similar countries. Finally, the review also assesses the current knowledge on challenges and difficulties of managing pipeline systems risks in Nigeria and similar developing countries.

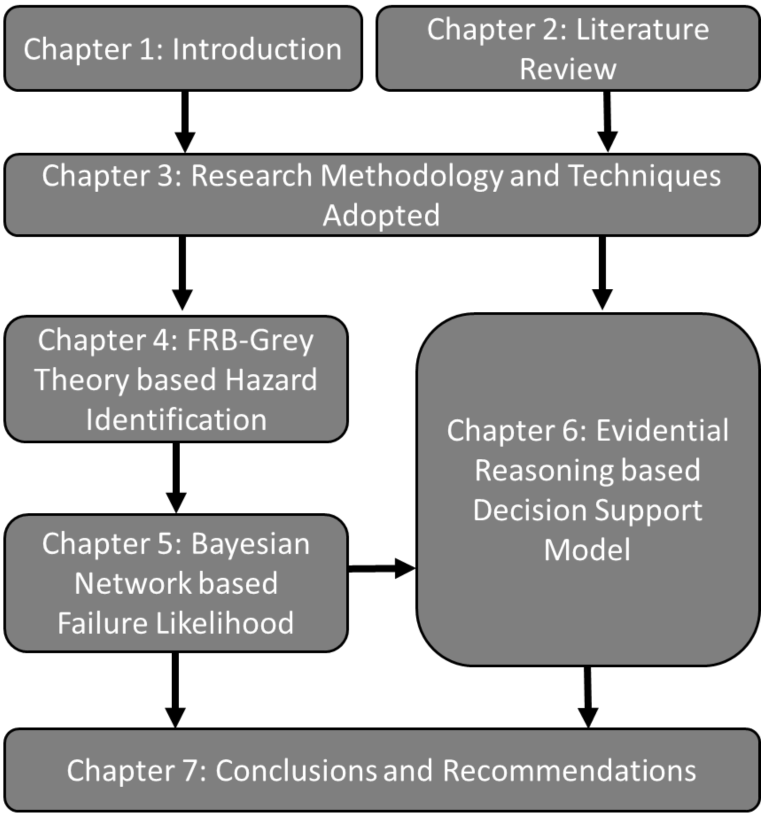


Figure 1-1: Thesis Outline

The general synopsis of the research methodology used throughout the thesis is detailed in Chapter 3. This includes the methodologies for identifying the hazards related to pipeline operation and determination of the failure likelihood using the subjectivist approach. The chapter also assesses methodology for risk management decision-making including the consideration of the cost benefits estimation of the pipeline failure in terms of life safety, economic loss and environmental damages.

Chapter 4 focuses on the development of the initial step of the risk assessment - hazards identification. There are multiple techniques for hazards identification; however, the majority of the mainstream techniques are unsuitable for this work due to the uncertainty associated with the lack of, or inadequate data. Therefore, a new technique which modifies the traditional FMEA has been adopted. The technique, which utilises Fuzzy Set Theory (or Fuzzy Rule Base) and Grey Relations Theory, ensures the weaknesses that FMEA has with respect to Nigeria's peculiar challenges are addressed.

The failure likelihood development is carried out in Chapter 5. The hazard identification carried out in the previous chapter has served as the input for this chapter. The failure likelihood development utilises the hazard identified with the highest score from Chapter 4. The BN model is then used to highlight the contributing failure factors to the identified hazard and their interrelationships. The model, therefore, provides the managers with dynamic information on how to prevent undesired outcomes and could be used for safety management plans.

In Chapter 6, an Evidential Reasoning (ER) algorithm has been employed to extend the previous chapter's works by identifying the predominant failure factor that gives rise to the hazard with the highest score. The predominant failure factor has been identified as theft/third-party intentional damage. The ER has been used with the help of experts, existing data and the literature to develop the evaluation matrix and generate weights and belief degrees for the assessment. The assessment aggregates the weights and the belief degrees to determine the probability masses and finally, the ER ranking of the interventions. This chapter also assesses the cost-benefit of the potential interventions against the failure costs which includes life safety, direct economic cost and the environmental restoration cost.

Error! Reference source not found. provides an overview of the relationship b etween the three previous chapters and how they all come together into the robust risk assessment framework in support of intervention decision making and resources allocation.

The overview of the conclusions of the results obtained in Chapter 4, Chapter 5 and Chapter 6 are detailed in Chapter 7, including the results' applicability to the identified research problem. The chapter includes an overview of the techniques and models developed in the work, outlining the conclusions derived from the results and provides an overview of the limitation of the work and recommendations for further research.

1.6 Research Design and Ethics Consideration

For all the technical chapters, experts' elicitation has been undertaken, as incorporation of experts' experience is key to the research work. The elicitation takes the form of:

1. Series of questionnaires that have been developed and sent out to individual experts to fill in and return to the researcher, who then aggregate the results and incorporate into the model.
2. Virtual workshop and brainstorming sessions, where the experts come together and have a focal discussion on the particular research issue and provide their expertise for incorporation into the research
3. Interviews, where individual experts were interviewed and their response forms part of the research.

In all of the options explored in this work, appropriate information about the issue being discussed is provided to the experts including, for example, the pipeline and fluid details (see Appendix E), the existing safety and instrumentation system in place and the operations and management policy.

The number of experts that participated in the session varies from three in chapter 4 and five in chapters 5 and 6. More experts participation could have been better however the challenge of getting the experts to participate due to their busy schedule and the limited research time has limit the number of participants. For example, first questionnaire took more than six months to be returned and only three have been found to be valid, two others had to be disqualified. On the subsequent chapters the questionnaire design and the type of questioning has to be greatly revamped to simplify it and thus increase the chances of participation by the experts.

The accuracy and reliability of the results depend on the quality and the reliability of the experts input and the weighting mechanism. The expertise and the competence of the experts used in this work ensure the results are reliable and consistent. However, in the future, it may be that using less experienced experts may introduce some bias, with a lack of consistency with the acquired data. Under such scenario it is recommended that a greater number of experts should be used, in addition to using techniques, such as Delphi method, to reduce the potential bias and subjectivity of the experts.

Although the research elicitation does not involve vulnerable people or ethical approval, the researcher has undertaken a certified training in research ethics, as part of the minimum research requirements at the University to ensure that the research has been carried out abiding by the appropriate ethical standards.

The experts that participated in the study are diverse both in terms of location (Nigeria, UK and Middle East) and expertise (outlined in the relevant chapters).

Chapter 2. Literature Review

Overview

This chapter analyses the up-to-date literature which has influenced this study. It reviews the background of cross-country pipelines including past and current trends in terms of reported incidents and general operational statistics as they affect integrity management. The background information and work carried out by previous researchers with respect to the risk assessment steps, such as the identification of failure sources, assessment of failure likelihood, and consequence and decision support, has also been investigated and outlined in this chapter.

2.1 Cross-country Oil and Gas Pipelines

Pipelines are an inherently safer means of transporting oil and gas in bulk than other modes such as freight trains or tankers. Environmental analysis comparing pipelines with other modes of transport, such as rail, finds that pipelines result in fewer incidents, fewer human casualties, less environmental damage and fewer greenhouse gas emissions (Walker, 2014). A recent study (Furchtgoth-Roth, 2013) has shown that transportation of oil and gas by road results in an accident rate of circa 20 per billion-ton miles and that of rail is circa 2 per billion-ton miles. When compared to pipelines, with an accident rate of 0.9 per billion-ton miles (for natural gas) and 0.6 per billion-ton miles (for hazardous liquid), the pipeline system proves to be the safest and most cost-effective means of transporting oil and gas.

In Nigeria and indeed sub-Saharan Africa, the safety indices and the cost-effectiveness led to an exponential increase in the total length of the laid downstream pipeline for cross-country product distribution; from 1978 to 1995, more than 5000km of pipeline was built (Ambisisi, 2016). However, due to a combination of poor installation, maintenance and operational factors, poor land-use planning, environmental erosion and deliberate sabotage, the country witnessed a significant proportion of pipeline failure per fuel length carried, with devastating human and environmental consequences. Carlson *et al.* (2015) produced a comprehensive study of petroleum pipeline explosions in sub-Saharan Africa, reviewing both academic and lay literature covering a ten-year period up to 2014. The study shows at least 28 separate petroleum pipeline-related incidents which caused injury and or death in sub-Saharan Africa. Of the 28 incidents, 23 occurred in Nigeria with the total number of reported deaths at 1,756. Achebe *et al.* (2012) studied and analysed oil pipeline failures with significant environmental consequences in the Niger Delta area of Nigeria between 1999 and 2005 and recorded about 146 cases, with an estimated failure rate of 1.14 per 1000km-years. Although Achebe *et al*. (2012) recorded mechanical failure as the most common cause of pipeline failure, other studies (Dawotola *et al.*, 2012; Omodanisi *et al.*, 2014) have shown external interference and sabotage as the cause of the majority of incidents. Another study (Fadeyibi *et al.*, 2011) assesses the pipeline failure incidents around the Lagos area between 2000 and 2006, finding nine recorded incidents with a total death count of 646. These deaths are from official records at the hospitals.

The rate of fatal accidents is exacerbated by Nigeria's rapid population increase of more than 60 million people, from 120 million to 185 million, since the turn of the century (World Bank, 2017), with the resulting attendant uncontrolled developments around the pipeline corridors.

Section 2.1.1 below provides a global overview of the pipeline systems and how that compares with that of Nigeria in terms of safety matrices. The comparison is limited to the EU and USA pipelines where data are readily available.

2.1.1 Trends

The global trend in pipeline failures has been on a downward trajectory for the regions and geographies with available data. In Europe, the European Oil Company Organisation for Environment, Health and Safety (CONCAWE) and the European Gas Pipeline Incident Data Group (EGIG) produce periodic pipeline incident reports. The latest report by EGIG (2018) covers a period of 1970 to 2016 and includes incident statistics of seventeen major gas transmission system operators across Europe. The report shows a total incident frequency equal to 0.31 per 1,000km-years over the 1970 to 2016 period. However, the 5-year moving average shows that in the five years leading up to 2016, the average incident frequency is 0.13 per 1,000km-years. This 5-year moving average and the overall frequency has reduced consistently over the years. The 5-year moving average has decreased by a factor of 5 since 1970, from 0.86 to 0.13. In 1970, the total failure frequency was 0.87 per 1,000km-years, this is reduced to 0.31 per 1,000km-years in 2016. For the five years leading up to 2016, the incidents with the highest frequency rates are external interference (28%), followed by corrosion (25%), mechanical defects (18%) ground defects (15%), hot tap (4%) and others (10%).

The Concawe report (2019) collects failure data of European cross-country oil pipelines, covering the period from 1971 to 2017. Its database has 62 companies and agencies operating a total of 32,136km of oil pipelines across Europe, transporting about 720Mm^3 of crude oil and refined products. Excluding incidents of theft, the report indicates a general downward trend of pipeline failure, with the 5-year moving average reducing from 1.1 per year per 1,000km in the 1970s to 0.15 per year per 1,000km in 2015. However, a recent phenomenon at the turn of the century is pipeline interdiction for products theft, which represents 90% of all failures (84 out of the reported 93 in 2015). If pipeline failure due to theft is included in the moving average, then the 2015 5-year moving average increases to 0.95. As with other geographical areas, third-party activity regarding the intentional theft of products has been gaining traction in Europe; 2015's rate of theft incidents are the highest on record and account for nearly half of all theft incidents since records began. 90% of all reported theft incidents happened in the reporting years 2013, 2014 and 2015. Excluding theft, other third-party activities such as accidental and incidental damages have recorded the highest failure frequency (39%) over the last

5 years, followed by mechanical failure (27%), corrosion (21%) and operational factors (12%).

In the USA, the Pipeline and Hazardous Material Safety Administration (PHMSA) are responsible for recording pipeline failures and their 2017 statistical data (PHMSA, 2017) has shown a downward trend for gas pipelines failures, with a 5-year moving average being reduced by up to 30% since 2010. However, the failure data for hazardous liquids indicates an upward trend with a more than 170% increase in the 5-year moving average since 1997. The report did not provide a breakdown of failure factors as Concawe reports do, but it is likely the rise in the failure incidences are as a result of products theft.

In Nigeria, there are a number of government agencies that keep some records on onshore products pipeline incidents. They include the Nigerian National Petroleum Corporation (NNPC) and the Department of Petroleum Resources (DPR). The records are disparate and often contradictory; however, the general trend for all the records is a significant rise in pipeline failure from the available data. For example, the NNPC (2016; 2012; 2006) statistical bulletins indicate a 5-year moving average increase in the general failure rates of more than 300% from 2003 to 2016. The 5-year moving average of the number of pipeline failure incidents in 2003 is 700. That increases to 2990 in 2016. Up until 2015, the NNPC statistical bulletin has provided a breakdown in the failure causes of between “sabotage” and “other” causes. Whilst the sabotage has been increasing consistently, other causes have remained relatively constant. For example, in 2004, the failure number due to other causes is 39; in 2015 the failure number is 38. The DPR annual statistics bulletins (2015; 2014; 2013) also indicate an upward trend in pipeline failures; in 2010 there were 537 failures, increasing to 1087 by 2014.

2.2 Nigerian Pipeline System

The pipelines covered within this study are the 5001km length for petroleum product distribution in Nigeria. The system carries mostly refined products from either a refinery or import jetties to local distribution depots. One of the pipelines carries crude oil to the three refineries in the country. Figure 2-1 shows the geographical distribution of the pipelines. The transmission pipelines, the pumps, and the compressor or booster stations and other facilities that form the transmission system all fall within the "pipeline system".

The pipeline system is distributed across the country and, for operational purposes, is divided into five regions with a total of nine pipeline system as shown in Figure 2-1 and Table 2-1. Each of the pipelines links the refineries/import jetties with depots. The Kaduna refinery is also linked to the Escravos terminal through Warri by a crude oil supply pipeline.

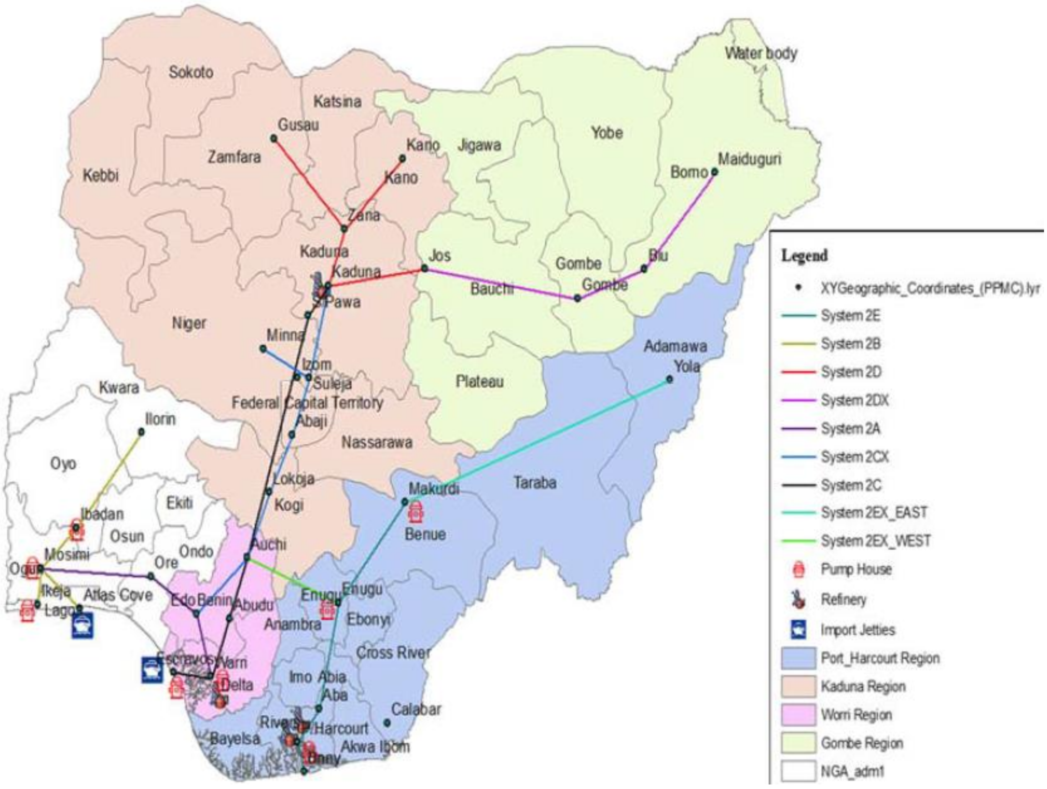


Figure 2-1: Pipeline Systems' Geographical Spread (Ambisisi, 2016)

Table 2-1 Nigeria Cross-Country Pipeline Network

System	Geographical Coverage	Pipeline Length (km)	Comments
2A	Warri-Benin-Ore-Mosimi	350	Commissioned in 1979, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate of 350m3/hr and pressure of 1450 psi. The pipeline diameter ranges from 12 inches to 15 inches.
2B	a) Atlas Cove – Mosimi – Ibadan – Ilorin b) Mosimi – Satellite (Ejigbo in Lagos) c) Mosimi – Ikeja	513	Commissioned in 1979, the pipeline is designed to carry PMS/AGO/DPK/ATK with a designed max flow rate between 160 to 1200m3/hr and pressure of 1450 psi. The pipeline diameter ranges from 8 inches to 26 inches.
2C	Escravos – Warri – Kaduna (Crude lines)	701	Commissioned in 1979, the pipeline is designed to carry crude oil with a designed max flow rate between 640 to 3250m3/hr and pressure of 1450 psi. The pipeline diameter ranges from 16 inches to 20 inches.
2CX	a) Auchi – Suleja-Kaduna b) Suleja – Minna	510	Commissioned in 1998, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate between 70 to 200m3/hr and pressure of 1450 psi. The pipeline diameter ranges from 8 inches to 12 inches.
2D	a) Kaduna – Zaria – Gusau b) Zaria – Kano c) Kaduna – Jos	1133	Commissioned in 1979, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate between 40 to 160m3/hr and pressure of 1450 psi. The pipeline diameter ranges from 6 inches to 12 inches.
2DX	Jos – Gombe – Maiduguri	265	Commissioned in 1998, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate of 90m3/hr and pressure of 1450 psi. The pipeline diameter is 8 inches.
2E	PH – Aba – Enugu – Makurdi	390	Commissioned in 1979, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate between 70 to 324m3/hr and pressure of 1450 psi. The pipeline diameter ranges from 6 inches to 12 inches.
2EX_ West	Port Harcourt – Enugu – Auchi – Benin	486	Commissioned in 1998, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate between 342 to 394m3/hr and pressure of 1450 psi. The pipeline diameter is 12 inches.
2EX_ East	Enugu - Makurdi - Yola.	650	Commissioned in 1998, the pipeline is designed to carry PMS/AGO/DPK with a designed max flow rate between 86 to 112m3/hr and pressure of 1450 psi. The pipeline diameter is 8 inches.

The pipelines are multiproduct systems for the supply of Premium Motor Spirit (PMS), Dual Purpose Kerosene (DPK), Aviation Turbine Kerosene (ATK) and Automotive Gas Oil (AGO). One pipeline – System 2C – supplies crude to the Kaduna Refinery. To ensure safe operation of the pipeline, they are buried about one metre deep on average. More details of the pipeline and fluid characteristics is provided in Appendix E

Similarly, the Nigeria Oil Pipeline Act (LFN, 1990) stipulates a 100-feet-wide (30m) right-of-way (ROW) buffer around pipelines, where human activities including buildings and farming are excluded. However, recent experience has shown that these safety measures have been compromised, resulting in rampant cases of pipeline sabotage, third-party interference and large-scale accidents (Onuoha, 2009).

Political instability, bad economic conditions and criminality result in a gradual poor to non-utilisation of the pipelines. The Nigerian Minister of Petroleum Resources is quoted to have indicated that the pipelines, and the depots they serve, have been out of service for more than a decade (Okafor, 2016) and within that period, the pipelines may not have undergone required maintenance. This, coupled with the population increase of circa 60 million in the last decade (World Bank, 2017) and, with the attendant uncontrolled developments around the pipeline corridors, means that the government desire to bring these pipelines back to service requires a rigorous risk analysis for the purposes of safety evaluation.

2.2.1 Case Study Pipeline System

The case study application of the models developed in this thesis would be on System 2B. The pipeline runs between Lagos and Ilorin in south-western Nigeria. The total length of the system is circa 500km with the following sections: SPM (Single Point Mooring) to Atlas Cove, Atlas Cove to Mosimi, Mosimi to Ikeja/Lagos, Mosimi to Ibadan and Ibadan to Ilorin. Figure 2-1 shows the pipeline location. The relevant pipeline is coloured light green. The system includes the following:

- Oil pipeline,
- Pipeline manifold,
- Pigging (pig launchers and receivers),
- Metering system,
- Pumps,
- Utility systems and
- Future tie-in connections.

Pipeline 2B is representative of the country's pipeline system as a whole with respect to failure frequency, as it is in the middle quartile overall in the failure records across the country.

2.3 Risk Assessment and Decision-Making

2.3.1 Risk Assessment

Risk assessment, including Quantitative Risk Assessment (QRA), is now regularly used for safety evaluation and land-use planning (Hopkins *et al.*, 2009; Haswell *et al.*, 2009; Pasman & Reniers, 2014) or when bringing pipelines back to service. The same QRA principle applies to the wider oil and gas industry and other high-risk industries such as the nuclear industry (Apostolakis, 1981).

Applying the principle of risk assessment to the pipeline system during design and operation enables better decision-making by forecasting potential failures and their resulting consequences.

Risk assessment is concerned with the concept of hazards and risk. Hazard, as a word, is borrowed from the Arabic *al-zahr*, meaning dice, and referred to the ancient game of chance (Muhlbauer, 2004). In relation to safety, a hazard could be defined as a physical state with the potential for human injury, damage to property, damage to the environment or some combination of these (Jones, 1992). On the other hand, risk is the likelihood or probability of realising such a physical state and its magnitude. The risk of a hazard being realised could be reduced either by addressing the hazard (that is, eliminating it), reducing the prospect of realising the harm that the hazard could cause or reducing the consequences that such a realised harm could present.

Risk assessment is, therefore, an evaluation of the likelihood of undesired events happening, the likelihood of harm or damage caused by such events, and a value judgement made concerning the significance of the harm. The risk assessment procedure is summarised in Figure 2-2 with the main elements highlighted in the "risk assessment" box (BSI, 2018b). The process outlined below is consistent with common practice and is similar to those adopted in other countries and international organisations including Norway (Standard Norway, 2010) and International Maritime Organization (IMO, 2018).

Worth highlighting from the Figure 2-2 is the integrated role of human factors at every stage of the risk assessment, indeed human and organisational issues have been variously implicated as the principal factors in accidents including in oil and gas accidents (Cullen, 1990).

The development of a risk assessment process is usually driven by the need for regulatory compliance of the jurisdiction where the pipelines are located. This initially results in assessment tools that are simple and qualitative, adopted to satisfy the regulatory requirements. However, as the number of pipeline projects increase and the locations of such pipelines get closer to human settlement or sensitive environments, a quantitative approach begins to be more widely adopted. The current and future trends of safety and risk management in the pipeline industry are moving away from qualitative to quantitative risk assessment approaches (Jo & Ahn, 2005).

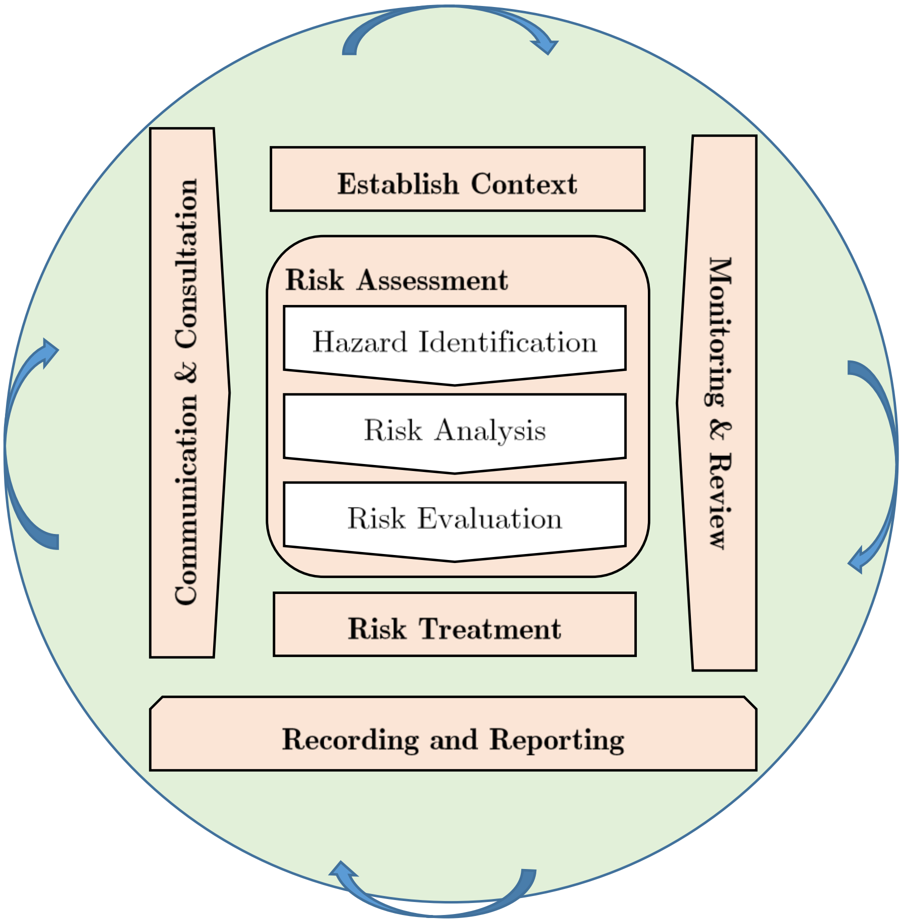


Figure 2-2: Risk Assessment Process (BSI, 2018b)

A qualitative approach generally estimates the risk by using the risk index method. It entails assessing and allocating numeric points to the factors behind pipeline failure such as mechanical damage, third-party damage, incorrect design and adding them together (Muhlbauer, 2004). The resulting sum is the risk index and gives a relative risk of a pipeline failure for a selected pipeline segment. However, the qualitative approach lacks rigour and is susceptible to the subjectivity of the assessor or participant, providing only the relative risks, so it is difficult to determine the acceptable risk level.

On the other hand, the development of QRA has focused on advanced methods of calculating the failure probability or assessing failure likelihood and the consequences thereof. QRA has become the predominant risk assessment tool in the area of safety and risk management in oil and gas industry. Its process entails:

- Identifying failure modes,
- Developing failure frequencies, using probabilistic models for release frequency,
- Developing failure consequences including identifying release rates, fire modelling, dispersion modelling, developing event trees and
- Risk estimation involving risk transects and individual risk calculations.

Different approaches have been developed to assess failure likelihood or probability, with the two main classes of assessment being the subjectivist as espoused in Finetti (1974) and the frequentist as promoted by von Mises (1981). Where relative frequencies for the identified hazards are limited or uncertain, then the subjectivist and other non-probabilistic uncertainty analysis approach seems more appropriate. Such approaches include Bayesian Theory, Fuzzy Set Theory, Evidence Theory and Plausibility Theory (Aven *et al.*, 2014; Aven & Zio, 2011).

The review of relevant literature for the various risk assessment steps is discussed further in the sub-sections below. These steps include identifying the sources of failure, developing failure likelihood, assessing failure consequences and estimating the risk which informs the risk-based decision-making.

2.3.2 Failure Sources

The first step in the risk assessment for any pipeline or infrastructure is to identify failure sources that may present a risk of pipeline failure. The types and the number of failure sources differ depending on the literature under review. For example, the CONCAWE report (Cech *et al.*, 2019) identifies the causes as including mechanical failure, operational failure, corrosion, natural hazards and third-party activity. The UKOPA (Goodfellow *et al.*, 2019) identifies the causes as corrosion, external interference, weld defects, ground movement, pipe defect, construction damage and others. The EGIG (2018) outlines the causes as being corrosion, external interference, ground movement, hot tapping, construction defects, material failure and others. On the other hand, Muhlbauer (2004) identifies the causes as being third-party damage, corrosion, design defects, incorrect operations, stress and human errors, and sabotage.

Identifying and forecasting the causes of oil and gas pipeline failure has been frequently studied. Many publications propose different approaches, including, for example, Bertolini *et al*. (2006) who developed a goal programming decision support system to predict the type and classification of oil spillage for a cross-country pipeline. Bertolini *et al.* (2006) use the Classification and Regression technique to build a decision tree which is then used to forecast the cause of a pipeline leakage. The model is built to identify and differentiate the pipelines that are prone to failure due to third-party intervention from the pipelines that are prone to failure due to natural hazards. It adopted failure variables such as the age of the pipe, pipe diameter, pipeline service type, where the pipes are located and the failure detection technology in use. Bertolini *et al*. (2006) collected data from Concawe (Davis *et al.*, 2010) to forecast the cause of failure.

El-Abbasy *et al.* (2014b; 2014a) assessed the potential failure sources for pipelines by using regression analysis and artificial neural network models. The models forecast failure likelihood using failure sources such as mechanical damage, operational failures, third-party damages and natural hazard as inputs. The failure data has also been taken from Concawe (Davis *et al.*, 2010) for the European cross-country pipelines. The models were well-validated, although the failure causes used are limited to only five variables: the pipe diameter, product type, location, age and land use. However, majority of the variables remain constant over the life of a pipeline and consequently have done little to influence the results. Additionally, this type of approach would be ill suited for application on pipeline systems where data availability and reliability is the main challenge.

A significant body of pipeline failure models in the literature used qualitative measures (Alex W. Dawotola *et al.*, 2011; Achilla, 2015) whilst some addressed only one source of failure such as corrosion (Sinha & Pandey, 2002; Ahammed, 1998). Such a body of work is therefore not comprehensive and lacks objectivity in assessing pipeline failure sources.

Recent research aims to address such weaknesses by addressing the uncertainty created by subjective input. For instance, Senouci *et al*. (2014) adopted the fuzzy logic technique to develop a model that predicts the failure type of hydrocarbon pipelines and compares the results with those of El-Abbasy *et al*. (2014b; 2014a). The comparison results prove that the fuzzy-based model developed by Senouci *et al*. (2014) outperforms the regression and Artificial Neural Networks-based (ANN) models with respect to the model validity.

Despite the recent efforts to model and predict the failure causes and types of hydrocarbon pipelines by including other causes apart from corrosion, the new models still focus on factors that cause failures linked to corrosion or third-party damage only. Additionally, little effort is paid to other issues such as the interdependency between different factors and addressing the uncertainty and the weights assigned to the factors.

All the failure causes from the various different sources could be combined into four broad types: third-party interference, corrosion, mechanical/structural defects and operational error.

2.3.2.1 Third-Party Interference

The recent trend of pipeline failures indicates third-party interference as the major cause of pipeline failure. Between 2013 and 2017, Concawe (Cech *et al.*, 2019) recorded 230 incidents related to third-party interference, mostly due to theft/intentional damage. The next failure cause, mechanical defects, records only four incidents. Third-party interference is subdivided into theft/intentional damage and accidental damage.

Theft/Intentional Damage

Pipeline failure due to sabotage or intentional damage has been a major cause of pipeline failure in developing countries such as Nigeria and Mexico (Ralby, 2017) but it is also becoming a source of concern in developed economies, as outlined by Cech in the Concawe report (2019). Initially, the major cause of sabotage, especially in developing economies, is thought to be rooted in the economic and social issues, mainly in geographical areas where such pipelines are located. Although economic and social issues are a contributing factor, the increased incidents of sabotage in developed economies indicate the influence of other factors such as politics and criminality.

In Nigeria, sabotage is linked to unemployment and environmental degradation (Onuoha, 2009) where the spate of product theft and vandalism has been at a very high level since the turn of the century. Figure 2-3 shows examples of third-party-linked sabotage for stealing oil products in Nigeria.

The impact of sabotage often leads to the loss of life, extensive environmental damage and economic losses. The rate of sabotage can be reduced by applying certain failure control measures such as carrying out regular patrols and surveillance along pipeline routes (Muhlbauer, 2004). Educating people on the dangers of tampering with pipelines and working together with the communities that live close to pipelines would also help reduce the likelihood of the sabotage.

Figure 2-3: Intentional Third-Party Interference to Steal Oil Products (Photo credit: BBC (left) and NOSDRA (right))

Accidental Damage

Accidental damage has often been the major cause of pipeline damage prior to sabotage becoming a major concern. Health and Safety Executive (HSE) sponsored research (Mather *et al.*, 2001) on gas pipelines indicates that the major contributory cause of accidental damage is earth-moving machinery, such as back actors and diggers, as a result of drainage work and construction. Different failure control measures have been outlined (Muhlbauer, 2004; Pettitt & Morgan, 2009) including vibration detection, the creation of a pipeline safety zone, electromagnetic techniques and satellite position techniques.

2.3.2.2 Mechanical/Structural Defects

Mechanical or structural defects present a major failure threat to the pipelines. These defects occur either due to deformation in the pipeline material or because of construction defects during the process of fabrication.

Material Defect

Material defects can originate during the fabrication process and propagate during the operation of the pipeline if left uncorrected, potentially leading to pipeline failure. The presence of material defects creates non-uniformity within the material layer, giving rise to electrochemical reactions that lead to oxidation and then corrosion. Material defects could also lead to other defects such as thinning of the pipe walls.

Construction Defect

Construction defects are primarily structural defects associated with pipeline fabrication and installation during construction projects. These defects include scratches, gouges and dents. Construction defects create an opportunity for corrosion due to the irregular surfaces or pores created; these permit air entrapment which in turn reacts with water or moisture to begin the corrosion of the pipeline.

2.3.2.3 *Operational Error*

Operational errors are the failures due to the operation of the pipeline and related equipment. Operational errors are mostly human-related errors due to, for example, negligence or a lack of knowledge. The error could also be due to operational management issues such as the lack of standardised operating procedures. The operational error may also be linked to equipment malfunction or inadequate instrumentation.

2.3.2.4 *Corrosion*

Corrosion is the loss of material from pipeline as a result of metal (pipeline) attempting to revert back to its original form (ore) when in contact with the natural environment (Orazem, 2014). For metal pipelines, the type of corrosion that occurs is called "electrochemical" corrosion. The process includes an electrical component (a transfer of electrons) and chemical component (oxidation and reduction reactions) that must be present at the same time, with equivalent reactions. The process must contain an anode, a cathode, an electrolyte and an external path. Figure 2-4 shows an example of the external corrosion of a pipe.

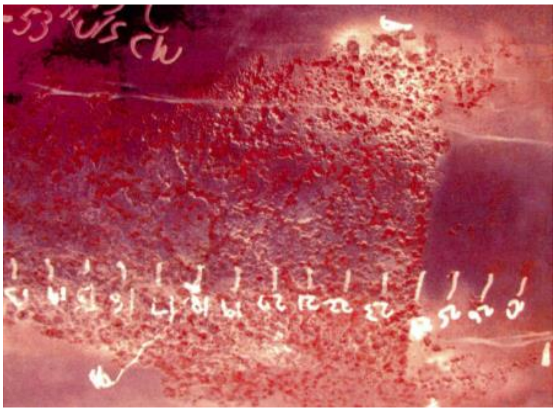


Figure 2-4: External Corrosion Showing the Measured Pit Depths (Singh, 2014)

Unprotected pipelines, especially the buried cross-country ones, are susceptible to corrosion. Corrosion can weaken the structural integrity of the pipeline system and make it unfit for transporting petroleum and natural gas.

Corrosion on pipelines can be grouped into internal corrosion and external corrosion. Internal corrosion takes place within the walls of the pipeline. External corrosion includes atmospheric and subsurface corrosion. Atmospheric corrosion affects the external wall of the pipelines that are located above ground. Subsurface corrosion attacks the surface of pipelines buried under corrosive soil. The type of corrosion found in pipelines includes uniform corrosion, pitting corrosion, stress corrosion cracking, microbial-induced corrosion and erosion control.

2.3.3 Failure Likelihood

Once the failure sources have been identified, the probability or likelihood of a failure arising from such failure sources requires identification as part of the risk assessment process. Guidance documents (BSI, 2006; Norske Veritas, 2010) provide guides for assessing failure likelihood or failure probability for engineering systems, including pipelines. Table 2-2 and Table 2-3 provide example approaches adopted in the BS EN 60812 (2006) and DNV-RP- F107 (2010) for assessing the failure likelihood of oil and gas pipelines.

Table 2-2: Failure Likelihood Qualitative Ranking (BSI, 2006)

Likelihood Level	Ranking	Description	Frequency	Probability(/yr.)
Very Low	1	Failure unlikely	≤ 0.010 per thousand	$\leq 1\times10^{-5}$
Low	2	Relatively few failures	0.1 per thousand	1×10^{-4}
	3		0.5 per thousand	5×10^{-4}
Average or Moderate	4	Occasional failures	1 per thousand	1×10^{-3}
	5		2 per thousand	2×10^{-3}
	6		5 per thousand	5×10^{-3}
High	7	Repeated failures	10 per thousand	1×10^{-2}
	8		20 per thousand	2×10^{-2}
Very High	9	Failure is almost inevitable	50 per thousand	5×10^{-2}
	10		>100 per thousand	$\geq 1\times10^{-1}$

Table 2-3: Failure Likelihood Qualitative Scale (Norske Veritas, 2010)

Category Level	Description	Annual Likelihood
1 (Low)	So low frequency that event considered negligible	$\leq 10^{-5}$
2	Event rarely expected to occur	$10^{-4} > 10^{-5}$
3 (Medium)	Event individually not expected to happen but when summarised over a large number of	$10^{-3} > 10^{-4}$

Category Level	Description	Annual Likelihood
	pipelines has the credibility to happen once a year	
4	Event individually may be expected to occur during the lifetime of the pipeline	$10^{-2}>10^{-3}$
5 (High)	Event individually may be expected to occur more than once during the lifetime	$> 10^{-2}$

Several research works have been undertaken to assess the probability or likelihood of failure for oil and gas pipelines (Dey, 2003; Al-Khalil *et al.*, 2005; Dey *et al.*, 2004; Dawotola *et al.*, 2009; Dawotola *et al.*, 2010). They all used multi-criteria decision-making models and the judgement of experts to estimate the failure likelihood or probability as part of the oil and gas pipeline risk assessment.

Dey (2003) used expert judgement to develop a risk-based cross-country pipeline failure analysis. The paper segmented the pipeline and used expert elicitation to assess and rank the pipeline risks in order to prioritise the inspection regime for the segments. Analytic Hierarchy Process (AHP) was used, with the experts' input, to calculate the weights for each pipeline segment. The calculated weights formed the basis for assessing the relative likelihood of failure ranking between the segments. Dey *et al*. (2004) used a similar approach to assess the failure likelihood for offshore oil and gas pipelines. The work elicits the judgement of experts on the importance of different sources of pipeline failures using the AHP approach and the relative ranking of the identified failure sources was evaluated based on the calculated weights. Subsequently, the expert opinion elicited was applied to rate the likelihood of the pipeline failing against each type of failure. This score was multiplied by the calculated weights to obtain the failure probability.

Al-Khalil *et al*. (2005) also assessed a number of cross-country pipelines carrying hydrocarbon products by applying the AHP principle. They identified and categorised failure modes such as corrosion, external interference, operational issues, structural defects and erosion. Experts were invited to score the likelihood of failure and associated cost implication for each pipeline against the identified risk factors, calculating the overall expected cost of pipeline failure for each identified failure factor. The ranking forms the basis for pipeline failure repair budget and prioritisation. Dawotola *et al*. (2009; 2010) proposed a model to calculate the failure likelihood for different causes of pipeline incidents by using a combination of AHP and Fault Tree Analysis. The model ranked the failure causes using expert elicitation and AHP weighting aggregation to evaluate the relative importance of each failure cause.

Some recent works apply machine learning to develop models for determining the failure likelihood of pipelines. Bersani *et al.* (2010) applied an Artificial Neural Networks-based (ANN) model to predict failure probabilities for different failure causes. For each of the identified failure causes, a set of factors was developed as independent variables. The results from Bersani *et al.* (2010) indicate that a good prediction of third-party failure was obtained. However, the work did not carry out sensitivity studies on the factors used to determine the importance of the particular factors selected. Ren *et al*. (2012) used a model incorporating back propagation neural networks to predict the corrosion rate of natural gas pipelines. Input provided in the model includes factors such as flow pressure, pipeline length and gradient. The model also considered the Reynolds number as an important factor in predicting the corrosion rate of various sections of the pipeline. Sinha and Pandey (2002) also used ANN to model the likelihood of hydrocarbon pipelines failure. The ANN model utilises the loss to a pipeline wall to predict the pressure at which the pipe could burst. The estimated pressure was used to forecast the remaining strength of the pipelines.

Inline inspection data is also used frequently as part of probabilistic assessment to determine the failure frequency or likelihood. Caleyo *et al*. (2009) developed probability distribution functions of corrosion depth and the rate of wall erosion using Monte Carlo simulation. Different curves were proposed for underground pipelines considering the properties of various soil types. Noor *et al*.(2010) used a semi-probabilistic method to forecast the residual life of a corroding offshore pipeline based on data from inline inspection tools. The method was developed based on the DNV's RP-F 101 (Norske Veritas, 2010) for corroded pipelines.

A large number of the research has been conducted and the models developed therein were either qualitative, such as in Dey (2003) and Dey *et al*. (2004), or only addressed single failure sources for pipelines, such as corrosion (Ahammed, 1998; Sinha & Pandey, 2002; Ren *et al.*, 2012). This means that a number of those studies are not fully comprehensive.

Shahriar *et al*. (2012) proposed a comprehensive model to assess the risk of oil and gas pipelines failure applying Bowtie analysis. The Bowtie analysis makes use of the graphical approach to assess different scenarios of pipeline failures. Shahriar combined Fault Tree Analysis with Event Tree Analysis to develop the Bowtie model. The Bowtie was developed to assess the risk of gas release from a pipeline, which is taken as the top event for the fault tree. The model identifies high-level failure events, including rupture, corrosion, geological hazards, incorrect operation and sabotage. It further identifies the low-level factors associated with each high-level event. For example, corrosion has low-level factors that include internal corrosion, external corrosion, stress corrosion cracking and corrosion fatigue. The ranking and assessment of the failure factors rely on expert opinion to assess the fuzzy likelihood of the low-level events.

Sadiq *et al*. (2004) used a fuzzy scale to determine the failure likelihood. The work uses triangular membership functions to develop the scale used to evaluate the likelihood of failure. The scale translated the linguistic terms into fuzzy numbers evaluating the likelihood of failure from a very low to a very high level. The likelihood of occurrence of high-level events was arrived at by multiplying the likelihood attributed to the low-level events. Expert opinion was adopted to rank and weight the failure factors, which gives the likelihood of failure of the pipelines. The model was built with about 40 low-level events; clearly asking experts to provide their opinion on such a large amount of factors is difficult and time-consuming and therefore could limit their participation. To minimise this limitation, Shahriar *et al*. (2012) used historical data in combination with the elicitation of experts.

Other researchers (Kabir *et al.*, 2016; Yang *et al.*, 2008; Li *et al.*, 2016; Zarei *et al.*, 2017; Ren *et al.*, 2009) have used the Bayesian Network model as part of the risk assessment process to assess and prioritise failure of safety systems under uncertainty. For instance, Yang *et al.* (2008) used a combination of fuzzy rule and Bayesian Network to prioritise the risk of collision between a Floating Production Storage and Offloading (FPSO) system and a shuttle tanker. The model first establishes the appropriate fuzzy rule base, estimates the failure factors using expert elicitation, conducts risk inference using fuzzy Bayesian reasoning and finally assigns utility functions to prioritise the failures. The model has been demonstrated to successfully utilise human knowledge to deliver risk criticality values in support of safety-based decision-making. The model, though, did not test the interdependency of the failure factors and how that may affect the model's sensitivity.

Various researchers used different failure variables to develop models that forecast the likelihood or probability of failure, as outlined earlier . The majority of the failure factors used a variation of either EU's Concawe (2019) or US DOT's pipeline data (PHMSA, 2018) as shown in Table 2-4.

2.3.4 Failure Consequences

A number of works have been carried out in the past to estimate the failure consequence for an oil and gas pipeline, ranging from qualitative to semi-quantitative and full quantitative assessments. For example, DNV (2010) developed guidance based on a qualitative assessment which provides consequence scale with respect to human (life) safety, environmental consequences and economic loss. Human safety assessment considers first party – that is, the personnel working for the operating company – and third party – that is, the personnel outside the company's facilities affected by the operating company's operations. The environmental consequences include pollution impacts on the ecosystem, coastal environment, farmlands and sealife. The economic loss includes production delays and claims arising from loss of revenue from customers.

Table 2-4: Failure Factors from Two Main Sources

US DOT	**Main Factors**	**Secondary Factors**	EU Concawe	**Main Factors**	**Secondary Factors**
	Material/Weld Failure	• Construction/installation/fabrication • Fitting defect • Failure of equipment body • Malfunction of control equipment • Non-threaded connection failure • Pump related seal failure • Others		Material defect	• Material • Construction • Design
	Natural Force Damage	• Flood/heavy rain • Earth movement • Lightning • Temperature • Others		Natural Hazard	• Ground movement • Other natural hazards
	Incorrect Operation	• Operator damage • Incorrect installation • Incorrect operation • Incorrect valve position • Others		Operational damage	• System malfunction • Human and organisational error
	Excavation Damage	• Operator/contractor excavation damage • 3rd party excavation damage • Other damages		Third party damage	• Incidental • Accidental • Theft
	Corrosion	• Internal • External • Unspecified		Corrosion	• Internal • External • Stress corrosion
	Other Outside Force	• Electrical arcing • Vehicle not engaged in excavation • Previous mechanical damage • Others			

Table 2-5 shows the qualitative ranking of human safety consequences as outlined in the DNV guidance (2010). Table 2-6 shows the qualitative ranking for environmental damage. The ranking in the table is due to the product spillage and type, the weather conditions and the time it takes to reach sensitive areas. Table 2-7 shows the qualitative ranking of the economic loss consequence which is related to the production delay and lost revenue. As outlined earlier, the methods in the guidance document are qualitative and rely mostly on expert opinion and past loss incidents, therefore giving a good ballpark guidance in the absence of detailed assessment.

Table 2-5: Human Safety Consequence Scale (Norske Veritas, 2010)

Category	Description
1 (low)	No person(s) are injured
2	(not used)
3 (medium)	Serious injury, one fatality (working accident)
4	(not used)
5 (high)	More than one fatality (gas cloud ignition)

Table 2-6: Environmental Safety Consequence Scale (Norske Veritas, 2010)

Category	Description	Amount of Release
1 (low)	None, small or insignificant on the environment. Either due to no release or only insignificant release.	-0
2	Minor release of polluting media. The released media will decompose or be neutralised rapidly by air or seawater.	<1000 tonnes
3 (medium)	Moderate release of polluting medium. The released media will take some time to decompose or be neutralised by air or seawater, or can easily be removed.	<10000 tonnes
4	Large release of polluting medium which can be removed, or will after some time decompose or be neutralised by air or seawater.	<100000 tonnes
5 (high)	Large release of high-polluting medium which cannot be removed and will take a long time to decompose or be neutralised by air or seawater.	>100000 tonnes

Table 2-7: Economic Consequence Scale (Norske Veritas, 2010)

Category	Description	Production Delay/Downtime
1 (low)	Insignificant effect on operation, small or insignificant cost of repair.	0 days
2	Repair can be deferred until scheduled shutdown, some repair costs will occur.	<1 month
3 (medium)	Failure causes extended unscheduled loss of facility or system and significant repair costs. Rectification requires unscheduled operation with pre-qualified repair system before further production.	1-3 months
4	Failure causes an indefinite shutdown and significant facility or system failure costs. Rectification requires unscheduled operation without pre-qualified repair system before further production. Or Failures resulting in shorter periods of shut down of major parts of (or all of) the hydrocarbon production for the field.	3-12 months
5 (high)	Total loss of pipeline and possible loss of other structural parts of the platform. Large cost of repair including a long time of shutdown of production. Or Failures resulting in shutdown of the total hydrocarbon production for a longer period.	1-3 years

Recent work has also been carried out using other approaches, such as probabilistic and semi quantitative measures to calculate the pipeline failure consequence. For instance, Brito *et al*. (2009) used event tree analysis to assess the failure consequence of natural gas pipelines. The initiating event is taken as the gas release which either results from rupture or puncture (failure mode). Both releases are either ignited immediately or delayed. Space confinement contributes to the severity of the consequence of the initiating event and hence has been accounted for. The resulting scenarios include jet fire, fireball, flash fire, vapour cloud explosion, detonation or an unignited gas release. To estimate the consequence likelihood of the event, additional information such as the environmental, economic and human consequences have been included. The case study pipeline has been divided into segments and analysis of the consequence likelihood is attempted using the probabilistic-based expert elicitation approach.

Using probability distribution function to assess the likelihood consequence has previously proven difficult for the experts, therefore, Brito *et al*. (2009) used the EGIG (European Gas Pipeline Incident Data Group) pipeline accident data instead, with some adjustment to allow for factors specific to the pipeline under consideration, such as land use and third-party activities. Experts were then asked to provide an opinion on the weighting of those factors for different pipeline segments. The combination of the two inputs – EGIG data and expert opinion has been used to rank the pipeline consequence for the segments. The challenge with this approach is the detailed requirement for data input that the experts are expected to provide, which could be time-consuming and may dissuade some experts from participating.

Shahriar *et al*. (2012) also developed an event tree to model post-failure events of gas pipelines to estimate the consequences of failure. The critical event in this case being natural gas release leading to immediate or delayed ignition and the consequences that space confinement could introduce. The output events after a gas release were identified as detonation, jet fire, fireball, vapour cloud explosion, flash fire and material loss. The occurrence probability of each output event is arrived at by combining the gas release probability and the occurrence probability of the ignition and space confinement events. The results of each combination represent the consequence occurrence probability.

Shahriar *et al*. (2012) used sustainability criteria to evaluate the economic, social, and environmental consequences of pipeline failures. The economic consequences include supply interruption, repair, material loss, property damages and third-party-related damages. The social consequences include the assessment of casualties and public response. The environmental consequences include the spill's impact on the air, endangered habitats, vegetation, soil, and water. The fuzzy scale is used to estimate the consequences of each failure scenario by relying on expert elicitation. The application of expert elicitation in the analysis combined the objectivity and the subjectivity of the input in the model. However, the weakness of this approach is that the experts were not able to provide their opinion on the consequence occurrence probability, which is the output event of the pipeline failure.

This thesis did not go into any detail in assessing the failure consequence, rather it uses a qualitative scale to inform the research as part of the decision-making process.

2.3.5 Risk Based Decision Support

Decisions in risk management and engineering involve a selection of different options or alternatives, with each alternative having both qualitative and quantitative attributes. Generally, the qualitative attributes are assessed using human judgement, which has the weakness of being subjective and often associated with uncertainties as a result of ignorance, incomplete information and fuzziness. Therefore, decisions may not be properly made without fully taking into account all the related attributes whilst quantifying their uncertainties (Mokhtari, 2011; Yang & Xu, 2002; Wang *et al.*, 2006).

An example of a decision-making model is provided by de Almeida *et al*. (2015). The model is a quantitative one and incorporates the decision maker's preferences and behaviour with respect to risk. This enables alternatives to be prioritised by making a hierarchical ranking of the risks. It also allows for a multidimensional risk approach to be taken with respect to different consequences. Figure 2-5 shows the stages of the model and its structure as used by Brito and Almeida (2009).

Different decision-making approaches that aim to capture and treat such uncertainties have been proposed; these include probabilistic and subjective approaches. Within the subjective methods, the Multiple Criteria Decision Methods (MCDM) have been widely used to solve practical challenges in engineering and particularly in risk, reliability and maintenance realms.

MCDM methods can be grouped into three generic categories: Utility-based or unique criterion of synthesis methods; Outranking methods; and Interactive or multi-objective linear problems (MOLP) methods. Details description and examples of MCDM categories is provided in Section 3.4.

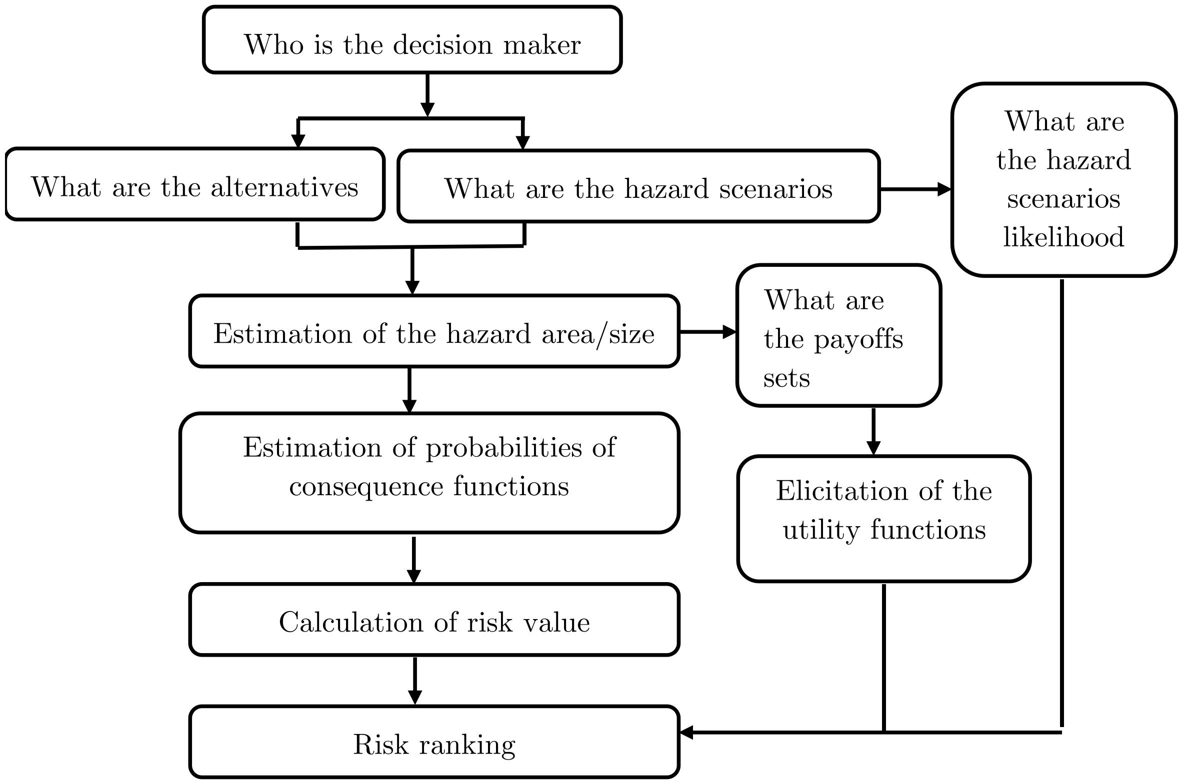


Figure 2-5: Structure of Decision Model (de Almeida *et al.*, 2015)

Several researchers have utilised MCDM models to aid decision-making for pipeline systems including Dey (2003; 2001), El-Abassy *et al.* (2015), Dawotola *et al.* (2010; 2009), Fadi *et al.* (2016) and Brito and Almeida (2009). Other researchers have used it for safety synthesis and evaluation, including Wang *et al.* (1995; 1996) and Liu *et al.*(2005).

Dey (2001) utilised AHP to propose a decision model that helps decision makers and pipeline operators select a suitable type of inspection or monitoring technique for pipelines. The pipeline was divided into segments, and datasets specific to each segment were obtained, in addition to failure data from Concawe. A risk structure framework in AHP is then developed with five risk factors, which enable pair-wise comparison of the alternative pipeline segments. This then allows for the segments to have their specific inspection/maintenance requirements based on the assessed risk.

El-Abbasy *et al*. (2015) developed a model that assesses the condition of oil and gas pipelines based on several factors, including corrosion, using both Analytic Network Process (ANP) and Monte Carlo simulation. The paper identified the pipeline conditions and conducted a questionnaire-based survey which provided input into the ANP model. The ANP process has seven steps, from employing pairwise comparison to calculation of the final global matrix. Monte Carlo simulation has subsequently been used to determine the attribute effect value and its probability distribution.

Dawotola *et al*. (2010; 2009) proposed a combined AHP and fault tree analysis model for the design, construction, inspection and maintenance of oil and gas pipelines. The model proposes an optimal selection strategy based on the probability and consequence of failure. Dawotola *et al* outlined the procedure, which includes problem formulation, pipeline segmentation, data collection, hierarchy structure development, expert elicitation and the fault tree analysis of important failure factors.

Fadi *et al.* (2016) utilised a combination of ANP, Fuzzy Set Theory (FST) and hierarchical Evidential Reasoning (ER) to develop a condition assessment model for offshore gas pipelines by using the inspection report from the pipeline operator as one input variable. The assessment first used the ANP module to determine the factors' mean final global weights. Then the FST module was used to assign the fuzzy thresholds and membership functions for the main model's inputs and outputs. Finally, the ER module was used to determine the degrees of belief for the main model's outputs, which were then defuzzified using the FST module.

Several applications of multidimensional risk evaluation and decision models have been conducted. Brito and Almeida (2009) contextualise the multidimensional risk view for natural and hydrogen gas pipelines by incorporating the decision maker's behaviour with respect to risk and representing it as a utility function. Thus, multidimensional risk analysis for natural gas pipelines has been carried out in order to calculate the occurrence likelihood of a hazard scenario and the possible consequences that could result from a pipeline failure. The model then ranks the pipeline sections in a multi-dimensional risk hierarchy, with three-dimensional risks considered, including the human, financial and environmental dimensions. The risk dimensions are those resulting from the operation of the pipeline segments under the study. The final results show the risk hierarchy ranking of these segments, which gives insights into the process of managing pipeline risks and helps in defining each segment's mitigating actions. The ranking also allows decision makers to allocate resources according to the risk hierarchy.

Wang *et al*. (1995; 1996) and Liu *et al*. (2005) used a combination of Fuzzy Set Theory and Evidential Reasoning to identify and synthesize information to assess the safety of engineering systems. The model used basic failure parameters to analyse the failure events. Fuzzy Set Theory is used, employing membership functions and linguistic variables, to define the categories and obtain a safety score. ER is then used to synthesise and evaluate the safety system for risk-based decision-making.

For this research, the evidential reasoning algorithm is deemed the most appropriate for synthesising the failure information and supporting the decision-making process, as outlined in detail in Chapter 3.

2.4 Conclusions

Several literatures have been reviewed in this chapter outlining the state of the art in the area of pipeline risk assessment especially for regions where data is lacking or is inadequate. However, from literature reviewed, a constant gap in addressing risk assessment in this domain is the lack of the integration of the multitude and complex interdependency between different factors and interrelations of technical human and organisational malfunctions. The challenges and limitation have been outlined in the relevant sections

Addressing the challenges of the different factors' relations and uncertainty of factors' severity weights simultaneously is one of the key contributions of this work. The work aims to close the gaps in the existing literature.

Chapter 3. Research Methodology and Techniques Adopted

Overview

A multi-product cross country pipeline installation is a complex system consisting of many subsystems that needs to constantly adapt to new approaches and new technologies due to the multiple hazards it portends. One of the major challenges regarding the application of the risk assessment process is the associated need to develop integrated and flexible approach taking into consideration the human and organisational elements.

To reduce the likelihood of occurrence of accidents, it is essential that scenarios that may result in loss of containment are assessed at an early stage in order to reduce or eliminate the threat. However, the operation of pipeline systems in developing countries is often associated with a high level of uncertainty because of lack of or inadequate data, complex socio-economic factors, among others. Its operation in such a challenging environment in which both technical and human and organizational malfunctions may contribute to a range of possible accidents requires a novel techniques and framework to address the identified challenges.

The approach proposed in this research is novel as it develops a framework for identifying pipeline failure, mitigating such failures and assessing the cost benefit of the mitigation measures by combining three techniques of safety risk management and decision making as described in this Chapter. Another novelty in the framework is the inclusion of the concept of risk mitigation as a quantifiable benefit, using the estimation of the cost of averting loss of containment in monetary terms.

This chapter provides the outline of the research methodology, research techniques and models adopted in the study including hazard identification, failure likelihood development and risk-based decision-making. The section outlines the scientific background of the research techniques and the justification for adopting the techniques. The application of these techniques and the steps required for the case studies are given in Chapters 4, 5 and 6.

3.1 Research Methodology Overview

This section outlines the approach on how the three models tie up together as part of the package for onshore cross-country pipeline risk assessment. Models and frameworks developed for the main chapters including Chapter 4 – Modified FMEA-Based Hazard Identification, Chapter 5 – Application of Bayesian Networks in Developing Failure Likelihood, and Chapter 6 – Pipeline Risk Management Decision Support Model. Figure 3-1 shows the framework overview and how the three technical chapters are linked.

Chapter 4 is the initial technical chapter and serves as the preliminary assessment chapter where the main hazards that contribute towards pipeline failure are identified, assessed and qualitatively ranked. The chapter used the literature available, case histories and local experience to identify the failure modes with the highest likelihood of occurrence, applying it to the case study pipeline system – System 2B – in Nigeria. The identified hazards form the basis for the Modified FMEA analysis using Fuzzy Rules Base and Grey Relations Theory, the aim of which is to address some of the inherent weaknesses of the traditional FMEA. The model ranks the identified failure modes based on their likelihood of occurrence, how the failure could be detected and severity of the event, utilising fuzzy linguistic terms. The assessment identified the failure mode with the highest likelihood of causing loss of containment and with the highest consequences as being a leak or a rupture. This failure mode ranked number one using the Fuzzy Rules Base approach and ranked second using the traditional FMEA and Grey Relations Theory approaches.

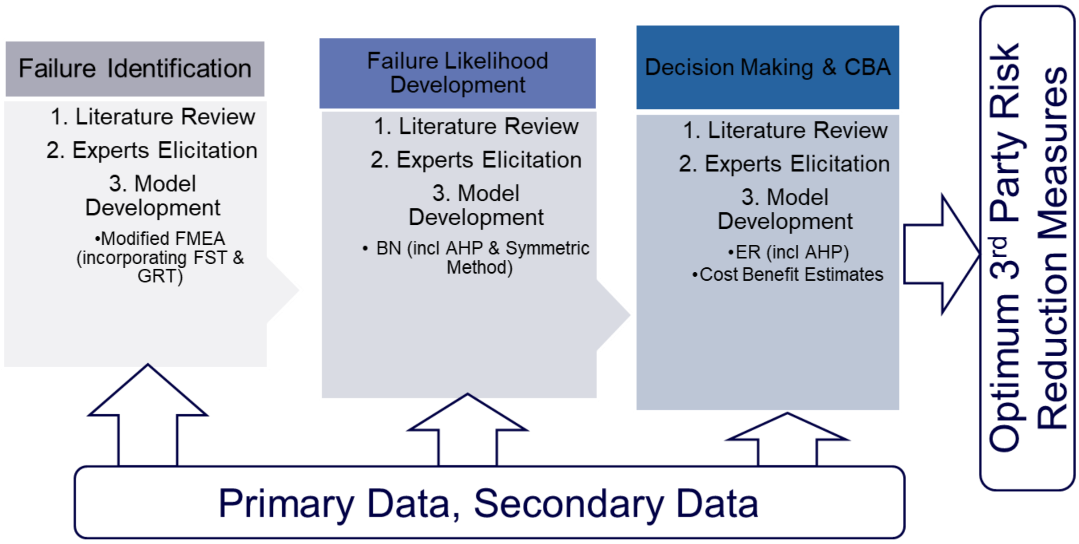


Figure 3-1: Research Framework Overview - Technical Chapters

Chapter 5 uses the results of Chapter 4 as an input, identifying the top failure mode as a pipeline failure due to leak or rupture. Chapter 5 then investigates the contributing factors of that failure using Bayesian Networks. The Bayesian Networks model that has been developed identifies all the factors that contribute to pipeline failure due to a leak or rupture and assesses their likelihood. The input data for the conditional probability tables of the parent nodes relies on the combination of case histories from pipeline operators in Nigeria, the EU and the USA. Where data is not available or inadequate, or in order to specify the conditional probability tables for the child nodes, expert elicitation using AHP has been applied to map the cause-and-effect relationship between failure factors and the pipeline failure condition. The results indicate that third-party damage is assessed to have a significant contribution on failure likelihood.

Chapter 6 models risk management decision support using Evidential Reasoning. The previous chapters have identified the failure factors and their likelihood contribution to a pipeline leak and rupture for the case study pipeline System 2B in Nigeria. The failure factor with the most significant contribution to pipeline failure has been identified as third-party damage. Therefore, any effort aimed at reducing the prevalence of this factor reduces the likelihood of a pipeline failure incident. An Evidential Reasoning model has therefore been developed which identifies main attributes as Risk Control Options, with each main attribute having a number of basic attributes, all contributing towards risk reduction of pipeline failure as a result of third-party damage. The attributes are all grouped into three alternatives and these include technical, government and management solutions. The results indicate that the most effective interventions that reduce the third-party damage potential are technical solutions, followed by the management and lastly government solutions. Additionally, a cost-benefit estimate has been carried out to highlight the cost of pipeline failure and the net benefit of implementing some or all of the Risk Control Options to help the operator with decision-making.

All the models that have been developed take input from the results of the preceding chapter. All the models contribute to the overall risk assessment and management of the selected case study pipeline, helping the operators and decision makers in their management of the pipeline's integrity.

3.2 Hazard Identification

Hazards associated with the cross-country pipelines are varied and so are the resulting consequences, which include loss of life, destruction of property and the environment, disruption to vital supplies, socio-economic setbacks and the loss of vital revenue to the government. The hazards of a pipeline system could be associated with the pipeline itself, the pigging apparatus, the pipeline manifold, the pumps, the metering package or the utility equipment.

Different models and approaches have been proposed to identify and analyse the hazards that may lead to pipeline failure. This section outlines those models and tools that have been utilised in this research.

3.2.1 Failure Mode and Effects Analysis (FMEA)

FMEA is one of suite of risk analysis tools that has gained wide adoption in the oil and gas sector. FMEA is a two or three parts study, with failure modes examining the manner in which an item or a piece of equipment potentially fails to meet or deliver the intended function and the associated requirements. This may include failure to perform a function within defined limits, inadequate or poor performance of a function or the occurrence of an unintended or undesired function (Carlson, 2014). The effects analysis examines the consequence of such a failure on the system, the people or the environment. This may be an identification of the top-level effects or multi-levels effects. There could be more than one effect for each failure mode but usually the FMEA team would concentrate on the effect with the most serious impact for the analysis. If the criticality of the component is to be considered, then the process becomes FMECA (Failure Mode, Effects and Criticality Analysis).

FMEA has its origin in the military and was developed to study problems that may occur from a system malfunction. It was first used by the US Army in the 1950s as a military procedure under the title MIL-P-1629 "Procedure for Performing a Failure Mode, Effects and Criticality Analysis" (Calixto, 2016). Navy-Air then turned it into standard MIL-STD-1629 in 1974 (Cameron *et al.*, 2017). The method was used for aerospace design and in the following decades other industrial sectors begin to apply the model. It is a qualitative approach to clear up failure modes in equipment analysis where there is insufficient information and data to carry out a quantitative analysis. In simplistic terms, failure modes and their effects shall be identified for a piece of equipment which is then followed by identifying causes and the required control measures to prevent the failures and implement the actions necessary. The process can also be used as an initial screening tool to identify high-risk events for further detailed analysis.

The model is a bottom-up approach to hazard analysis and is a powerful tool for a complete risk model (Singh, 2014). Unlike hazard and operability study (HAZOP), which is operational function-oriented, FMEA is oriented towards components, their functions and potential failure. It supports qualitative hazard identification decisions at design stage or other stages where there is insufficient information or when there is a lack of data for quantitative hazard identification.

The FMEA process is summarised in Figure 3-2.

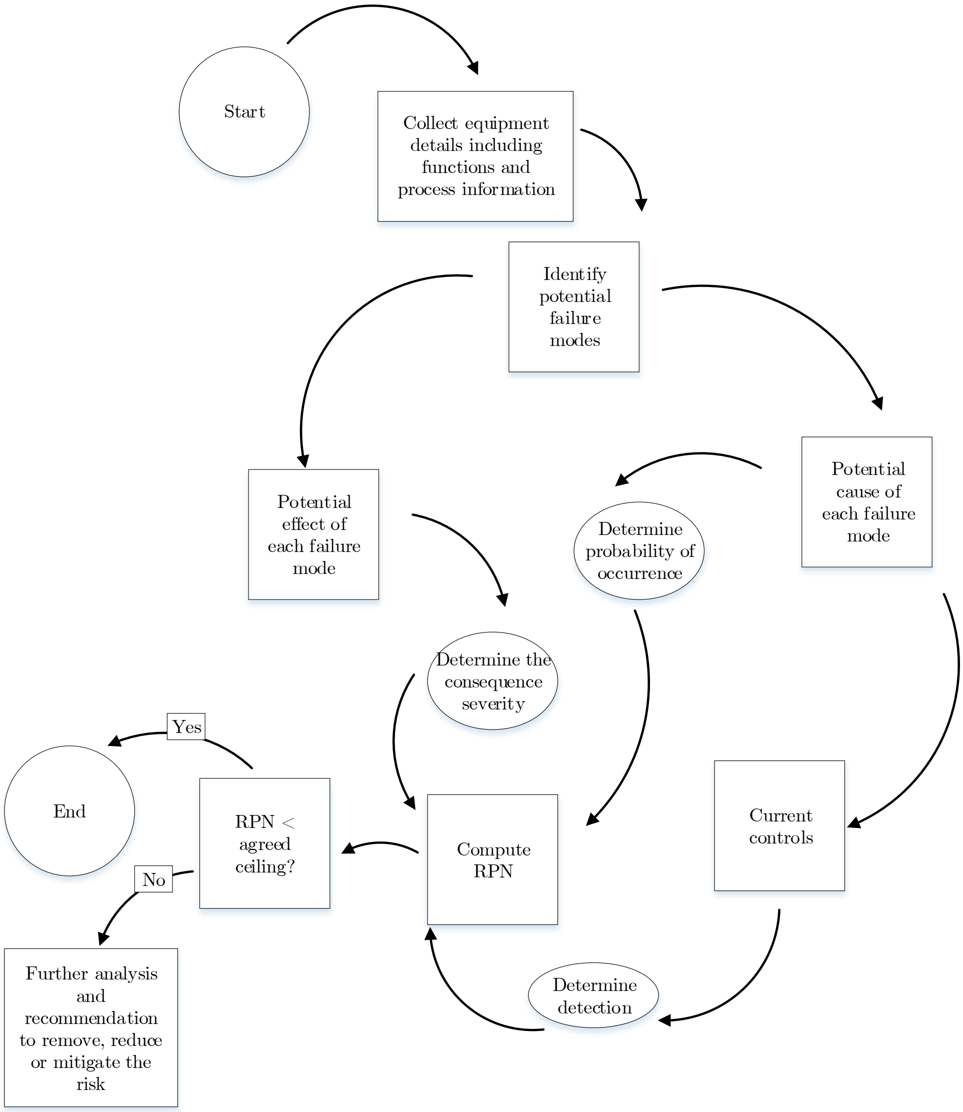


Figure 3-2: Example of Traditional FMEA Process

Examples of pipeline failure modes include corrosion, external damage and material defects. The severity could be marginal, critical or catastrophic and it is linked to the 'effects' numbers.

The FMEA can be applied during all stages of the project lifecycle, including design, installation, operations and decommissioning. FMEA types include product Development FMEA (DFMEA), Process FMEA (PFMEA), and System FMEA (SFMEA).

FMEA, when used during the design stage, has the potential to prevent failures thus avoiding a costly redesign, or enabling weaknesses to be identified and rectified before going on-site. The FMEA has a qualitative risk prioritisation RPN (Risk Priority Number) which is a product of the three characteristics of failure Likelihood, consequence Severity and failure Detectability. The RPN gives a hierarchy of the criticality of the failures identified and can be arrived at by allocating qualitative numbers to the three criteria, often based on expert elicitation, loss data and previous experience of the assembled team. Each of the three criteria has a numerical ranking which is associated with the qualitative explanation for each of the numbers and is usually agreed with the assembled team before the commencement of the analysis. Examples of a typical ranking for the three criteria are shown in Table 3-1, Table 3-2 and Table 3-3 (BSI, 2018a; Norske Veritas, 2010).

Table 3-1: Failure Likelihood Qualitative Ranking

Likelihood Level	Description	Probability	Ranking
Very Low	Failure unlikely	$\leq 1x10^{-5}$	1
Low	Relatively few failures	$1x10^{-4}$	2
Average	Occasional failures	$1x10^{-3}$	3
High	Repeated failures	$1x10^{-2}$	4
Very High	Failure is almost inevitable	$\geq 1x10^{-1}$	5

Table 3-2: Failure Consequence Severity Qualitative Ranking

Severity Level	Description	Ranking
Negligible	A failure mode which could potentially degrade the system's functions but will cause no damage to the system and does not constitute a threat to life or injury.	1
Marginal	System operational with minor performance degradation.	2
Moderate	A failure mode, which could potentially degrade system performance function(s) without damage to system or threat to life or injury.	3

Severity Level	Description	Ranking
Critical	A failure mode which could potentially result in the failure of the system's primary functions and therefore cause considerable damage to the system and its environment, but which does not constitute a serious threat to life or injury.	4
Catastrophic	A failure mode which could potentially result in the failure of the system's primary functions and therefore cause serious damage to the system and its environment and/or personal injury.	5

Table 3-3: Failure Detectability Qualitative Ranking

Detection Level	Description	Ranking
Highly Likely	Controls will almost certainly detect failure.	1
Likely	High chance for the design controls to detect failure.	2
Reasonably Likely	Reasonably likely chance for the design controls to detect failure.	3
Unlikely	Remote chance for the design controls to detect failure.	4
Highly Unlikely	Very remote chance for the design controls to detect failure.	5

3.2.1.1 FMEA Assessment Steps

The FMEA assessment steps (Carlson, 2014) include:

i. Define system boundaries for analysis including identifying system or subsystem being analysed.

ii. Understand the system or the item requirements and functions. Collect information on the item, its process disaggregation, failure history if available, manuals and Piping and Instrumentation (P & I) diagrams. If possible and if the information is available, conduct a Pareto analysis of the failure frequencies.

iii. Define the assessment criteria and agree with the participants, including the ranking to use.

iv. Determine each item's potential failure modes.

v. Determine the causes of the failures for each mode.

vi. Determine the effects and consequence of the failure for each mode.

vii. Establish item's Severity (S) score.

viii. Determine item occurrence Likelihood (L) score.

ix. Determine item Detectability (D) score.

x. Assess the risk priority (RPN) for each failure mode.

xi. Assess whether the risks are within an acceptable range or not.

xii. Develop remedial measures to eliminate or mitigate the potential fault or failure.

xiii. Re-assess a revised risk priority for the failure modes.

3.2.1.2 Shortcomings of FMEA

Although the FMEA process is very powerful and widely adopted in the industry, it has many shortcomings which reduce its usefulness. The shortcomings are summarised below.

Subjectivity: the process relies on the subjective judgement of the team members in the absence of data for full quantitative analysis, or where the number of failure modes is such that quantitative analysis is not possible.

The subjectivity of the process means that two separate teams assigned to undertake FMEA on the same equipment might come up with completely different results.

RPN duplication: the process often results in many duplicate RPN values representing different combinations of Severity, occurrence Likelihood and Detectability ranking. This may give a misleading conclusion, implying those risks have the same priority whilst they may have widely different priorities in reality. For example, if two events each have a Likelihood (L), Severity (S) and Detectability (D) of 5, 1, 10 and 2, 25, 1 respectively, they both will have a RPN of 50, which implies the same level of attention is required to mitigate the two risks even though they may be different. This may cause misapplication of limited resources and or cause a high-risk failure mode to be missed.

Disproportionate impact of small variation: small variations in the rating of one failure factor may have a significant effect on the RPN depending on the value of other factors (Liu *et al.*, 2011). For example, a change in the Detectability (D) factor from 1 to 2 will have little effect on the RPN if Likelihood (L) and Severity (S) both have lower values of, for example, 1 and 2. However, if S and L have values of 10 and 10, the change of the D value from 1 to 2 will double the RPN value from 100 to 200.

Weighting: another weakness of FMEA is the assumption that all three failure factors contribute in equal measure towards the risk factor (RPN) of the event. This is simplistic and in practice is unlikely to be the case in most circumstance. The Severity failure factor is often more important than other failure factors, which is why practitioners would often look at the Likelihood and Severity columns of the FMEA in isolation in addition to looking at the overall RPN.

Non-linear failure modes relationship: the relationship between the numerical ranking of the failure factors is not linear. For illustration, Table 3-1 and Table 3-2 show a linear relationship between the failure Likelihood value and consequence Severity, in terms of levels and ranking. However, if both Likelihood and Severity are compared with the failure's Detectability - Table 3-3 – then it shows an inverse relationship between the levels and ranking. For example, whilst ranking 1 for failure Likelihood is "very low" the equivalent ranking for Detectability is 5 which is "highly unlikely".

Lacking natural language synthesis: The current measure of using numerical rankings to score failure Likelihood, Severity and Detectability which, though precise, can be inaccurate and difficult to assign in the absence of quantitative data. Natural language utilisation could be preferable for practitioners and operatives, especially in developing countries, where the field operating staff are unlikely to be numerate and would struggle with linking an arbitrary number with the state of a piece of equipment's potential failure Likelihood, Severity or Detectability.

A modified FMEA process that addresses some of these limitations is required to improve the effectiveness of the process and ensure the FMEA continues to be fit for the future. Integrating Fussy Set and Grey Theory would address some of the shortcomings.

3.2.2 Fuzzy Set Theory (FST)

FST was proposed and developed by Lofti Zadeh (1965) whilst at the University of California Berkeley. The theory was initially intended for application on industrial controllers but this has advanced and found application in wider fields, including engineering, operational research, mathematics, expert systems, pattern recognition, robotics, medicine and computer science (Zimmermann, 2010).

Its application in the area of risk analysis in general and in the risk assessment of safety systems in geographical areas where there is limited or unreliable data can be revolutionary. This is because FST can explicitly accommodate the subjective and the uncertain nature of the input variables. The main benefit of FST is its introduction of the continuum of grades of membership and gradual transition between states. This enables and extends the Boolean logic from the traditional (crisp) variables to human intuitive fuzzy variables that allow for measurements and observation of uncertainties. Whilst crisp sets allow for full membership or non-membership at all, the fuzzy sets allow for partial membership, assigning a degree that ranges from 0 to 1.

Equally significant is the flexibility offered by the FST in allowing the use of linguistic variables in estimating probabilities. The use of linguistic variables encompassing words and sentences in a natural or artificial language, as opposed to quantitative variables, ensures complex or ill-defined phenomena are better characterised and represented (Lavasani, 2010; Pillay & Wang, 2003).

The weakness of Boolean logic or the classical set is that they are mutually exclusive; an object can either belong to one set or not. This set of precision assumes that the structures and parameters of the model are clearly known and there is no ambiguity or vagueness. This bivalent membership is represented mathematically by:

$$X_A = \begin{cases} 1, x \in A \\ 0, x \notin A \end{cases} \tag{3-1}$$

The above indicates that element x in universe X can only be a full member of set A or not. With the fuzzy set, the membership can be denoted as:

$$\bar{A} = \{(x, \mu_{\bar{A}}(x) \mid x \in X) \ \textit{and} \ 0 \leq \mu_{\bar{A}}(x) \leq 1\} \tag{3-2}$$

where $\mu_{\bar{A}}(x)$ is the membership function of the element x in universe X for the fuzzy set $\bar{A}$. A $\mu_{\bar{A}}(x)$ of 1 indicates full membership, and 0 indicates no membership. Any number in between represents a degree to which $\mu_{\bar{A}}(x)$ belongs to a certain membership class.

Fuzzy numbers can be represented by different graph shapes depending on the application context. The most common of the fuzzy numbers are triangular and trapezoidal. This study adopts the triangular numbers as they are simple to compute and useful in supporting illustration and information processing. These can be represented as follows:

$$\mu_{\bar{A}}(x) = \begin{cases} 0, x \leq b \\ \dfrac{x-b}{m-b}, x \in (b, m) \\ 1, x = m \\ \dfrac{c-x}{c-m}, x \in (m, c) \\ 0, x \geq c \end{cases} \tag{3-3}$$

where m is the mean value, b and c are the lower and upper bounds respectively, for the values of $\mu_{\bar{A}}(x)$ above zero. Figure 3-3 shows the graphical representation of the triangular fuzzy numbers.

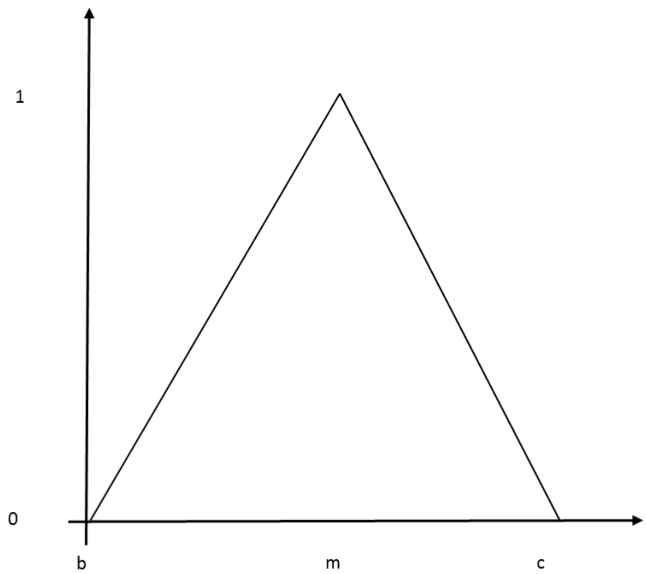


Figure 3-3: Graphical Representation of Triangular Fuzzy Number

There are various operations that can be carried out on triangular fuzzy numbers including addition, subtraction, multiplication, division and inverse. For example, if there are two fuzzy numbers $\bar{A}_1 = (b_1, m_1, c_1)$ *and* $\bar{A}_2 = (b_2, m_2, c_2)$, their basic operations are as below:

$$Addition: \bar{A}_1 \oplus \bar{A}_2 = (b_1, m_1, c_1) \oplus (b_2, m_2, c_2) = (b_1 \oplus b_2, m_1 \oplus m_2, c_1 \oplus c_2) \tag{3-4}$$

$$Subtraction: \bar{A}_1 - \bar{A}_2 = (b_1, m_1, c_1) - (b_2, m_2, c_2) = (b_1 - b_2, m_1 - m_2, c_1 - c_2) \tag{3-5}$$

$$Mutiplication: \bar{A}_1 \otimes \bar{A}_2 = (b_1, m_1, c_1) \otimes (b_2, m_2, c_2) = (b_1 b_2, m_1 m_2, c_1 c_2) \tag{3-6}$$

$$Division: \bar{A}_1 \div \bar{A}_2 = (b_1, m_1, c_1) \div (b_2, m_2, c_2) = \left(\frac{b_1}{b_2}, \frac{m_1}{m_2}, \frac{c_1}{c_2} \right) \tag{3-7}$$

$$Inverse: \bar{A}^{-1} = (b, m, c)^{-1} = \left(\frac{1}{b}, \frac{1}{m}, \frac{1}{c} \right) \tag{3-8}$$

$$change\ of\ sign: -\bar{A} = -\left(b, m, c\right) = \left(-b, -m, -c\right) \quad (3\text{-}9)$$

3.2.3 Grey Relations Theory (GRT)

The proposed approximate reasoning approach for this work is GRT. The theory was developed by Deng (1989; 1982) and addresses decisions characterised by incomplete information, incorporating known and unknown variables. It also explores system behaviour using relational analysis and model construction, and deals with uncertain systems with partially-known information through generating, excavating and extracting useful information from what is available (Liu *et al.*, 2016). GRT can also be used to analyse relationships between discrete qualitative and quantitative series whose components are existent, countable, extensible and independent (Zhou & Thai, 2016).

As uncertainty and poor information pervades every aspect of society, GRT receives a wide application in different fields including agriculture, medicine, geography traffic and the judicial system (Julong, 1989)

GRT application within a modified FMEA has been shown in a number of works, (Chang *et al.*, 1999; Pillay & Wang, 2003; Zhou & Thai, 2016); this is made possible as FMEA has all the characteristics that enable GRT to be applied. Its major benefits include the ability to assign different weighting coefficients to the failure factors and that it does not require a utility function of any form.

The building of the model involves multiple stages as shown in detail in Chapter 4, including establishing a comparative series, a standard series and calculating the difference between the two series. Using the Chen and Klein formula (Chen & Klein, 1997), the comparative series formula is shown below as Equation 3-10.

$$K(x) = \frac{\sum_{i=0}^{n}(b_i - c)}{\sum_{i=0}^{n}(b_i - c) - \sum_{i=0}^{n}(a_i - d)} \quad (3\text{-}10)$$

$K(x)$ is the comparative series, a_i and b_i are the middle numerical values of the selected linguistic variable, d is the maximum membership function, c is the minimum membership function, a_0 is the minimum numerical value of the linguistic variable and b_0 is the maximum numerical value of the linguistic variable. n is the number of decision factors.

The next step is the determination of the Grey Relations Coefficient, represented as $\gamma\left(x_0(1), x_n(1)\right)$, which can be obtained using Equation 3-11 below for each Risk factor of the failure modes identified.

$$\gamma\left(x_0(m), x_n(m)\right) = \frac{\min_n \min_m |x_0(m) - x_n(m)| + \zeta \max_n \max_m |x_0(m) - x_n(m)|}{|x_0(m) - x_n(m)| + \zeta \max_n \max_m |x_0(m) - x_n(m)|} \qquad (3\text{-}11)$$

where $x_0(m)$ is the value from the standard series and can either be the minimum or maximum value; $x_n(m)$ is the value from the comparative series and also can be the minimum or maximum. ζ is an identifier and can be assumed as 0.5 (Julong, 1989). Finally, the Degree of Relations and ranking of the factor is carried out using the following equation

$$\Gamma(x_i, x_j) = \sum_{k=1}^{n} \beta_k \gamma\{x_i(k), x_j(k)\} \qquad (3\text{-}12)$$

where β_k is the weighting coefficient for the failure factors and $\gamma\{x_i(k), x_j(k)\}$ is the Grey Relation Coefficient, as obtained from Equation 3-11. The sum of all weighting coefficients $\sum_{k=1}^{n} \beta_k$ shall be equal to unity.

3.2.4 Modified FMEA

The traditional FMEA, as outlined earlier, whilst simple and widely adopted in the industry, has a number of weaknesses that makes its outcome inconsistent and may inadvertently result in directing limited resources to wrongly prioritised risks.

To address these shortfalls, a modified FMEA is proposed, using a combination of FRB and GRT approaches. These approaches would correct some of the flaws in the traditional FMEA by ensuring that each expert and factor can be assigned a weighting, and further expand the RPN so that different risk implications are outlined for events with similar RPN values when assessed using the traditional FMEA (Pillay & Wang, 2003).

3.3 Failure Likelihood

Once the failure sources have been identified, the probability or likelihood of a failure arising from such failure sources is estimated using a Bayesian Network model as part of the pipeline risk assessment process.

The model input will be obtained by a combination of loss of databases and experts' elicitation. The data used is selected based on its suitability and in discussion with the domain matter experts. The BN model has undergone a series of verification, validation and sensitivity analyses to ensure a robust model structure and reliable results.

3.3.1 Bayesian Network

Bayes' Theorem (also known as Bayes' Rule or Bayes' Law) is one of the probability theories credited to Thomas Bayes in 1763, with further input from people such as Laplace and Bernoulli (Olshausen, 2004). At its early stages, the Theorem was controversial in the statistics community and therefore never reached its full potential for nearly two centuries. The Theorem has experienced a renaissance in the last few decades resulting in its wide application in different fields, ranging from computing to engineering and medicine.

Bayesian Networks (BNs) are the Directed Acyclic Graph (DAG) that encodes Conditional (or Node) Probability Distribution (CPD) of the underlying variable. BNs have two components, the physical graph structure that shows the interconnections between nodes and the quantitative part that encodes the probability distribution.

3.3.1.1 Conditional Probabilities

Bayesian Networks use the conditional probability concept of statistics, among other concepts, to represent the relationship between the discrete events or variables, employing either CPD or joint probability distribution (JPD).

Events that interact within a given sample space can be best shown in a Venn diagram in Figure 3-4. In the diagram, the two events, X and Y, interact in a sample space Z. The sum of the two events, termed as a union, represents the probability that both events occurred. This is called combined probability and is written as $P(X \cup Y)/Z$ in probability theory, that is the probability of X union Y given Z. Conversely, to find out the commonality of X and Y, which is where the two events overlap, the intersection rule is used. For the probability of the two events intersecting, called a joint probability, the written form $P(X \cap Y)/Z$ is used.

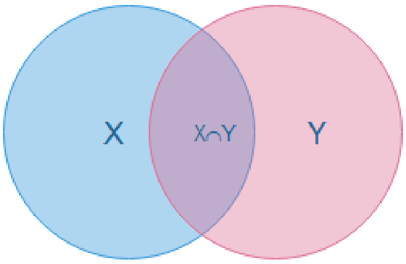


Figure 3-4: Venn Diagram

The conditional probability of events can thus be derived from the above. For dependent events - those events whose outcome influences the probability of the other - a general multiplication rule is used to derive the probability equation.

$$P(X \cap Y) = P(Y) \cdot P(X / Y) \qquad (3\text{-}13)$$

Assuming both *X* and *Y* are interchangeable, that is, it does not matter which one is *X* event and which one is *Y* event, then the equation can be rewritten as below.

$$P(X \cap Y) = P(Y) \cdot P(X / Y) = P(X) \cdot P(Y / X) \qquad (3\text{-}14)$$

Equation 3-14 is termed the Bayes Theorem and both *P(X/Y)* and *P(Y/X)* are the conditional probabilities, that is, the probability of *X* given *Y* and the probability of *Y* given *X*. It means a probability that one event is happening given that the other has already happened. The conditional probability forms the foundation of the Bayes Theorem, in that it is the factors that get updated whenever new evidence is obtained, to become posterior.

3.3.1.2 Bayes' Theorem

Bayes' Theorem relates to conditional and marginal probabilities of events *H* and *E*, for instance. It describes the probability of an event based on the prior knowledge of related events or conditions. The Theorem interprets probability as a measure of a degree of belief. This degree of belief is then used to account for evidence given a certain proposition.

The Theorem is developed from the conditional probability product rule as outlined in Section 3.3.1.1. Assuming the *H* event is the hypothesis and *E* is the evidence and we want to assess the relative belief degree of *H* given *E*, the Bayes Theorem probability (*P*) is invoked as *P(H/E)*, which is called probability of *H* given *E*. The Bayes Rule is presented as shown below (Eleye-Datubo, 2005):

$$P(H/E) \cdot P(E) = P(E/H) \cdot P(H) \qquad (3\text{-}15)$$

Dividing through and making the *P(H/E)* the subject gives Equation 3-16.

$$P(H/E) = \frac{P(E/H) \cdot P(H)}{P(E)} \qquad (3\text{-}16)$$

P(H) is called the *prior or marginal* probability of *H* and represents the state of knowledge of *H* at the initial stage before the evidence is considered, whilst *P(H/E)* is called the *posterior* probability and represents the updated knowledge given the evidence *E*. *P(E/H)* is the likelihood and also referred to as the *conditional* probability of *E* given *H*. *P(E)* is the marginal probability of *E* and the evidence to enable *P(H)* to be updated. The inverse of the derivation is taken as the normalising constant. Linguistically, Bayes' Theorem can be represented as:

$$Posterior = \frac{Likelihood \times Prior}{Evidence} \tag{3-17}$$

For sets of Evidence (*E*) variables, a joint probability distribution of a hypothesis (*H*), given variables E = {e_1, e_2,.........e_n} is computed using the conditional probability rule as:

$$P(H/e_1, e_2, ...e_n) = \frac{P(e_1, e_2, ...e_n/H) \cdot P(H)}{P(e_1, e_2, ...e_n)} \tag{3-18}$$

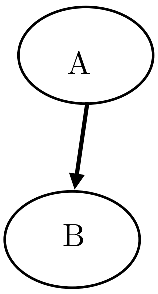
Bayes' Rule models a probability that updates beliefs about uncertain parameters given new data. Once new evidence is observed, the prior probability is updated by carrying out posterior probability analysis. It is noted, though, that not all Bayesian researchers apply the rule. For instance, Vose (2008) has shown that some analysts re-evaluate the prior whenever new data becomes available, effectively deferring the application of Bayes' Rule to an indefinite future. However, as a general rule, Bayes' Rule entails a loop process of continuous updating of the hypothesis (*H*) as new evidence (*E*) emerges. As more evidence is observed, the influence of the prior beliefs reduces in significance; given adequate evidence, the results of the Bayesian Rule approach that of the frequentist approach.

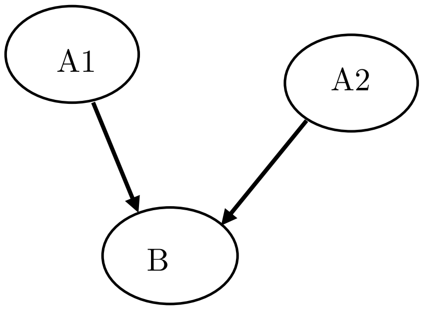
3.3.1.3 Bayesian Networks Formulation

A Bayesian Network is a tool that models and reasons with uncertain beliefs. A BN is described as a network of nodes and directed edges or arcs that outlines the causal relationship between random variables. It depicts a graphical probability model, DAG, that holds the CPD at its nodes based on the influence from the arcs. The DAG is so called due to its directed edges and non-directed cycles of the graph, implying that it is impossible to return to any point when following arrows in the graph.

Generally, a Bayesian Network over variable B is a pair of DAG and a set of Conditional Probability Tables (CPTs), with one CPT for each variable as b, and its parent as a, for example. This can be written as $C_{B|A}$ and maps each instantiation of $b\boldsymbol{a}$ to a probability $\theta_{b|a}$, such that $\sum_x \theta_{b|\boldsymbol{a}} = 1$ (Darwiche, 2008). The upper-case letters represent variables, lower-case letters represent individual values and bold lower-case letters represent an instantiation of the values.

The qualitative component of the BN is the DAG, which consists of nodes and edges. The nodes represent variables of interest and the DAG provides the directed influence amongst the nodes. The relationship is represented by the connecting edges with the arrow showing the influence direction. The connection types depict a dependence or independence relationship. Figure 3-5 shows the principles of the two types of relationships.





(a) (b)

Figure 3-5: Bayesian Networks Example with Conditionally Dependent (a) and Independent (b) DAG.

In Figure 3-5(a), B which is the child node is conditionally dependent on A which is the parent node. In Figure 3-5(b), A1 is conditionally independent of A2.

3.3.1.4 Bayesian Networks Structural Properties

Bayesian Networks have a defined structural property that propagates conditional dependency which determines what node is updated given new evidence. The arc structure linking the variables designates the dependency as a cause-and-effect relationship. Understanding the different types of relationships between variables and how they are structured is key to determining how to build the directed arcs linking the variables; it also enables the identification of the relevance of the variables' relationship visually, without the need for mathematical computation.

The DAG structure explicitly shows dependence or independence relationship amongst variables; this forms the basis for the formulation of a powerful determinant of conditional independence called directional separation or d-separation. d-separation will be discussed further below.

To understand the different types of connections topology and formalise the different notions of conditional independence, the three ways the links can be directed, namely serial connection, diverging connection and converging connection, are briefly described below (Fenton & Neil, 2012).

<u>Serial Connection</u>

Serial Bayesian Networks connection propagates causal and evidential inference; this could be either forward propagation, in which case it is causal, or backward propagation, in which case it is evidential. Figure 3-6 gives an example of a serial connection. Assuming A1 represents pipeline loss of containment due to malicious intent, A2 represents pipeline rupture and B represents oil volume spilled. Supposing there is evidence of a malicious attack on the pipeline (that is, there is evidence for A1), that evidence will inform the belief that the pipeline may be ruptured (A2) and also the oil has spilled (B). It can be concluded that the evidence in A1 has transmitted through to A2 and B.

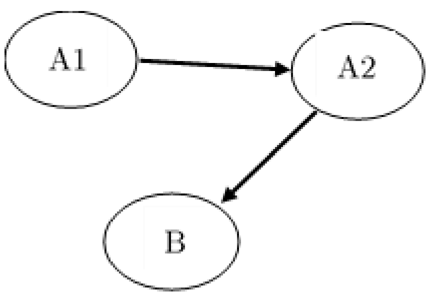


Figure 3-6: Serial Connection Example

If we already have hard evidence (also referred to as instantiation) of a pipeline rupture (A2) however, then any evidence or knowledge about A1 becomes irrelevant to B, as the hard evidence in A2 blocks the path of A1 to B. Any information about A1, after evidence of A2, will not affect our belief in the oil volume spilled. This is called conditional independence and is formally written as A1 and B are condition-independent given A2.

Diverging Connection

In diverging connections, referring to Figure 3-7, the evidence is transmitted from the central node (A2) to the diverging nodes A1 and B. Continuing on the analogy for the serial connection, assuming A2 represents pipeline failure, A1 represents environmental damage resulting from the spill and B represents a fire or explosion consequent upon the release. Any evidence that becomes apparent about pipeline failure (A2) is propagated on the belief of both environmental damage (A1) and of a fire or explosion (B). If further evidence, for instance, becomes apparent regarding A1, inserting that evidence in the network in addition to evidence of A2 already in place will not change the belief in B and vice versa.

Conversely, if there is no evidence on A2 and new evidence becomes apparent for A1, inserting that information into the network will result in the evidence being transmitted to A2 and onward to B.

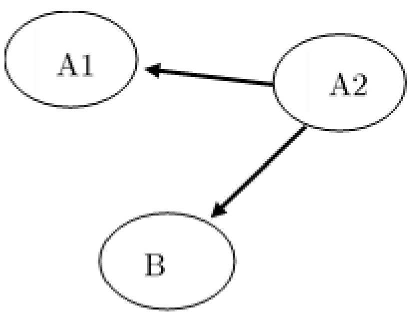


Figure 3-7: Diverging Connection Example

Therefore, in a BN diverging connection, A1 and B are conditionally independent given evidence in A2; information can be transmitted from A1 to B through the connection unless evidence is inserted for A2.

Converging Connection

The converging connection works in the opposite direction to the diverging connection. If we take Figure 3-8 as an example, assuming A1 is internal corrosion, B is external corrosion and A2 a failure due to combined corrosion. If there is no evidence that the pipeline has failed because of corrosion (A2), then any knowledge about A1 (internal corrosion) or B (external corrosion) will not change A2 and will not be transmitted further to A1 or B. However, if A2 is instantiated, then any further information on either of the two will be transmitted via A2 to the other.

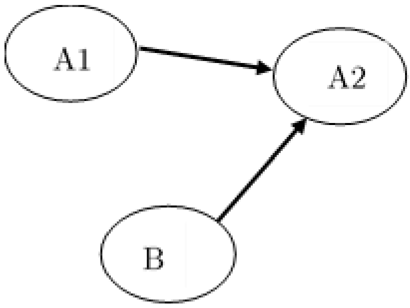


Figure 3-8: Converging Connection Example

Therefore, in a BN converging connection, A1 and B are conditionally dependent given evidence in A2; information cannot be transmitted from A1 to B through the connection unless evidence is inserted for A2.

d-Separation

In the topology of the connections outlined above, conditions leading to node connections being classified as dependent or independent have been established. This dependency notion of a pair of nodes is either called d-separation or d-connection.

Bayesian Network connections can be analysed to determine whether they are d-separated or d-connected. This principle, though not the main aim, can be used to inspect the influence of evidence on network propagation and hence determines whether the model is behaving as expected. It also helps generally to understand the BN algorithm better.

In the previous sections, we have established, based on three types of connections, that:

1. For serial connections, A1 is conditionally independent of B only when A2 is instantiated. This is written as $A_1 \perp B / A_2 = a_2$ where a_2 represents the instantiation (that is, evidence propagation) of the variable A_2.

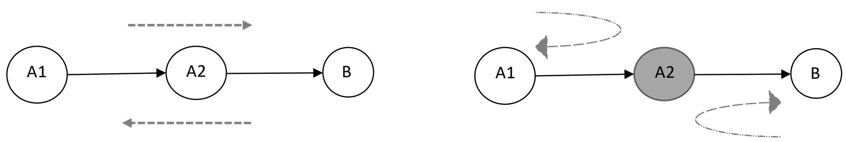


Figure 3-9: Evidence Propagation Serial Connection.
The greyed-out box is an instantiated variable. Information cannot be passed through A2 if instantiated

2. For diverging connections, as with serial connections, A1 is conditionally independent of B only when A2 is instantiated. This is also written as $A_1 \perp B / A_2 = a_2$ where a_2 represents the instantiation (that is, evidence propagation) of the variable A_2.

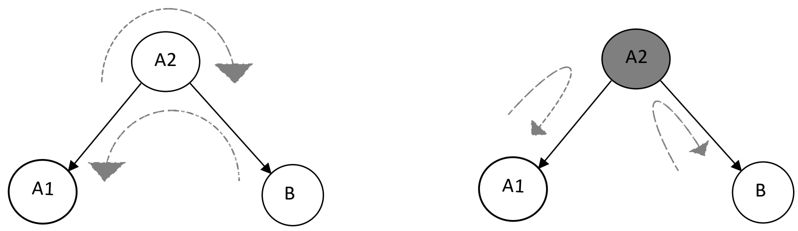


Figure 3-10: Evidence Propagation Diverging Connection.
In a diverging connection, information cannot be passed through A2 if instantiated

3. For converging connections, this is opposite of the diverging connections in that A1 is conditionally independent of B when A2 is not instantiated. This is written as $A_1 \perp B / A_2$

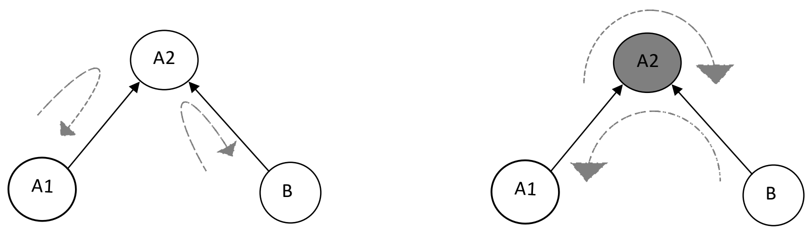


Figure 3-11: Evidence Propagation Converging Connection.
In a converging connection, information can only pass through A2 if it receives evidence

3.3.1.5 Node or Conditional Probability Table

Determining the prior probabilities for parent nodes *P(A1)* and *P(A2)* in Figure 3-5 is straightforward given hard data. However, it is not often straightforward to determine the conditional probability of the children nodes given the influence of the parent nodes, that is, *P(B|A1, A2)*. The Bayesian Theory approach would require the prior probability details for the distribution to be provided which sometimes could be obtained via field data or historical cases. In reality, however, this is difficult, especially in geographical areas where the basic data is often not available or not reliable and detailed data to form prior probabilities is rare. Even where the data is available, it is often not suitable as an input into the Bayesian Network analysis. To overcome this unreliability or lack of data, the subjective probability distribution is relied upon, often provided by domain experts' elicitation, representing their degrees of belief.

Different methods have been proposed to address the conditional probability distribution, including Noisy-Or (Jensen & Nielsen, 2007) and symmetric methods (Das, 2004). The symmetric method will be adopted in this research and, therefore, is described further below. The symmetric method is better suited for this research as it addresses some of the problems encountered when using the Noisy-Or method. The problems include its inability to consider multiple causes for the presence of a child node (leaky Noisy-Or is supposed to address that problem) and the fact that the model is asymmetric in nature, that is, it is only true in one direction.

Symmetric Model

The symmetric model provides input as a set of relative weights which maps the relative strength of the parent nodes as they influence child nodes. This is represented as a probability distribution table and grows linearly as the number of parent nodes increases. The symmetric model can take input either in the form of experimental data, expert elicitation or a combination of the two.

To understand the model, we will use the BN example given in Figure 3-5. Let's assume the two parents nodes A1 and A2 each has three states whilst the child node B has two states respectively. The possible states configurations at the child node CPT will be 3x3x2 which is 18. The task is to enter meaningful and relevant probability values for the 18 states. An 18-state CPT will be difficult to fill with hard data or experimental results; it could just be manageable with expert elicitation. However, if the states of the child node were to be changed to three from two, for example, the possible states' configuration will increase from 18 to 27. This will increase further as additional parent nodes are introduced or a new state is introduced, leading to a combinatorial explosion.

The use of a symmetric model would ease the input requirements for such a CPT and ensure objective and consistent input. Assuming the two parents nodes *A1* and *A2* all have three states of low (*L*), medium (*M*) and high (*H*), whilst the child note B has two states of yes (*Y*) and no (*N*), the influence of one of the parent states over the child state can be represented thus: $P(B{=}yes|A1{=}low) = P(B_y|A1_l)$. That is the probability of obtaining *yes* for *B* given *A1* is in the state of *low*; all other states of *A1* are assumed absent.

Since the model distributes the expert's opinion on the relative importance of each parent to its associated child node (normalised weight), the normalised space *($P(B_y \mid \hat{A}1_l)$)* stands for the relative importance of the first parent's state *L* to the child node assuming all other states do not occur. Thus:

$$\mathrm{P}(B = yes \mid A_1 = low) = P(B/\hat{A}1_l) = \frac{P(B/A1_l)}{\sum_{i=1}^{n} P(A_i)}$$

$$\vdots$$

$$\mathrm{P}(B = yes \mid A_n = low) = P(B/\hat{A}1_n) = \frac{P(B/An_l)}{\sum_{i=1}^{n} P(A_i)} \tag{3-19}$$

$$\therefore$$

$$P(B/\hat{A}1_l) + P(B/\hat{A}1_m) + ... + P(B/\hat{A}1_n) = 1$$

Using axioms of probability theory:

$$P((B/\hat{A}1_l) \cup (B/\hat{A}1_m) \cup .... \cup (B/\hat{A}1_n)) =$$
$$P(B/\hat{A}1_l) + P(B/\hat{A}1_m) + P(B/\hat{A}1_n) - P((B/\hat{A}1_l) \cap P(B/\hat{A}1_m)) - P((B/\hat{A}1_m) \cap P(B/\hat{A}1_h)) ....$$

If in a normalised space $(B/\hat{A}1_l),(B/\hat{A}1_m),..........,(B/\hat{A}1_n)$ remain disjointed, then

$$(P((B/\hat{A}1_l) \cap (B/\hat{A}1_m)) = P((B/\hat{A}1_m) \cap (B/\hat{A}1_h)) = ... = 0)$$

$$\therefore \tag{3-20}$$

$$P((B/\hat{A}1_l) \cup P(B/\hat{A}1_m) \cup .... \cup P(B/\hat{A}1_n)) = P(B/\hat{A}1_l) + P(B/\hat{A}1_m) + ... + P(B/\hat{A}1_n)$$

The influence of an individual parent node on the CPT of the child node for each Boolean parent node *Ar*, where r can be 1,2,…..n is obtained as below:

$$\mathrm{P}(B = yes \mid A_1 = yes) = \omega_1$$

$$\mathrm{P}(B = yes \mid A_2 = yes) = \omega_2$$

$$\vdots \tag{3-21}$$

$$P(B = yes \mid A_r = yes) = \omega_n$$

$$\sum_{r=1}^{n} \omega_r = 1$$

Equations 3-20 and 3-21 can be combined where there is symmetry (normalisation) to produce:

$$P(B / A_1, A_2 ....A_r) = \sum_{r=1}^{n} \varpi_r \tag{3-22}$$

where:

$\varpi_r = \omega_r$ if the state of the parent node r is identical to the state of the child,

$\varpi_r = 0$ if the state of the parent node r is not identical to the state of the child node.

<u>Analytic Hierarchy Process Pairwise Comparison</u>

To obtain the relative weight of the parent node as it affects the child node, the AHP model has been employed. The AHP, introduced by Thomas Saaty (1980), is an effective tool for dealing with decision-making, reducing complex decisions to a series of pairwise comparisons, helping to synthesise the results. AHP can take into account both objective and subjective aspects of decision-making and has a self-checking technique to ensure consistency of the output to help reduce biases.

It works by evaluating a set of given criteria against a set of alternative options amongst which the best decision is to be made. The AHP would generate a weight for evaluation criteria based on the decision maker's pairwise comparison of each criterion against the other. The more important the criterion, the higher its corresponding weight.

The next assessment involves assigning scores to each option in accordance with the decision maker's pairwise comparison of the options based on that criterion. For example, this study has developed a scale from one-ninth (1/9) to nine (9), with a value of 1 signifying parity (X is equally important as Y) with the two chosen criteria, where 1/9 signifies absolutely unimportant and 9 signifies absolutely important. Table 3-4 shows the numerical weightings and their corresponding description of entry X_{jk} showing the importance of the jth criterion relative to the kth criterion. If $X_{jk}>1$, then the jth criterion is more important than the kth criterion and the opposite is true if $X_{jk}<1$.

Next step in the AHP is the combination of the criteria weights and option scores, to determine the global score for each option and thus the consequent ranking. The global score for any option is the weighted sum of the scores it gets with respect to all assessed criteria.

Table 3-4: AHP Pairwise Comparison Weighting Numerical Values and Descriptors

Value of X_{jk}	**Description**
9	j is absolutely more important than k
7	j is strongly more important than k
5	j is more important than k
3	j is slightly more important than k
1	j is equally as important as k
2,4,6,8	Intermediate descriptors
1/3	j is slightly more unimportant than k
1/5	j is more unimportant than k
1/7	j is strongly more unimportant than k
1/9	j is absolutely more unimportant than k
1/2, 1/4, 1/6, 1/8	Intermediate values

For instance, to obtain a qualitative judgements from experts on pair of attributes A_i and A_j represented in a form of n x n matrix, Equation 3-23 below could be used (Koczkodaj & Szybowski, 2015).

$$A = (a_{ij}) = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a / a_{12} & 1 & \cdots & a_{2n} \\ . & . & \cdots & . \\ 1 / a_{1n} & 1 / a_{2n} & \cdots & 1 \end{bmatrix} \tag{3-23}$$

Where i, j = 1,2,3,…..,n and each a_{ij} is the relative importance of the attribute A_i to attribute A_j.

A weight vector, required to indicate the priority of each element in the pair wise comparison matrix, is represented in the Equation 3-24 below. The weight determines the overall contribution of each element to the decision making process.

$$W_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{t=1}^{n} a_{ij}}\right) \; (k = 1, 2, 3, \ldots n) \tag{3-24}$$

where a_{ij} is the entry of row i and column j in the matrix of order n.

to check for consistency of the calculated weights, Consistency Ratio (CR) value is assessed using equations from Saaty (1980).

$$CR = CI/RI \tag{3-25}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{3-26}$$

$$\lambda_{\max} = \frac{\sum_{j=1}^{n}\left(\frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}\right)}{n} \tag{3-27}$$

Where n is the number of items being compared, λ_{max} is the value of the maximum weight for n x n matrix, RI is the random index shown in Table 3-5 and CI is the consistency index as outlined in (Saaty, 1980).

Table 3-5: Saaty's RI Values

Order of Matrix	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Saaty's CI	0	0.58	0.9	1.12	1.24	1.32	1	1.45	1.49

CI with a value of above 0.10 indicated an inconsistent pairwise comparison whilst a CI with a value of 0.10 and below indicates a consistent pairwise comparison assessment and considered reasonable (Saaty, 1980).

3.3.1.6 Hugin Software

For this assessment, the Hugin software tool has been adopted (Hugin, 2018). The software implements the BN algorithms and makes it accessible to non-programmers using a graphical user interface (GUI) and an applicable programmer's interface (API). The Hugin software can be used to make higher number of nodes in BN modelling faster and error free. The graphical representation of the node properties in the software simplifies the process of network analysis and understanding the results. However using the Hugin software for BN modelling must obey the general BN principle, as with any other method (Wang & Trbojevic, 2007). The BN principles are:

i. The Bayesian Networks nodes must be mapped.
ii. The states of the nodes must be defined by, for example, observing what effect the evidence will have on the dependent variables.
iii. The probability of each state must be provided as that will determine the output probabilities.

3.4 Risk-Based Decision-making

Decisions in risk management and engineering involve the selection of different alternatives with each alternative having both qualitative and quantitative attributes. Generally, the qualitative attributes are assessed using human judgement, which has the weakness of being subjective and often associated with uncertainties as a result of ignorance, incomplete information and fuzziness. Therefore, decisions may not be properly made without fully taking into account all the related attributes whilst quantifying the uncertainties (Mokhtari, 2011; Yang & Xu, 2002; Wang *et al.*, 2006).

Different decision-making approaches that aim to capture and treat such uncertainties have been proposed; these include probabilistic and subjective approaches. Within the subjective methods, the Multiple Criteria Decision Methods (MCDM) have been widely used to solve practical challenges in engineering and particularly in risk, reliability and maintenance realms.

3.4.1 Evidential Reasoning

An MCDM can be described as a method of choice among decision alternatives in the presence of multiple and often conflicting criteria (Xu & Yang, 2001). The method considers the decision makers' preference structure and their value judgements. The judgements and preferences will inform the choice of the alternatives and by doing so, the multiple criteria will be analysed simultaneously (de Almeida *et al.*, 2015).

MCDM methods can be grouped into three generic categories:

- Utility-based or unique criterion of synthesis methods.
- Outranking methods.
- Interactive or multi-objective linear problems (MOLP) methods.

The unique criterion of synthesis methods uses an analytical combination of all criteria in order to produce a global evaluation or score for all alternatives and as such is determined based on a global score that synthesises all the criteria. These methods, for a deterministic set of consequences, may be referred to as multi-attribute (utility) value theory. The outranking methods are those that often produce a final recommendation with no scores for the alternatives but rather consider the incomparability relation and use that to produce a partial pre-order. ELECTRE (ELimination and Choice Expressing Reality) and PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) methods are good examples. MOLP methods are those associated with discrete or continuous problems These are often mathematical programming that deals with decision problems in which the optimisation of conflicting and multiple objective functions is the key. Decisions made with these methods are implicitly defined as a mathematical function constraint. The aim of MOLP is often to find a decision alternative that is as near to the ideal solution as possible and often associated with concepts like “distance from ideal” and “reference point” (Wierzbicki, 1980).

Most MCDMs handle problems quite well. However, when there is information uncertainty for a particular problem, it is often impossible for most MCDMs to assess it as they will only give it a single number output, which will not capture the uncertainty adequately (Shan, 2015). Different solutions have been proposed to address these concerns including Probability Theory (PT), Dempster-Shafer Theory and Fuzzy Set Theory.

Probability Theory can represent a subjective degree of belief or objective frequency and address uncertainty about the current knowledge by a probability distribution. The new knowledge is then learned by conditionalization. However, Probability Theory has limitations, such as its inability to adequately capture ignorance and the constraint that the sum probability of all possible states must be equal to one. Ignorance is captured in Probability Theory by assigning equal probabilities to all possible states; however, this can also be used to represent randomness and it is difficult to differentiate the two. On the second weakness that forces the sum probability of all states to be one, this invariably implies that a belief in one state must lead to a decrease in belief in another. This has been shown to be not necessarily the case in real life (Zadeh, 1965).

Dempster-Shafer Theory is also a powerful tool that was proposed to accommodate and quantify uncertainty to address the two limitations outlined under Probability Theory. However, studies have shown that when this method is applied to problems requiring aggregating conflicting evidence, the ensuing results may be irrational. The assessment for certain problems can also result in an exponential increase in computational complexity (Buchanan & Shortliffe, 1984).

Fuzzy Set Theory, on the other hand, handles uncertainty by using fuzzy membership functions to represent imprecise information. Fuzzy Set Theory is discussed in detail in Section 3.2.2. It works well when applied to MCDM problems, however, the concern is how it defines information, rather than its measurements. Therefore when applied to measurement-oriented problems, the final fuzzy set - whose assessment is individually aggregated – find it generally difficult to arrive at any accurate prescription (Kangari & Riggs, 1989).

As a result of the above-mentioned weaknesses of the existing MCDMs, Evidential Reasoning (ER) has been developed, which is a modification of the Dempster-Shafer Theory. ER is considered a good alternative that addresses the weaknesses of Probability Theory and Dempster-Shafer Theory. It aims to provide a rigorous reasoning process for aggregating conflicting information. This is achieved by using an extended decision matrix in which each attribute of an alternative is described by a distributed assessment using a belief structure (Xu & Yang, 2001; Shan, 2015). For example, a distributed assessment for a quality of intervention measures to prevent pipeline loss of containment could be {(Excellent, 25%), (Good, 30%), (Average, 35%), (Poor, 10%), (Worst, 0%)}, which means that the intervention is taken as Excellent with a 25% belief degree, Good with a 30% belief degree, Average with a 35% belief degree, Poor with a 10% belief degree and Worst with a 0% belief degree. Using a belief structure approach, ER is able to deal with MCDM problems with uncertainties and the hybrid nature of the information.

The uncertainties relate to (Xu & Yang, 2001):

- The **absence of data**, where no data is available to assess an attribute. This results in the allocation of zero-sum total belief degrees in the distributed assessment for that attribute.
- The **incomplete description of an attribute**, where the data is partially available. This results in the allocation of the total sum of belief degrees in

the distributed assessment to be between zero and a hundred for that particular attribute.

- The **random nature of an attribute** is when some attributes are random in nature. This results in a probability distribution that will be transformed into degrees of belief in the distributed assessment of the attribute.

The hybrid nature of the information relates to:

- A mixture of data from incommensurable criteria.
- A mixture of data from qualitative and quantitative criteria.
- A mixture of data from deterministic and probabilistic criteria.

The ER method has been widely adopted, since its development, in MCDM problems such as engineering safety analysis (Liu *et al.*, 2005), pipeline leak detection (Xu *et al.*, 2007) and maritime safety and security (Wang *et al.*, 1995; Liu *et al.*, 2005) among many other applications.

Chapter 4. Modified FMEA Based Hazard Identification

Overview

Failure Mode and Effects Analysis (FMEA) has been used as a safety assessment tool in various industries, including oil and gas, for systems integrity assessment and as part of the risk assessment process. The results of the traditional FMEA, expressed as the Risk Priority Number (RPN), are often sufficient where historical data input is available and the data is reliable. However, even where data is available, the process is noted for its drawbacks as outlined in Section 3.2.1.2. In developing countries where data is lacking or unreliable, an improved and better approach could be ground-breaking.

This chapter proposes the application of a modified FMEA approach by FST based Fuzzy Rule Base (FRB) with linguistic terms and a Grey Relation Theory (GRT). The modified approach addresses some of the drawbacks of the traditional FMEA process and is more intuitive for field operatives and practitioners. It also allows for the incorporation of expert knowledge and experience into the model.

4.1 Introduction

Failure to detect, prevent and mitigate losses associated with pipeline systems can be attributed to an inadequate hazard identification process. Hazard identification is the first part of risk analysis and entails identifying sources of hazards, areas of impact and events that would result in unwanted releases, which could develop into fires, explosions or environmental damage. Inadequate hazard identification may be a result of applying wrong hazard identification tools, which may lead to a wrong diagnosis or non-identification of the hazards.

Lack of reliable data on the failure history, maintenance and management of the pipelines makes any hazard identification and risk analysis process difficult (Shan *et al.*, 2017). The use of a novel approach with the modified FMEA is shown in this chapter to be more appropriate under a scenario similar to Nigeria's pipeline systems, which lacks the data for a data-driven assessment (Iqbal, 2018).

Hazards associated with cross-country pipelines are varied and so are the resulting consequences, which include the loss of life, destruction of property and the environment, disruption to vital supplies, socio-economic setbacks and the loss of vital government revenue. The hazards of a pipeline system could be associated with the pipeline itself, the pigging apparatus, the pipeline manifold, the pumps, the metering package or the utility equipment. A fault, failure, blockage, leakage or loss of supply are some of the main hazards that can affect the pipeline system. The main contributors to pipeline failure in Nigeria include deliberate damage, soil erosion and lack of maintenance.

This chapter carries out detailed hazard identification of a selected section of Nigeria's cross-country pipeline – called 'Section 2B'. A detailed description of the system is given in Chapter 2.

4.2 Methodology

This modified hazard identification methodology is developed to provide a framework upon which the pipeline risk assessment work will be anchored. FMEA is used to identify, screen and rank hazards according to their perceived risk levels. This enables the risks that meet a certain threshold to be assessed further or mitigated. The FMEA process has been improved by modifying it to include Fuzzy Rule Set and Grey Relation Theory to enable a better and more refined ranking, using linguistic terms. This modified FMEA has been used for fishing vessel hazard identification and ranking (Pillay & Wang, 2003) and tanker equipment failure (Zhou & Thai, 2016), among other applications.

This subsection presents the general outline of the methodology and the steps involved in carrying out the analysis. Descriptions of the techniques used are given in Chapter 3. The methodology and the steps involved in carrying out the case study assessment are outlined in Section 4.2.1 for the FMEA, Section 4.2.2 for the Fuzzy Set Theory and Section 4.2.3 for the Grey Relation Theory. Section 4.2.4 provides the modified FMEA framework based on the combination of Sections 4.2.1, 4.2.2 and 4.2.3, including assessment steps and data/input required.

4.2.1 FMEA

The traditional FMEA has been used as the basis of the initial stage of the pipeline risk assessment. The method is then modified using the FRB and GRT as enumerated in Section 4.2.4. The FMEA approach provides the baseline for the study and affords comparison with the modified approach, so as to assess the potential improvements which the new approach may provide.

FMEA activity is often recorded in a worksheet or bespoke software. An example of the worksheet is given in Figure 4-1 and consists of eleven columns, from the identification of the system through to the safeguards in place.

The first column (S/N) in Figure 4-1 provides the number of failure modes that are being assessed. The number to be assessed depends on the complexity of the system being considered and the level of refinement required for the assessment.

The second column (System) identifies the system or the subsystem that is being assessed. This could be a unit or a whole complex. For the pipeline system that is being evaluated in this assessment, the entire system is divided into subsystems encompassing the geographical coverage of the pipeline and includes associated equipment like the pigging and the pumps.

The third column (Item) lists the number of items that are being assessed, which represents the equipment, listed in column five (Equipment), whose failure mode is to be identified and analysed. The fourth column (Event) represents an event, which is the failure mode identified in column six (Failure Mode). This would be the individual unit that is the subject of detailed analysis.

S/N	System	Item	Event	Equipment	Failure Mode	Cause	Detectability / Revealed	Effects - Local	Effects - System	Safeguards
1	2B	1	1	Oil Pipeline	Product Leak/Rupture	External leakage from pinhole, flange or following impact, welding failure, etc.	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Pipeline leak detection system, buried pipeline with impact protection at crossings, increased inspection.
2 1	2B	1	2 4	Oil Pipeline	Product Leak/Rupture 6	Deliberate - pipeline interdiction for product theft or vandalism	Pressure alarms, flow alarms, surveillance, third party 8 rting.	Flammable hydrocarbon pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take 10 em out of action for a long time	Pipeline leak detection system, theft and vandalism prevention e.g., by deep burying of pipeline with impact protection, regular patrols and adoption of technology aim at detering the threat.
3	2B	1	3	Oil Pipeline	Product Leak/rupture	Pipeline failure due to - corrosion - structural weakness	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Pipeline leak detection system, buried pipeline, providing adequate support where pipelines are exposed, regular inspection to monitor corrosion and identify and prevent failures .
4	2B	1	4	Oil Pipeline	Blockage	Line restricted by partial or complete blockage.	Pressure alarms, flow alarms	Reduced or no hydrocarbon flow in pipeline	Unable to operate pipeline or part of it or operation at reduced capacity.	Pressure alarms, flow alarms
5	2B	2	1	Pipeline Manifold/Block Valve	Product Leak/Rupture	External leakage from pinhole, flange or following impact, welding failure, etc	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Leak detection system, regular inspection
6	2B	2	2	Pipeline Manifold/Blo[illegible] Valve	[illegible]	Deliberate - interdiction for product th[illegible]	Pressure [illegible], flow [illegible] third	Flammable hydrocarbon pool	Unable to operate pipeline leading to [illegible]	Leak detection system, theft and vandalism [illegible] burying [illegible]

Figure 4-1: Example FMEA Worksheet (from main worksheet used for this work)

Column seven (Cause) outlines the cause(s) of the failure, including both primary and secondary causes. These include, for example, corrosion, structural failure and sabotage. The next column, column eight (Detectability), details the systems in place, if any, to detect or reveal the failure and includes provisions such as alarms, surveillance and third-party reporting. Columns nine (Effects – Local) and ten (Effects – System) summarise the effect of the failure event both local to where the event has taken place and systems-wide. Examples of such effects include leak, lack of flow and inability to operate the pipeline. The final column (Safeguards) provides the safeguards put in place to reduce the likelihood and the potential consequence of any failure event and includes, for example, leak detection, impact protection and burial depth of the pipes.

After the worksheet has been filled with the causes and their detectability, and the effects have been agreed, the numerical ranking is assigned as shown in Figure 4-2. Usually every member of the FMEA team will assign their ranking and the average is taken. The ranking for the three factors is then multiplied together to obtain the RPN.

S/N	Item ID	Event ID	Equipment Description/ Function	Failure Mode	Likelihood	Detection	Severity	RPN
1	1	1	Oil Pipeline	Product Leak/Rupture	2.3	2.7	3.3	21
2	1	2	Oil Pipeline	Product Leak/Rupture	4.0	1.3	4.3	23
3	1	3	Oil Pipeline	Product Leak/rupture	3.0	3.0	3.3	30
4	1	4	Oil Pipeline	Blockage	2.7	2.0	3.3	18
[illegible]	[illegible]	1	Pipeline Manifold/Block	Product Leak/Rupture	[illegible]	2.0	3.3	[illegible]

Figure 4-2: Example FMEA Results (from result summary sheet used in this thesis)

4.2.2 Fuzzy Set

4.2.2.1 Fuzzy Rule Base Method

The proposed Fuzzy Rule Base (FRB) method improves the traditional FMEA by doing away with the utility functions when determining the Likelihood, Severity and Detectability ratings during the assessment. It also offers a new way of determining the risk rankings of failure events. The new method – FRB – compensates for lack of data by integrating the experts' elicitation into the analysis to arrive at the results. The use of linguistic variables ensures the method aligns with natural or artificial language synthesis for decision making under uncertainty.

The process is achieved by following the proposed steps outlined in Section 4.2.2.2 through to Section 4.2.2.7 below.

4.2.2.2 Expert Selection

The first task of the assessment includes selecting and appointing multiple experts with relevant experience on pipeline operations and management or any other equipment being assessed. The expert selection process ensures that the broad spectrum of the equipment's life cycle is covered by their experience, including but not limited to, design, construction, operation, maintenance and process safety. The proposed experts being used for this study are all experienced in the pipeline industry, including those working for the pipeline infrastructure owner and operator, designer, contractor and regulator. Due to the differences in the relevance of their experience and competence, a weighting could be introduced for a holistic consideration of each expert's contribution. This can be achieved by using the following expression.

$$A(x) = \sum_{i=1}^{n} C_i a_i(x) \tag{4-1}$$

where

$$\sum_{i=1}^{n} C_i = 1 \tag{4-2}$$

C_i is the degree of competence of experts *i*, $a_i(x)$ is the given proposition and $A(x)$ is the weighted failure factor.

The weighting outlining the degree of competence of the experts is determined based on their relevant experience in pipeline design, operations and management. The weighting has been agreed on upfront by all the stakeholders participating in the study.

The next step is to agree on the assessment baselines with the selected experts, including the qualitative ranking of the Likelihood, Severity and Detectability ratings and their linguistic variables. The ranking could be 5-point or 10-point, depending on the agreed criteria. However, the 5-point ranking criteria will align with IF-THEN rules (Wang, 1997). For this study therefore, the 5-point ranking criteria will be used, as outlined in Table 3-1, Table 3-2 and Table 3-3.

4.2.2.3 Fuzzy Membership Function Construction

The next step is to set up the fuzzy membership functions for the Likelihood, Severity, Detectability and Risk factors. These membership functions will be based on the five linguistic variables equivalent to the qualitative ranking that was established in Section 3.2.

The fuzzy membership function will be developed with the experts' involvement and agreement. The selection criteria of the experts and the eventual membership function developed should be realistic and non-biased, resulting from the collective agreement of all the experts.

Using the experts' contribution, the membership function can be generated thus (Pillay, 2001): if *n* experts are asked for $x \in X$ to evaluate the suggestion that "x belongs to A" as either true or false, where A is a fuzzy set on X that represents a linguistic term associated with a given linguistic variable. For $x \in X$ value and assuming $a_i(x)$ represents the response of expert *i*, when the x value is true $a_i(x) = 1$ and if the x value is false $a_i(x) = 0$, then

$$A(x) = \frac{\sum_{i=1}^{n} C_i a_i(x)}{n} \tag{4-3}$$

could be taken as the probabilistic interpretation of the built membership function.

The five linguistic terms vary depending on the failure factor chosen. For example, the Likelihood factor has *very low*, *low*, *average*, *high* and *very high* as linguistic terms. The five linguistic terms have been chosen based on the guidance from (BSI, 2018a; Norske Veritas, 2010) and to align with the 125 IF-THEN rule (Wang, 1997). The full linguistic terms and their descriptions are given in Table 3-1, Table 3-2 and Table 3-3. The membership functions can be represented graphically for the three failure factors and the Risk factor, as shown in Figure 4-3, Figure 4-4, Figure 4-5 and Figure 4-6.

4.2.2.4 Brainstorming using Traditional FMEA Approach

The traditional FMEA approach is used to brainstorm on the failure factors by the selected experts using the linguistic terms. For each failure factor identified, each expert will assign a linguistic term for it covering the potential Likelihood, consequence Severity and its Detectability. Each of the linguistic terms assigned by the experts is then converted into ranking values and, together with the agreed weight of each expert, Equation 4-3 is used to determine the weighted ranking for each of the failure factors identified.

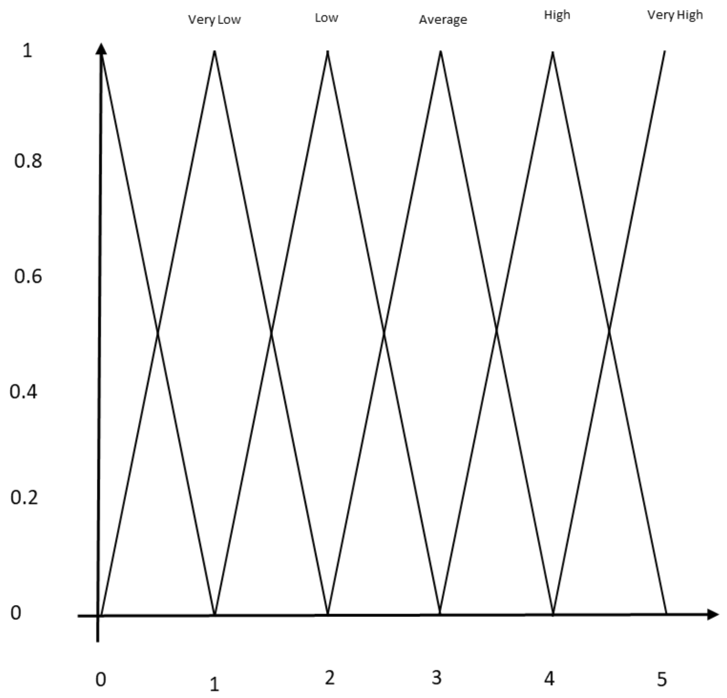


Figure 4-3: Membership Function for Likelihood

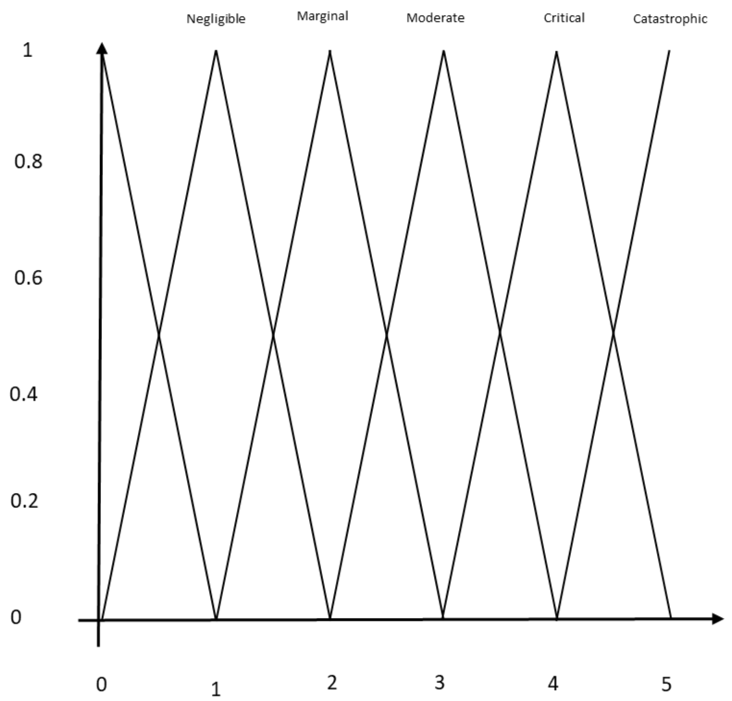


Figure 4-4: Membership Function for Severity

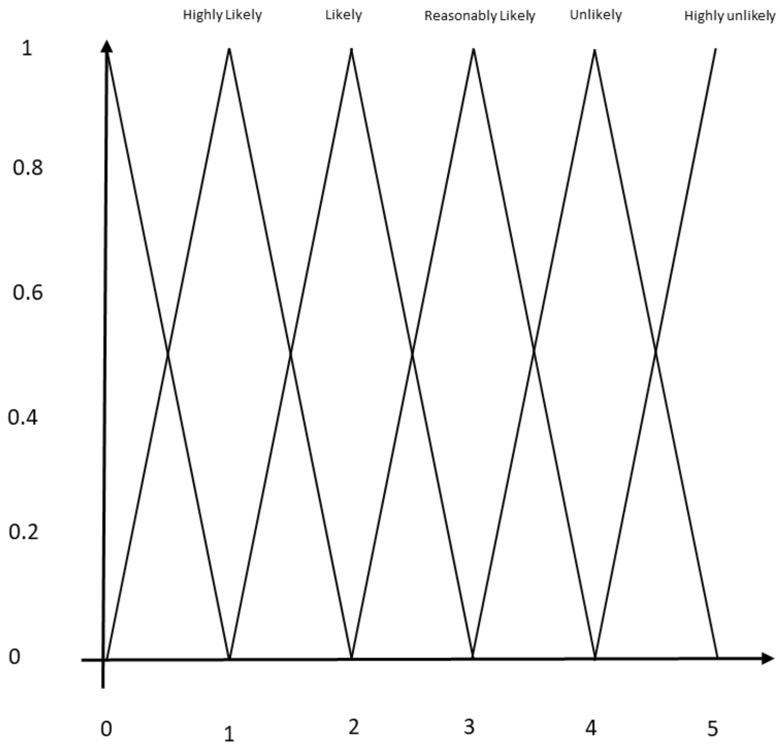


Figure 4-5: Membership Function for Detectability

4.2.2.5 Application of IF–THEN Rule

Once the experts provided their linguistic terms for each of the failure factors, those linguistic terms are converted into numerical values using Table 3-1, Table 3-2 and Table 3-3 and the average weighted values obtained for each of the potential failure factors. The membership function diagrams, outlined in Figure 4-3, Figure 4-4 and Figure 4-5, are then employed to obtain belief degree values. For example, if the crisp weighted value for the Likelihood of a potential failure is 2.3, the corresponding membership functions and belief degrees will be *0.67 low*, *0.33 average*.

The 125 IF-THEN rules base (Wang, 1997) is then invoked to obtain the consequent Risk linguistic variables for each of the failure factors identified. The IF-THEN rule provides structured statements by using continuous membership functions. The rule requires inputs, which are the three failure factors combined in a structured manner to give an output variable that determines the linguistic term and belief degree for the Risk priority. The Risk linguistic terms could be "0.5 *very low* and 0.5

low" or "0.1 *moderate* and 0.9 *high*". The 125 rule is derived from the combination of the five linguistic terms for the three failure factors, given a total possible combination of $5^3 = 125$. One of the novelties of this work is that it added belief structure to the consequent terms such that, for example, consequent terms for *very low* likelihood, a *likely* detection and *marginal* severity is *0.57 very low and 0.43 low*. Without belief structure the consequent terms would be *very low and low*. The same consequent linguistic terms are shared with other combinations like *very low* likelihood, *highly likely* detection and *negligible* severity. The belief structure ensure that each consequent term is unique to each combination and are mapped to that combination's risk profile. Appendix A shows the complete 125 IF-THEN rules, including how they have been developed, which is used to arrive at the Risk linguistic terms.

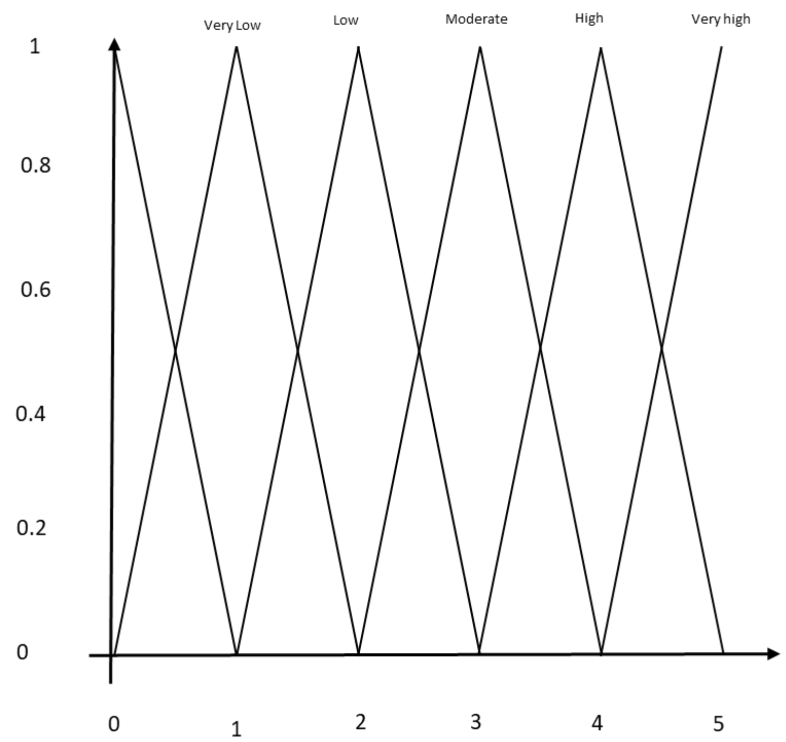


Figure 4-6: Membership Function for Risk Priority

The membership function diagram gives two outcomes of membership functions and belief degrees for each failure factor. For example, a crisp weighted value of

2.3 for a failure Likelihood will give *0.67 low* and *0.33 average* membership functions and belief degrees. If it is repeated for the three failure factors, this gives 6 membership functions and belief degrees, resulting in 8 IF-THEN rule combinations for each of the potential risk factors. Table 4-1 and Table 4-2 show an example assessment of one Risk factor.

Table 4-1: Membership Functions and Belief Degrees Example

Failure Factors	Ranking	Membership Function
Likelihood	2.3	0.67 low, 0.33 average
Severity	3.3	0.67 moderate, 0.33 critical
Detectability	2.7	0.33 likely, 0.67 reasonably likely

Table 4-2: IF-THEN Rules for an Example Potential Failure

	IF-THEN Rules			
	If **Likelihood** is	**Severity** is	**Detectability** is	Then **Risk** would be
1	low	moderate	likely	0.79 low, 0.21 moderate
2	low	moderate	reasonably likely	0.53 moderate, 0.47 low
3	low	critical	likely	0.58 low, 0.42 moderate
4	low	critical	reasonably likely	0.84 moderate, 0.16 low
5	average	moderate	likely	0.53 moderate, 0.47 low
6	average	moderate	reasonably likely	1 moderate
7	average	critical	likely	0.84 moderate, 0.16 low
8	average	critical	reasonably likely	0.76 moderate, 0.24 high

4.2.2.6 Truth Value of the Membership Function

Using the min-max inference method (Zadeh, 1992; Wang *et al.*, 2004; Dantsoho, 2015), a fuzzy membership function of the Risk factor is arrived at using the IF-THEN consequences. The minimum or truth values of the rule are assumed as the lowest non-zero belief degrees of the antecedents' rule for the failure factors. Those truth value belief degrees are then used as the consequent (Risk) values together with the linguistic terms. For example, if a potential Risk factor has *0.67 low* Likelihood, *0.33 likely* Detectability and *0.67 moderate* Severity, the fuzzy truth values for the consequent Risk factor will be the lowest combination of non-zero belief degrees as ((min (0.67, 0.33, 0.67, 0.79), *low*) and (min (0.67, 0.33, 0.67, 0.21), *moderate)* giving *0.33 low* and *0.21 moderate*. The Risk factor's consequent linguistics terms are obtained using the IF-THEN Rule. Table 4-3 provides truth values example based on the IF-THEN results from Table 4-2.

Table 4-3: Example of Truth Values for Consequent Risk Factors

	Minimum Values				
	If **Likelihood** is	**Severity** is	**Detectability** is	And the **Risk** is	Then **Min value of Risk** is
1	0.67, low	0.67, moderate	0.33, likely	0.79 low, 0.21 moderate	0.33, low & 0.21, moderate
2	0.67, low	0.67, moderate	0.67, reasonably likely	0.53 moderate, 0.47 low	0.53, moderate & 0.47, low
3	0.67, low	0.33, critical	0.33, likely	0.58 low, 0.42 moderate	0.33, low & 0.33, moderate
4	0.67, low	0.33, critical	0.67, reasonably likely	0.84 moderate, 0.16 low	0.33, moderate & 0.16, low
5	0.33, average	0.67, moderate	0.33, likely	0.53 moderate, 0.47 low	0.33, moderate & 0.33, low
6	0.33, average	0.67, moderate	0.67, reasonably likely	1 moderate	0.33, moderate
7	0.33, average	0.33, critical	0.33, likely	0.84 moderate, 0.16 low	0.33, moderate & 0.16, low
8	0.33, average	0.33, critical	0.67, reasonably likely	0.76 moderate, 0.24 high	0.33, moderate & 0.24, high

In most instances, the same linguistic terms for the Risk factors appear more than once, sometimes with the same or a different truth value. In such instances, the maximum of the truth values of the consequent Risk factor with the same linguistic term would be selected. In Table 4-3 above, the consequent linguistic term "low" has truth values of 0.16, 0.33 and 0.47. The resultant Risk membership function/value is therefore *0.47, low*. Table 4-4 shows the maximum truth values for the two linguistic terms.

Table 4-4: Max Truth Value

	Risk Membership Function/Value for Low	**Risk Membership Function/Value for Moderate**	**Risk Membership Function/Value for High**
	0.33, low	0.21, moderate	0.24, high
	0.47, low	0.53, moderate	
	0.33, low	0.33, moderate	
	0.16, low	0.33, moderate	

	Risk Membership Function/Value for Low	Risk Membership Function/Value for Moderate	Risk Membership Function/Value for High
	0.33, low	0.33, moderate	
	0.16, low	0.33, moderate	
		0.33, moderate	
		0.33, moderate	
Max	**0.47, low**	**0.53, moderate**	**0.24, high**

The belief degree with support value for this potential Risk factor is *0.24 high*, *0.53 moderate* and *0.47 low.*

4.2.2.7 Defuzzification using Expected Utility Method

The expected utility method, developed by Yang (2001), is adopted here for the defuzzification process. Defuzzification aims to combine the linguistic terms and the support values to create a crisp value representing the risk results, which enables ranking of all the identified risks. The ranking determines the prioritisation of the decision-making in selecting the failure modes to expend resources on or to assess the risk further in detail.

The expected utility method is derived thus (Dantsoho, 2015):

Assuming

- H_n is the evaluation grade, and
- $u(H_n)$ is the evaluation grade's utility value.

$u(H_n)$ can be arrived at by using experts' preference or, if there is no such preference, by assuming the value to be equidistantly distributed in a normalised utility space. $u(H_n)(n = 1, \ldots \ldots N)$ can be calculated using:

$$u(H_n) = \frac{V_n - V_{\min}}{V_{\max} - V_{\min}} \tag{4-4}$$

where V_n is the ranking value for evaluation grade or linguistic term (H_n) under consideration, V_{max} is the ranking value for the most ideal evaluation grade (H_n) and V_{min} is the ranking value for the least preferred evaluation grade (H_1).

The expected utility value, $u(S(E))$, for the potential risk can be calculated using:

$$u(S(E)) = \sum_{n=1}^{N} \beta_n(E)\, u(H_n) \qquad (4\text{-}5)$$

$\beta_n(E)$ is the belief degree for the evaluation grade H_n.

Combining the two equations will give the following expression, which will be used to determine the utility value.

$$u(S(E) = \sum_{n=1}^{N} \beta_n(E)\, (\frac{V_n - V_{\min}}{V_{\max} - V_{\min}}) \qquad (4\text{-}6)$$

For example, the belief degree and support value for the Risk identified in Table 4-4 is *0.24 high*, *0.53 moderate* and *0.47 low*; using equation 4-6, the utility value will be:

$$u\big(S(E)\big) = 0.24\ x\ \left(\frac{4-1}{5-1}\right) + 0.53\ x\ \left(\frac{3-1}{5-1}\right) + 0.47\ x\left(\frac{2-1}{5-1}\right) = 0.563$$

where:

V_{max}	5
V_{min}	1
V_n(high)	4
V_n(moderate)	3
V_n(low)	2
β_n(high)	0.24
β_n(moderate)	0.53
β_n(low)	0.47

4.2.3 Approximate Reasoning

The proposed approximate reasoning approach for this work is the Grey Relation Theory (GRT). GRT application within a modified FMEA has been shown in numerous studies (Chang *et al.*, 1999; Pillay & Wang, 2003; Zhou & Thai, 2016); this is made possible as FMEA has all the characteristics that enable GRT to be applied.

Its major benefits include the ability to assign different weighting coefficients to the failure factors and the fact that it does not require a utility function of any form (Chang *et al.*, 2001).

The building of the model involves multiple stages, as shown in Section 4.2.3.1 through to Section 4.2.3.5.

4.2.3.1 Establish Comparative Series

Comparative series are the linguistic terms for the Likelihood, Severity and Detection factors, and the decision factors for the case to be assessed. The comparative series are obtained using the Chen and Klein formula (Chen & Klein, 1997) as reproduced in Equation 3-10.

Figure 4-7 shows an example input for the equation of an "average" Likelihood ranking.

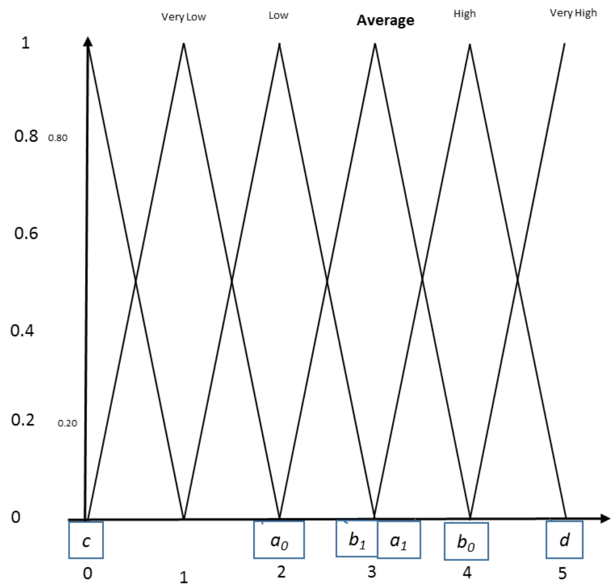


Figure 4-7: Example Input for Chen And Klein Expression

The comparative series for use in this project can be expressed as

$$x_n = (x(L), x(D), x(S)) \in x$$

where

$x_n(l) = L, D, S$ represents the failure factors of Likelihood, Detectability and Severity of the failure mode x_n.

If there are failure modes of $(x_1, x_2, ...x_n)$ for instance and the linguistic terms for the failure modes are $(x_1(L), x_1(D), x_1(S))$, $(x_2(L), x_2(D), x_2(S))$, ... $(x_n(L), x_n(D), x_n(D))$, then the series can be represented as a matrix as shown in Equation 4-7.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{bmatrix} = \begin{bmatrix} x_1(L) & x_1(D) & x_1(S) \\ x_2(L) & x_2(D) & x_2(S) \\ . & . & . \\ . & . & . \\ x_n(L) & x_n(D) & x_n(S) \end{bmatrix} \tag{4-7}$$

4.2.3.2 Determine the Standard Series

This is the objective series that represents the desired level of risk and is expressed as $x_0(L), x_0(D), x_0(S)$. Since the ideal level of risk is no risk at all, the standard series could be taken as the lowest level of all the failure factors for the linguistic terms, for example, *very low* for the Likelihood failure factor. The standard series could be represented as:

$$x_0 = [x_0(L), x_0(D), x_0(S)] \tag{4-8}$$

4.2.3.3 Determine Difference Between Comparative and Standard Series

The difference between the two series, D_0, can be calculated as shown in Equation 4-9.

$$D_0 = \begin{bmatrix} \Delta_{01}(L) & \Delta_{01}(D) & \Delta_{01}(S) \\ \Delta_{02}(L) & \Delta_{02}(D) & \Delta_{02}(S) \\ . & . & . \\ . & . & . \\ \Delta_{0N}(L) & \Delta_{0N}(D) & \Delta_{0N}(S) \end{bmatrix} \tag{4-9}$$

where $\Delta_{0n}(m)=\left\|x_0(m)-x_n(m)\right\|$, $x_0(m)$ is the standard series and $x_n(m)$ is the comparative series.

4.2.3.4 *Grey Relation Coefficient*

The Grey Relation Coefficient, represented as $\gamma\left(x_0(1),x_n(1)\right)$, can be obtained using Equation 3-11 for each Risk factor of the failure modes identified.

4.2.3.5 *Grey Relation and Ranking*

The final stage of the assessment is calculating the Degree of Relations and the ranking of the failure modes. To obtain the degree of relation, the weighting coefficient of each failure factor will have to be decided depending on its contribution to the severity of the consequent event.

The Grey Relation is obtained by using Equation 3-12.

4.2.4 Modified FMEA Methodology

The traditional FMEA, as outlined earlier, whilst simple and widely adopted in the industry, has a number of weaknesses that make its outcomes inconsistent and may inadvertently result in directing limited resources to wrongly prioritised risks. The drawbacks were described in Section 3.2.1.2.

To address the shortfalls, a modified FMEA is proposed, using a combination of FRB and GRT approaches. These approaches would correct some of the flaws in the traditional FMEA by ensuring that each expert and factor can be assigned a weighting. This would further expand the RPN so that different risk implications are outlined for events with similar RPN values when assessed using the traditional FMEA (Pillay & Wang, 2003).

The methodology for the modified FMEA, which is the underlying method for this chapter, is proposed as follows:

i. Define pipeline system boundaries for analysis, including identifying the system.
ii. Obtain the details of the equipment on the selected pipeline section and its component functions and gather all the data available for the system.
iii. Generate equipment failure modes using brainstorming session or by using a historical failure data, if available.
iv. Using experts' elicitation, establish Likelihood, Severity and Detectability values of each identified failure mode using linguistic terms. Where quantitative data is available, this will be incorporated into the assessment.
v. Defuzzify the failure factors to obtain crisp values for use with the membership function graph. Include the weighting for each of the experts based on their relevant expertise.

For Fuzzy Base Rule:

vi. Use fuzzy membership function, IF-THEN rule, min-max rule to establish the failure Risk belief degree and support value.
vii. Defuzzify the belief degree and support value using the expected utility value and rank the risk numbers obtained.

For Grey Relation Theory:

viii. Establish comparative and standard series and calculate the difference between the two.
ix. Introduce weighting to each of the failure factors.
x. Calculate the degree of relation and rank the risk numbers obtained.

Figure 4-8 shows the flowchart of the proposed approach.

4.2.5 Data Required

The data required for the analysis varies depending on the assessment approach. The data requirement for traditional FMEA is different from that of the modified

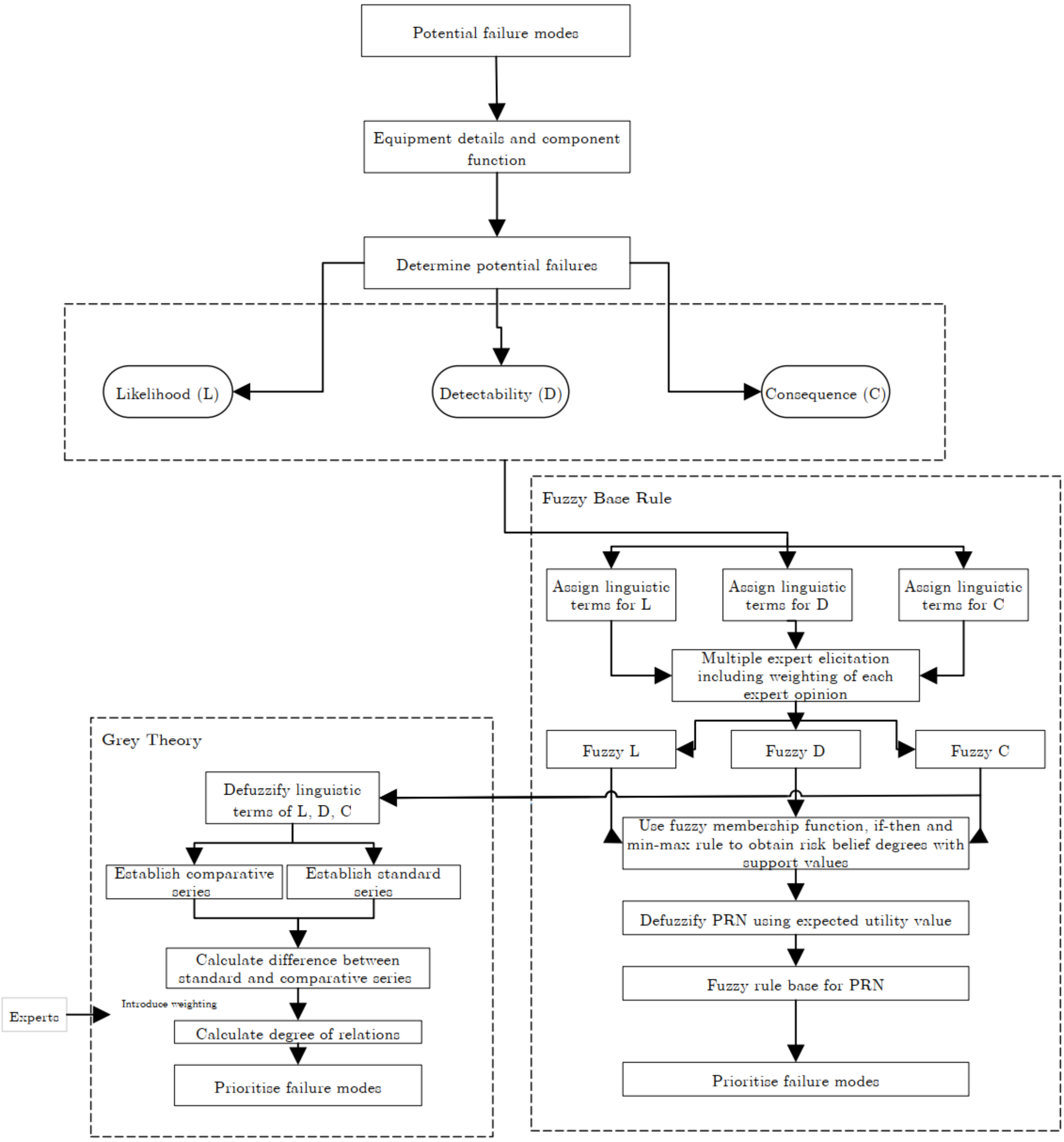


Figure 4-8: Modified FMEA Approach

FMEA approach. However, the majority of the input data required is common to both the two approaches and includes:

i. What does the pipeline system or subsystem do?
ii. The function of the item or subsystem being assessed.
iii. The item's failure mechanism, that is, how could it fail to perform its function?

iv. What will happen if it fails?
v. The Likelihood of failure - occurrence Likelihood (L).
vi. The consequence of failure - Severity (S).
vii. The predictability of failure - Detectability (D).

In addition to the above, the modified FMEA requires information on the agreed linguistic terms and the corresponding ranking, as well as the selected linguistic variables for each failure factor and the agreed weighting assigned to each expert and each failure factor.

4.3 Case Study: Application to Cross-Country Pipeline

The proposed modified FMEA incorporating FRB and GRT is implemented in an example case study of one of Nigeria's pipeline systems, which is System 2B. The system is described in Chapter 2.

The modified FMEA case study will investigate all the equipment highlighted above. However, not all potential failure modes will be identified. This study will outline the common failures based on case histories, experts' input and those failures with the most severe outcomes. The study will review the failure modes, their causes, the effect of those failures locally on the equipment itself and globally on the system as a whole. It will also highlight the systems in place to reveal such failures and any safeguards in the system to reduce or mitigate the consequences of the failures.

Generic failure events have been generated from the possible failures of each equipment obtained from global case history for similar pipelines, literature (Muhlbauer, 2004), the local failure data and input from field operatives and experts, based on their experience. These are provided in Table 4-5.

Table 4-5: Pipeline System 2B Failure Modes used as a Basis for the Analysis

No	Item ID	Event ID	Equipment Function	Failure Mode	Cause
1	1	1	Oil Pipeline	Product Leak/Rupture	External leakage from pinhole, flange or following impact or welding failure.
2	1	2	Oil Pipeline	Product Leak/Rupture	Deliberate - pipeline damage for product theft or vandalism.
3	1	3	Oil Pipeline	Product Leak/Rupture	Pipeline failure due to corrosion and structural weakness.
4	1	4	Oil Pipeline	Blockage	Line restricted by a partial or complete blockage.
5	2	1	Pipeline Manifold/Block Valve	Product Leak/Rupture	External leakage from pinhole, flange or following impact or welding failure.
6	2	2	Pipeline Manifold/Block Valve	Product Leak/Rupture	Deliberate - damage for product theft or vandalism.
7	2	3	Pipeline Manifold/Block Valve	Product Leak/Rupture	Pipeline failure due to corrosion and structural weakness.
8	2	4	Pipeline Manifold/Block Valve	Blockage	Line restricted by a partial or complete blockage.
9	2	5	Pipeline Manifold/Block Valve	Line Valve Failure	Actuated valve failed to shut.
10	2	6	Pipeline Manifold/Block Valve	Line Valve Failure	Actuated valve failed to open.
11	2	7	Pipeline Manifold/Block Valve	Line Valve Failure	Actuated valve failed, partly open.
12	3	1	Pumps	Product Leak	External leakage from pinhole, flange, seals, following impact or sabotage.
13	3	2	Pumps	Pump Fault	Pump reduced performance due to bearing, impeller problem or partial blockage.
14	3	3	Pumps	Pump Failure	Pump stops due to power loss or shaft breakage.
15	3	4	Pumps	Pump Failure	Pump stops due to loss of common power supply.
16	3	5	Pumps	Pump Failure	Standby pump fails to start on demand when duty pump fails.
17	4	1	Utility	Loss of Supply	Loss of utility or power.
18	4	2	Utility	Reduced Supply	Restriction in supply due to faulty instrument, valve, controller or pump.
19	4	3	Utility	Electrical Over-supply	High supply due to power surge.

No	Item ID	Event ID	Equipment Function	Failure Mode	Cause
20	5	1	Metering Package	Instrumentation Fault	Flow mismatch or inaccurate reading.
21	5	2	Metering Package	Product Leak	Leakage from pinhole, flange, following impact or sabotage.
22	5	3	Metering Package	Blockage	Line restricted by partial or complete blockage, for example, a stuck sphere.
23	6	1	Pig Launcher/ Receiver	Product Leak/Rupture	Leakage from pinhole, flange, following impact or sabotage.
24	6	2	Pig Launcher/ Receiver	Blockage	Line restricted blockage, for example, stuck sphere across main isolation valve.
25	6	3	Pig Launcher/ Receiver	Valve Failure / Problems with Valve Sequencing	Unable to isolate pig unit due to jammed, passing or failed valve.
26	6	4	Pig Launcher/ Receiver	Door Failure	Unable to seal pig unit due to jammed or failed door mechanism.
27	7	1	Future Tie-in Connection	Product Leak/Rupture	External leakage from pinhole, flange, following impact or sabotage.

Three experts have been selected for the assessment; their position and expertise are summarised in Table 4-6. For anonymity, both their names and the organisations they represent are not shown in the table but have been documented for the record.

Table 4-6: Experts Selected for the Research

No	Area of Expertise	Organisational Sector	Years of Experience
1	HSE Engineer	Pipeline regulator	>10 years
2	Project Engineer	Pipeline infrastructure owner and operator	>10 years
3	Loss Prevention Engineer	Pipeline consultants	>5 years

4.3.1 Traditional FMEA

The aim of the modified FMEA process is to improve the traditional process. In order to appreciate the proposed improvement and to afford comparison, it is proposed that this study undertakes a traditional FMEA using numerical rankings as the basis for comparison. The process entails the selected experts to identify the numerical ranking of each failure mode representing the failure Likelihood, consequent Severity and its Detectability.

In assigning the numerical ranking by the experts, the operator of the pipeline has provided as much information about the state of the pipeline as possible. The summary of the numerical ranking is shown in Table 4-7. Details and the description of the failure modes and failure factors are given in Appendix B.

Table 4-7: Traditional FMEA Results

S/N	Item ID	Event ID	Equipment Description/ Function	Failure Mode	Likelihood	Detection	Severity	RPN
1	1	1	Oil Pipeline	Product Leak/Rupture	2.3	2.7	3.3	21
2	1	2	Oil Pipeline	Product Leak/Rupture	4.0	1.3	4.3	23
3	1	3	Oil Pipeline	Product Leak/Rupture	3.0	3.0	3.3	30
4	1	4	Oil Pipeline	Blockage	2.7	2.0	3.3	18
5	2	1	Pipeline Manifold/Block Valve	Product Leak/Rupture	1.7	2.0	3.3	11
6	2	2	Pipeline Manifold/Block Valve	Product Leak/Rupture	2.7	2.3	4.3	27
7	2	3	Pipeline Manifold/Block Valve	Product Leak/Rupture	2.7	2.7	4.0	28
8	2	4	Pipeline Manifold/Block Valve	Blockage	2.3	2.0	3.7	17
9	2	5	Pipeline Manifold/Block Valve	Line Valve Failure	1.7	1.7	3.3	9
10	2	6	Pipeline Manifold/Block Valve	Line Valve Failure	1.3	2.7	3.0	11
11	2	7	Pipeline Manifold/Block Valve	Line Valve Failure	2.3	3.3	2.7	21
12	3	1	Pumps	Product Leak	4.0	1.3	3.0	16
13	3	2	Pumps	Pump Fault	3.3	2.7	2.7	24
14	3	3	Pumps	Pump Failure	3.3	1.0	3.7	12
15	3	4	Pumps	Pump Failure	3.7	1.0	4.0	15
16	3	5	Pumps	Pump Failure	2.7	2.0	4.0	21
17	4	1	Utility	Loss of Supply	3.7	1.0	4.0	15
18	4	2	Utility	Reduced Supply	2.7	3.3	2.3	21
19	4	3	Utility	Electrical Over-supply	3.0	1.3	3.7	15
20	5	1	Metering Package	Instrumentation Fault	3.0	3.3	2.0	20
21	5	2	Metering Package	Product Leak	3.0	2.7	3.0	24
22	5	3	Metering Package	Blockage	2.7	2.3	3.3	21
23	6	1	Pig Launcher/Receiver	Product Leak/Rupture	3.7	2.7	3.3	33
24	6	2	Pig Launcher/Receiver	Blockage	2.0	2.0	3.3	13
25	6	3	Pig Launcher/Receiver	Valve Failure/Problems with Valve Sequencing	2.0	2.0	2.3	9
26	6	4	Pig Launcher/Receiver	Door Failure	2.3	2.0	2.7	12
27	7	1	Future Tie-in Connection	Product Leak/Rupture	2.0	3.3	2.7	18

4.3.2 Fuzzy Base Rule Modified FMEA

The modified FMEA using the Fuzzy Base Rule has been applied to the 2B Pipeline system's hazards identification. The process uses the same experts' input as the traditional FMEA but utilises the FRB linguistic terms in allocating ranking for the failure modes, which is the failure occurrence Likelihood, Severity of failure and its Detectability. The fuzzy terms include, for example, *very low, low, average, high and very high* for Likelihood failure mode. The details of the linguistic terms for the failure modes are outlined in Table 3-1, Table 3-2 and Table 3-3.

The experts' selection and their weighting, based on their relevant experience, is outlined in Table 4-8 and forms the basis of obtaining the average ranking of the failure modes as shown below.

Table 4-8: Experts' Weighting

No	Area of Expertise	Relevant Experience Weighting
1	HSE Engineer	0.33
2	Project Engineer	0.33
3	Loss Prevention Engineer	0.33

The equal weighting used in Table 4-8 enables comparison to be made between the results of the modified approaches and that of the traditional approach. Section 4.4 shows the impact on the results when the experience of the experts is reflected in the assigned weighting where 0.4, 0.1 and 0.5 are assigned to the HSE, Project and Loss Prevention Engineers respectively.

The linguistic terms assigned by each expert for each of the failure modes are converted into the relevant numerical ranking and each is then multiplied with the weighting as was established in Equation 4-1. Table 4-9 gives two examples of the experts' assigned linguistic terms for failure Likelihood, Severity and Detectability failure modes and their corresponding numerical value equivalent, including the weighted ranking for the failure mode.

An example calculation of how the numbers in Table 4-9 have been arrived at is given below.

For product leak failure Likelihood,

$$A_{(1)} = C_1 a_{11} + C_2 a_{12} + C_3 a_{13}$$

$$A_{(1)} = (4\times 0.33) + (4\times 0.33) + (4\times 0.33) = 4.0$$

For blockage failure Likelihood,

$$A_{(2)} = C_1 a_{21} + C_2 a_{22} + C_3 a_{23}$$

$$A_{(2)} = (3\times 0.33) + (2\times 0.33) + (3\times 0.33) = 2.7$$

The weighted ranking is required in obtaining belief degrees with support values

Table 4-9: Example Linguistic Terms and Ranking Oil Pipeline.

Failure Mode	**Likelihood Linguistic Terms**			**Likelihood Ranking Equivalent**			**Weighted Ranking**
Experts	**#1**	**#2**	**#3**	**#1**	**#2**	**#3**	
Likelihood							
Product Leak	High	High	High	4	4	4	4.0
Blockage	Average	Low	Average	3	2	3	2.7
Detection							
Product Leak	Highly Likely	Highly Likely	Likely	1	1	2	1.3
Blockage	Highly Likely	Likely	Reasonably Likely	1	2	3	2.0
Severity							
Product Leak	Catastrophic	Critical	Critical	5	4	4	4.3
Blockage	Catastrophic	Moderate	Marginal	5	3	2	3.3

One of the strengths of the FRB system is its continuity of membership, allowing the use of the crisp values to obtain membership functions and belief degrees. Figure 4-3, Figure 4-4 and Figure 4-5 are employed to obtain the membership functions and the belief degrees for the Likelihood, Severity and Detectability values respectively.

The belief function for the Likelihood of a failure due to a product leak with 4.0 ranking is *1 high*. The belief function for the Likelihood of failure due to a blockage with a 2.7 ranking is *0.33 low* and *0.67 average*. This is shown in Figure 4-9 and Figure 4-10.

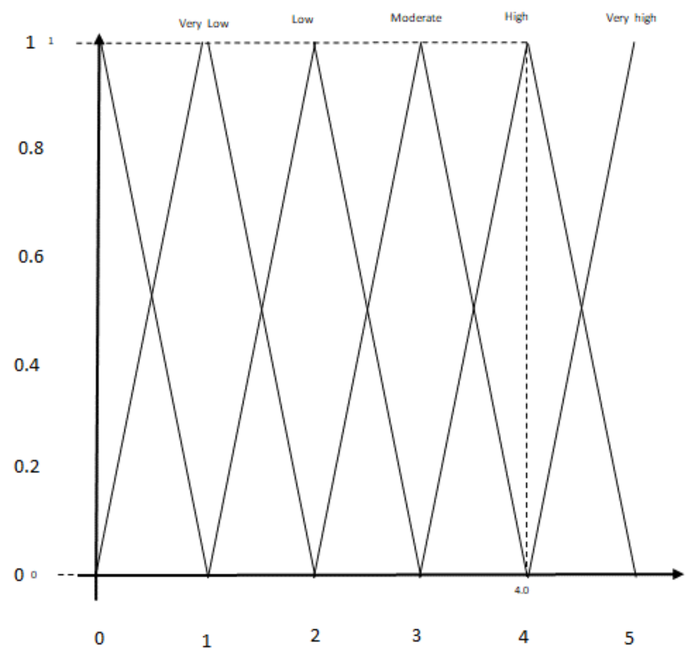


Figure 4-9: Membership Function of Product Leak Failure Likelihood with 4.0 Ranking

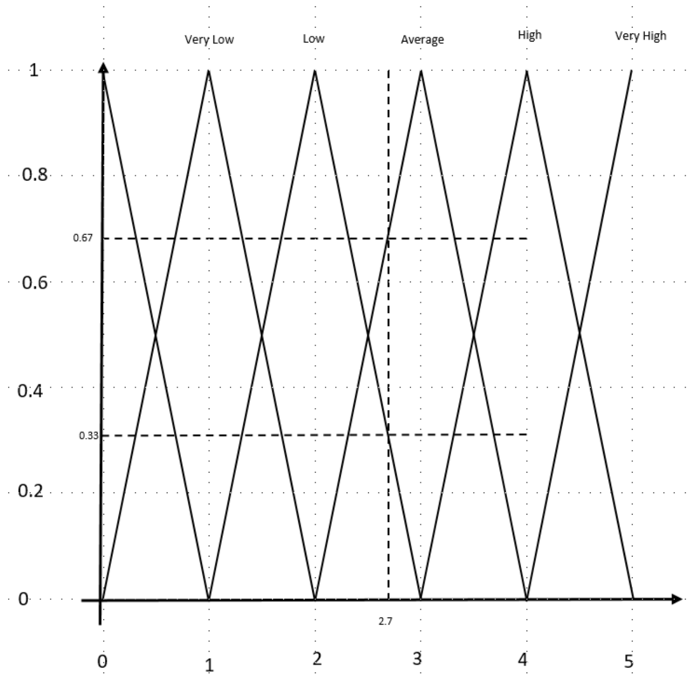


Figure 4-10: Membership Function of Blockage Failure Likelihood with 2.7 Ranking

Table 4-10 shows the membership functions and their belief degrees values for an oil pipeline product leak and blockage failure modes for the Likelihood, Detection and Severity values.

Table 4-10: Membership Functions for Oil Pipeline Failure Modes

Failure Mode	**Likelihood**		**Detectability**		**Severity**	
	Ranking	M'ship Function	Ranking	M'ship Function	Ranking	M'ship Function
Product Leak	4.0	*1, high*	1.3	*0.67, highly likely & 0.33, likely*	4.3	*0.67, critical & 0.33 catastrophic*
Blockage	2.7	*0.33, low & 0.67, average*	2.0	*1, likely*	3.3	*0.67, moderate & 0.33, critical*

The next step is applying the 125 IF-THEN rules with a belief structure (Wang, 1997) to the linguistic terms to determine the consequent Risk function of the failure modes.

For example, for the product leak failure mode that is being used, the consequent risk function would be determined as (See Table A1.2):

If **Likelihood** is	high
Detectability is	highly likely
Severity is	critical
Then the Risk is	0.58 low, 0.42 moderate

Once the Risk linguistic variables are determined, the min-max rule is used to obtain the minimum truth value of the belief degrees. For example, for the product leak failure mode that is being used, one of the minimum values of the consequent Risk factor is determined as:

If **Likelihood** is	1, high
Severity is	0.67, critical
Detectability is	0.67, highly likely
And Risk	0.58 low, 0.42 moderate

The minimum value for the Risk factor is, therefore *0.42 moderate* and *0.58 low*. The 0.42 is the minimum value of 1 (for Likelihood), 0.67 (for Severity), 0.67 (for

Detectability) and 0.42 (for Risk) associated with *moderate*. In the same vein, 0.58 is the minimum value of 1, 0.67, 0.67 and 0.58 associated with *low*. Table 4-11 shows the rest of the minimum values of the consequent Risks for the product leak and blockage failure modes.

The maximum rule is then applied to determine the maximum truth value associated with each of the Risk linguistic variables. Table 4-12 shows how the maximum rule has been applied to determine the truth value.

The Risk linguistic terms and their respective maximum belief values are then used to arrive at the expected utility value, which is the final element required to prioritise the failure modes. The expected utility values are obtained using Equation 4-6.

For the product leak failure mode, the expected utility value is

$$u(S(E)) = 0.58\ x\ \left(\frac{2-1}{5-1}\right) + 0.42\ x\ \left(\frac{3-1}{5-1}\right) + 0.33\ x\ \left(\frac{4-1}{5-1}\right) = 0.603$$

For the blockage failure mode, the expected utility value is:

$$u(S(E)) = 0.47\ x\ \left(\frac{2-1}{5-1}\right) + 0.53\ x\ \left(\frac{3-1}{5-1}\right) = 0.383$$

where

Product Leak		**Blockage**	
V_{max} =	5	V_{max} =	5
V_{min} =	1	V_{min} =	1
V_n (low) =	2	V_n (low) =	2
V_n (moderate) =	3	V_n (moderate) =	3
V_n (high) =	4		
β_n (low) =	0.58	β_n (low) =	0.47
β_n (moderate) =	0.42	β_n (moderate) =	0.53
β_n (high) =	0.33		
$u(S(E))$ =	0.603	$u(S(E))$ =	0.383

Table 4-13 details the fuzzy inputs and the defuzzified ranking of the failure modes.

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Table 4-11: Application of IF-THEN and Min Rules to Determine Risk Linguistic Variables and Min Membership Function.

Metering Package		Minimum Values							
Product leak	If **Likelihood** is	1, high	1, high	1, high	1, high				
	Severity is	0.67, critical	0.67, critical	0.33, catastrophic	0.33, catastrophic	0.67, critical	0.67, critical	0.33, catastrophic	0.33, catastrophic
	Detectability is	0.67, highly likely	0.33, likely	0.67, highly likely	0.33, likely	0.67, highly likely	0.33, likely	0.67, highly likely	0.33, likely
	Consequent **Risk** with belief structure	0.58 low, 0.42 moderate	0.86 moderate, 0.14 high	0.63 moderate, 0.37 low	0.65 moderate, 0.35 high	0.58 low, 0.42 moderate	0.86 moderate, 0.14 high	0.63 moderate, 0.37 low	0.65 moderate, 0.35 high
	Then **Min value of Risk** is	0.58, low & 0.42, moderate	0.33, moderate & 0.14, high	0.33, moderate & 0.33, low	0.33, moderate & 0.33, high	0.58, low & 0.42, moderate	0.33, moderate & 0.14, high	0.33, moderate & 0.33, low	0.33, moderate & 0.33, high
Blockage	If **Likelihood** is	0.33, low	0.33, low	0.33, low	0.33, low	0.67, average	0.67, average	0.67, average	0.67, average
	Severity is	0.67, moderate	0.67, moderate	0.33, critical	0.33, critical	0.67, moderate	0.67, moderate	0.33, critical	0.33, critical
	Detectability is	1, likely		1, likely		1, likely		1, likely	
	Consequent **Risk** with belief structure	0.79 low, 0.21 moderate	0.79 low, 0.21 moderate	0.58 low, 0.42 moderate	0.58 low, 0.42 moderate	0.53 moderate, 0.47 low	0.53 moderate, 0.47 low	0.84 moderate, 0.16 low	0.84 moderate, 0.16 low
	Then **Min value of Risk** is	0.33, low & 0.21, moderate	0.33, low & 0.21, moderate	0.33, low & 0.33, moderate	0.33, low & 0.33, moderate	0.53, moderate & 0.47, low	0.53, moderate & 0.47, low	0.33, moderate & 0.16, low	0.33, moderate & 0.16, low

Table 4-12: Application of Max Rule to Determine Maximum Value for Risk

	Pipeline – Product Leak			**Pipeline Blockage**	
	Risk membership function/value for				
	Low	Moderate	High	Low	Moderate
	0.58, low	0.33, moderate	0.14 high	0.33, low	0.53, moderate
	0.58, low	0.33, moderate	0.33 high	0.33, low	0.53, moderate
	0.33, low	0.33, moderate	0.14 high	0.33, low	0.33, moderate
	0.33, low	0.33, moderate	0.33 high	0.33, low	0.33, moderate
		0.33, moderate		0.47, low	0.21, moderate
		0.33, moderate		0.47, low	0.21, moderate
		0.42, moderate		0.16, low	0.33, moderate
		0.42, moderate		0.16, low	0.33, moderate
Max	**0.58, low**	**0.42, moderate**	**0.33, high**	**0.47, moderate**	**0.53, moderate**

4.3.3 Grey Relation Theory Modified FMEA

The application of the GRT to the modified FMEA is similar to that of the FRB in that it requires similar inputs and shares similar natural language utilisation. The input values for the Likelihood, Severity and Detectability factors are the linguistic variables, which have the same meaning as described in Section 4.2.2. The linguistic terms for the Likelihood of failure are *very low, low, average, high* and *very high*; the linguistic terms for Severity are *negligible, marginal, moderate, critical* and *catastrophic,* whilst the linguistic terms for Detectability are *highly likely, likely, reasonably likely, unlikely* and *highly unlikely*.

Using the Chen and Klein formula, the comparative series of the failure factors are obtained. The Chen and Klein formula is outlined in Equation 3-10.

The comparative series calculation is undertaken for the linguistic terms provided by the experts for the three failure factors. As an example, the Likelihood linguistic term selected by expert #3 for the pipeline product leak failure factor used in the previous example is *high,* thus the comparative series is:

$$K(x) = \frac{(4-0)+(5-0)}{((4-0)+(5-0))-((4-5)+(3-5))}$$

$$= 0.75$$

Table 4-13: Fuzzy FMEA Ranking

No	Equipment Description/ Function	Failure Mode	Likelihood	Severity	Detectability	Fuzzy Risk Ranking	De-fuzzified Ranking
1	Oil Pipeline	Product Leak/Rupture	0.67, low & 0.33, average	0.67, moderate & 0.33, critical	0.33, likely & 0.67, reasonably likely	0.47, low & 0.53, moderate & 0.24, high	0.563
2	Oil Pipeline	Product Leak/Rupture	1, high	0.67, critical & 0.33, catastrophic	0.67, highly likely & 0.33, likely	0.58, low & 0.42, moderate & 0.33, high	0.603
3	Oil Pipeline	Product Leak/Rupture	1, average	0.67, moderate & 0.33, critical	1, reasonably likely	0.67, moderate & 0.67, high	0.838
4	Oil Pipeline	Blockage	0.33, low & 0.67, average	0.67, moderate & 0.33, critical	1, likely	0.47, low & 0.53, moderate	0.383
5	Oil Pipeline	Line Valve Failure	0.33, very low & 0.67, low	0.67, moderate & 0.33, critical	1, likely	0.67, low & 0.29, very low & 0.33, moderate	0.333
6	Pipeline Manifold/Block Valve	Product Leak/Rupture	0.33, low & 0.67, average	0.67, critical & 0.33, catastrophic	0.67, likely & 0.33, reasonably likely	0.33, low & 0.67, moderate & 0.33, high	0.665
7	Pipeline Manifold/Block Valve	Product Leak/Rupture	0.33, low & 0.67, average	1, critical	0.33, likely & 0.67, reasonably likely	0.33, low & 0.67, moderate & 0.49, high	0.785
8	Pipeline Manifold/Block Valve	Blockage	0.67, low & 0.33, average	0.33, moderate & 0.67, critical	1, likely	0.58, low & 0.42, moderate	0.355
9	Pipeline Manifold/Block Valve	Line Valve Failure	0.33, very low & 0.67, low	0.67, moderate & 0.33, critical	0.33, highly likely & 0.67, likely	0.33, very low & 0.67, low & 0.33, moderate	0.333
10	Pipeline Manifold/Block Valve	Line Valve Failure	0.67, very low & 0.33, low	1, moderate	0.33, likely & 0.67, reasonably likely	0.67, low & 0.33, moderate & 0.29, very low	0.333
11	Pipeline Manifold/Block Valve	Line Valve Failure	0.67, low & 0.33, average	0.33, marginal & 0.67, moderate	0.67, reasonably likely & 0.33, unlikely	0.47, low & 0.53, moderate & 0.24, high	0.563
12	Pumps	Product Leak	1, high	1, moderate	0.67, highly likely & 0.33, likely	0.67, low & 0.37, moderate & 0.08, high	0.413
13	Pumps	Pump Fault	0.67, average & 0.33, high	0.33, marginal & 0.67, moderate	0.33, likely & 0.67, reasonably likely	0.33, low & 0.67, moderate & 0.24, high	0.598
14	Pumps	Pump Failure	0.67, average & 0.33, high	0.33, moderate & 0.67, critical	1, highly likely	0.67, low & 0.33, moderate	0.333
15	Pumps	Pump Failure	0.33, average & 0.67, high	1, critical	1, highly likely	0.58, low & 0.42, moderate	0.355
16	Pumps	Pump Failure	0.33, low & 0.67, average	1, critical	1, likely	0.33, low & 0.67, moderate & 0.24, high	0.598
17	Utility	Loss of Supply	0.33, average & 0.67, high	1, critical	1, highly likely	0.58, low & 0.42, moderate	0.355
18	Utility	Reduced Supply	0.33, low & 0.67, average	0.67, marginal & 0.33, moderate	0.67, reasonably likely & 0.33, unlikely	0.47, low & 0.53, moderate & 0.24, high	0.563
19	Utility	Electrical Over-supply	1, average	0.33, moderate & 0.67, critical	0.67, highly likely & 0.33, likely	0.67, low & 0.33, moderate	0.333
20	Metering Package	Instrumentation Fault	1, average	1, marginal	0.67, reasonably likely & 0.33, unlikely	0.53, moderate & 0.67, low	0.433
21	Metering Package	Product Leak	1, average	1, moderate	0.33, likely & 0.67, reasonably likely	0.67, moderate & 0.24, high & 0.33, low	0.598
22	Metering Package	Blockage	0.33, low & 0.67, average	0.67, moderate & 0.33, critical	0.67, likely & 0.33, reasonably likely	0.47, low & 0.53, moderate & 0.24, high	0.563
23	Pig Launcher/Receiver	Product Leak/Rupture	0.33, average & 0.67, high	0.67, moderate & 0.33, critical	0.33, likely & 0.67, reasonably likely	0.67, moderate & 0.33, high & 0.33, low	0.665
24	Pig Launcher/Receiver	Blockage	1, low	0.67, moderate & 0.33, critical	1, likely	0.67, low & 0.33, moderate	0.333
25	Pig Launcher/Receiver	Valve Failure	1, low	0.67, marginal & 0.33, moderate	1, likely	0.67, low & 0.21, moderate	0.273
26	Pig Launcher/Receiver	Door Failure	0.67, low & 0.33, average	0.33, marginal & 0.67, moderate	1, likely	0.67, low & 0.33, moderate	0.333
27	Future Tie-in Connection	Product Leak/Rupture	1, low	0.33, marginal & 0.67, moderate	0.67, reasonably likely & 0.33, unlikely	0.47, low & 0.53, moderate	0.383

The input for the calculation and the results are shown in Table 4-14.

Av K(x) is the average of the comparative series of the three experts, taking into consideration the weight assigned to each expert based on their relevant experience and expertise.

Table 4-14: Comparative Series - Product Leak/Blockage Failure Modes

		Likelihood			Detection			Severity		
Experts		1	2	3	1	2	3	1	2	3
Product leak		HI	HI	HI	HL	HL	LI	CA	CR	CR
	d	5	5	5	5	5	5	5	5	5
	c	0	0	0	0	0	0	0	0	0
	a_0	3	3	3	0	0	1	4	3	3
	b_0	5	5	5	2	2	3	5	5	5
	a_i	4	4	4	1	1	2	5	4	4
	b_i	4	4	4	1	1	2	5	4	4
	K(x)	0.75	0.75	0.75	0.25	0.25	0.42	0.91	0.75	0.75
	Av	**0.75**			**0.31**			**0.80**		
Blockage		AV	LO	AV	HL	LI	RL	CA	MO	MA
	d	5	5	5	5	5	5	5	5	5
	c	0	0	0	0	0	0	0	0	0
	a_0	2	1	2	0	1	2	4	2	1
	b_0	4	3	4	2	3	4	5	4	3
	a_i	3	2	3	1	2	3	5	3	2
	b_i	3	2	3	1	2	3	5	3	2
	K(x)	0.58	0.42	0.58	0.25	0.42	0.58	0.91	0.58	0.42
	Av	**0.53**			**0.42**			**0.64**		

Note: HI is high, HL is highly likely, CA is catastrophic, CR is critical, AV is average, LO is low, LI is likely RL is reasonably likely, MO is moderate and MA is marginal.

The comparative series of the two failure modes are summarised as below, using Equation 4-7.

For product leak

$$S_c(leak) = \left[\ |0.75| \quad |0.31| \quad |0.80|\ \right]$$

For blockage

$$S_c(blockage) = \left[\ |0.53| \quad |0.42| \quad |0.64|\ \right]$$

Once a comparative series is obtained, a standard series is also calculated; this enables the difference between the two to be assessed. The standard series are the ideal failure factors values to be aimed at, which for Likelihood should be *very low,* for Severity should be *negligible* and for Detectability should be *highly likely*.

Using Equation 3-10, the standard series for the three failure factors is calculated as 0.25.

$$K(x) = \frac{(1-0)+(2-0)}{((1-0)+(2-0))-((1-5)+(0-5))}$$

$$= 0.25$$

The difference between the standard series and the comparative series for the two failure modes is shown below. The difference is obtained by subtracting the standard series from the average comparative series for the three failure factors using Equation 4-9.

For the product leak, the difference (D_0) is:

$$D_0(leak) = \begin{bmatrix} \|0.75-0.25\| & \|0.31-0.25\| & \|0.80-0.25\| \end{bmatrix}$$

$$D_0(leak) = \begin{bmatrix} |0.50| & |0.06| & |0.55| \end{bmatrix}$$

For the blockage, the difference D_0 is:

$$D_0(blockage) = \begin{bmatrix} \|0.53-0.25\| & \|0.42-0.25\| & \|0.64-0.25\| \end{bmatrix}$$

$$D_0(blockage) = \begin{bmatrix} |0.28| & |0.17| & |0.39| \end{bmatrix}$$

The next step is obtaining the Grey Relations coefficient, $\gamma\left(x_0(1), x_n(1)\right)$, for the three failure factors – Likelihood, Severity and Detectability. This is obtained by applying Equation 3-11. The Grey Relations coefficients are as calculated below:

$$\gamma_m(leak\ /\ Likelihood) = \frac{0.25+0.5\times 0.8}{0.75+0.5\times 0.8}$$

$$= 0.565$$

$$\gamma_m(leak\,/\,Severity) = \frac{0.25 + 0.5 \times 0.8}{0.8 + 0.5 \times 0.8}$$

$$= 0.540$$

$$\gamma_m(leak\,/\,Detection) = \frac{0.25 + 0.5 \times 0.8}{0.31 + 0.5 \times 0.8}$$

$$= 0.921$$

$$\gamma_m(blockage\,/\,Likelihood) = \frac{0.25 + 0.5 \times 0.8}{0.53 + 0.5 \times 0.8}$$

$$= 0.701$$

$$\gamma_m(leak\,/\,Severity) = \frac{0.25 + 0.5 \times 0.8}{0.64 + 0.5 \times 0.8}$$

$$= 0.627$$

$$\gamma_m(leak\,/\,Detection) = \frac{0.25 + 0.5 \times 0.8}{0.42 + 0.5 \times 0.8}$$

$$= 0.796$$

Finally, the degree of relation is calculated using Equation 3-12, taking into account the agreed weighting coefficient for each of the failure factors. The input for the two failure modes is shown in Table 4-15.

Table 4-15: Example Degree of Relations Input

Equipment Description	Failure Modes	Failure Factors	Grey Relation Co-efficient	Weighting Co-efficient
Oil Pipeline	Product Leak	Likelihood	0.565	0.33
		Severity	0.540	0.33
		Detectability	0.921	0.33
Oil Pipeline	Blockage	Likelihood	0.701	0.33
		Severity	0.627	0.33
		Detectability	0.796	0.33

For the product leak failure mode, the degree of relation would be:

$\Gamma = (0.565 \times 0.33)+(0.540 \times 0.33)+(0.921 \times 0.33)$

$\Gamma = 0.676$

For the blockage failure mode, the degree of relation would be:

$\Gamma = (0.701 \times 0.33) + (0.627 \times 0.33) + (0.796 \times 0.33)$

$\Gamma = 0.708$

Note that for Grey Relation, the higher the value obtained for a failure mode, the lower the relative risk the failure has compared to other failure modes.

Table 4-16 shows the input and the results of all the failure modes.

Table 4-16: Degree of Relation Inputs for all Failure Modes

#	Equipment Description	Failure Modes	Failure Factors	Grey Relation Co-efficient	Weighting Co-efficient	Degree of Relation
1	Oil Pipeline	Product Leak/Rupture	Likelihood	0.75	0.33	0.69
			Severity	0.63	0.33	
			Detection	0.70	0.33	
2	Oil Pipeline	Product Leak/Rupture	Likelihood	0.57	0.33	0.68
			Severity	0.54	0.33	
			Detection	0.92	0.33	
3	Oil Pipeline	Product Leak/Rupture	Likelihood	0.66	0.33	0.65
			Severity	0.63	0.33	
			Detection	0.66	0.33	
4	Oil Pipeline	Blockage	Likelihood	0.70	0.33	0.71
			Severity	0.63	0.33	
			Detection	0.80	0.33	
5	Oil Pipeline	Line Valve Failure	Likelihood	0.85	0.33	0.76
			Severity	0.63	0.33	
			Detection	0.80	0.33	
6	Pipeline Manifold/ Block Valve	Product Leak/Rupture	Likelihood	0.70	0.33	0.66
			Severity	0.54	0.33	
			Detection	0.75	0.33	
7	Pipeline Manifold/ Block Valve	Product Leak/Rupture	Likelihood	0.70	0.33	0.66
			Severity	0.57	0.33	
			Detection	0.70	0.33	
8	Pipeline Manifold/ Block Valve	Blockage	Likelihood	0.75	0.33	0.71
			Severity	0.60	0.33	
			Detection	0.80	0.33	
9	Pipeline Manifold/ Block Valve	Line Valve Failure	Likelihood	0.85	0.33	0.78
			Severity	0.63	0.33	
			Detection	0.85	0.33	
10	Pipeline Manifold/ Block Valve	Line Valve Failure	Likelihood	0.92	0.33	0.76
			Severity	0.66	0.33	
			Detection	0.70	0.33	
11	Pipeline Manifold/ Block Valve	Line Valve Failure	Likelihood	0.75	0.33	0.69
			Severity	0.70	0.33	
			Detection	0.63	0.33	
12	Pumps	Product Leak	Likelihood	0.57	0.33	0.72
			Severity	0.66	0.33	
			Detection	0.92	0.33	

#	Equipment Description	Failure Modes	Failure Factors	Grey Relation Co-efficient	Weighting Co-efficient	Degree of Relation
13	Pumps	Pump Fault	Likelihood	0.63	0.33	0.68
			Severity	0.70	0.33	
			Detection	0.70	0.33	
14	Pumps	Pump Failure	Likelihood	0.63	0.33	0.74
			Severity	0.59	0.33	
			Detection	1.00	0.33	
15	Pumps	Pump Failure	Likelihood	0.60	0.33	0.72
			Severity	0.57	0.33	
			Detection	1.00	0.33	
16	Pumps	Pump Failure	Likelihood	0.70	0.33	0.69
			Severity	0.57	0.33	
			Detection	0.80	0.33	
17	Utility	Loss of Supply	Likelihood	0.60	0.33	0.72
			Severity	0.57	0.33	
			Detection	1.00	0.33	
18	Utility	Reduced Supply	Likelihood	0.70	0.33	0.69
			Severity	0.75	0.33	
			Detection	0.63	0.33	
19	Utility	Electrical Over-supply	Likelihood	0.66	0.33	0.73
			Severity	0.59	0.33	
			Detection	0.92	0.33	
20	Metering Package	Instrumentation Fault	Likelihood	0.66	0.33	0.69
			Severity	0.80	0.33	
			Detection	0.63	0.33	
21	Metering Package	Product Leak	Likelihood	0.66	0.33	0.67
			Severity	0.66	0.33	
			Detection	0.70	0.33	
22	Metering Package	Blockage	Likelihood	0.70	0.33	0.69
			Severity	0.63	0.33	
			Detection	0.75	0.33	
23	Pig Launcher/ Receiver	Product Leak/Rupture	Likelihood	0.59	0.33	0.64
			Severity	0.63	0.33	
			Detection	0.70	0.33	
24	Pig Launcher/ Receiver	Blockage	Likelihood	0.80	0.33	0.74
			Severity	0.63	0.33	
			Detection	0.80	0.33	
25	Pig Launcher/ Receiver	Valve Failure	Likelihood	0.80	0.33	0.78
			Severity	0.75	0.33	
			Detection	0.80	0.33	
26	Pig Launcher/ Receiver	Door Failure	Likelihood	0.75	0.33	0.75
			Severity	0.70	0.33	
			Detection	0.80	0.33	
27	Future Tie-in Connection	Product Leak/Rupture	Likelihood	0.80	0.33	0.71
			Severity	0.70	0.33	
			Detection	0.63	0.33	

4.4 Results and Discussion

The results of the analyses have been provided in Section 4.3.1 for the traditional FMEA, Section 0 for the Fuzzy Base Rule FMEA and Section 4.3.3 for the Grey Relation Theory FMEA. The results are also summarised and the rankings compared in Table 4-17. The results show the variation of the Risk rankings depending on the FMEA approach adopted. However, they broadly agreed with each other.

Table 4-17: Comparison of the Different FMEA Results and Ranking

S/N	Equipment Description	Failure Mode	RPN	Fuzzy Rule Base	Grey Theory	RPN Ranking	FRB Ranking	GRT Ranking
1	Oil Pipeline	Product Leak/Rupture	21	0.563	0.690	9	9	9
2	Oil Pipeline	Product Leak/Rupture	23	0.603	0.676	7	5	6
3	Oil Pipeline	Product Leak/Rupture	30	0.838	0.650	2	1	2
4	Oil Pipeline	Blockage	18	0.383	0.708	14	15	15
5	Pipeline Manifold/Block Valve	Product Leak/Rupture	11	0.333	0.759	24	20	24
6	Pipeline Manifold/Block Valve	Product Leak/Rupture	27	0.665	0.662	4	3	4
7	Pipeline Manifold/Block Valve	Product Leak/Rupture	28	0.785	0.656	3	2	3
8	Pipeline Manifold/Block Valve	Blockage	17	0.355	0.712	16	17	16
9	Pipeline Manifold/Block Valve	Line Valve Failure	9	0.333	0.778	27	20	26
10	Pipeline Manifold/Block Valve	Line Valve Failure	11	0.333	0.762	25	20	25
11	Pipeline Manifold/Block Valve	Line Valve Failure	21	0.563	0.690	11	9	9
12	Pumps	Product Leak	16	0.413	0.716	17	14	17
13	Pumps	Pump Fault	24	0.598	0.676	6	6	7
14	Pumps	Pump Failure	12	0.333	0.740	23	20	22
15	Pumps	Pump Failure	15	0.355	0.721	18	17	19
16	Pumps	Pump Failure	21	0.598	0.687	8	6	8
17	Utility	Loss of Supply	15	0.355	0.720	18	17	18
18	Utility	Reduced Supply	21	0.563	0.690	11	9	9
19	Utility	Electrical Over-supply	15	0.333	0.725	18	20	20
20	Metering Package	Instrumentation Fault	20	0.433	0.695	13	13	13
21	Metering Package	Product Leak	24	0.598	0.674	5	6	5
22	Metering Package	Blockage	21	0.563	0.690	9	9	9
23	Pig Launcher/Receiver	Product Leak/Rupture	33	0.665	0.641	1	3	1
24	Pig Launcher/Receiver	Blockage	13	0.333	0.739	21	20	21
25	Pig Launcher/Receiver	Valve Failure	9	0.273	0.779	26	27	27

S/N	Equipment Description	Failure Mode	RPN	Fuzzy Rule Base	Grey Theory	RPN Ranking	FRB Ranking	GRT Ranking
26	Pig Launcher/Receiver	Door Failure	12	0.333	0.747	22	20	23
27	Future Tie-in Connection	Product Leak/Rupture	18	0.383	0.707	14	15	14

The analyses assume that all the experts have the same weighting in terms of experience and all the failure factors have the same weighting. The results indicate that each of the approaches produces similar but different risk priority rankings, but with the majority of the results broadly following the same pattern. The potential failures that have the same input produce fairly similar results. For example, failure events 15 (pump failure) and 17 (loss of supply) have the same linguistic variables and qualitative ranking. With the equal weighting that has been applied to the experts and the failure factors, the resulting risk ranking for the traditional FMEA is 18 for both events, the ranking of the FRB approach is 17 for both events whilst the GRT ranking is 19 and 18, respectively.

As it would be expected when the experience of the experts is taken into consideration by assigning a weighting of 0.4, 0.1 and 0.5 to experts 1, 2, and 3, respectively, the FRB ranking has changed from 17 to 25 for the two failure events.

The impact of the use of a failure factor's weighting in the GRT can also be seen on the failure items 15 (pump failure) and 17 (loss of supply). The two failure events have the same weighting of 0.33 for the Likelihood, Severity and Detectability factors, giving a risk ranking of 19 and 18 respectively. However, when the weighting factors are changed to 0.4, 0.4 and 0.2, the risk ranking changes to 6 and 5 respectively.

4.5 Conclusions

FMEA has been a versatile tool in safety assessments to maintain systems integrity and anticipate and prevent failures. The process is effective when there is historical data for a precise numerical input. However, where there is inadequate or unreliable data, especially in developing countries, the FMEA can produce a wrong output, resulting in the misdirection of limited resources and the creation of a false sense of security (Liu *et al.*, 2011). The use of the FRB and GRT ensures that, in addition to the limited data available, the experience of experts and operatives will be incorporated. Additionally, the use of linguistic terms ensures that the input is more aligned with the natural language synthesis, which is more familiar to field operatives and practitioners.

The modified FMEA approach has several benefits and these are summarised below:

- It provides an opportunity to incorporate experts' experience and knowledge as part of the input where data is limited or uncertain.
- It augments the lack of data, allowing for more refined and representative results. It affords the operatives and experts the chance to express the failure modes in the language they normally use on a day-to-day basis.
- The process makes up for the weakness of the traditional FMEA where a small variation of one failure input can produce a disproportionate impact on the results.
- It introduces a weighting to both the input of experts based on their experience and to each failure factor, thus ensuring that the results reflect the actual contribution of each expert and which failure factor has the most or least impact on the results.

The approach still suffers from some of the drawbacks of the traditional FMEA, such as the fact that it still relies on the subjective input of the selected experts and the assumptions made by the analyst.

The comparison of the results of the modified approach with that of the traditional approach provides a partial validation of the approach. Sensitivity studies would have provided additional support to the partial validation process; however, time constrain did not allow the sensitivity studies to be carried out.

The modified FMEA proposed in this chapter can be a useful additional tool for pipeline risk analysis in Nigeria and any other geographical area with similar challenges.

Chapter 5. Bayesian Networks Application in Estimating Failure Likelihood

Overview

This chapter reviews the Bayesian Network (BN) model and its application in the pipeline risk assessment in geographical areas where data is inadequate or not available. The chapter proposes a model which has been applied to a case study focusing on estimating the failure probabilities of the 2B pipeline system in Nigeria. The failure factors identified are the leak and rupture of the pipeline, which are the highest ranked factors determined from the analysis in Chapter 4.

The model input has been obtained by a combination of loss databases and experts' elicitation. The data used is selected based on its suitability and in discussion with the domain matter experts.

The BN model has undergone a series of verification, validation and sensitivity analyses to ensure a robust model structure and reliable results.

5.1 Introduction

The pipeline industry in developed economies has a structured process of data collection in regard to pipeline failures, which informs the failure probability analysis. However, in developing countries where data is either unavailable or unreliable, failure probability analysis may produce unreliable results. This, in addition to peculiar local environmental and other conditions, leads to higher-than-average pipeline failure scenarios. These scenarios are vulnerable to escalation into catastrophic events with a significant loss of life, in addition to economic losses. For example, Nigeria's premier oil company, NNPC, is reported to have said that in the first half of 2019, the country lost about 22 million barrels of oil to pipeline theft (George, 2019).

To ensure a more reliable assessment of the likelihood or probability of the failure, the BN model is adopted as described fully in Section 3.3. The approach is apt for this research because it accommodates data uncertainty, or the lack of it, and can integrate the expert's knowledge. The model is especially good at updating the uncertainty whenever new data becomes available.

The BN can be constructed in a variety of ways, depending on the available information and the intended application. For example, the BN can be constructed either using the traditional knowledge engineering sessions with domain experts and automatically synthesizing them with high level specifications or by learning from data, or both.

Before receiving new information (evidence), the BN represents 'a priori' beliefs about the failure that it models. By obtaining new information or data about the state of one or more of the variables, the BN can then be updated to represent 'a posteriori' beliefs about the problem.

This chapter shows a methodology and a case study on how to input and update the variables in the BN.

5.2 Methodology

5.2.1 Developing Failure Likelihood with Bayesian Networks

Developing Bayesian Networks involves a clear delineation of the domain it is to represent. The nodes, their states and their directional arcs must be properly defined; this ensures that there is no misinformation or misinterpretation in terms of the relationships between the nodes and what each represents.

The main advantage of the Bayesian Network is its ability to deliver meaningful results using its graphical structures from the input data. Therefore, precision in node connections and the provision of prior probabilities is important (Loughney, 2017).

As part of the analysis, a BN assessment using Hugin (2018) has been developed for a section of a cross-country pipeline's failure probabilities. The model is built with input from relevant past case histories, literature and experts' elicitation.

To develop the node, a determination must be carried out of the parent or root nodes and the child or the target node. The root nodes are not directly influenced by any other node in the BN and it is defined as a level-1 node (first stage). The child node is defined as a level 2 node (second stage) and the target node is defined as the level 3 node (third stage).

5.2.2 Construction and Data for BN Modelling

To analyse primary pipeline failure data and predict failure characteristics using the BN model, a generic model building and analysis procedure has been adapted and is explained in this section. The steps as outlined here are key to error-free analysis and form part of the quality control procedure that ensures that the model performs consistently as expected irrespective of the domain of application. It also ensures processes and results comparability.

The number of steps and the details contained vary from application to application and are also dependant on the level of modelling details envisaged. However, the basic procedure shares a similarity and has been adapted for this work as described below.

5.2.2.1 Identification of a Set of Variables Appropriate to the Problem

This step entails identifying the number of variables that are required in the model. In identifying the variables, care must be taken to ensure that the number is kept to the minimum that is necessary to provide expected results. In this research, the determination of the factors that affect cross-country pipeline integrity and loss prevention mechanisms are the main driver of the variables' development. To reduce complications and difficulties that will arise from unwieldy variables (and hence the data for the Conditional Probability Tables - CPTs), the number of the parent nodes for each child node is limited to three. This ensures all the necessary identified major factors affecting pipeline failure are included whilst the variables' number is kept manageable for a less complicated assessment. The granularity of the analysis is balanced with the practicality of the available information and modelling effort.

5.2.2.2 Creation of Nodes Corresponding to all Variables Identified

Having identified all the variables, this step involves creating nodes that will describe the problem to be addressed. The nodes represent the relevant variables identified in Section 5.2.2.1. The nodes' development involves a determination as to whether each node will be discrete, continuous or if it will have several states.

5.2.2.3 Identification of a Set of States for Each Variable

The states of each variable are to be determined based on the available data, the modeller's perspective and the limit of complexity envisaged. As identified in Section 5.2.2.2, the states of the nodes could be discrete, continuous or involving several states.

5.2.2.4 Specification of the State of Each Node

For this assessment, a Boolean state with the option of "yes" and "no" has been adopted. Only the top-level node has three states – *leak*, *rupture* and *operational*. The use of three states as opposed to two that were used on other nodes is to mirror the major failure modes mostly associated with pipelines, that is, "leak" and "rupture". The "operational" state indicates that the pipe did not encounter any failure and thus is still operational.

5.2.2.5 Identification of a Node's Dependency

The identified nodes are connected to the influencing/influenced nodes via the arc connections. This creates the Directed Acyclic Graph (DAG) that the BN relies on for information parsing and probability propagation. The nodes which represent the cause and effect are linked to one another via directed edges or arcs.

The connection is enabled via the software package adopted. The model ensures that the assessment nodes established are connected, as appropriate, to the variables identified, and the levels of information propagation via arc direction are correct.

5.2.2.6 Construction of Conditional Probability Table

CPT for each node will be set at this step and can be specified based on either available data or expert elicitation. The number of probabilities required depends on the structure of the model. This is where the decisions made in Section 5.2.2.1 will either simplify this stage or make it complex.

In this assessment, the information that makes up the CPT is obtained from the Concawe database (Cech *et al.*, 2018), the US DOT (PHMSA, 2017) and the NNPC (NNPC, 2016), among others. Where direct data is not available, expert elicitation and a symmetric model (Riahi *et al.*, 2014) is used to complete the CPT.

5.2.3 Analysis and Decision-Making

Once all the data required is provided, and the correct connections are made, the next stage is ensuring that all the values entered for the CPT are normalised so that each set of nodes has a sum total value equivalent to 1.

The model is then executed for results and decision analysis. This includes extracting marginal probabilities and interrogating the data to extract the belief values for certain assumptions and inputs. The baseline model gives the marginal probabilities of the end event, given the various input conditions of the contributing variables. These baseline results can be interrogated further given additional evidence to observe the impact of that new evidence on the final results. The analysis can then be used for “what if” scenarios to better understand the impact of each input variable or sub-variable.

Predictive, diagnostic and sensitivity analysis can also be carried out as part of the decision-making process and model validation (refer to Section 5.2.4) to provide insight, supporting managers in predicting the consequences of certain decisions or the impact of a certain intervention. It can also help with post-accident analysis, where the failure is diagnosed to find the likely contributing factors leading to it.

5.2.4 Validation and Sensitivity Studies

5.2.4.1 Validation and Sensitivity Analysis

The validation process entails checking for the accuracy of the model's representation of the real system. A correctly validated model offers confidence to the users that the results are a good representation for the given assumptions made.

There are several approaches for model validation, ranging from subjective to objective statistical assessment. The common approach for validation is based on a series of tests. For this model, the validation process will be in the form of sensitivity studies as described in Section 5.2.4.1, employing the three axioms as outlined by Jones *et al.* (2010).

To ensure that the BN model behaves as expected, a sensitivity analysis will be carried out. The aim is to test how sensitive the model is to the incremental or decremental changes to the input on the nodes. A representative model will have a relative increase or decrease in the results for a similar increase or decrease in the input.

A sound model with logical inference reasoning should be able to pass the following three axioms (Cai *et al.*, 2013).

Axiom 1: A slight increase/decrease in the prior subjective probability of each parent node should certainly result in the effect of a relative increase/decrease of the posterior probabilities of child nodes.

Axiom 2: Given the variation in subjective probability distributions of each parent node, its influence magnitude to child node values should be kept consistent.

Axiom 3: The total influence magnitude of the combination of the probability variations, from x attributes, on the values should always be greater than that of the set of x-y (y∈x) attributes.

5.2.4.2 Verification

In the context of this analysis, the model verification aims to confirm that the model is correctly implemented as it was conceptually designed, that any errors identified with the model are fixed and that the model implementation is correct. For this model, a verification process has been adopted that involves logic flows and examines the model output for reasonableness under different input parameters.

5.3 Case Study: Application to Pipeline System 2B

5.3.1 Introduction

The BN model described in Section 5.2 is used in this chapter, with a case study demonstrating the model's practical application for a cross-country onshore pipeline failure analysis. Pipeline 2B is the case study pipeline system. Description of the pipeline is provided in Section 2.2. The case study will be a continuation of Chapter 4, where a modified FMEA approach has been utilised to identify and rank all potential failure modes for the pipeline system. The failure mode that ranks highest is the pipeline's loss of containment due to a leak or rupture. This case study will take the failure mode and assess all its contributing variables for the purposes of analysis and the decision-making process.

The BN model incorporates a symmetric model and AHP pairwise comparison technique to generate conditional probability tables for nodes with multiple parents where data is insufficient or not available. The proposed model is then analysed for prediction and diagnosis of the problem assuming certain evidence. Verification and sensitivity analyses have been carried out to ensure that the model is constructed correctly and behaves as expected. This provides a level of confidence in the model's analysis and the results.

5.3.2 Events Flow

To identify the initial variables for the modelling, assessment of the primary failure factors that affect onshore oil and gas pipelines, both globally and locally in Nigeria, has been carried out. As a result of incomplete information on the Nigeria and Africa's pipeline failure factors, it has been decided that the European and American experience will be used to augment the primary failure factors that will inform the variables. Within the selected regions, Europe and the USA, the database for the onshore cross-country refined products pipelines is the most relevant. There are issues around regional nomenclature and differences in recording techniques, but the main failure factors are broadly similar and are grouped under tier 1 factors, listed below, that lead to a pipeline leak or rupture.

For a pipeline to fail, there is either going to be (i) a human interference consisting of a third-party or operational damage, (ii) a mechanical failure consisting of corrosion and a material defect or (iii) a natural hazard. These are the tier 1 factors. Directly beneath each of the tier 1 factors are tier 2 factors. The tier 2 factors cause the occurrence of the main (tier 1) factors, and the root events (tier 3) are the basic failure factors. These are outlined in Table 5-1 and Figure 5-1.

The Concawe database (Cech *et al.*, 2018) is more appropriate for Nigeria's system compared to the US DOT database (PHMSA, 2017) and therefore the Concawe nomenclature and the majority of its data has been used in this research.

5.3.3 BN Model Development

This section details and describes all the variables outlined in Figure 5-1 that form the BN model, including assumptions made and the states of the variables.

5.3.3.1 Root and Mid Events

A. Human Intervention

Damage events due to human intervention are those related to a third party or due to operational upheaval. They are a result of an intervention by an operator or a third party. These events are described below.

Table 5-1: Primary and Secondary Pipeline Failure Factors

	Tier 1/2 Factors	Tier 3 Factors		Tier 1/2 Factors	Tier 3 Factors
US DOT	Material/ Weld Failure	• Construction/installation /fabrication • Fitting defect • Failure of equipment body • Malfunction of control equipment • Non-threaded connection failure • Pump-related seal failure • Other	EU Concawe	Material defect	• Material • Construction • Design
	Natural Force Damage	• Flood/heavy rain • Earth movement • Lighting • Temperature • Others		Natural Hazard	• Ground movement • Other natural hazards
	Incorrect operation	• Operator damage • Incorrect installation • Incorrect operation • Incorrect valve position • Others		Operational damage	• System malfunction • Human and organisational error
	Excavation damage	• Operator/contractor excavation damage • 3rd party excavation damage • Other damages		Third-party damage	• Incidental • Accidental • Theft
	Corrosion	• Internal • External • Unspecified		Corrosion	• Internal • External • Stress corrosion
	Other outside force	• Electrical arcing • Vehicle not engaged in excavation • Previous mechanical damage • Others			

A.1 Third-Party Damage

A significant factor that is particularly specific to Nigeria, or a similar developing economy that is battling with insecurity, is the third-party related pipeline interference. Generally, third-party damage is any failure resulting from an action by a third party, either accidental, incidental or theft/intentional.

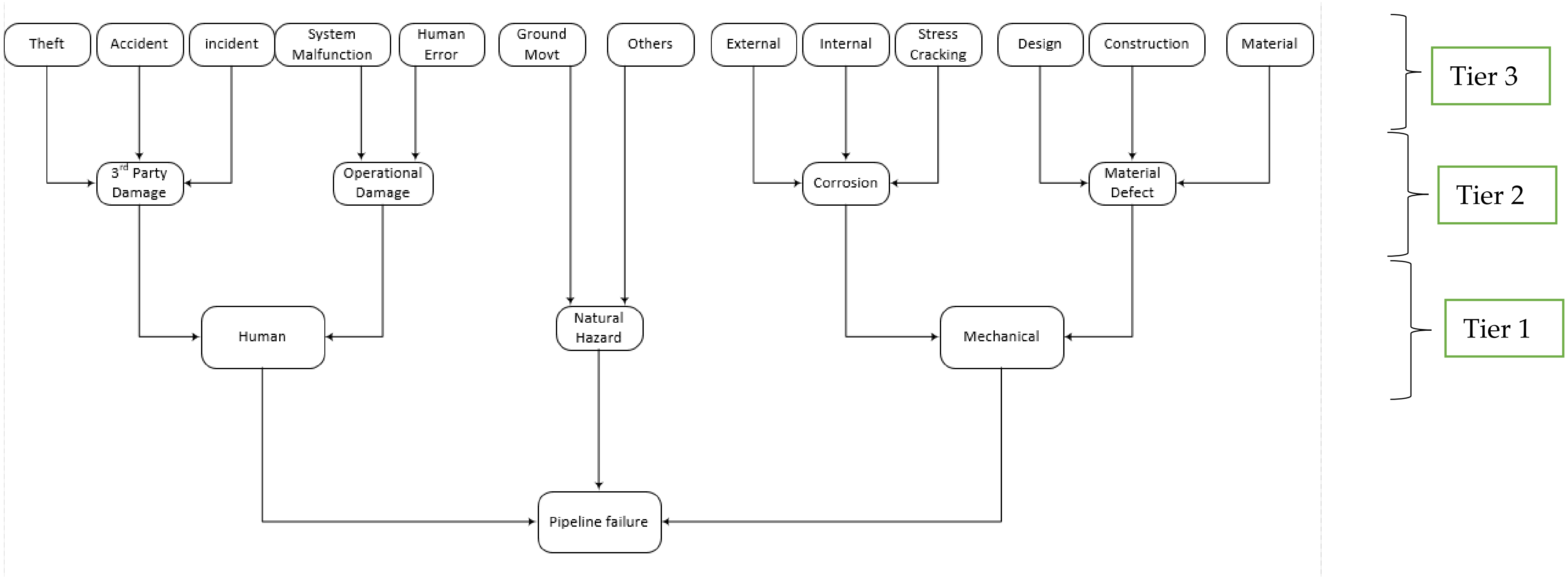

Figure 5-1: Failure Factors Variables Flow Diagram

A significant sub-category of third-party related issues is theft. Several referenced publications (Achebe *et al.*, 2012; Anifowose *et al.*, 2012; Omodanisi *et al.*, 2014; Carlson *et al.*, 2015) and popular media (Campbell, 2017; Ezeobi, 2018; Ugwu, 2018) indicate the level of petroleum product lost as a result of theft and vandalism in Nigeria.

The other hazards relevant to third-party interference include accidental and incidental damages.

Third-party damage can be reduced by applying some of the more common risk reduction measures, including pipeline safety zones, increased wall thickness, increased depth of cover, warning marker posts, plastic marker tape, concrete slabbing, a physical barrier within the pipeline trench, vibration detection, regular inspections of pipelines right of way (ROW) and intelligent pigging.

A.1.1 Accidental

Accidental third-party damage can be caused by such activities as construction work, agricultural activity and underground infrastructure. For onshore cross-country pipelines that pass through farmlands, high density areas and road construction sites, accidental damage remains a big failure factor.

A.1.2 Incidental

Incidental third-party damage includes damage that is undetected when it originally occurs, but which results in failure at some point later in time.

A.1.3 Theft/Intentional

Intentional third-party activities include terrorism, vandalism and theft.

A.2 Operational Damage

This is a failure that occurs either due to a system malfunction or human and organisational error. An example of such a failure can be a failure of control and safety system, resulting in a pressure surge.

Operational damage can have catastrophic consequences, especially when the operational upset happens outside the design boundaries of the pipelines.

A.2.1 Human and Organisational Error

Human and organisational error has been variously mentioned as the biggest factor in oil and gas accidents (Cullen, 1990). Factors that contribute to human and organisational errors can be categorised into individual, organisational and systematic errors (Bai & Bai, 2005). Individual errors are those made by an operator that contributes to an accident, often caused by insufficient knowledge, fatigue, lack of training or experience. The organisational error can be defined as institutional due to, for example, poor communication, unsafe activities, lack of appropriate equipment and a lack of systems capable of supporting operator activities.

A.2.2 System Malfunction

Errors can also be observed with a human-machine interface, such as the equipment in use, the structures present, the software in use, or an instruction manual. These are described as system (hardware) errors and procedure (software) errors that eventually result in an operator making decisions that result in accidents.

B. Mechanical Failure

B.1 Material Damage

Material damage affects the structural integrity of the pipelines and is divided into three categories – material and welding defects, construction defects and design defects. Their influence on pipeline failure varies and depends on the rigorous quality control process applied during the design, manufacturing and construction of the pipelines.

B.1.1 Material Defect

Material and weld defects account for an insignificant percentage of pipeline failures due to advancements in material science and fabrication. These defects mostly take place as a result of pipeline deformation or because of construction defects that occur during the manufacturing and construction of the pipeline.

B.1.2 Construction Defect

A pipeline's raw materials, such as steel, can be defective during the construction or manufacturing process where impurities remain in the molten steel. These impurities can cause an incomplete bonding of the material in the steel plate or the solid round steel billet used to produce a pipe. The defect, if not discovered during the hydrostatic pressure testing that occurs before the pipeline is placed in service, will eventually grow during the pipeline's operational life until a failure occurs (Sulaiman, 2017).

B.1.3 Design Defect

Design defects are failure-induced factors that occur from the conceptual design stage, including the selection and appropriate combination of materials and controls.

B.2 Corrosion

Corrosion plays a significant role in pipeline integrity issues in the oil and gas industry. Corrosion accounts for over 25% of assets failures (Capcis Limited, 2001) and is found to be prevalent in every stage of the production cycle. For cross-country refined products pipelines, the failure rate ranges from 14% to 18%.

Corrosion occurs as a result of the deterioration of the pipelines due to the electrochemical action of the coating and other materials on the pipeline. The electrochemical action is detrimental to internal corrosion, especially when the fluid being transported has corrosive properties. There are generally three identified types of corrosion – internal, external and stress-induced.

For Nigerian pipelines, the rate of internal pipeline corrosion due to locally refined oil is limited because of the so-called sweet crude oil that is predominantly produced in the country. However, there are also significant numbers of refined products imported into the country whose corrosive properties are unascertained.

B.2.1 Internal

For internal corrosion, the fluid's properties – including its corrosive elements (either sweet or sour) – determine the rate of corrosion of the pipeline's internal lining. Major elements contributing towards pipeline corrosion include, for example, hydrogen sulphide, sulphur dioxide and carbon dioxide. Other factors that affect the internal corrosion rate of the pipeline include fluid temperature, flow rate and the protection measures in place.

B.2.2 External

External corrosion is caused by the properties of the external environment in contact with the pipeline. These external environments are water, soil, air or a mixture of them. The pipeline under consideration in this study is mostly buried in a shallow trench, therefore it is predominantly covered in soil. However, the temperature, water content and the type of soil present are all additional factors. External protection measures may be present to help reduce the rate of corrosion and elongate the pipeline's useable life. These protection measures include coating and cathodic protection.

B.2.3 Stress Corrosion

The effect of stress as it applies to an onshore cross-country pipeline is less important compared to offshore subsea pipelines. However, as the pipeline crosses different terrains and geological formations, parts of the pipeline will pass through rivers and above-ground formations. Stress corrosion cracking (SCC) may happen when a pipeline under stress poses a lag crack or breaks. Typically, two major forms of stress which contribute to the stress corrosion are internal pressure and residual stress. SCC is considered in this study, together with the load from external forces.

C. Natural Hazards

Natural hazard accidents are accidents that may be caused by pipelines traversing unstable mountainous terrain, where landslides, flash-flooding and land subsidence are responsible for pipeline failure. Two sub-events are included in the assessment – ground movement and other natural hazards.

C.1 Ground Movement

Ground movement includes landslides and earth movements such as those resulting from mining and heavy rain. Earth movement resulting in gully erosion is a common occurrence in southern Nigeria and along the pipeline route and is, therefore, a significant factor.

C.2 Other Natural Hazards

Other natural hazards include extreme temperatures and land subsidence. These are uncommon failure factors and therefore represent an insignificant percentage of the failure statistics.

5.3.3.2 Top Event

Top events are the events whose results the analysis aims to obtain. In most cases, all the input information and evidence in other nodes propagation feeds into them; they are usually the subject of interest in the analysis.

D. Pipeline Failure – loss of containment

The pipeline condition is represented as the top event. This gives the final results of the analysis and could determine whether the pipeline is in operational condition or if it has lost its integrity.

5.3.3.3 Assumptions

The BN model is developed based on certain assumptions. These assumptions need to be declared so that they can inform the user of the model and support informed decision-making.

The model is developed with a specific focus on:

- Countries or geographical areas where there is inadequate or unreliable data for quantitative risk analysis of the pipeline.
- Areas where there are above-average incident rates of third-party-related damages to the pipeline, especially those relating to hot-tapping and criminal destruction.

The scope of the top events is limited only to two classes of pipeline failure - leak and rupture.

The model is developed with the aim of highlighting the principle of its application in pipeline risk analysis in geographical areas with the features outlined above, irrespective of the data entered or the data source. Therefore, the accuracy of the input data will not affect the model's validity, rather, inaccurate data will only affect the end results.

The assessment is limited to finding out the likelihood of the loss of containment for the pipeline. It does not assess the consequences in terms of the human, economic, political or environmental effects.

Several data sources appropriate to the model have been used, including the Concawe database (Cech *et al.*, 2018), the US DOT database (PHMSA, 2017) and the NNPC database (NNPC, 2016). The choice of the data depends on its relevance.

The predominant data source for the primary variables is the Concawe database. However, where NNPC data is available, it has been used. In the event of particular cases, such as operational damage, the US DOT database is deemed more relevant and has therefore been used. Where no data is available, expert elicitation has been utilised.

5.3.3.4 Model Structure

The BN model has been developed based on the details outlined in Section 5.3.3.1, which shows the relationship between failure factors and their conditional dependencies. The BN simulates the cause and effect of pipeline failure and the various factors affecting it, including mechanical factors, corrosion damage, human and organisational failure, and third-party damages. The Hugin representation of the Bayesian model is shown in Figure 5-2. The description of all nodes and their states is given in Table 5-2.

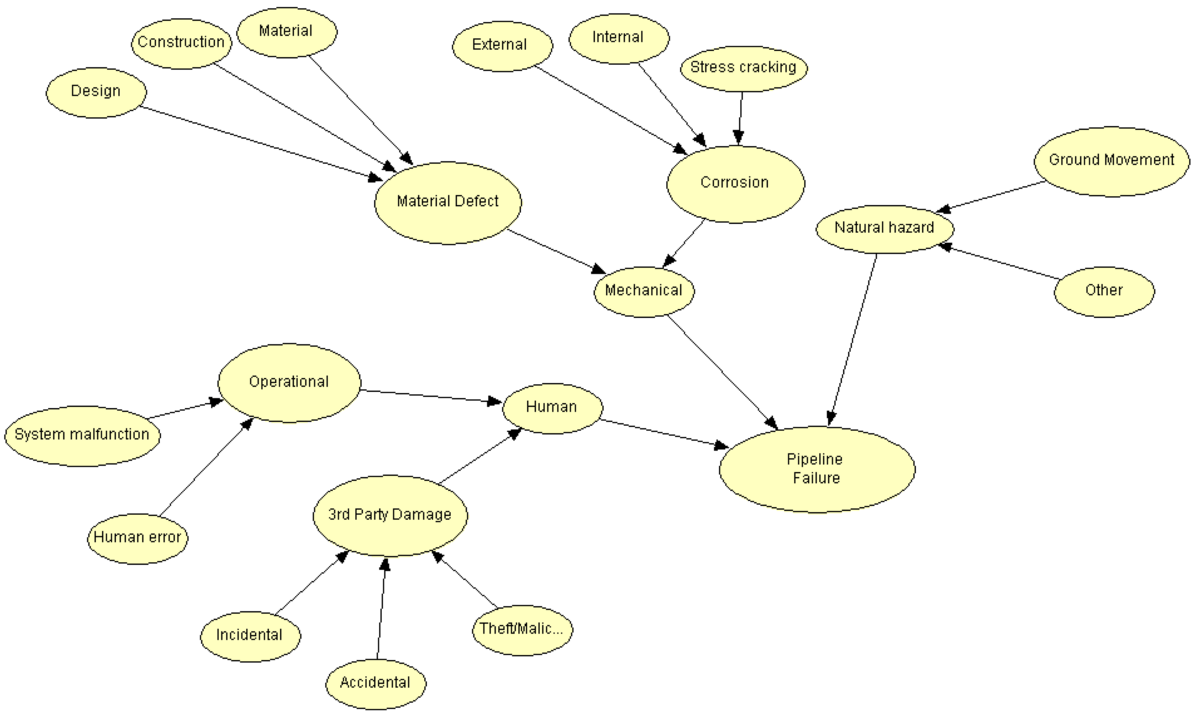

Figure 5-2: Hugin Graphical Output of the BN Model

Table 5-2: Variables used in the BN and their Descriptions

Variables	States	Description
Human Damage	Yes/No	This is the total likelihood of all human related interventions resulting in pipeline integrity issues
Third-Party Damage	Yes/No	Total likelihood of pipeline failure due to all third-party related activities
Incidental Damage	Yes/No	Likelihood of pipeline damage due to an event that is not immediately obvious but later developed into a failure
Accidental Damage	Yes/No	Damage due to accidental intervention, like construction or farming
Theft/Intentional	Success/Failure	A failure likelihood due to deliberate damage, to tap the pipeline content or to vandalise the system
Operational Damage	Yes/No	Likelihood of damage due to unintended operations
System Malfunction	Yes/No	Failure due to mechanical, electrical/electronic systems malfunction
Human (and org) Error	Yes/No	This is the potential for human and organisational error, like lack of training or quality assurance (QA) to cause accidents leading to failure
Mechanical Failure	Failed/Not Failed	This is the combined contribution of the mechanical-related defects affecting pipeline integrity
Material Defect	Yes/No	Likelihood of defective materials used in design and construction contributing to pipeline failure
Material	Yes/No	Likelihood of defective materials only contributing to pipeline failure
Construction	Yes/No	Likelihood of defective construction only contributing to pipeline failure
Design	Yes/No	Likelihood of defective design only contributing to pipeline failure
Corrosion	Yes/No	Pipeline failure due to corrosion
External Corrosion	Yes/No	Corrosion damage due to external corrosion
Internal Corrosion	Yes/No	Likelihood of corrosion damage due to internal corrosion
Stress Cracking	Yes/No	Likelihood of corrosion damage due to applied stress on the pipeline
Natural Hazard	Yes/No	The likelihood that a pipeline has failed due to natural related events like flash flood and frost
Ground Movement	Yes/No	Likelihood of ground movement affecting pipeline integrity
Other Natural Hazards	Yes/No	Likelihood of other types of natural hazards affecting pipeline integrity
Pipeline Failure – Loss of Containment	Leak, Rupture, Operational	Likelihood of all of the above resulting in a pipeline integrity failure

5.3.4 Parameter Estimation

5.3.4.1 Pipeline Failure Data

The pipeline failure data relevant to the pipeline system under consideration has been collected and used to inform the model. The most relevant data applicable to this assessment is the Concawe database (Cech *et al.*, 2018). Even though this database is for European cross-country pipelines, a qualitative assessment carried out and the opinion of the experts sought as part of this BN model development indicate that it is the most relevant to Nigeria's pipeline system. The Concawe report (Cech *et al.*, 2018) documents loss of containment incidents in European cross-country pipelines and their underlying statistics from 1971 to 2016. The pipelines covered in the report include over 140 pipeline systems provided by 66 pipeline operators, with a total length of about 38,000 km. The reported throughput of the pipelines is in the region of 755Mm^3 of refined products and crude oil. The report analyses the short and long-term trends of containment loss.

Most of the failure factors identified and their long-term failure trends are deemed appropriate for use in this assessment in the absence of local specific data for Nigeria's pipeline systems, with the exception of operational and third-party factors. For operational factors, the high quality of management regimes and supervision means that failure probabilities in the European pipelines are very low compared to those of Nigeria; the US DOT database for operational factors is more suitable in this instance.

Additionally, third-party intervention and especially theft/intentional and incidental damages are very low for both the Concawe and US DOT databases compared to the reported incidences for Nigeria. The patchy data obtained from Nigeria is very unreliable but seems to indicate that a significant percentage, up to ninety percent of failures, is due to third-party intervention, specifically intentional and theft. However, the domain experts consulted for this work, as outlined in section 5.3.4.2, agreed that the Concawe data, which has an up to sixty percent reported failure probability due to third-party damage in 2015, should be used but adjusted upwards.

In all other areas where direct data is not available, or if it is not applicable in the given context, expert elicitation, as explained in Section 5.3.4.2, has been adopted. Table 5-3 shows the data sources for each variable.

Table 5-3: Variables and Data Sources

	Variables	Parents	No of CPT Input	Failure Data Source	Comment
A Human Damage		2	8	Expert Elicitation	
A.1 Third Party Damage		3	16	Expert Elicitation	
A.1.1	Accidental Damage	0	2	Concawe (Cech *et al.*, 2018)	
A.1.2	Incidental Damage	0	2	Concawe (Cech *et al.*, 2018)	Concawe data and experts' agreed upward adjustment
A.1.3	Theft/Intentional	0	2	Concawe (Cech *et al.*, 2018)	Concawe data and experts' agreed upward adjustment
A.2 Operational Damage		2	8	US DOT (PHMSA, 2017), Expert Elicitation	Concawe data not suitable. Lack of robust management regime in Nigeria means failure due to operational issues is more similar to US DOT data.
A.2.1	Human (& org) Error	0	2	Concawe (Cech *et al.*, 2018)	
A.2.2	System Malfunction	0	2	Concawe (Cech *et al.*, 2018)	
B Mechanical Failures		2	8	NNPC (Achebe *et al.*, 2012); Expert Elicitation	NNPC data, via a published journal, is used.
B.1 Material Defect		3	16	Expert Elicitation	
B.1.1	Material	0	2	Concawe (Cech *et al.*, 2018).	
B.1.2	Construction	0	2	Concawe (Cech *et al.*, 2018).	
B.1.3	Design	0	2	Concawe (Cech *et al.*, 2018).	
B.2 Corrosion		3	16	Expert elicitation	
B.2.1	Internal Corrosion	0	2	Concawe (Cech *et al.*, 2018).	
B.2.2	External Corrosion	0	2	Concawe (Cech *et al.*, 2018).	
B.2.3	Stress Cracking	0	2	Concawe (Cech *et al.*, 2018).	

	Variables	Parents	No of CPT Input	Failure Data Source	Comment
C Natural Hazard		2	8	Expert elicitation	
C.1	Ground Movement	0	2	Concawe (Cech *et al.*, 2018).	
C.2	Other Natural Hazards	0	2	Concawe (Cech *et al.*, 2018).	
D Pipeline Failure – Loss of Containment		3	24	Expert Elicitation	

5.3.4.2 *Expert Elicitation*

The key strength of the BN method is the opportunity to integrate the input of subject matter experts in the absence of hard data for some of the variables required for the analysis. In this model, probability tables for some of the child nodes cannot be completed with the hard data available. As a result, expert elicitation is utilised to compensate for the lack of data. Typically, the direct estimates from such experts for the nodes are elicited for the probabilities. However, this approach often leads to inconsistencies and unreliable results due to subjective biases, especially when a node has more than two states (Chin *et al.*, 2009). The experts also find it difficult to provide input for the high number of conditional probabilities in CPTs.

To address these shortcomings, an AHP pairwise comparison is adopted to elicit expert input into the model. The AHP method is combined with the symmetric method, described in Section 3.3.1.5, to efficiently obtain the data and integrate it into the model. The method simplifies decision-making by the domain experts in that they are only presented with two variables to compare at any given time. Their decisions are reduced to compare two factors in terms of their importance. This approach reduces the potential bias inherent in their responses.

A questionnaire has been developed for the AHP pairwise comparison for all variables for which expert input is required. The questionnaires were sent to the selected experts for their response. The sample questionnaire is shown in

Appendix C. The experts are chosen based on their relevant experience and qualification. The backgrounds of these experts are summarised in Table 5-4.

Table 5-4: Experts Selected for the Research

No	Area of Expertise	Organisational Sector	Years of Experience
1	HSE Engineer	Pipeline regulator	>10 years
2	Project Engineer	Pipeline infrastructure owner and operator	>10 years
3	Loss Prevention Engineer	Pipeline consultants	>5 years
4	Pipeline Engineer	Contractor	>5 years
5	Research Engineer	Academic	>3 years

<u>AHP Questionnaire and Pairwise Comparison</u>

Expert elicitation has been obtained for all children nodes where data is not sufficient to fill the prior probabilities. Questionnaires in the form of AHP and pairwise comparison have been utilised. The process of obtaining the AHP results from the questionnaire is outlined here.

Each expert received a questionnaire similar to the one shown in Table 5-5 for the child nodes entitled material defects and corrosion. Details of all the questionnaires are shown in Appendix C. Once the questionnaire responses come back, they are summarised in the matrix table, as shown in Table 5-6. The table shows the relative importance of each variable compared to the others. For example, when considering material defects, the design factor (DF) is less important than the construction factor (CF), hence the value is 0.5, where the two intersect. The value for the opposite statement–construction factor (CF) being more important than the design factor (DF) – is 0.5^{-1} which is 2.

Table 5-5: Questionnaire Sample

	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Material Defect																	
To achieve the stated objective, how important is a design failure, compared to construction failure?								x									
To achieve the stated objective, how important is a design failure, compared to failure due to material quality?									x								
To achieve the stated objective, how important is a construction failure, compared to failure due to material quality?										x							
Corrosion																	
To achieve the stated objective, how important is an external corrosion, compared to internal corrosion?																x	
To achieve the stated objective, how important is an external corrosion, compared to stress cracking?																	x
To achieve the stated objective, how important is an internal corrosion, compared to stress cracking?										x							

The next step is assessing the weighting ratio of each of the variables as a percentage of the total for each child node using Equation 3-24. A total sum for each column in Table 5-6 is required to assess the weighting. Then each of the ratings in the table is divided by the total for each column. This gives the ratio of each rating as a percentage of the total for each variable. For example, column *DF* has a total of 2.5; each of the column ratings of 1, 0.5 and 1 will have a ratio equal to $\frac{1}{2.5} = 0.4$, $\frac{0.5}{2.5} = 0.2$ and $\frac{1}{2.5} = 0.4$ respectively.

To obtain the relative weighting for each variable, an average weighting across the row of the matrix is calculated. For the *EC* variable under *corrosion*, the average weighting of the three variables of 0.06, 0.04 and 0.07 is 0.05 (refer to Table 5-7). To ensure that the assessment is behaving as expected and is devoid of errors, the total of each variable's values along each column and the total of the average weighting should sum to 1. Table 5-7 gives the relative weighting figures from the standard matrix for two child nodes – material defect and corrosion.

The average weightings in Table 5-7 are the values required along with the symmetric model to populate the node probability table of each respective child node.

Table 5-6: Pairwise Comparison Matrix

Material Defect					Corrosion			
	DF	CF	MQ			EC	IC	SC
DF	1.00	2.00	1.00		EC	1.00	0.13	0.11
CF	0.50	1.00	0.50		IC	8.00	1.00	0.50
MQ	1.00	2.00	1.00		SC	9.00	2.00	1.00
Total	2.50	5.00	2.50		Total	18.00	3.13	1.61

Note: DF is a design fault, CF is construction fault, MQ is material quality EC is external corrosion, IC is internal corrosion, and SC is stress cracking.

Table 5-7: Standard Matrix Relative Weighting Calculation

Materials Defect				Weight		Corrosion				Weight
DF	0.40	0.40	0.40	0.40		EC	0.06	0.04	0.07	0.05
CF	0.20	0.20	0.20	0.20		IC	0.44	0.32	0.31	0.36
MQ	0.40	0.40	0.40	0.40		SC	0.50	0.64	0.62	0.59
Total	1.00	1.00	1.00	1.00		Total	1.00	1.00	1.00	1.00

However, to ensure that the above assessment has been carried out in compliance with the AHP procedure and that the results are within the acceptable consistency bounds for a pairwise comparison, a consistency check is carried out using Equations 3-25, 3-26 and 3-27. Note that a consistency check is only carried out for a *3×3* matrix in this work. The other matrix, *1×1,* does not require a consistency check (Saaty, 1987).

To carry out the consistency check, a consistency ratio calculation will first be undertaken. This is carried out by multiplying the standard matrix relative weighting in Table 5-7 with the three values of each variable in Table 5-6.

For example, the first value in column *SC* of Table 5-6 is multiplied with *0.05*, which is the first relative weighting in Table 5-7. The calculated values for the SC are *0.49 (9 × 0.05)*, *0.72* (*2 × 0.36*) and *0.59* (*1 × 0.59*), respectively. The next step is to find the sum weight by adding the calculated figures above, giving *1.8* (*0.49 + 0.72 + 0.59*) and dividing it with the relative weighting of the *SC* variable, *0.59*. The sum weight of the SC variable is thus *3.06* (*1.8/0.59*).

Table 5-8 below shows the complete results for the material defect and corrosion variables.

Table 5-8: AHP Pairwise Comparison Matrix Consistency Check

				Row Total	Sum Weight
		Material defect			
DF	0.40	0.40	0.40	1.20	3.00
CF	0.20	0.20	0.20	0.60	3.00
MQ	0.40	0.40	0.40	1.20	3.00

				Row Total	Sum Weight
Corrosion					
EC	0.05	0.04	0.07	0.16	3.01
IC	0.44	0.36	0.29	1.09	3.04
SC	0.49	0.72	0.59	1.80	3.06

To calculate the consistency index, λmax is calculated first. This is arrived at by adding the sum weights and dividing the total by the number of variables (3) in the matrix.

The λmax is calculated for the corrosion, using Equation 3-27,:

$$\lambda_{\max} = \frac{3.01 + 3.04 + 3.06}{3} = 3.04$$

The consistency index is then calculated using Equation 3-26 by subtracting the number of variables (3) from the λmax, divided by subtraction of one (*1)* from the number of variables (3) as shown below.

$$Consistency\ Index = \frac{3.04 - 3}{3 - 1} = 0.02$$

The consistency ratio (CR) is thus calculated using Equation 3-25 by dividing the Consistency Index (CI) (*0.02*) with the Random Index (RI). The RI for the *3 × 3* matrix is *0.58*. A consistent pairwise comparison assessment should produce a CR less than *0.1*. The CR results below, *0.03,* indicate a consistent assessment.

$$Consistency\ Index = \frac{0.02}{0.58} = 0.03$$

For all the AHP pairwise assessments carried out, this calculation procedure has been undertaken, first to obtain the weighting ratios for input into the symmetric model and also to ensure that the consistency of the results is in line with the Saaty RI values (Saaty, 1987).

Symmetric Method and Relative Weight Development

The determination of conditional probabilities requires the filling of the CPT, using the symmetric model and relative weight development that has been introduced in Section 3.3.1. The application of the symmetric model in the CPT development is shown below, with the two example nodes – material defect and corrosion - used to show the process. The required input for the assessment includes the failure probabilities of the parent nodes, obtained from historical data, and the AHP pairwise comparison, derived from the expert elicitation. The AHP pairwise comparison method has been used to identify the relative influence of each parent node to the associated child node. That relative influence is shown as the average weighting in Table 5-9. The average weighting of each variable is multiplied with its failure probability to obtain the variable's specific importance. This is then used to calculate the symmetric method weighting ω_r , and that would be the input value for the CPTs of the child nodes. In all cases $\sum_{r=1}^{n} \omega_r = 1$. n is the number of decision factors.

Table 5-9 shows the process and the results for the child nodes *material effect* and *corrosion*. Appendix C shows the AHP questionnaire and the results.

Table 5-9: Symmetric Method Relative Weight for Variables

Variables	Failure Probabilities	AHP Av. Weight	Variable Specific Wgt	Symmetric Method Weight for Use in the Assessment
Material defect				
DF	0.069	0.40	0.028 (i.e., 0.069x0.40)	$\omega_1 = \frac{0.028}{0.028+0.015+0.028} = 0.395$
CF	0.073	0.20	0.015	$\omega_2 = \frac{0.015}{0.028+0.015+0.028} = 0.209$
MQ	0.069	0.40	0.028	$\omega_3 = \frac{0.028}{0.028+0.015+0.028} = 0.395$
Corrosion				
EC	0.108	0.05	0.006	$\omega_1 = \frac{0.006}{0.006+0.009+0.004} = 0.312$
IC	0.026	0.36	0.009	$\omega_2 = \frac{0.009}{0.006+0.009+0.004} = 0.499$

Variables	Failure Probabilities	AHP Av. Weight	Variable Specific Wgt	Symmetric Method Weight for Use in the Assessment
SC	0.006	0.59	0.004	$\omega_3 = \frac{0.004}{0.006+0.009+0.004} = 0.189$

Note: The failure probabilities for the main failure factors – material defects and corrosion - is obtained from Concawe (2017) for data from 1971 to 2015 which is more conservative than the five-year moving average. The failure probabilities for the variables, e.g., DF, CF, is derived by weighting each sub-variable, based on its recorded failures, against the main factors' failure probabilities.

The sum of the relative weights for each of the two variables is:

$$\sum_{r=1}^{n} \omega_r(\text{material defect}) = \omega_1 + \omega_2 + \omega_3 = 0.395 + 0.209 + 0.395 = 1$$

$$\sum_{r=1}^{n} \omega_r(\text{corrosion}) = \omega_1 + \omega_2 + \omega_3 = 0.312 + 0.499 + 0.189 = 1$$

From the values calculated in Table 5-9, and using Equation 3-21, the node or conditional probability table is completed, as shown in Table 5-10. The values for material defect (*MD*), are arrived at as below, for a probability of material defect leading to pipeline failure being 'yes'. The probability for 'no' is 1 minus that of 'yes'.

$$\mathrm{P}(MD = yes \mid MQ = yes, CF = yes, DF = yes) = \omega_1 + \omega_2 + \omega_3 = 0.395 + 0.209 + 0.395 = 1$$

$$\mathrm{P}(MD = yes \mid DF = no, CF = yes, MQ = yes) = 0 + \omega_2 + \omega_3 = 0 + 0.209 + 0.395 = 0.605$$

$$\mathrm{P}(MD = yes \mid DF = yes, CF = no, MQ = yes) = \omega_1 + 0 + \omega_3 = 0.395 + 0 + 0.395 = 0.791$$

$$\mathrm{P}(MD = yes \mid DF = no, CF = no, MQ = yes) = 0 + 0 + \omega_3 = 0 + 0 + 0.395 = 0.395$$

$$\mathrm{P}(MD = yes \mid MQ = no, CF = yes, DF = yes) = \omega_1 + \omega_2 + \omega_3 = 0 + 0.209 + 0.395 = 0.605$$

$$\mathrm{P}(MD = yes \mid MQ = no, CF = yes, DF = no) = \omega_1 + \omega_2 + \omega_3 = 0 + 0.209 + 0 = 0.209$$

$$\mathrm{P}(MD = yes \mid MQ = no, CF = no, DF = yes) = \omega_1 + \omega_2 + \omega_3 = 0 + 0 + 0.395 = 0.395$$

$$P(MD = yes \mid MQ = no, CF = no, DF = no) = \omega_1 + \omega_2 + \omega_3 = 0 + 0 + 0 = 0$$

Similar process is used to obtain the CPT for the corrosion and the results are shown in Table 5-10.

Table 5-10: Node Probability Table for Material Defect and Corrosion

Material Defect								
Material	Yes				No			
Construction	Yes		No		Yes		No	
Design	Yes	No	Yes	No	Yes	No	Yes	No
Yes	1.000	0.605	0.791	0.395	0.605	0.209	0.395	0
No	0	0.395	0.209	0.605	0.395	0.791	0.605	1.00
Corrosion								
External Corrosion	Yes				No			
Internal Corrosion	Yes		No		Yes		No	
Stress Cracking	Yes	No	Yes	No	Yes	No	Yes	No
Yes	1	0.81	0.50	0.31	0.69	0.50	0.19	0
No	0	0.19	0.50	0.69	0.31	0.50	0.81	1.00

5.3.5 Analysis of the Model

The model has now been built, and all prior probabilities have been computed based on the failure data and the AHP pairwise comparison method applied. Figure 5-3 shows the BN nodes for the probability of a pipeline failure, including its marginal probabilities.

The BN shows that the likelihood of pipeline failure resulting in full rupture is 7.51% per year whilst that of a leak is 14.72% per year. The leak likelihood being double compared to that of a rupture's likelihood is not surprising because the biggest threat to oil pipelines in Nigeria is theft due to drilling intended to create a tapping point on the pipeline (Ralby, 2017). The other threat is the deliberate destruction of the pipeline system by insurgency, which is rife in the country for political and socio-economic reasons (Hopkins, 2008).

To assess the robustness of the model, predictive, diagnostic and sensitivity analyses have been performed.

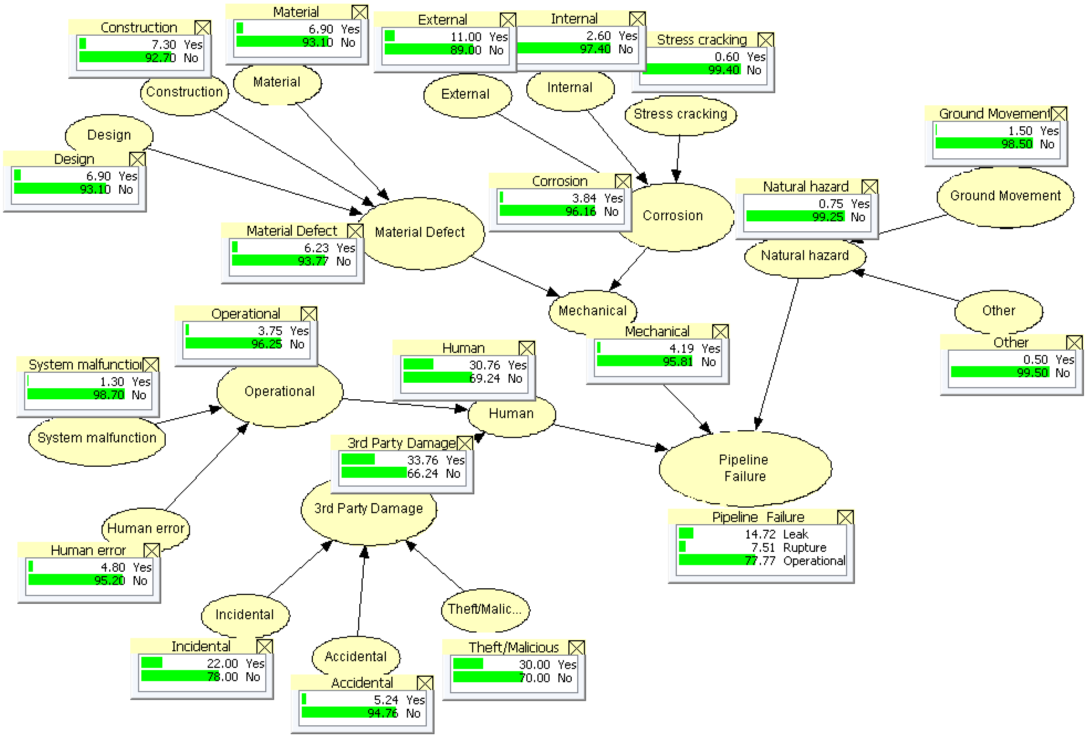

Figure 5-3: BN Model Showing Marginal Probabilities for Pipeline Failure

5.3.5.1 *Evidence Propagation*

In undertaking BN model analysis, certain assumptions are made, and certain inputs are provided based on data which may not be directly relevant to this particular case. Evidence propagation gives the analyst the opportunity to observe changes in probability distribution if some of the assumptions were to be amended, either in isolation or in combination with other changes. For instance, in order to find out what combination of factors must be avoided, different scenarios and combinations of events can be propagated as new evidence and compared with the baseline probability distribution. Figure 5-3 shows that human-related intervention has a higher failure likelihood on the selected Nigerian pipeline system, with a 30.76% failure likelihood, compared to mechanical failure which has a value of 4.19% and natural hazards which have a value of 0.75%. However, it is also known that the pipelines are ageing, and the impact of climate change on them can be devastating. The operator may wish to model a situation whereby one or both of the failure factors were realised and how that affects the probability distribution. On the other hand, the significantly higher number of politically motivated pipeline destruction events and criminally linked hot taps may be brought down by deliberate government policy and an increase in security provisions. The operator may want to find what is likely going to be the impact of the policies on the pipeline failure probability distribution.

To propagate any evidence and assess the impact of those scenarios compared with the baseline results, two scenarios have been generated thus:

Scenario 1: the government's effective security policies and political intervention result in a significant drop in third-party intervention due to intentional and incidental damages. This scenario will assume a best-case scenario of a 5 percent failure factor for those variables compared with the baseline model.

Scenario 2: the ageing pipeline may deteriorate further with time, resulting in increased cases of corrosion failure and material defect. This scenario will assume a worst-case scenario of a 90 percent failure probability for those factors, compared with the baseline model.

Table 5-11 shows the baseline model input and the results compared for the two scenarios. The baseline model results indicate failure probabilities of 14.72% for leaks and 7.51% for ruptures. The pipeline remains operational 77.77% of the time. The scenario 1 results (best case) give an indication of the level of loss reduction that is possible if efforts were to be made to reduce the occurrence of the two factors – theft and incidental damages. A reduction of up to 75.00% and 55.00% for leaks and ruptures is possible if the failure probabilities of theft and incidental damages can be reduced from the baseline 30.00% and 22.00% down to 5.00% and 5.00% respectively. The leak and rupture failure probabilities are reduced from 14.72% and 7.51% to 3.90% and 3.30% respectively. Pipeline availability increases from 77.77% to 92.80%.

Table 5-11: Evidence Propagation

<table>
<tr><th>Variables</th><th colspan="3">Best Case (Scenario 1)</th><th colspan="3">Baseline Model</th><th colspan="3">Worst Case (Scenario 2)</th></tr>
<tr><td colspan="10">Probability Distribution</td></tr>
<tr><td></td><td>Y</td><td colspan="2">N</td><td>Y</td><td colspan="2">N</td><td>Y</td><td colspan="2">N</td></tr>
<tr><td>Human Damage</td><td>6.6</td><td colspan="2">93.4</td><td>30.8</td><td colspan="2">69.2</td><td>30.8</td><td colspan="2">69.2</td></tr>
<tr><td>Third Party Damage</td><td>7.0</td><td colspan="2">93.0</td><td>33.8</td><td colspan="2">66.2</td><td>33.8</td><td colspan="2">66.2</td></tr>
<tr><td>Incidental Damage</td><td>5</td><td colspan="2">95</td><td>22.0</td><td colspan="2">78.0</td><td>21.6</td><td colspan="2">78.4</td></tr>
<tr><td>Accidental Damage</td><td>5.2</td><td colspan="2">94.9</td><td>5.2</td><td colspan="2">94.9</td><td>5.2</td><td colspan="2">94.9</td></tr>
<tr><td>Theft/Intentional</td><td>5</td><td colspan="2">95</td><td>30.0</td><td colspan="2">70.0</td><td>30.0</td><td colspan="2">70.0</td></tr>
<tr><td>Operational damage</td><td>12.0</td><td colspan="2">88.0</td><td>3.8</td><td colspan="2">96.2</td><td>3.8</td><td colspan="2">96.2</td></tr>
<tr><td>System Malfunction</td><td>1.3</td><td colspan="2">98.7</td><td>1.3</td><td colspan="2">98.7</td><td>1.3</td><td colspan="2">98.7</td></tr>
<tr><td>Human (& org) Error</td><td>4.8</td><td colspan="2">95.2</td><td>4.8</td><td colspan="2">95.2</td><td>4.8</td><td colspan="2">95.2</td></tr>
<tr><td>Mechanical Failure</td><td>4.2</td><td colspan="2">95.8</td><td>4.2</td><td colspan="2">95.8</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Material Defect</td><td>6.2</td><td colspan="2">93.8</td><td>6.2</td><td colspan="2">93.8</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Material</td><td>6.9</td><td colspan="2">93.1</td><td>6.9</td><td colspan="2">93.1</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Construction</td><td>7.3</td><td colspan="2">92.7</td><td>7.3</td><td colspan="2">92.7</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Design</td><td>6.9</td><td colspan="2">93.1</td><td>6.9</td><td colspan="2">93.1</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Corrosion</td><td>3.8</td><td colspan="2">96.2</td><td>3.8</td><td colspan="2">96.2</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>External Corrosion</td><td>11.0</td><td colspan="2">89.0</td><td>11.0</td><td colspan="2">89.0</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Internal Corrosion</td><td>2.6</td><td colspan="2">97.4</td><td>2.6</td><td colspan="2">97.4</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Stress Cracking</td><td>0.6</td><td colspan="2">99.4</td><td>0.6</td><td colspan="2">99.4</td><td>90</td><td colspan="2">10</td></tr>
<tr><td>Natural Hazard</td><td>0.8</td><td colspan="2">99.2</td><td>0.8</td><td colspan="2">99.2</td><td>0.8</td><td colspan="2">99.2</td></tr>
<tr><td>Ground Movement</td><td>1.5</td><td colspan="2">98.5</td><td>1.5</td><td colspan="2">98.5</td><td>1.5</td><td colspan="2">98.5</td></tr>
<tr><td>Other Natural Hazards</td><td>0.5</td><td colspan="2">99.2</td><td>0.5</td><td colspan="2">99.2</td><td>0.5</td><td colspan="2">99.2</td></tr>
<tr><td rowspan="2">Pipeline Failure – Loss of Containment</td><td>O</td><td>L</td><td>R</td><td>O</td><td>L</td><td>R</td><td>O</td><td>L</td><td>R</td></tr>
<tr><td>92.8</td><td>3.9</td><td>3.3</td><td>77.77</td><td>14.72</td><td>7.5</td><td>39.8</td><td>27.3</td><td>32.9</td></tr>
</table>

Note: O is when the pipeline is operational, L is leak and R is rupture.

For scenario 2, which assumes a worst-case scenario of progressive pipeline deterioration due to ageing and lack of maintenance, the availability of the pipeline drops significantly, from 77.77% to 39.80%. The scenario assumes a 90.00% failure probability from a mechanical failure, which encompasses material defect and corrosion. All other factors remain the same. The failure probabilities for leaks and ruptures jump twofold and fourfold from 14.72% and 7.51% to 27.30% and 32.90% respectively.

From the above analyses, the importance of evidence propagation in decision-making and forecasting is clear. The assessment easily allows the decision-maker to assess the infinite combination of what-if scenarios in order to see what impact it will have on the operation. This will help direct scarce resources into areas where they will have the most impact.

Figure 5-4 and Figure 5-5 show the BN model and failure probabilities for the two scenarios.

5.3.5.2 *Posterior Probabilities Assessment*

The main advantage of Bayesian Network modelling is its ability to support the decision-making process by allowing for an update to the model in the presence of new observation or evidence. That evidence can be propagated in either direction.

However, diagnostic analysis, which is the determination of the posterior probabilities of the parent nodes given new evidence for the child node, is the most popular (Khakzad *et al.*, 2011). Therefore, diagnostic analysis inference will be used to calculate the posterior probability distribution of each risk factor in case of a confirmed pipeline failure.

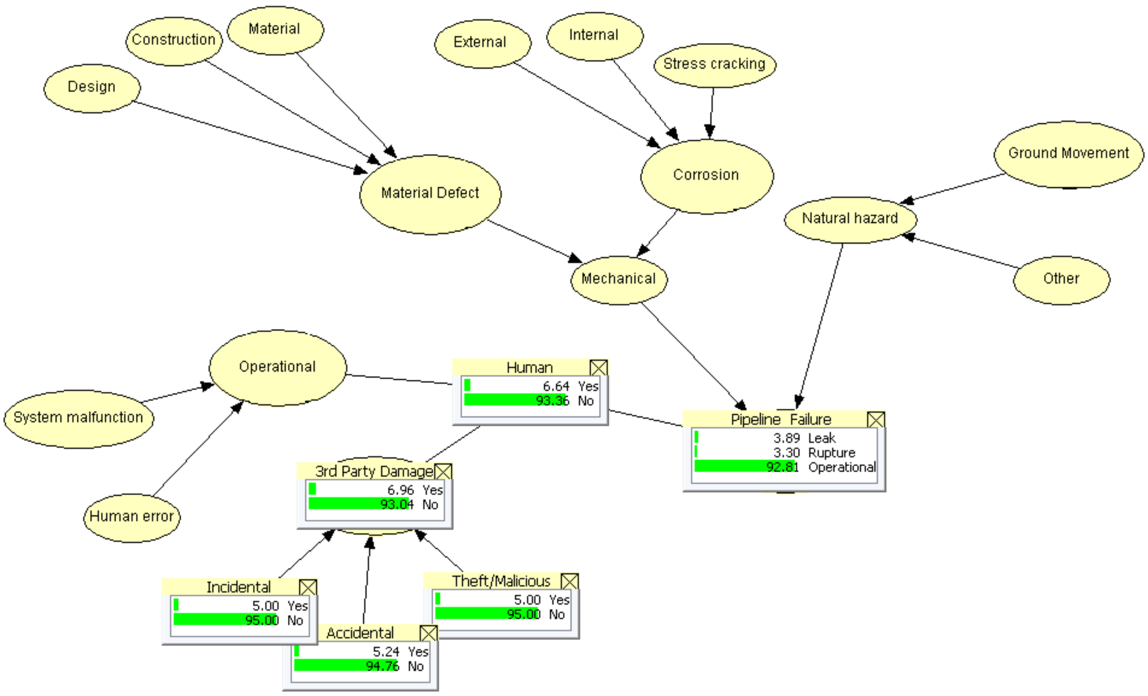

Figure 5-4: Evidence Propagation Scenario 1 – Reduced Risk due to Specified Actions

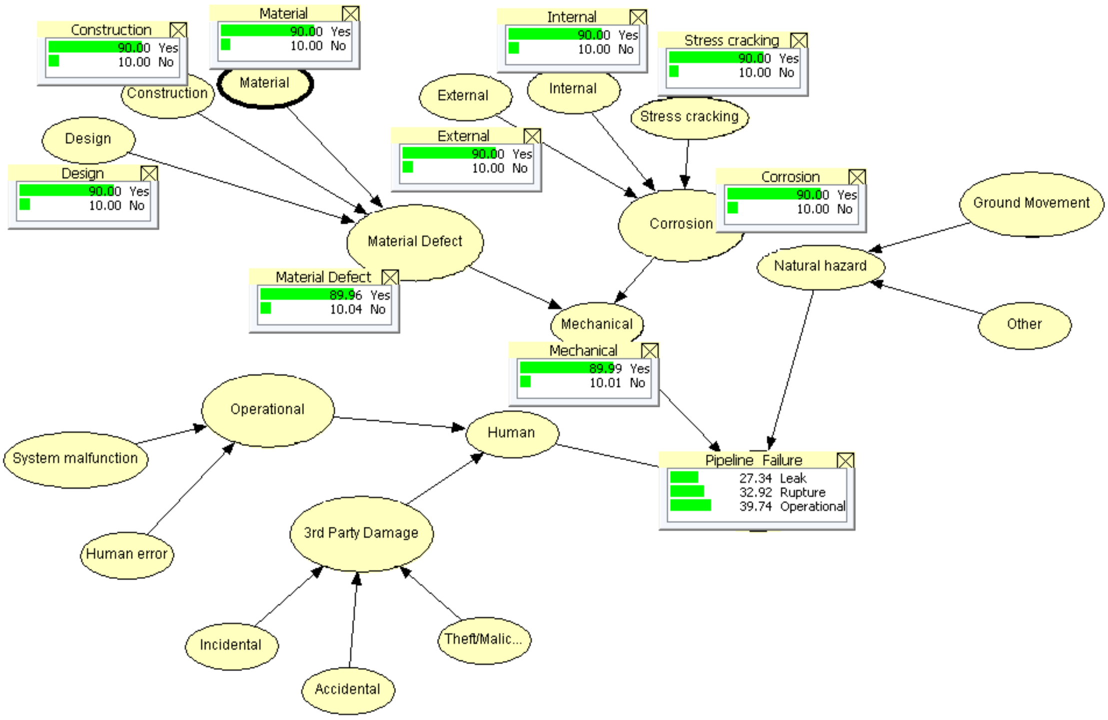

Figure 5-5: Evidence Propagation Scenario 2 – Increased Risk due to Ageing Pipeline

The first part of diagnostic analysis assesses the impact of evidence given for the node *pipeline failure* on its parent nodes. The effect of such evidence can easily be propagated backwards to see which of the parent nodes has the most impact on the confirmed condition of a pipeline. Two different pieces of evidence have been propagated – a confirmed pipeline leak and a confirmed pipeline rupture. Figure 5-6 and Figure 5-7 show the BN model with both leak and rupture evidence inserted. The new failure probabilities for the parent nodes – human, mechanical and natural hazard – as a result of the evidence are also shown. For comparison, the baseline model failure probabilities are 30.76%, 4.19% and 0.75% for human damage, mechanical failure and natural hazards respectively.

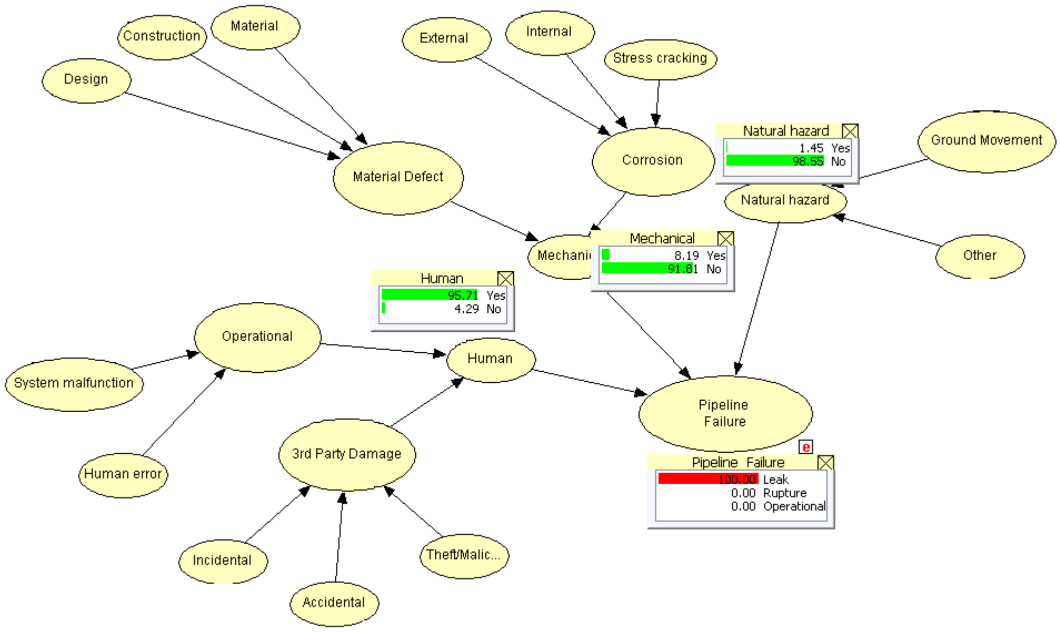

Figure 5-6: Posterior Probabilities for Parent Nodes Given Evidence of a Leak

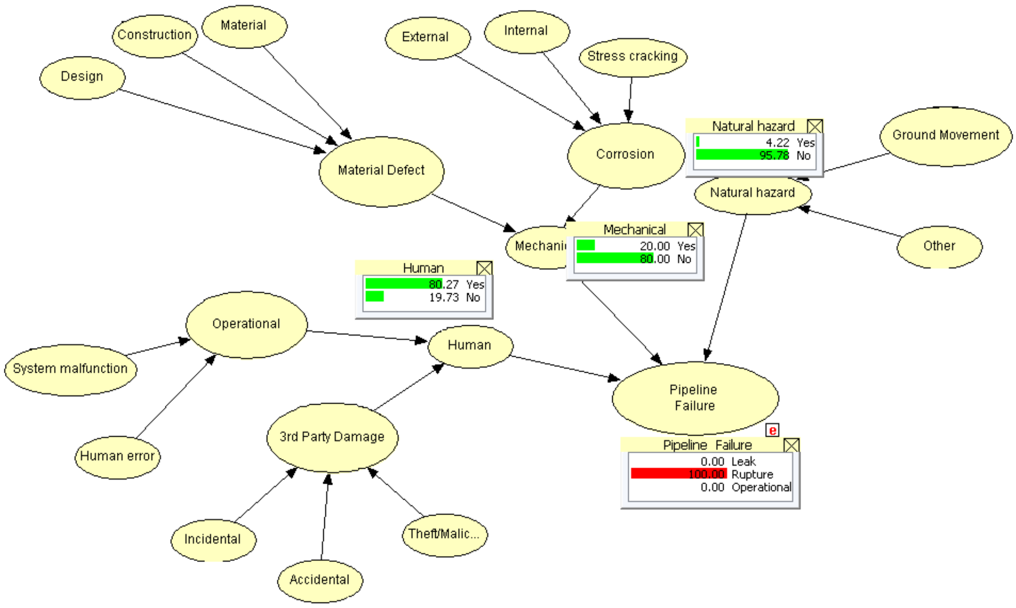

Figure 5-7: Posterior Probabilities for Parent Nodes Given Rupture Evidence

Figure 5-8 and Figure 5-9 show a 3-D chart showing the changes in failure probabilities as a result of new evidence. In Figure 5-8, the impact of new evidence on the parent node is clear, with the highest change affecting human intervention, which increases from 0.31 to 0.96 for a confirmed leak and from 0.31 to 0.80 for a confirmed rupture. This shows, counter-intuitively, that the impact of human intervention resulting in a pipeline leak is greater than such impact resulting in a pipeline rupture. This can be explained by the fact that the human intervention factor is skewed by a disproportionate failure rate due to third-party theft/intentional intervention, as shown in Figure 5-9, and there are more incidents of theft via hot-tapping than there are for the intentional destruction of the pipelines for political reasons.

Conversely, the failure probabilities of both mechanical failure and natural hazards have been affected more by new evidence due to a confirmed rupture than due to a confirmed leak, as shown in Figure 5-8. There is an increase of two times for a leak and of five times for a rupture for both mechanical failure and natural hazards respectively. Unlike human damage, the contribution of primary variables to the failure probability changing is spread amongst both the corrosion and materials defect factors and not skewed by a single factor, as shown in Figure 5-9.

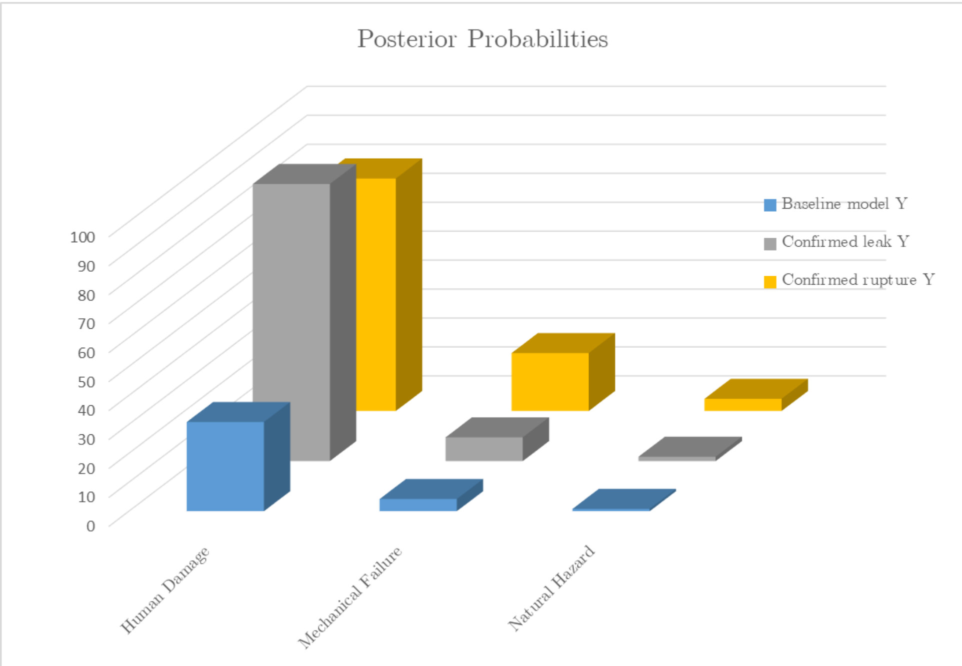

Figure 5-8: Posterior Probabilities for the Parent Nodes Given New Evidence

Figure 5-9 also shows how the new evidence only accentuates the contribution made by the largest three factors to the overall failure probability. For the baseline model, the three largest primary failure rate contributors are theft/intentional damage (22%), incidental (18%) and external corrosion (8%). Upon finding new evidence of a confirmed leak, the contribution of theft/intentional damage to the overall failure probability jumps to 65%, that of incidental damage to 32% and that of external corrosion to 10%.

The results obtained in this analysis are generally in agreement with the Concawe database (Cech *et al.*, 2018), with the exception of the outsized contribution of theft or intentional damage and incidental damage. These are particularly high due to the peculiar challenges resulting from a prevalence of criminality and politically motivated actions. The European pipeline database also shows an astronomical increase in third-party damage due to intentional actions, from two incidents in 2012 to 87 incidents in 2015. The prevalence of incidental damage has not seen any increase in Europe, but it has seen an increase in Nigeria due to a significant population increase over the past two decades and encroachment into the pipeline's right of way due to weak implementation of the law. The encroachment into pipeline's right of way, including construction activities and farming, increases the likelihood of damages occurring, which subsequently lead to pipeline loss of containment.

The revised failure probabilities due to new evidence can be further interrogated by providing additional evidence. For example, given the assumption that a leak is more likely to occur as a result of theft/intentional damage, inserting a 100% chance of failure due to intentional damage reduces the failure probability contribution of other factors; incidental damage contribution is reduced from 18% to 10%, whilst external corrosion reduces from 8% to 6%. This intercausal inference attempts to explain the contribution of other variables by reducing their failure rates in place of plausible reasons to assume one variable caused the incident.

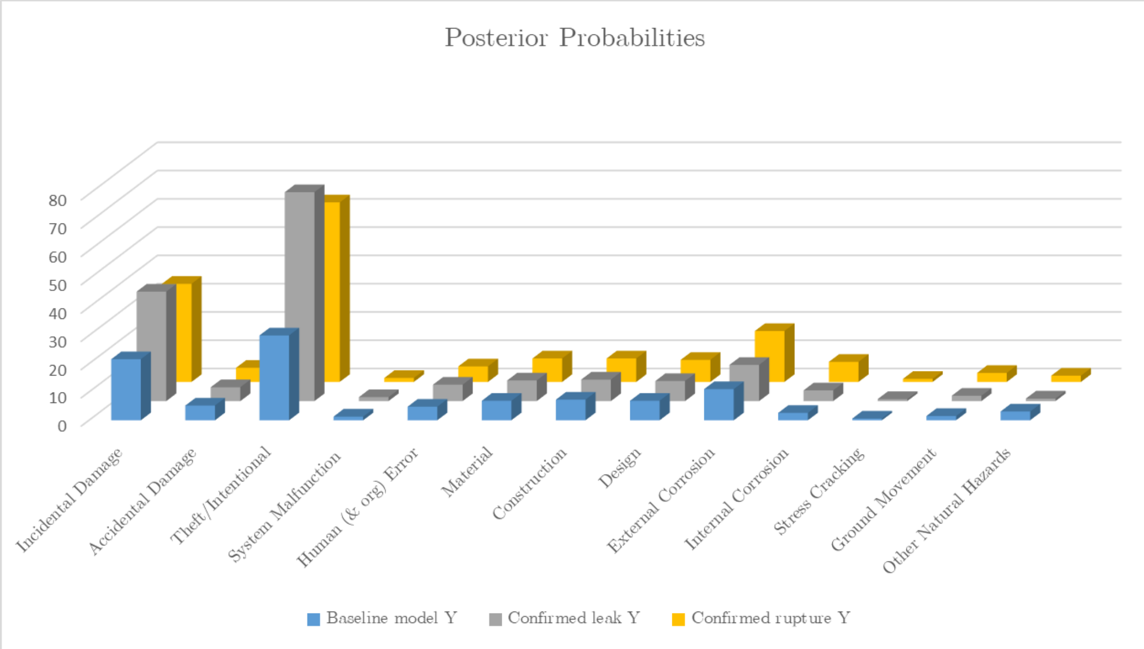

Figure 5-9: Primary Variables' Posterior Probabilities Given New Evidence

The main benefit of diagnostic analysis such as this is affording fault diagnosis and investigation by identifying the variables that are more likely to contribute to a pipeline failure. Additionally, the diagnostic analysis can be used to identify factors that will likely cause a certain failure in the future, hence concentrating the mind of the operator on what to focus on. By performing these analyses, the posterior joint probabilities of all the variables, given new evidence of an event, are very useful for safety evaluation. Additionally, the causal path of an accident can be identified using this model, thus reducing the need for dependence on subject matter experts at all times.

5.3.6 Validation and Sensitivity Analysis

5.3.6.1 Validation

In ensuring the robustness of the model, a validation process, which aims to provide reasonable confidence that the model meets the minimum specifications in order to produce sound and realistic results, is necessary. However, a full validation will be time-consuming; a partial validation is therefore performed based on the sensitivity analysis results as enumerated in Eleye-Datubo (2005).

The validation is limited to the usability and face validation aspects. These include:

- The sensitivity analysis carried out in Section 5.3.6.2 supports the validation because it assesses the results of the model for small incremental changes to the inputs. The Hugin software has an in-built parameter sensitivity analysis which has been deployed for this assessment. The outcome indicates that the model results are sensible for the level of changes in regards to the input variables.
- The face validation evaluates the results generated by a model and compares it with the failure statistics in the public domain. In this case, the results of the model are compared with the Concawe database (Cech *et al.*, 2018), as outlined in Section 5.3.5. The results generally agreed with the data with the exception of the theft and intentional damage variable within third-party intervention.

5.3.6.2 Sensitivity Analysis

Sensitivity analysis measures the sensitivity or responsiveness of the model's results to a variation of the inputs. The accuracy, robustness and reliability of the model are linked to the posterior probability distribution for changes to the input of the likelihood value. Sensitivity analysis offers the confidence that is necessary to show that the model is built correctly and produces results that are within the bounds of reality. This section examines the BN properties by applying incremental changes to the likelihood input values and observing the output values to ensure that it follows a similar trend. As outlined in Figure 5-9, the most influential variables have been identified and they will assist in the analysis, as they will affect the model more than other variables with an insignificant influence on the model.

Parameter sensitivity or one-way sensitivity analysis has been used for this analysis and this is incorporated into the Hugin software. The sensitivity function is such that the probability of causes (P_c) is a function of the parameter $z = P(Y = y_i \mid \pi)$ where y_i is the one state of variable Y and π is the combination of the states for Y's parent nodes (Sulaiman, 2017).

The sensitivity analysis is carried out by selecting the hypothesis variable (in this case a *pipeline failure),* the desired state(s) of the hypothesis variable (in this case a *leak)* and finally selecting the parameter variable. The parameter variables can be parent nodes of the hypothesis variable or they can be any other nodes whose input variation will influence the outcome of the hypothesis variable. For the parameter variables, the primary failure factors have been chosen and only the *yes* state is assessed.

Figure 5-10 shows the sensitivity graph of various variables against pipeline failure (leak). When assessed against the three axioms outlined 5.2.4, it can be seen in Figure 5-10 that a slight increase and decrease in the prior probabilities of the parent node, 3rd party damage, results in a relative increase and decrease in the child node, human factor. Also, the magnitude of the influence of the parent node, 3rd party damage, to the child node, human factor, remain consistent for the assessed input variation.

Figure 5-11 shows a graph of sensitivity analyses output for a given evidence. It can be observed that theft/intentional damage has the highest sensitivity value, implying that the incremental increase of this variable results in the greatest influence on the outcome of pipeline failure. This would be aligned with the outcome of the analysis in Figure 5-9, where the posterior probability distribution for theft is shown as the largest and the most significant influence for any new evidence entered in regards to pipeline failure.

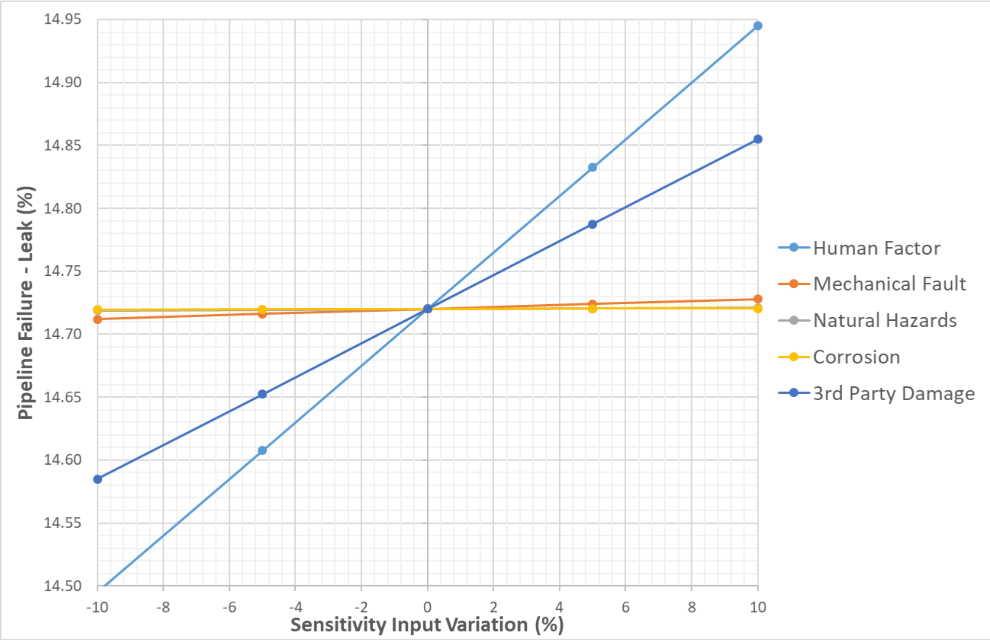

Figure 5-10: Sensitivity for Pipeline Failure (Leak) Against Other Variables

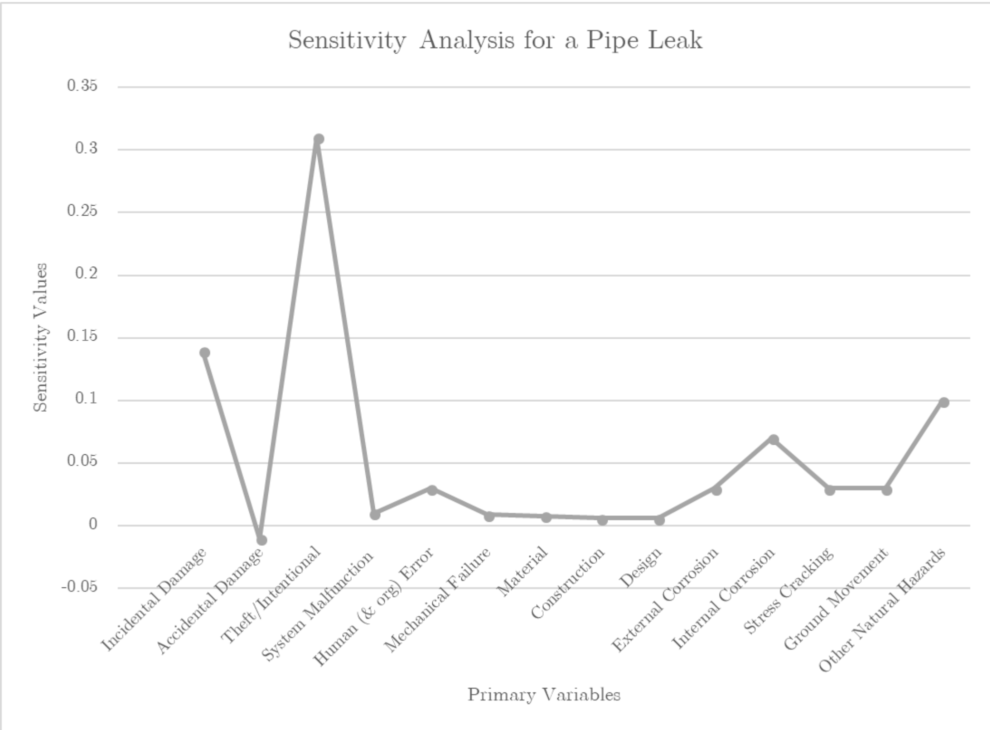

Figure 5-11: Sensitivity Values for Given Evidence

5.4 Discussion and Conclusion

The Bayesian Network model described in this chapter enumerates the cause and effect relationship that can be established between failure factors and pipeline failure conditions for the pipeline systems where there is inadequate or unreliable data. The proposed model, as indicated in Figure 5-3, shows the variables, the causes and effects, evidence propagation and the incorporation of uncertainty into the analysis.

This chapter is an extension of Chapter 4, where the Modified FMEA model has identified and ranked the failure factors responsible for loss of containment in the pipeline, with the most common factor identified as pipeline failure due to a leak or rupture. The BN model then looks at this failure mode in detail, including all the initiating failure factors, that is, the contributing factors behind a pipeline leak or rupture.

Identifying and inserting conditional probabilities for the primary failure factors is straightforward. However, specifying marginal probabilities for the CPTs of the child nodes is challenging in the absence of relevant data. Generally, the CPTs are filled using elicitation of domain experts. This is not usually simple if the node has multiple states or multiple probability tables, as it burdens the experts and is prone to biases. To address this shortcoming, both the AHP pairwise comparison method and the symmetric model have been adopted to generate the CPT by synthesising the experts' opinions. This approach ensures that the seeming weakness of the BN is addressed.

The BN model for this chapter has been used to show the contributing factors behind pipeline failures and their interrelationships. The model therefore provides managers with dynamic information on how to prevent undesired outcomes and can be used for a safety management plan.

The assessment carried out in this chapter can be used to predict pipeline integrity issues and diagnose recent loss events to identify the most likely responsible failure factor. The assessment can also be used to update the degree of beliefs given any new information or evidence. The predictive analysis serves to provide valuable information during the design and operation of the system and helps in directing resources to the factors with the most influence on a particular integrity issue. The diagnostic analysis helps to determine the critical failure factors that may lead to a catastrophic loss event. The diagnostic analysis can also help with the identification of an accident event path. Figure 5-4 and Figure 5-5 show the predictive analysis, which outlines the marginal failure probability of the loss events. Figure 5-6 and Figure 5-7 outline the diagnostic analysis, which shows the significant failure factor that contributes towards the pipeline failure. The human damage node is shown as the parent node that has the most influence on the rupture state of the pipeline failure node.

Table 5-11 shows the evidence propagation in the presence of new information, for example, if the operator wants to assess the impact of certain actions or spending on pipeline integrity improvements. It shows that if the third party and incidental damage probabilities were to be reduced, from 30.00% to 5.00% and from 21.60% to 5.00% respectively, this would lead to a reduction in the hypothesis variable, by fourfold for leak and twofold for rupture. On the other hand, if the material defect and corrosion probabilities were to be increased from 6.20% to 90.00% and from 3.80% to 90.00% respectively, the hypothesis variable will see an increase in failure probability. This jumps from 14.72% and 7.50% to 27.30% and 32.90%, respectively.

Model validation and sensitivity analysis have been carried out to ensure that the model has been built and is operating within the bounds of expectation and that the model is sensitive to the incremental changes of the input variable. The sensitivity analysis is especially important as it also gives an indication of the variable with the most influence on the final event. As indicated in Figure 5-10, theft/intentional damage is found to have the most influence on the leak failure state of the pipeline failure variable. The sensitivity analysis shows that the BN developed to help in pipeline failure identification decision-making is reliable and accurate, although the accuracy can be improved with more objective data.

The next chapter deals with decision making and CBA including the evaluation of the performance of the safety and prevention barriers using Evidential Reasoning (ER) which is considered more suitable than using BN.

Chapter 6. Pipeline Risk Management Decision Support Model

Overview

This chapter outlines a decision support model based on Evidential Reasoning (ER) and Cost-Benefit-Analysis (CBA) to support the reduction of pipeline loss of containment as a result of third-party damage, particularly theft/intentional third-party damage. The model identifies the main Risk Control Options (RCOs) as main attributes. Each RCO has basic attributes which contributes to the overall risk reduction or elimination of the threat. The attributes have been grouped into three categories: technical or technological solutions, governmental solutions and company or managerial solutions. The CBA looks at the costs to the operator associated with the loss of containment in regard to human safety, the economic and environmental aspects. These costs are required to reduce or eliminate the threat using a number of RCOs. The benefit for each of the options in monetary terms is the damage cost averted by introducing the RCO.

As outlined in Section 3.4, ER is chosen because it is able to deal with MCDM problems with uncertainties, aggregation of conflicting information and the hybrid nature of the information. This fits in with the challenges of analysing different and often conflicting information and data that has been identified for this thesis in general and this chapter in particular.

The results provide guidance for the infrastructure operator by reducing the complexity of the decision-making into a simple hierarchical output. The results also show the attributes of each decision, their effectiveness in reducing the failure likelihood and the estimated cost of each attribute. The operator would then be able to select one or more risk reduction attributes and will immediately see how the RCO reduces the failure likelihood. It would also give the operator an idea of the budgetary expenditure required to implement the RCO.

Sensitivity analysis and validation of the ER model has also been undertaken to ensure that the model is fit for its intended purpose and that it provides reasonable results under the anticipated circumstances.

6.1 Evidential Reasoning Decision-Making

Chapter 3 outlined the detailed review of decision making techniques and their weaknesses. Evidential Reasoning (ER) has been used to develop the model in this chapter because it addresses the weaknesses of Probability Theory and Dempster-Shafer Theory and provides a rigorous reasoning process for aggregating conflicting information.

As outlined in Chapter 3, The ER method has been widely used, since it was first formulated, in solving MCDM problems in different area including engineering safety analysis (Liu *et al.*, 2005), pipeline leak detection (Xu *et al.*, 2007) and maritime safety and security (Wang *et al.*, 1995; Liu *et al.*, 2005).

6.2 Evidential Reasoning Application/Methodology

This section provides a methodology for the proposed ER model that is applied to the problem of loss of containment due to third-party intervention in a pipeline. The methodology takes into account and builds upon the previous work carried out as part of the suite of risk assessment processes for cross-country pipelines.

6.2.1 Identification of Predominant Failure Factors

This is the first step in the modelling process. In this step, the predominant failure factors are identified. These are the factors that will rely on the Evidential Reasoning algorithm for insight. Generally, the failure factors should be identified from a separate study which forms the foundations for the analysis. For this study, the identification of the major failure factors for the pipeline under consideration has been carried out in Chapter 4. The identified failure factors and their potential consequences have been assessed further using the Bayesian Network in Chapter

5. The assessment also identified the failure factor with the highest probability of occurrence as being third-party related pipeline failure.

6.2.2 Developing the Evaluation Matrix

The second step in the analysis is the identification and development of the evaluation matrix. The matrix that will be used depends on the problem at hand but will include the general attributes, the basic attributes, the alternatives and their interconnectivity. In identifying and developing these attributes, reference will be made to the literature including industrial and international standards and other jurisdictional guidance documents, which identify the risk control measures necessary for reducing the threat of third-party related pipeline damage.

6.2.3 Weights and Belief Degrees Development Using Experts' Elicitation

The third step in the process is the calculation of the weight of each of the identified general and basic attributes. The belief degrees of the attributes must also be determined. Such information informs the evaluation grades and ensures that the attributes and alternatives have a relationship in terms of their effectiveness with respect to the overall analysis.

Analytical Hierarchy Process (AHP) and the pairwise comparison method were used to determine both the weight and belief degrees by utilising experts' elicitation for qualitative assessment through questionnaires. The AHP process has been described in Section 5.3.4.2. A questionnaire is developed to address the subjective questions which form part of the input of the ER. The questionnaire has two parts: part one assesses the weighting of the basic attributes for each of the main attributes, while part two assesses the belief degrees associated with each attribute.

A minimum of five experts were invited to give their professional opinion based on their expertise and experience. The experts all have experience in the pipeline industry supply chain – varying from operators to consultants and academics.

Their input forms the foundation of the assessment and ensures that a wide view is taken on board for the assessment.

6.2.4 Determine the Basic Probability Mass

The ER approach utilises a belief structure to represent an assessment as a distribution. Assuming there is a threat of a loss of containment in a pipeline and intervention measures are to be evaluated and assuming the problem has D alternatives $O_j\,(j=1,....,D)$, an upper-level criterion called 'general attribute' or an RCO and lower-level criteria $C_i\,(i=1,.....L)$ called 'basic attributes'. The ER decision matrix is developed by:

i. Assigning weightings $W=\{w_i,\ i=1,.....L\}$ to the basic attributes which show their relative importance. The weights of the basic attributes need to be normalised, such that $\sum_{i=1}^{L} w_i = 1$ and $0 \le w_i \le 1$. L is the number of basic attributes sharing the same general (RCO) attribute.

ii. Defining a set of evaluation grades (H) to enable alternatives of the basic attributes to be assessed and can be represented as $H = \{H_n,\ n=1,.....N\}$ where H_n is evaluation grade n.

Using the evaluation grades, the assessment S of an attribute C_i on an alternative O_j, denoted by $S(C_i(O_j))$, can be represented as:

$$S(C_i(O_j)) = \{(\beta_{n,i}(O_j), H_n),\ n=1,....N,\quad i=1,.....L;\quad j=1,.....D\} \tag{6-1}$$

where $1 \ge B_{n,i} \ge 0$ represents the degrees of belief that an attribute C_i is assessed to an evaluation grade H_n to a degree of $B_{n,i}$ (x100%) for an alternative O_j. The degrees of beliefs distributed assessment must be $\sum_{n=1}^{N} \beta_{n,i} \le 1$. If $\sum_{n=1}^{N} \beta_{n,i} = 1$ then $S(C_i(O_j))$ can be considered a complete assessment and if $\sum_{n=1}^{N} \beta_{n,i} < 1$ it is considered an incomplete assessment.

To aggregate the two assessments, the ER approach employs an algorithm that is different from the traditional MCDM approaches because it aggregates average scores only. Continuing from the previous example of preventing loss of containment in the pipeline, there are five evaluation grades to assess the effectiveness of a certain intervention, such that:

$$\begin{aligned} H &= \{H_1, H_2, H_3, H_4, H_5\} \\ &= \{Very\ Low,\ Low,\ Medium,\ High,\ Very\ High\} \end{aligned}$$

Furthermore, suppose two assessments are represented by Equations 6-2 and 6-3:

$$S\left(C_1\left(O_1\right)\right) = \{(H_1, \beta_{1,1}),\ (H_2, \beta_{2,1}),\ (H_3, \beta_{3,1}),\ (H_4, \beta_{4,1}),\ (H_5, \beta_{5,1})\} \qquad (6\text{-}2)$$

$$S\left(C_2\left(O_1\right)\right) = \{(H_1, \beta_{1,2}),\ (H_2, \beta_{2,2}),\ (H_3, \beta_{3,2}),\ (H_4, \beta_{4,2}),\ (H_5, \beta_{5,2})\} \qquad (6\text{-}3)$$

The steps below are followed to determine the basic probability mass as part of the aggregation of the two assessments.

Combining the evidence requires the belief degrees to be transformed into a basic probability mass. Supposing both assessments are complete to generate a combined assessment of the two $S\left(C_1\left(O_1\right)\right) \oplus S\left(C_2\left(O_1\right)\right)$. Let:

$$m_{n,j} = w_i \beta_{n,i} \quad (n = 1, \ldots., N; \quad i = 1, \ldots.L; \quad j = 1, 2) \qquad (6\text{-}4)$$

$$m_{H,j} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i} \quad (n = 1, \ldots., N; \quad i = 1, \ldots.L; \quad j = 1, 2) \qquad (6\text{-}5)$$

$m_{n,j}$ is the basic probability mass and $m_{H,j}$ is the remaining belief for attribute j, unassigned to any of the evaluation grades $H_n (n = 1, \ldots..N)$. w_i is weighting of the *i*th attribute, $\beta_{n,i}$ represents the degrees of belief.

Applying Equations 6-4 and 6-5, the basic probability mass for $S\left(C_1\left(O_1\right)\right) \oplus S\left(C_2\left(O_1\right)\right)$ aggregation will be:

$$m_{n,1} = w_1 \beta_{n,1} \ and \ m_{H,1} = 1 - w_1 \sum_{n=1}^{N} \beta_{n,1}$$

$$m_{n,2} = w_2 \beta_{n,2} \; and \; m_{H,2} = 1 - w_2 \sum_{n=1}^{N} \beta_{n,2}$$

6.2.5 Aggregate Basic Probability Mass for Combined Probability Mass

The ER algorithm requires the aggregation of the basic probability masses to generate combined probability masses, represented as $m_{n,I(j+1)}$ $(n = 1,...N)$ and $m_{H,I(j+1)}$ using the following equations:

$$m_{n,I(j+1)} = k_{I(j+1)}(m_{n,j}m_{n,j+1} + m_{n,j+1}m_{H,j} + m_{n,j}m_{H,j+1}), \; n = 1,..N; \; j = 1,..L-1 \quad (6\text{-}6)$$

$$m_{H,I(j+1)} = k_{I(j+1)}(m_{H,j} \; m_{H,j+1}) \quad (6\text{-}7)$$

where

$$k_{I(j+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{n=1 \\ n \neq t}}^{N} m_{t,j} \; m_{n,j+1} \right]^{-1} \quad (6\text{-}8)$$

Applying the above equations to $S\left(C_1\left(O_1\right)\right) \oplus S\left(C_2\left(O_1\right)\right)$, the aggregation will give:

$$m_{n,I(2)} = k_{I(2)}(m_{n,1}m_{1,2} + m_{n,2}m_{H,1} + m_{n,1}m_{H,2});$$

$$m_{H,I(2)} = k_{I(2)}(m_{H,1}m_{H,2})$$

$$k_{I(2)} = \left[1 - \sum_{t=1}^{5} \sum_{\substack{n=1 \\ n \neq t}}^{5} m_{t,1}m_{1,2} \right]^{-1}$$

$k_{I(2)}$ is the normalising factor so that for example $\sum_{n=1}^{5} m_{n,I(2)} + m_{H,I(2)} = 1$.

6.2.6 Belief Degrees Combination

The next step is the combination of the belief degrees β_n as part of the decision-making process. It is calculated using the Equation below:

$$\beta_n = \frac{m_{n,I(j+1)}}{1 - m_{H,I(j+1)}}, \quad n = 1,....N \tag{6-9}$$

$$\beta_H = 1 - \sum_{n=1}^{N} \beta_n$$

Applying it to this example, β_n will thus be:

$$\beta_n = \frac{m_{1,I(2)}}{1 - m_{H,I(2)}}$$

β_H is the belief degree that is unassigned to any individual evaluation grade after all of the basic attributes have been properly assessed. It indicates assessment incompleteness (Liu *et al.*, 2005).

Thus, the combined assessment for the alternative O_1 can be represented as

$S(O_1) = \{(H_1, \beta_1),\ (H_2, \beta_2),\ (H_3, \beta_3),\ (H_4, \beta_4),\ (H_5, \beta_5)\}$

6.2.7 Ranking of the Attributes

The final stage is the ranking of the attributes based on their aggregated belief degrees from the ER approach. This uses a utility assessment method. If an evaluation grade, H_n, is denoted by $u(H_n)$, the utility of the evaluation grade must be predetermined. If there are five evaluation grades, $u(H_1)$ will be taken as zero whilst $u(H_5)$ is taken as one. If there is no information with which to give a selection preference, then the values of $u(H_n)$ can be taken to be equally distributed as shown below:

$$u(H_n) = \{\, u(H_1) = 0,\ u(H_2) = 0.25,\ u(H_3) = 0.5,\ u(H4) = 0.75,\ u(H5) = 1 \} \tag{6-10}$$

and the utility for the attributes, denoted as *(Oj),* for the given sets of evaluation grades is given as:

$$u(O_j) = \sum_{n=1}^{N} u(H_n)\beta_n \tag{6-11}$$

$u(H_n)$ is the utility of the n-th evaluation grade of H_n as established in Equation 6-10 for an assumption that it is equidistantly distributed. β_n is as defined in Equation 6-9.

6.3 Case Study: Application to Pipeline Third-Party Damage

The proposed ER decision model is applied to model the risk control measures for theft/intentional third-party pipeline damage. This is based on a case study of a cross-country pipeline segment in Nigeria, specifically pipeline Section 2B, as described fully in Chapter 2. Pipeline 2B is representative of the country's pipeline system as a whole with respect to third-party damage failure frequency, as it is in the middle quartile overall in the failure records across the country.

In Chapter 5, theft/intentional third-party damage has been identified as the major cause of pipeline failure in Nigeria. Therefore, measures must be put in place to ensure the threat is reduced or eliminated. The ER approach is a suitable tool for this assessment as it allows for the aggregation of multiple attributes and sub-attributes within the control measures, affording a ranking of alternatives.

The literature survey (e.g. (Muhlbauer, 2004)) and the experts that have been interviewed to as part of this study have identified numerous control measures that can contribute towards risk reduction and control of the threat. The most significant ones and those that are practical for a geographical area like Nigeria have been grouped broadly into four general categories:

1. Detection measures.
2. Prevention measures.
3. Mitigation measures.
4. Other measures.

Each of the four general attributes has basic attributes that outline the intervention that is being assessed for their effectiveness and ranking of alternatives.

6.3.1 Identification of the Predominant Failure Factor

Identification of the major failure factors for the pipeline under consideration has been carried out in Chapter 4. The identified failure factors and their potential consequences have been assessed further using the Bayesian Network in Chapter 5. This Bayesian Network assessment also identified the failure factor with the highest probability of occurrence, in this case, third-party related pipeline failure. The Bayesian Network analysis indicated that theft/intentional third-party damage contributes to about a third of all the pipeline's failure probability. Additionally, the assessment has shown that any effort to reduce intentional third-party damage will reduce pipeline failure incidences significantly for the representative scenarios considered.

Third-party damage /theft incidences are becoming a recurring issue for pipeline operators as they affect a number of countries, including developed economies. The latest Concawe report (Cech *et al.*, 2018) shows that the number of intentional third-party damage incidents recorded on European pipelines since 2013 is almost ten times the number of incidents recorded in all of the preceding 40 years up to 2012.

Intentional third-party damage or theft could be the result of various factors, including product theft, an indirect attack against a government, a terrorism-related attack or a protest for political, social and environmental reasons. Unlike other failure factors, an intentional third-party threat involves a focused human effort to cause a failure. Any aspect of the pipeline system can be a target. Therefore, the full suite of measures must be considered in an analysis for identifying effective risk control measures.

6.3.2 Developing the Evaluation Matrix

The Evidential Reasoning algorithm requires a structure to be developed that maps the variables and their attributes against the risk control measures. The algorithm also requires an outline of how it is to be applied in a particular case scenario. The attributes that have been developed are tailored for a cross-country pipeline and the identified threat which is particular to geographical areas similar to that of Nigeria. However, other geographical areas may find that this model and the proposed solutions apply to them.

As outlined earlier, the main attributes of the risk control measures are taken as detection, prevention, mitigation and other measures. Each of the main attributes has sub-attributes or basic attributes. These have been developed from the literature survey and the expert elicitation in this study and are shown to be the most effective in addressing third-party intentional damage (Muhlbauer, 2004). The attributes include:

1. **Detection Measures**
    1.1. Surveillance: surveillance can take the form of video, with images recorded aerially using helicopters, drones or satellite surveillance. This is proven to be effective, especially for a pipeline system with a large geographical expanse, but it can be expensive in terms of financial outlay. However, for pipelines with records of hefty losses like the Nigerian pipeline system, the measure could be cost-effective.
    1.2. Leak detection: this is a very important aspect of the overall risk control measures as it provides early notice of a potential event and can then allow a quick intervention. The detection can be via Supervisory Control and Data Acquisition (SCADA), acoustic methods, proprietary leak detection measures and human detection.
    1.3. SCADA/Staff measures: SCADA is the transmission of the pipeline's operational status at various points along its length so that the operational health of the pipeline can be monitored remotely. This is integrated with staffing measures as the information relayed by SCADA needs to be acted upon by the staff. The SCADA information may include, for example, leak detection and overall system diagnosis.

1.4. Patrol: undertaking patrolling of the pipeline and its infrastructure at a relevant interval is very effective in both preventing and detecting pipeline damage due to third-party intervention. Patrol operation should be able to proactively detect impending or ongoing third-party activities, as any such activity requires preparation and machinery. It can also identify any encroachment onto the Right of Way or detect any recent activity in order to repair it. Due to the length of a cross-country pipeline, the frequency of the patrol and areas to concentrate on should be determined based on the level of threat and availability of resources.

2. **Prevention Measures**

2.1. Pipeline cover: pipeline cover includes all measures provided to protect the pipeline from any impact leading to its failure. Measures in this category include concrete coating, pipe casing, concrete slabs at the top of the pipeline and protection mesh. Wall thickness can also be included in this attribute. Any wall that is thicker than the minimum required for the design pressure and loading can help reduce the likelihood of damage.

2.2. Burial depth: this is the minimum depth at which the pipeline is to be buried to help protect the pipe from the activities of any third party. The required burial depth across the industry varies depending on many factors, but generally, a depth of 900mm is the norm and required by many regulators. However, that depth may not be adequate and could be easily reached by potential saboteurs. The benefit of this attribute is that it is the most cost-effective when laying new pipelines.

2.3. Public education: this attribute entails both the government and the pipeline operator to reach out to the public and educate them on the importance of pipeline infrastructure to the economy of the country and the community around its corridor. Experience has shown that public education can play a sizeable role in preventing theft/intentional third-party activities (Muhlbauer, 2004). Even if public education does not stop the perpetrators, it can make the community living where the infrastructure passes through be more vigilant, informing authorities of any suspicious activity.

Examples of public education include regular visits and presentations to the community, door-to-door contact and informational pamphlets.

2.4. Barriers: these are physical structures such as fences and alarms, aiming to provide some layer of defence on a specific segment of the pipeline that is more vulnerable to attack.

3. Mitigation Measures

3.1. Right of Way (RoW) control: the level at which the pipeline corridor is being maintained and inspected has a direct relation with intentional third-party damage, especially in areas where there is a high level of physical development or human settlement. There have been several examples of incidences where houses built on top of a pipeline route are being used by criminals as a cover to get into the pipeline for product theft. Also, a clear RoW, especially where pipelines are located not far from the public road and with no vegetation, is likely to expose any criminal intent easily. In these instances, there is not enough vegetation cover for criminal activities to be carried out for a long time without being noticed.

3.2. Spill response: the availability and effectiveness of the emergency response to a spill determine whether the consequences can be minimised, by minimising the spill volume.

3.3. Industry cooperation: this is when the industry shares data, intelligence and best practices between one another. It can also mean pooling resources together to look after facilities, thus multiplying the effectiveness of the measures in place. Cooperation like this is often cost-neutral and very effective.

4. Other Measures

4.1. Security forces: this could be government security, private security employed by the pipeline infrastructure company or a combination of the two. Depending on the circumstances, one approach is sometimes better than the other. For example, in the Nigerian delta, communities often complain that the presence of government security over-militarises the community, thus achieving the opposite of what is intended (Wennerbeck, 2015).

4.2. Punishment: strict enforcement and the fear of punishment is generally a deterrent for any criminal activity. This is more effective for those people that are not habitually criminals but may be contemplating engaging in such activity. Effective publicity of what awaits the perpetrators and well-publicised cases of successful prosecutions are a good messaging point (Muhlbauer, 2004). Successful punishment also increases government perception as being in control of the situation, thus increasing their resolve to stop the crime.

4.3. Community partnering: this can be said to be similar to public education, but it is more focused in that the aim is specifically to bring the community on board by making them supportive of the infrastructure. The support is best obtained when the community can see a tangible benefit to them (Muhlbauer, 2004), such as jobs for community members and the provision of infrastructures like pipe-borne water and electricity. Community partnering could generate the most benefit in reducing the threat to the pipeline if thought-out and implemented well.

Figure 6-1 shows the graphical relationships between the main attributes, the basic attributes and the alternatives used in the analysis. All of the attributes contribute towards the control measures (alternatives), which are defined as management solutions, technical (or technological) solutions and government (or enforcement) solutions.

6.3.3 Weight and Belief Degrees using Experts' Elicitation

The first step in the ER analysis is the calculation of the weight of each of the identified general and basic attributes, as outlined in Figure 6-1. The belief degrees of these attributes must also be determined. Such information informs the evaluation grades and ensures that the attributes have a relationship in terms of their effectiveness to the overall analysis.

Analytic Hierarchy Process (AHP) and the pairwise comparison method are used to determine both the weight and belief degrees by utilising the elicitation of experts for qualitative assessment through questionnaires. The sample questionnaire and the anonymised results are provided in Appendix D. The questionnaire has two parts; part 1 assesses the weighting of the basic attributes for each of the main attributes while part 2 assesses the belief degrees associated with each attribute.

Five experts have been asked to give their professional opinion based on their expertise and experience, ranking each attribute in relation to the others. The experts cut across the pipeline industry supply chain – from an operator to consultants and academics. Their input forms the foundation of this assessment and ensures that a wide range of views are taken on board. The expertise and experience of the experts who have responded are provided below:

Expert 1 is currently in the employ of a major pipeline infrastructure owner and operator in Nigeria, holds a university qualification at an MSc level and has circa 15 years of experience in pipeline operation, maintenance and management.

Expert 2 is currently in the employ of a major pipeline infrastructure owner and operator in Nigeria, holds a university qualification at BSc level and has circa 11 years of experience in pipeline safety.

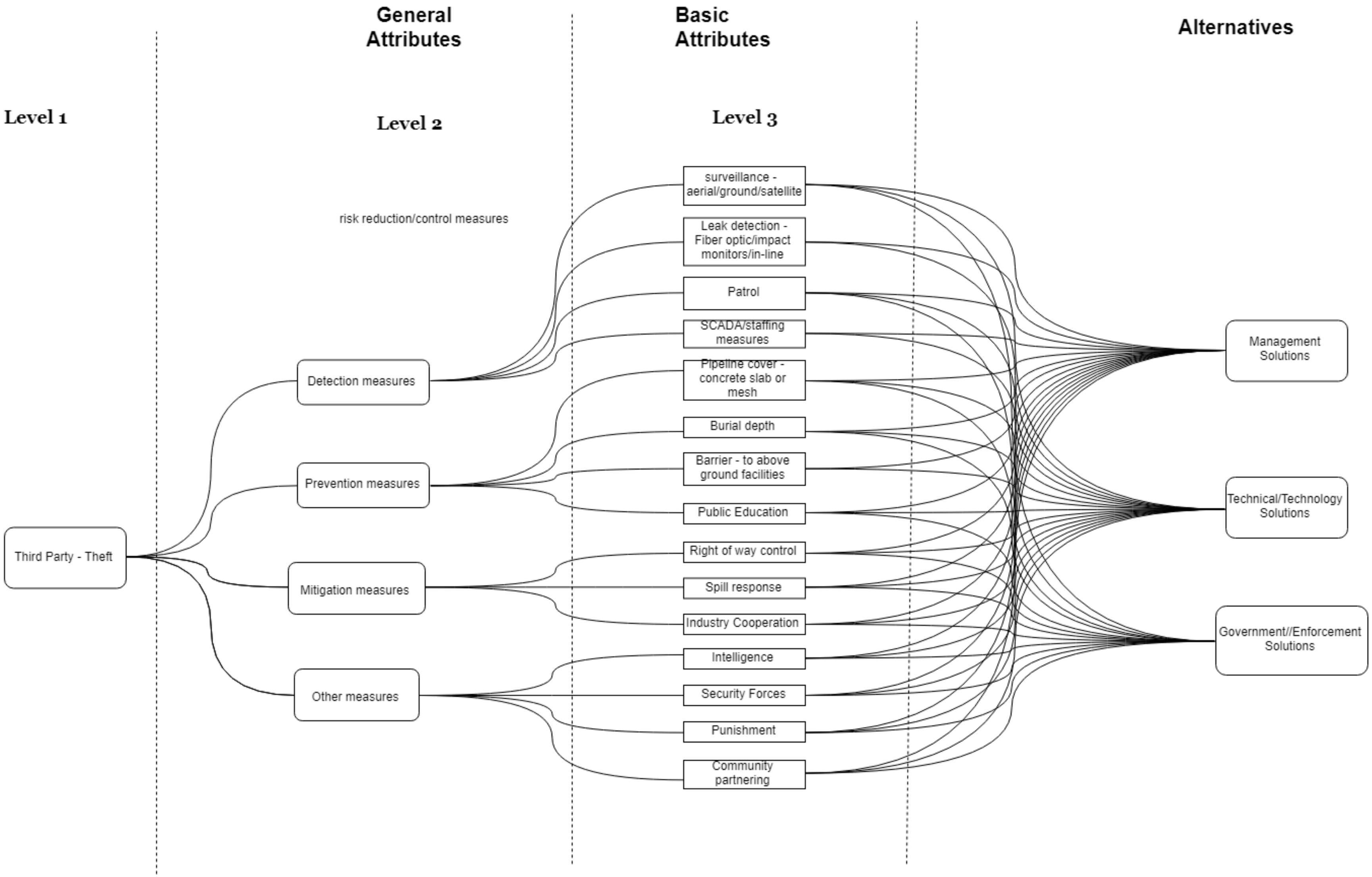

Figure 6-1: Attributes Matrix for the Control Measures

Expert 3 is currently in the employ of a major pipeline contracting company, holds a university qualification at PhD level and has circa 20 years of experience in pipeline design.

Expert 4 is currently in the employ of a consulting company, holds a university qualification at an MSc level and has ten years of experience in consultancy.

Expert 5 is employed by a Nigerian university as a senior lecturer and researcher. The expert has more than ten years of experience in research, consultancy and teaching of oil and gas in general and pipeline systems in particular. The expert is educated to a PhD level.

The input provided by the experts allows for the completion of the belief degrees for the basic attributes. The belief degrees are arrived at by averaging the responses provided by all the experts for each of the attributes. The matrix and (normalised) weights of all attributes are demonstrated in Table 6-1. Additionally, the assessed belief degrees for each of the basic attributes are also shown in Table 6-1.

The number of experts that have been chosen ensures a balance and a diversity of opinions, thus balanced belief degree inputs for the basic attributes. If more experts were to be involved, that could help refine and narrow the standard deviation of the results. Therefore, it is deemed unlikely that it would affect the overall assessment outcome.

6.3.4 Aggregation of the Normalised Weight and Belief Degrees

The weights and belief degrees of all the attributes as derived from the expert elicitation are shown in Table 6-1. The next step in the process is to extract the weights and belief degree values for input into the ER model.

Table 6-1: Attribute Weightings and Belief Degrees

General Attributes	ω		Basic Attributes	Ω		Alternatives														
						Management Solutions					**Govt Solutions**					**Technical Solutions**				
						H1	H2	H3	H4	H5	H1	H2	H3	H4	H5	H1	H2	H3	H4	H5
Detection (*a*)	$\omega_1=$	0.29	Surveillance (*a1*)	$\omega_{11}=$	0.298	0.30	0.30	0.40	0.00	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.14	0.38	0.48
			Leak Detection (a2)	$\omega_{12}=$	0.355	0.30	0.00	0.30	0.40	0.00	0.80	0.20	0.00	0.00	0.00	0.00	0.10	0.00	0.40	0.50
			SCADA/Staffing (a3)	$\omega_{13}=$	0.211	0.00	0.11	0.17	0.44	0.28	0.90	0.10	0.00	0.00	0.00	0.00	0.20	0.60	0.20	0.00
			Patrol (a4)	$\omega_{14}=$	0.136	0.00	0.27	0.20	0.53	0.00	0.00	0.50	0.20	0.30	0.00	0.50	0.30	0.20	0.00	0.00
Prevention (*b*)	$\omega_2=$	0.45	Pipeline Cover (b1)	$\omega_{21}=$	0.161	0.90	0.10	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.13	0.60	0.27	0.00
			Burial Depth (b2)	$\omega_{22}=$	0.214	0.00	0.90	0.10	0.00	0.00	0.50	0.30	0.20	0.00	0.00	0.00	0.00	0.14	0.38	0.48
			Public Education (b3)	$\omega_{23}=$	0.174	0.00	0.00	0.50	0.30	0.20	0.00	0.00	0.00	0.17	0.83	0.90	0.10	0.00	0.00	0.00
			Barrier (b4)	$\omega_{24}=$	0.452	0.10	0.90	0.00	0.00	0.00	0.90	0.10	0.00	0.00	0.00	0.00	0.13	0.38	0.50	0.00
Mitigation (*c*)	$\omega_3=$	0.17	Right of Way Control (c1)	$\omega_{31}=$	0.553	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.32	0.42	0.26	0.50	0.50	0.00	0.00	0.00
			Spill Response (c2)	$\omega_{32}=$	0.225	0.00	0.11	0.15	0.21	0.53	0.00	0.30	0.30	0.40	0.00	0.90	0.10	0.00	0.00	0.00
			Industry Cooperation (c3)	$\omega_{33}=$	0.222	0.00	0.00	0.00	0.35	0.65	0.00	0.20	0.50	0.30	0.00	0.80	0.20	0.00	0.00	0.00
Other Measures (*d*)	$\omega_4=$	0.09	Intelligence (d1)	$\omega_{41}=$	0.439	0.00	0.00	0.13	0.00	0.87	0.00	0.50	0.30	0.20	0.00	0.50	0.50	0.00	0.00	0.00
			Security Forces (d2)	$\omega_{42}=$	0.138	0.00	0.00	0.00	0.25	0.75	0.07	0.14	0.43	0.00	0.36	0.60	0.40	0.00	0.00	0.00
			Punishment (d3)	$\omega_{43}=$	0.156	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.50	0.22	0.28	0.40	0.40	0.20	0.00	0.00
			Community Partnering (d4)	$\omega_{44}=$	0.266	0.00	0.00	0.00	0.55	0.45	0.00	0.00	0.00	0.20	0.80	0.40	0.40	0.20	0.00	0.00

$H_1=$ Very Low **$H_2=$ Low** **$H_3=$ Medium** **$H_4=$ High** **$H_5=$ Very High**

An example is taken from Table 6-1 to demonstrate the calculation. The example uses the general attribute of Mitigation (*c*), which has three basic attributes: right of way control (*c1*), spill response (*c2*) and industry cooperation (*c3*). The weighting and the belief degrees for the attributes are shown below:

Weights:

			Right of Way Control (c1)	ω_{31}=	0.553
Mitigation (*c*)	ω_{3}=	0.17	Spill Response (c2)	ω_{32}=	0.225
			Industry Cooperation (c3)	ω_{33}=	0.222

Belief degrees (government solutions):

$\beta_{1,1}$ =	0	$\beta_{2,1}$ =	0	$\beta_{3,1}$ =	0.32	$\beta_{4,1}$ =	0.42	$\beta_{5,1}$ =	0.26
$\beta_{1,2}$ =	0	$\beta_{2,2}$ =	0.30	$\beta_{3,2}$ =	0.30	$\beta_{4,2}$ =	0.40	$\beta_{5,2}$ =	0
$\beta_{1,3}$ =	0	$\beta_{2,3}$ =	0.20	$\beta_{3,3}$ =	0.50	$\beta_{4,3}$ =	0.30	$\beta_{5,3}$ =	0

6.3.5 Determining the Basic Probability Mass

Equation *6-4* is then used to calculate the basic probability masses. For example, $m_{1,1} = w_{31}\beta_{1,1} = 0.553 \text{ x } 0 = 0$. The rest of the results are given below.

c1		*c2*		*c3*	
$m_{1,1}$=	0.000	$m_{1,2}$=	0.000	$m_{1,3}$ =	0.000
$m_{2,1}$=	0.000	$m_{2,2}$=	0.0674	$m_{2,3}$ =	0.0444
$m_{3,1}$ =	0.1748	$m_{3,2}$ =	0.0674	$m_{3,3}$ =	0.1110
$m_{4,1}$ =	0.2330	$m_{4,2}$ =	0.0898	$m_{4,3}$ =	0.0666
$m_{5,1}$ =	0.1456	$m_{5,2}$ =	0.000	$m_{5,3}$ =	0.000

$$\sum_{n=1}^{5} m_{n,1} = 0.5534 \qquad \sum_{n=1}^{5} m_{n,2} = 0.2246 \qquad \sum_{n=1}^{5} m_{n,3} = 0.2220$$

$$m_{H,1} = 0.4466 \qquad m_{H,2} = 0.7754 \qquad m_{H,3} = 0.7780$$

6.3.6 Determining the Combined Probability Mass

The combined probability mass is calculated using Equations 6-6, 6-7 and *6-8*. First, Equation 6-8 (reproduced below) is used to aggregate the first two attributes, *c1* and *c2*.

$$k_{I(j+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{n=1 \\ n \neq t}}^{N} m_{t,j} m_{n,j+1} \right]^{-1}$$

The staged calculation of the aggregation is shown here.

$$\sum_{\substack{n=1 \\ n \neq t \\ t=1}}^{5} m_{t,1} m_{n,2} = (m_{1,1} m_{2,2}) + (m_{1,1} m_{3,2}) + (m_{1,1} m_{4,2}) + (m_{1,1} m_{5,2})$$

$$= 0 + 0 + 0 + 0 = 0$$

$$\sum_{\substack{n=1 \\ n \neq t \\ t=2}}^{5} m_{t,2} m_{n,2} = (m_{2,1} m_{1,2}) + (m_{2,1} m_{3,2}) + (m_{2,1} m_{4,2}) + (m_{2,1} m_{5,2})$$

$$= 0 + 0 + 0 + 0 = 0$$

$$\sum_{\substack{n=1 \\ n \neq t \\ t=3}}^{5} m_{t,3} m_{n,2} = (m_{3,1} m_{1,2}) + (m_{3,1} m_{2,2}) + (m_{3,1} m_{4,2}) + (m_{3,1} m_{5,2})$$

$$= 0 + 0.012 + 0.0157 + 0 = 0.0277$$

$$\sum_{\substack{n=1 \\ n \neq t \\ t=4}}^{5} m_{t,4} m_{n,2} = (m_{4,1} m_{1,2}) + (m_{4,1} m_{2,2}) + (m_{4,1} m_{3,2}) + (m_{4,1} m_{5,2})$$

$$= \quad 0 \quad + \quad 0.0157 \quad + \quad 0 \quad + \quad 0 \quad = \quad 0.0157$$

$$\sum_{\substack{n=1 \\ n \neq t \\ t=5}}^{5} m_{t,5} m_{n,2} = (m_{5,1} m_{1,2}) + (m_{5,1} m_{2,2}) + (m_{5,1} m_{3,2}) + (m_{5,1} m_{4,2})$$

$$= \quad 0 \quad + \quad 0.0098 \quad + \quad 0.0157 \quad + \quad 0.0131 \quad = \quad 0.0386$$

$$k_{1(2)} = \quad [1- (0 + 0 + 0.0277 + 0.0157 + 0.0386)]^{-1} \quad = \quad 1.0891$$

Once the $k_{I(2)}$ value is obtained, Equations *6-6* and *6-7* (reproduced below) are used, together with the probability masses calculated earlier to calculate the combined probability masses.

$$m_{n,I(j+1)} = k_{I(j+1)}(m_{n,j} m_{n,j+1} + m_{n,j+1} m_{H,j} + m_{n,j} m_{H,j+1}), \quad n = 1,...N;\ j = 1,2$$

$$m_{H,I(j+1)} = k_{I(j+1)}(m_{H,j} m_{H,j+1})$$

$$m_{1,I(2)} = k_{1(2)}(m_{1,1} m_{1,2} + m_{1,1} m_{H,2} + m_{H,1} m_{1,2}) = 0$$

$$m_{2,I(2)} = k_{1(2)}(m_{2,1} m_{2,2} + m_{2,1} m_{H,2} + m_{H,1} m_{2,2}) = 0.0328$$

$$m_{3,I(2)} = k_{1(2)}(m_{3,1} m_{3,2} + m_{3,1} m_{H,2} + m_{H,1} m_{3,2}) = 0.1932$$

$$m_{4,I(2)} = k_{1(2)}(m_{4,1} m_{4,2} + m_{4,1} m_{H,2} + m_{H,1} m_{4,2}) = 0.2633$$

$$m_{5,I(2)} = k_{1(2)}(m_{5,1} m_{4,2} + m_{5,1} m_{H,2} + m_{H,1} m_{5,2}) = 0.1230$$

$$m_{H,I(2)} = k_{1(2)}\, m_{H,1}\, m_{H,2} = 0.3771$$

This is the end of the first stage aggregation, which is the aggregation of the c_1 and c_2. The next step is the combination of c_3 with the aggregated c_1 and c_2 above. This is done by first using Equation 6-8 for $k_{1(3)}$.

$$\sum_{\substack{n=1\\n\neq t\\t=1}}^{5} m_{t,1}m_{n,3} = (m_{1,I(2)}m_{2,3}) + (m_{1,I(2)}m_{3,3}) + (m_{1,I(2)}m_{4,2}) + (m_{1,I(2)}m_{5,2})$$

$$= \quad 0 \quad + \quad 0 \quad + \quad 0 \quad + \quad 0 \quad = \quad 0$$

$$\sum_{\substack{n=1\\n\neq t\\t=1}}^{5} m_{t,2}m_{n,3} = (m_{2,I(2)}m_{1,3}) + (m_{2,I(2)}m_{3,3}) + (m_{2,I(2)}m_{4,3}) + (m_{2,I(2)}m_{5,3})$$

$$= \quad 0 \quad + \quad 0.0040 \quad + \quad 0.0020 \quad + \quad 0 \quad = \quad 0.0060$$

$$\sum_{\substack{n=1\\n\neq t\\t=1}}^{5} m_{t,3}m_{n,3} = (m_{3,I(2)}m_{1,3}) + (m_{3,I(2)}m_{2,3}) + (m_{3,I(2)}m_{4,3}) + (m_{3,I(2)}m_{5,3})$$

$$= \quad 0 \quad + \quad 0.0090 \quad + \quad 0.0130 \quad + \quad 0 \quad = \quad 0.0220$$

$$\sum_{\substack{n=1\\n\neq t\\t=1}}^{5} m_{t,4}m_{4,3} = (m_{4,I(2)}m_{1,3}) + (m_{4,I(2)}m_{2,3}) + (m_{4,I(2)}m_{3,3}) + (m_{4,I(2)}m_{5,3})$$

$$= \quad 0 \quad + \quad 0.0120 \quad + \quad 0.0290 \quad + \quad 0 \quad = \quad 0.0410$$

$$\sum_{\substack{n=1\\n\neq t\\t=1}}^{5} m_{t,5}m_{5,3} = (m_{5,I(2)}m_{1,3}) + (m_{5,I(2)}m_{2,3}) + (m_{5I(2)}m_{3,3}) + (m_{5,I(2)}m_{4,3})$$

$$= \quad 0 \quad + \quad 0 \quad + \quad 0.0140 \quad + \quad 0.0080 \quad = \quad 0.0220$$

$$k_{1(3)} = \quad [1- (0 + 0.0060 + 0.0220 + 0.0410 + 0.0220)]^{-1} \quad = 1.1001$$

Once $k_{1(3)}$ is obtained, the next step is to apply Equations *6-6* and *6-7*, together with the basic probability masses to aggregate for the attributes ($c1 \oplus c2$) and $c3$.

$$m_{1,I(3)} = k_{1(3)}\left(m_{1,I(2)}m_{1,3} + m_{1,I(2)}m_{H,3} + m_{H,I(2)}m_{1,3}\right) = 0$$

$$m_{2,I(3)} = k_{1(3)}\left(m_{2,I(2)}m_{2,3} + m_{2,I(2)}m_{H,3} + m_{H,1}m_{2,3}\right) = 0.0481$$

$$m_{3,I(3)} = k_{1(3)}\left(m_{3,(I)2}m_{3,3} + m_{3,I(2)}m_{H,3} + m_{H,1}m_{3,3}\right) = 0.2350$$

$$m_{4,I(3)} = k_{1(3)}\left(m_{4,(I)2}m_{4,3} + m_{4,I(2)}m_{H,3} + m_{H,1}m_{4,3}\right) = 0.2722$$

$$m_{5,I(3)} = k_{1(3)}\left(m_{5,(I)2}m_{5,3} + m_{5,I(2)}m_{H,3} + m_{H,1}m_{5,3}\right) = 0.1053$$

$$m_{H,I(3)} = k_{I(3)}\, m_{H,I(2)}\, m_{H,3} = 0.3228$$

6.3.7 Combining Degrees of Belief

The next step is using Equation *6-9* (reproduced below) to calculate the combined belief degrees, as shown here.

$$\beta_n = \frac{m_{n,I(j+1)}}{1 - m_{H,I(j+1)}}, \quad n = 1,....N$$

$$\beta_H = 1 - \sum_{n=1}^{N} \beta_n$$

$\beta_1 = \dfrac{m_{1,I(3)}}{(1 - m_{H,I(3)})} =$ 0/(1 - 0.32) = 0

$\beta_2 = \dfrac{m_{2,I(3)}}{(1 - m_{H,I(3)})} =$ 0.048/(1 - 0.32) = 0.0710

$\beta_3 = \dfrac{m_{3,I(3)}}{(1 - m_{H,I(3)})} =$ 0.235/(1 - 0.32) = 0.3470

$\beta_4 = \dfrac{m_{4,I(3)}}{(1 - m_{H,I(3)})} =$ 0.272/(1 - 0.32) = 0.4020

$\beta_5 = \dfrac{m_{5,I(3)}}{(1 - m_{H,I(3)})} =$ 0.105/(1 - 0.32) = 0.1554

$$\sum_{n=1}^{5} B_n = 1$$

$$\beta_H = 0$$

The step above completes the assessment. The effectiveness of the mitigation approach as part of the risk control measures, using the attributes right of way control (c_1), spill response (c_2) and industry cooperation (c_3) is thus:

$$S(mitigation\ (gov't\ solutions)) = S(c_1 \oplus c_2 \oplus c_3)$$

= {(very low, 0), (low, 0.071), (medium, 0.347), (high, 0.402), (very high, 0.155)}

6.4 ER Results and Analysis

The assessment carried out in Section 6.3 examines the general attributes of mitigation and their basic attributes under government solutions. This assessment has been repeated for other RCOs and under all the proposed solution groupings. Table 6-1 shows the number of the general attributes, their corresponding basic attributes and the proposed solution grouping that each basic attribute belongs to. The calculations have been carried out on Microsoft Excel following the Yang and Xu (2005) approach, as Excel allows for more flexibility. The results for aggregation are shown in Figure 6-2 through to Figure 6-5. H1 is when an approach has a very low likelihood of being effective, H2 is when an approach has a low likelihood of being effective, H3 is when it is medium, H4 is when it is high and H5 is when it has a very high likelihood of being effective.

Figure 6-2 shows the detection attributes aggregation for management, government and technical solutions. The results show that technical solutions have a higher very high (H5) belief degree, meaning that it is more effective than other proposed solutions. The government solutions have the highest *H1* and virtually no *H5* rating. This is consistent with the types of basic attributes under the detection main attribute, which are mostly technical.

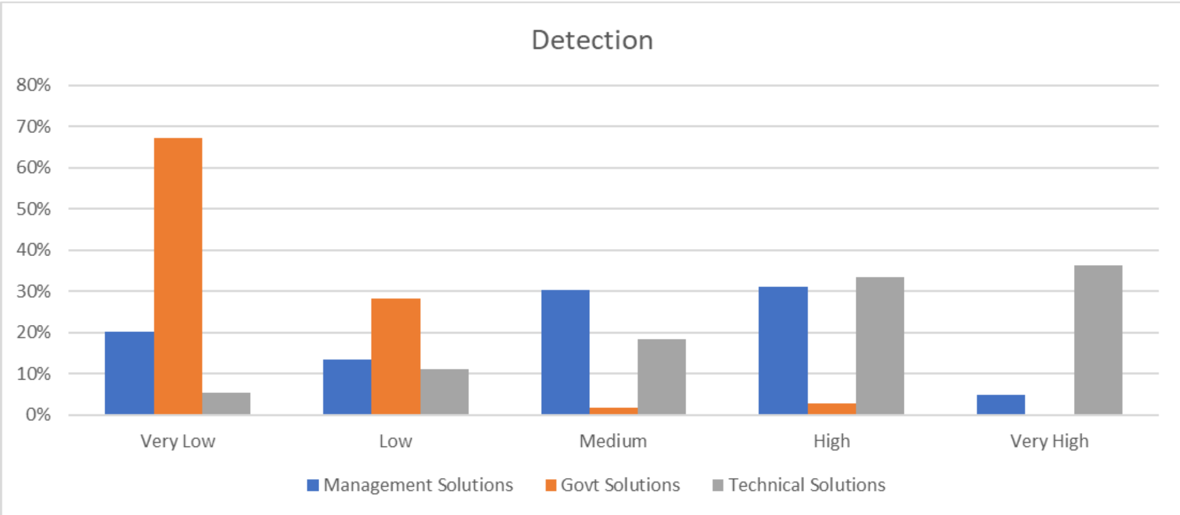

Figure 6-2: Detection Attributes Aggregation for the Solution Groupings

Figure 6-3 shows the aggregation results of the prevention attributes against the three proposed solutions. The results do not indicate clearly the most effective solution but they did show that, overall, technical solutions are better than the other two solutions. Again, government solutions are shown to have the highest *H1* score. Although technical solutions do not have the highest *H5* rating, they have the fewest *H1* and *H2* ratings. Their individual ranking will be better appreciated when the utility value calculation is undertaken. This is shown in Table 6-3.

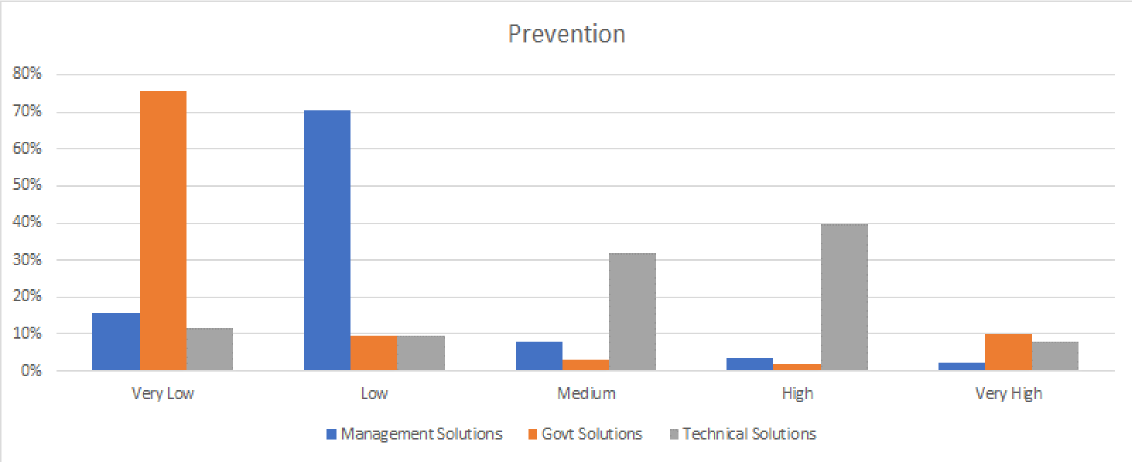

Figure 6-3: Prevention Attributes Aggregation for the Solution Groupings

Figure 6-4 shows the aggregation of the mitigation attributes. The results indicate technical solutions as the least effective solution. This is understandable since the basic attributes of mitigation are the RCOs that require management and government solutions. Such RCOs include ensuring that the right of way control enforced, that there is adequate provision for spill control and the presence of industry cooperation.

Figure 6-5 shows the aggregation of the 'other measures' attributes. These are the risk control measures not included under the three measures above. The results show that management and government solutions have a highest belief degree of providing better control over identified third-party pipeline failure. The technical solutions are the least effective. The basic attributes for these RCOs include intelligence sharing, security forces, punishment and community partnering.

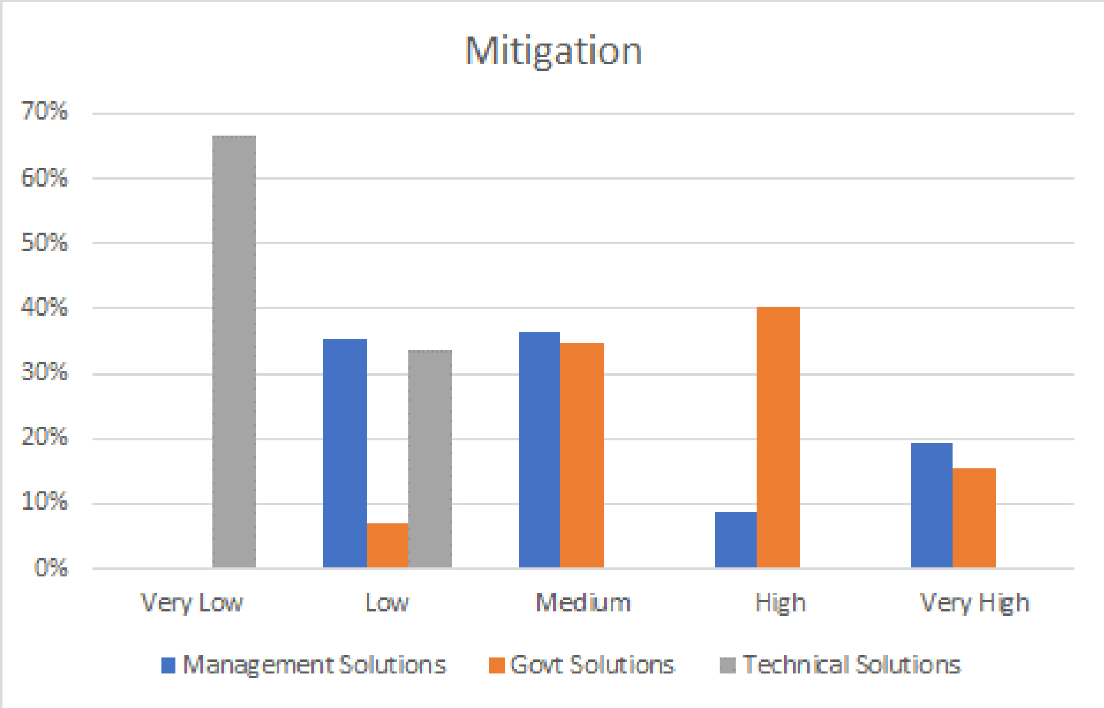

Figure 6-4: Mitigation Attributes Aggregation for the Solution Groupings

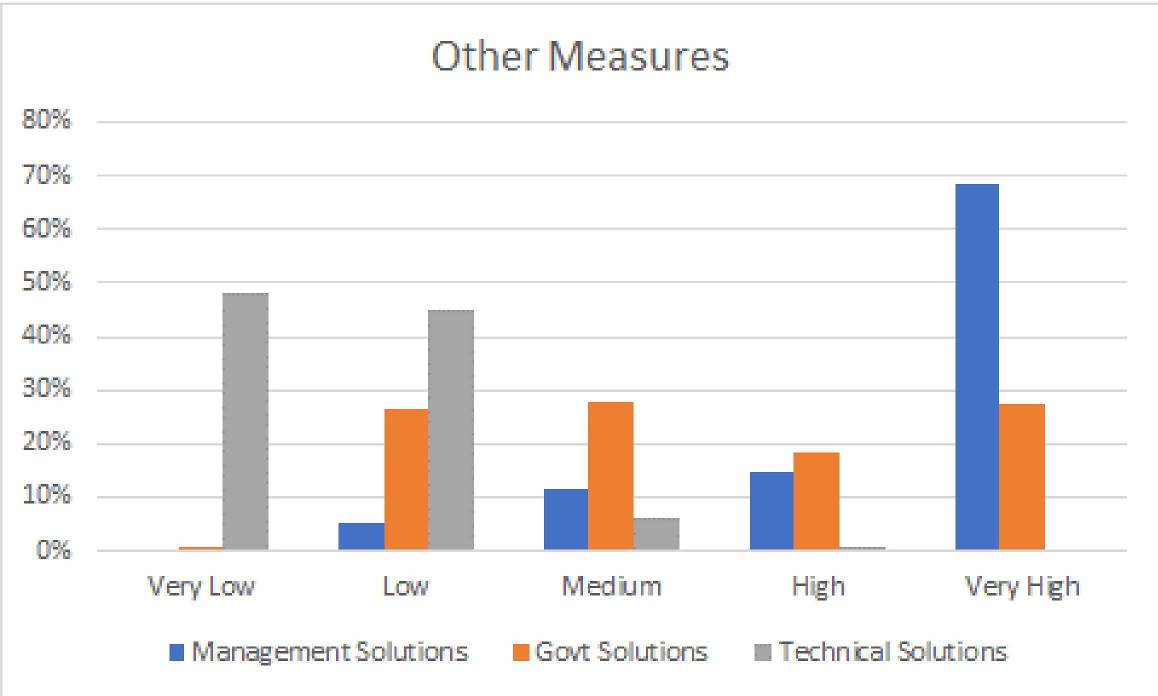

Figure 6-5: Other Measures' Attributes Aggregation for the Solution Groupings

Figure 6-6 and Figure 6-7 show the overall aggregation results based on the assessed risk control options and intervention solutions respectively. The results show a clustering of attributes, making it difficult to identify which of attributes have the most effective likelihood of success across all the main RCO groupings. To address this and calculate the ranking in a numerical format, Equations *6-10* and *6-11* are utilised to calculate their utility values.

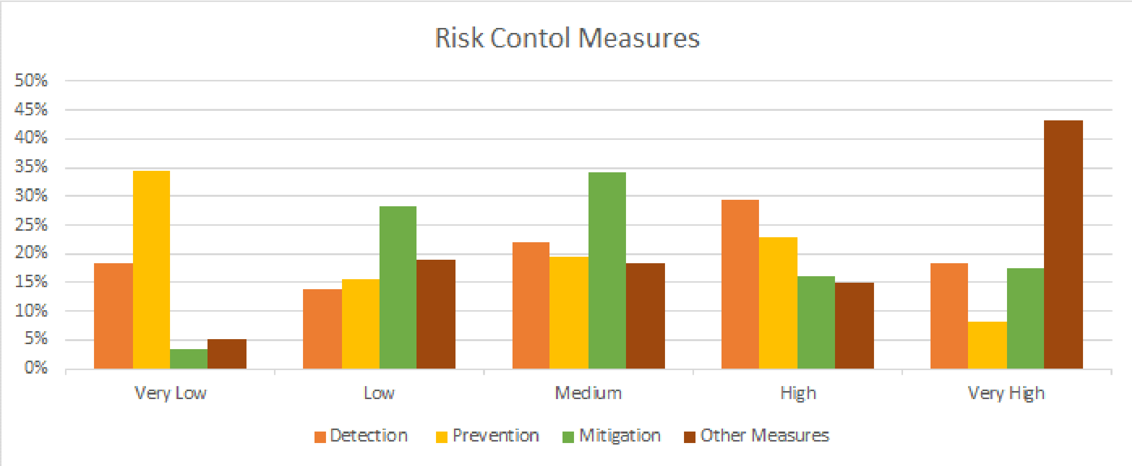

Figure 6-6: General Attributes Aggregation

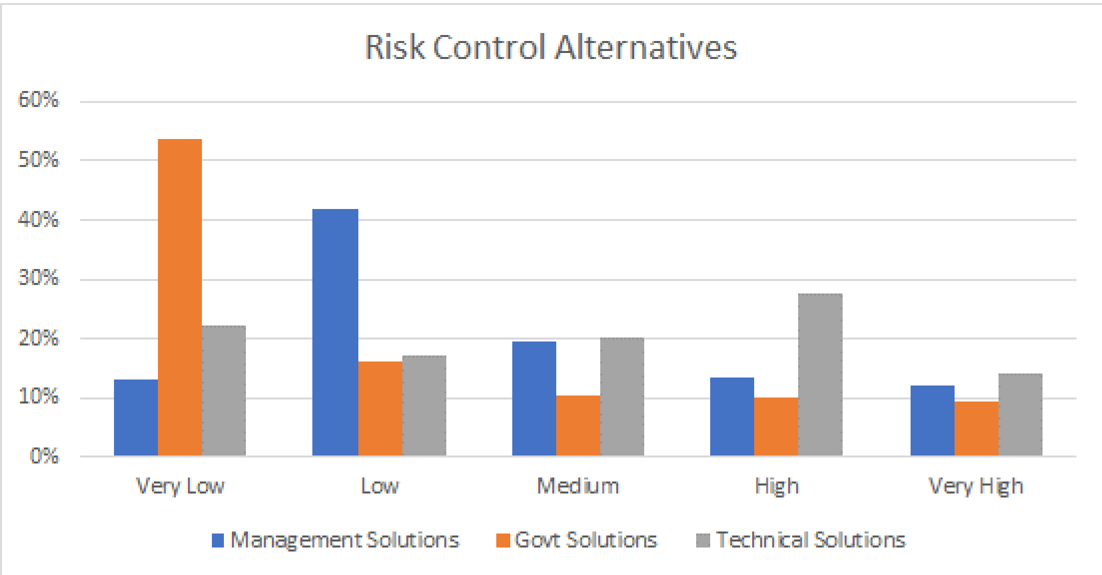

Figure 6-7: Aggregation of Alternatives for their Effectiveness

If the utility for an evaluation grade H_n is denoted by $u(H_n)$, the utility of all the evaluation grades must be predetermined such that $u(H_1)$ will be taken as zero whilst $u(H_5)$ is taken as one. If there is no information for a giving selection preference, then the values of $u(H_n)$ can be taken to be equally distributed as in Equation *6-10*, reproduced here:

$$u(H_n) = \{ u(H_1) = 0,\ u(H_2) = 0.25,\ u(H_3) = 0.5,\ u(H4) = 0.75,\ u(H5) = 1\}$$

and the utility for the attributes, denoted as O_J, for the given sets of evaluation grades is as in Equation 6-11, reproduced below:

$$u(O_j) = \sum_{n=1}^{N} u(H_n)\beta_n$$

β_n determines the likelihood that O_J is assessed to a grade H_n on the lower boundary whilst $\beta_n + \beta_H$ determines the same likelihood but from the upper boundary, assuming a complete belief degree. If there is an incomplete belief degree, then the rank of each attribute can be determined from the equations below. Assuming the least effective intervention is H_1 and the most effective is H_N, then the maximum, minimum and average utilities of Oj are given by:

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

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

$$u_{aver}(O_j) = \frac{u_{\max}(O_j) + u_{\max}(O_j)}{2}$$

With the above equation, a single utility value can be calculated for each main attribute and the overall effectiveness of the intervention options to allow ranking. For example, for the mitigation general attribute (for government solutions) that was calculated in Section 6.3 above, the utility value (complete belief) can be calculated as:

$$U(S(mitigation(gov't\ solutions\ ))$$

$$= u(H_1)\beta_1 + u(H_2)\beta_2 + u(H_3)\beta_3 + u(H_4)\beta_4 + u(H_5)\beta_5$$

= (0 x 0) + (0.25 x 0.071) + (0.5 x 0.347) + (0.75 x 0.402) + (1 x 0.155)}

= 0.65

This utility calculation has been carried out for all the main attributes and also the risk control solutions. The assessment also combines the overall effectiveness of all of the attributes and risk control solutions to enable ranking for decision-making. Table 6-2 shows the utility value and ranking for the detection attribute. It can be deduced that, for detection measures – which have basic attributes that include surveillance, leak detection, SCADA/staffing measures and patrols – technical solutions have a higher belief degree of being the most effective. The assessment shows that they are the most effective measures in reducing the risk of pipeline failure due to third-party activities.

Table 6-2: Utility Values and Ranking for the Detection Main Attribute

Detection							
Grades	H1 (Very low)	H2 (Low)	H3 (Medium)	H4 (High)	H5 (Very high)	u (Total)	Ranking
u (Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.203	0.136	0.303	0.311	0.048	0.47	2
Gov't Solutions	0.672	0.283	0.018	0.027	0.000	0.10	3
Technical Solutions	0.053	0.111	0.183	0.335	0.362	0.73	1

For the prevention main attribute, Table 6-3 shows that the most effective risk control solutions are technical solutions. The prevention main attribute has pipeline cover, burial depth, public education and physical barriers as its basic attributes. When compared with Figure 6-3, it can be seen that the higher ranking of technical solutions is because they have the smallest negative grade (H1).

Table 6-3: Utility Values and Ranking for the Prevention Main Attribute

Prevention							
Grades	H1 (Very low)	H2 (Low)	H3 (Medium)	H4 (High)	H5 (Very high)	U (Total)	Ranking
u(Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.156	0.704	0.079	0.037	0.024	0.27	2

Gov't Solutions	0.757	0.095	0.030	0.020	0.098	0.15	3
Technical Solutions	0.117	0.096	0.320	0.395	0.080	0.56	1

For the utility calculation and ranking of the mitigation main attribute, Table 6-4 indicates that government solutions emerge as the most effective intervention in reducing the threat, followed by management solutions. The mitigation main attribute has as its basic attributes RoW control, spill response and industry collaboration. The enforcement of RoW control and spill response is mainly driven by government intervention.

Table 6-4: Utility Values and Ranking for the Mitigation Main Attribute

Mitigation							
Grades	H1 (Very low)	H2 (Low)	H3 (Medium)	H4 (High)	H5 (Very high)	u (Total)	Ranking
u(Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.000	0.353	0.366	0.088	0.194	0.53	2
Gov't Solutions	0.000	0.071	0.347	0.402	0.155	0.65	1
Technical Solutions	0.664	0.336	0.000	0.000	0.000	0.08	3

The 'other measures' main attribute has as its basic attributes as intelligence, security forces, punishment and community partnering. Table 6-5 shows the utility values and the ranking. Surprisingly, management solutions, not government solutions, emerge as the most effective intervention. This may have been due to the experts believing that the over-militarization of pipeline security in Nigeria's delta region has not yielded any positive results for a long time. The experts, therefore, believe that a less combative and more collaborative approach with the host community along the pipeline corridor would produce better results.

Table 6-5: Utility Values and Rankings for Other Measures Main Attribute

Other Measures

Grades	H1 (Very low)	H2 (Low)	H3 (Medium)	H4 (High)	H5 (Very high)	u (Total)	Ranking
u(Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.000	0.052	0.116	0.145	0.687	0.87	1
Gov't Solutions	0.007	0.267	0.278	0.184	0.273	0.62	2
Technical Solutions	0.480	0.450	0.061	0.009	0.000	0.15	3

Table 6-6 shows the total ranking taking into account all the main and basic attributes. The technical solutions emerge as the set of intervention options that will provide the most effective tool to reduce the threat of third-party activities on the pipeline. The next most effective set of options are management solutions, followed by government intervention. The results are deemed consistent in that technical solutions are mostly aimed at preventing the third-party incident in the first instance. The technical solutions make any attempt to get to the pipeline difficult. If technical solutions are effective, then only a minimal amount of sabotage attempts will be successful.

Table 6-6: Utility Values and Rankings for Overall Effectiveness of Different Interventions

Overall							
Grades	**H1 (Very low)**	**H2 (Low)**	**H3 (Medium)**	**H4 (High)**	**H5 (Very high)**	**u (Total)**	**Ranking**
u(Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.130	0.419	0.194	0.136	0.121	0.42	2
Gov't Solutions	0.537	0.162	0.103	0.101	0.095	0.26	3
Technical Solutions	0.223	0.173	0.203	0.276	0.142	0.49	1

Assessment has been carried out also using Non-linear utility grade $u(H_n)$ assuming a risk seeking approach such that

$$u(H_n) = \{ u(H_1)=0,\ u(H_2)=0.8,\ u(H_3)=0.9,\ u(H4)=0.95,\ u(H5)=1\}$$

The results of the rankings for all the attributes and the interventions remain unchanged even with the different utility grades. This further indicates the stability of the results.

Table 6-7 shows the comparison and the ranking for the two utility grades. The next subsection reviews the sensitivity analysis of the results.

Table 6-7: Utility Values and Rankings Comparison for Linear and Non-linear Utility Grades

	Grades	Linear Utility		Non-linear Utility	
u(Grades)		u (Total)	Ranking	u (Total)	Ranking
Detection	Management Solutions	0.47	2	0.72	2
	Govt Solutions	0.10	3	0.27	3
	Technical Solutions	0.73	1	0.93	1
Prevention	Management Solutions	0.27	2	0.69	2
	Govt Solutions	0.15	3	0.22	3
	Technical Solutions	0.56	1	0.82	1
Mitigation	Management Solutions	0.53	2	0.89	2
	Govt Solutions	0.65	1	0.906	1
	Technical Solutions	0.08	3	0.27	3
Other Measures	Management Solutions	0.87	1	0.97	1
	Govt Solutions	0.62	2	0.91	2
	Technical Solutions	0.15	3	0.42	3

6.4.1 Sensitivity Studies

To ensure that the model is working as expected when different and varied inputs are provided, a sensitivity study has been carried out. The sensitivity analysis uses the same general and basic attributes examples that have been utilised in Section 6.3. The general attribute of mitigation has the three basic attributes of the right of way control (RoW), spill response and industry cooperation. The weighting of RoW, with a value of 0.55, is twice as high as that of the other two attributes, hence it will have the most impact on the aggregation of this particular main attribute.

The sensitivity process entails varying the weighting of the baseline input by +5%, +10%, -5% and -10% respectively for the basic attributes RoW, spill response and industry cooperation. If, for example, RoW inputs are the subject of the sensitivity analysis, to ensure the total of all the weights comes to 100%, the weightings of the other basic attributes will need to be adjusted in a similar proportion. If, for instance, RoW control is increased by 10%, the spill response and industry cooperation would have to be decreased by 5% each. Table 6-8, Table 6-9 and Table 6-10 show the new weights for each of the basic attributes when the main sensitivity analysis weight variation is carried out for one attribute. The tables also show the results of the normalisation process that ensures all the weights for the three attributes sum up to 100%.

Table 6-8: Sensitivity Analysis - RoW Control Weighting Variation

Right of Way Control						
% changes	**Right of Way Control**	% Changes	Spill Response	% changes	Industry Cooperation	Sum of Weightings
10.0%	**0.609**	5.0%	0.236	5.0%	0.233	1
5.0%	**0.581**	2.5%	0.230	2.5%	0.228	1
0.0%	**0.553**	0.0%	0.225	0.0%	0.222	1
-5.0%	**0.526**	-2.5%	0.219	-2.5%	0.216	1
-10.0%	**0.498**	-5.0%	0.213	-5.0%	0.211	1

Table 6-9: Sensitivity Analysis – Spill Response Weighting Variation

Spill Response						
% changes	**Spill Response**	% Changes	Industry Cooperation	% changes	Right of Way Control	Sum of weightings
10.0%	**0.247**	5.0%	0.233	5.0%	0.581	1
5.0%	**0.236**	2.5%	0.228	2.5%	0.567	1
0.0%	**0.225**	0.0%	0.222	0.0%	0.553	1
-5.0%	**0.213**	-2.5%	0.216	-2.5%	0.540	1
-10.0%	**0.202**	-5.0%	0.211	-5.0%	0.526	1

Table 6-10: Sensitivity Analysis – Industry Cooperation Weighting Variation

Industry Cooperation						
% changes	Industry Cooperation	**% Changes**	**Spill Response**	**% Changes**	**Right of Way Control**	**Sum of Weightings**
10.0%	**0.244**	5.0%	0.236	5.0%	0.581	1
5.0%	**0.233**	2.5%	0.230	2.5%	0.567	1
0.0%	**0.222**	0.0%	0.225	0.0%	0.553	1
-5.0%	**0.211**	-2.5%	0.219	-2.5%	0.540	1
-10.0%	**0.200**	-5.0%	0.213	-5.0%	0.526	1

The results of the analysis and the comparison between the utility values of the basic attributes are shown below. Figure 6-8 shows the utility values across three basic attributes for a 5% variation from +10% to -10%. The results show that the three attributes are all trailing each other in terms of the impact they have on the results. However, as expected, RoW control has the most impact of the three attributes. The behaviour of the model for the input variation follows an expected pattern. As the weighting is varied between 0 and +10%, the utility values decrease whilst a reduced weighting of the same magnitude results in increased utility values.

6.4.2 Validation

Validation is used to ensure that the model is fit for its intended purpose and meets the expected requirements. There are four axioms that the model needs to satisfy to ensure that it is fit for use and can produce the expected outcome for a range of inputs (Loughney, 2017; Yang & Xu, 2002). These axioms are Independence, Consensus, Completeness and Incompleteness.

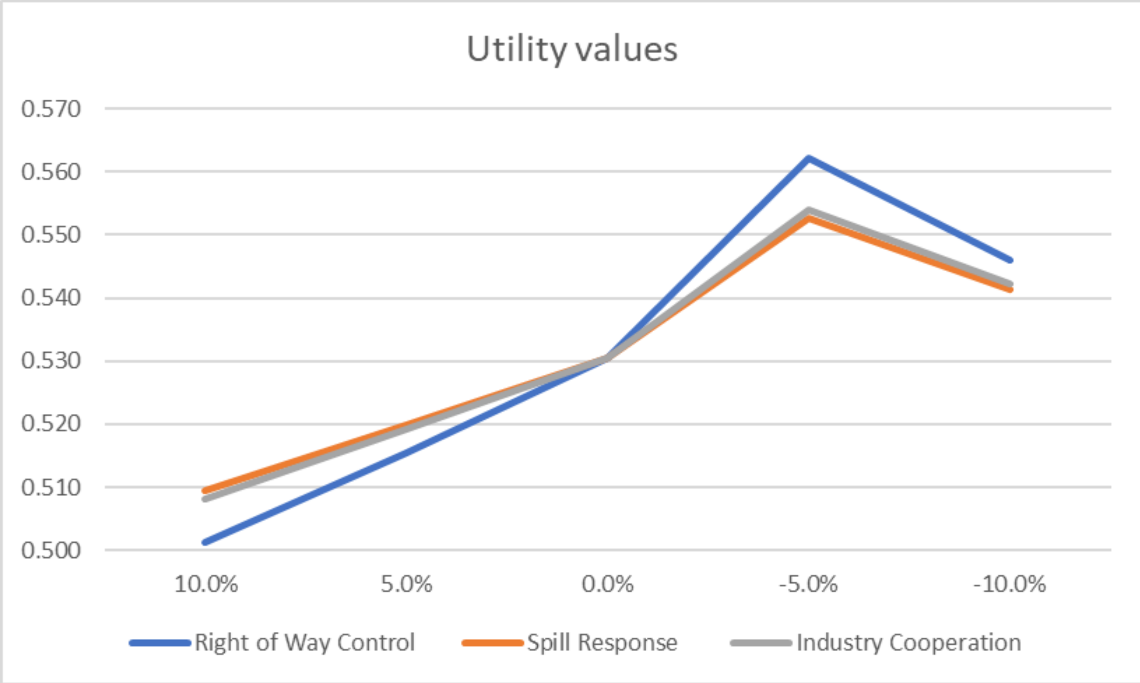

Figure 6-8: Sensitivity Analysis – Weighting Variation of Basic Attributes and How it affects Utility Values

- **Independence axiom:** this synthesis axiom gauges that if no basic attribute is assessed to an evaluation grade at all, then the general attribute should not be assessed to the same grade either. Continuing with the "mitigation" general attribute evaluated in Section 6.3, it can be seen that the general attribute grade 'very low' is assessed as zero., i.e., $\beta_n = 0$. The basic attribute grade 'very low', $\beta_{n,i} = 0$ for *i* = *1, 2, 3* is also assessed as zero. The assessment thus follows the principle of this axiom.
- **Consensus axiom:** this synthesis axiom determines that if all basic attributes are precisely assessed to an individual grade, then the general attribute should also be precisely assessed to the same grade. On this assessment, there are no identical basic attributes that have been precisely assessed to the same individual grade to afford direct validation for this axiom. However, the RoW control (C1), spill response (C2) and industry cooperation (C3) initial belief degrees for low (H2) and medium (H3) grades (management solutions) are (H2, C1 =0.50, H2, C2=0.11, H2, C3=0.00) and (H3, C1=0.50, H3, C2=0.16, H3, C3=0.00)

and are therefore similar. Hence the axiom could be said to be satisfied if the aggregated value produces similar aggregated results.

When the general attribute is aggregated, the belief degrees for the low ($\beta 2$) and medium ($\beta 3$) grades are 0.353 and 0.366 respectively. The results share a close similarity. Therefore, they can be taken as evidence that the axiom is satisfied.

- **Completeness:** this axiom determines that, if all basic attributes are completely assessed to a subset of grades, then the general attribute should be completely assessed to the same subset as well. This axiom is satisfied throughout the analysis as all the aggregation has been carried out using the five evaluation grades of very low, low, medium, high and very high.
- **Incompleteness:** this axiom determines that, if any basic assessment is incomplete, then a general assessment obtained by aggregating the incomplete and complete basic assessments should also be incomplete with the degree of incompleteness properly assigned. As there are not any incomplete belief degrees in this assessment, this axiom is satisfied. The initial belief degrees for both the general and basic attributes are all equal to one. The aggregated belief degrees for all the general attributes are also equal to one.

The model is therefore deemed validated as it satisfies the four axioms. The model's methodology and procedure are, therefore, fit for purpose and behave as expected.

6.5 Cost and Benefit Estimation and Ranking

The loss of containment of a pipeline is associated with the financial cost, and so are the risk control measures that would be put in place to minimise or mitigate such losses. The cost of pipeline losses could broadly be categorised into:

1. Cost of compensation for loss of life or injuries sustained (including hospital treatment and other compensation for the injured).

2. Cost of damage to the environment, habitat, population livelihood and physical property.
3. Cost as a result of economic loss, which includes production losses, contract penalties and repair losses.

Obtaining a total cost of each of the individual cost components above is difficult due to different variables. Additionally, Nigeria's Employee's Compensation Act (Federal Government of Nigeria, 2010) has created an agency with the responsibility to compensate the families of employees that suffer work-related injuries or fatalities. However, the law does not outline the compensation procedure if the accident affects a third party (that is, members of the public). Evidence from previous incidents shows that the majority of those affected by pipeline accidents are members of the public, not the personnel working for the pipeline operator or the pipeline contractor (Carlson *et al.*, 2015). The affected third parties often resort to civil law for compensation by the courts in the absence of any specific relevant law.

The main cost associated with any loss of containment in a pipeline in Nigeria, therefore, includes all three components – cost due to loss of life or injury, direct economic loss cost and the cost of environmental restoration. Sections 6.5.1, 6.5.2 and 6.5.3 shows how the those costs have been estimated. Section 6.5.4 provides the total cost.

6.5.1 Loss of Life and Injury-Related Costs

The costs associated with the loss of life or due to injury can be included in the analysis in several ways, including using one of the following approaches, Cost of Saving Lives (CSX) value, willingness to pay (WTP), human capital, life-quality index (LQI) or value of statistical life (VSL) (Arends *et al.*, 2005; Sánchez-Silva & Klutke, 2016). The most widely used approaches are LQI and VSL.

The LQI uses a criterion to define a threshold that separates efficient from inefficient lifesaving investments, where the cost of saving lives is used as a restriction in the analysis, as opposed to a direct cost. The VSL approach, on the other hand, consists of estimating the potential number of casualties and assigning them a value often based on the value of statistical life. VSL is assessed as the value assigned for compensation to the relatives of any individual in case of an accident.

VSL is deemed as the most appropriate analysis to use for the purpose of ascertaining the direct cost for compensation.

VSL is defined as Robinson, Hammitt and O'Keefe (2019):

$$VSL_t = VSL_b \times (\frac{Y_t}{Y_b})^n \quad \textit{(6-12)}$$

where VSL_t is the VSL for the target country, VSL_b is the VSL for the baseline country, Y_t is the target country's income and Y_b is the baseline country's income, both in GNI (Gross National Income) per capita. n is the elasticity which measures the rate at which VSL changes with income.

The VSL for Nigeria can thus be calculated from Equation *6-12)*, as outlined below.

$$VSL_{Nig} = VSL_{US} \times (\frac{Y_{Nig}}{Y_{US}})^n$$

where

VSL_{Nig} is Nigeria's VSL, to be calculated,

VSL_{US} is the baseline country VSL, in this case the USA, with a value of \$9.6 million,

Y_{Nig} is Nigeria's income in GNI per capita which is \$2,820,

Y_{US} is the USA's income in GNI per capita which is \$ 55,980, and

n is the elasticity, which is taken as 1.

The USA VSL figure and the GNI numbers are based on 2015 figures (Viscusi & Masterman, 2017).

Therefore,

$$VSL_{Nig} = 9600000 \times (\frac{2820}{55980})^1 = \$485{,}000$$

The $485,000 compares well with the average VSL for a lower middle-income economy of $420,000 (Viscusi & Masterman, 2017). Therefore, based on a statistical value of life of $485,000, the expected annual economic benefit of averting 652 fatalities per year is equal to $315.3 million. The estimates for the annual fatalities and how it is arrived at is given below.

Qualitative assessment of the consequence of a pipeline accident in terms of life safety would use the guidance provided in industrial standards (IMO, 2018; Norske Veritas, 2010) and the results of the FMEA carried out in Chapter 4. The International Maritime Organization (IMO) guide (IMO, 2018) and the Der Norske Veritas (DNV) recommended practice (Norske Veritas, 2010) have qualitative rankings for safety consequences as outlined in Table 6-11.

Table 6-11: Safety Consequence Qualitative Ranking

DNV Guide		IMO Guide		
Category	**Description**	**Category**	**Description**	**Equivalent fatalities**
1 (low)	No person(s) are injured	1 (minor)	Single or minor injury	0.01
2	(not used)	2 (significant)	Multiple or severe injuries	0.1
3 (medium)	Serious injury, one fatality	3 (severe)	Single fatality or multiple severe injuries	1
4	(not used)	4 (catastrophic)	Multiple fatalities	10
5 (high)	More than one fatality	5	(not used)	

The rankings for the DNV guide and the IMO guide differ slightly but are all consistent, although the two rankings both use less than five categories. On the other hand, the FMEA ranking used in Chapter 4 uses five categories. This research adapts the two qualitative rankings in Table 6-11 to develop a five-category ranking that will be compatible with the FMEA results. This is shown in Table 6-12.

Table 6-12: Modified Safety Consequence Qualitative Ranking (Modified from Table 6-11)

Category	Description	Equivalent Fatalities
1 (negligible)	No person(s) are injured	0.001
2 (marginal)	Single or minor injury	0.01
3 (moderate)	Multiple or severe injuries	0.1
4 (critical)	Single fatality or multiple severe injuries	1
5 (catastrophic)	Multiple fatalities	10

The FMEA assessment has been carried out using expert elicitation with the experts' details outlined in Table 4-6. The FMEA results for third-party damage shows that the three experts have assigned consequence severity rankings of 5, 4 and 4 respectively. This would put the consequence severity of pipeline accidents in Nigeria's System 2B to be between critical and catastrophic. However, not all third-party pipeline damage results in a fire, explosion or any safety consequences. Nevertheless, the few pipeline accidents that result in safety consequences do have significantly higher fatalities than the 10-fatality value assigned for the catastrophic ranking. For example, Carlson *et al.* (2015) report several pipeline accidents in Nigeria where more than 100 people were reported dead. It could, therefore, be reasonably argued that using a conservative approach, where it is assumed that each pipeline incident is assigned a ranking of five – catastrophic – is more appropriate. However, this research takes a less conservative approach of assigning a ranking of four – critical – for assessing life safety consequences, with sensitivity assessment carried out in section 6.5.5 to assess the changes to the results if different ranking is used.

The number of equivalent fatalities is based on the number of annual pipeline accidents. Table 6-13 shows the annual pipeline failures for a decade up to 2015, which gives an average of 652 failures annually. As noted earlier, the majority of these failures do not result in any life safety consequence. However, the few that result in fires and explosions often record higher fatality or fatality equivalent numbers.

Table 6-13: 10-Year Failure Statistics for Pipeline System 2B (NNPC, 2016)

Year	Number of Pipeline Failures	Product Loss ('000 mt)
2006	486	183
2007	479	142
2008	530	13
2009	609	110
2010	191	145
2011	468	127
2012	481	163
2013	1080	269
2014	1077	333
2015	1114	471
Annual Average	652	196

With a critical consequence severity assumption equivalent to one fatality per accident, the estimated number of fatalities for the number of incidents stands at 652 per year. This figure is higher than the annual average of circa 250 incidents for the previous decade up to 2006 (Okoli & Orinya, 2013). This should not be surprising since the spate of pipeline damage due to third-party events has increased significantly in the decade up to 2015 compared to the previous decade. Previously reported incidents (Hopkins, 2008; Carlson *et al.*, 2015) also indicate that one accident can result in several hundred fatalities.

6.5.2 Direct Economic Cost to the Operator

This covers the cost of business interruption, including loss of production, contract penalties, the cost of repair or replacement of the affected pipeline section. As the costs increase, the more time it takes to repair the pipeline, which is often assumed to be a linear relationship. Previous research (Ekwo, 2011) has estimated the approximate number of pipeline failures and their total cost due to product shut-in and repairs. Therefore, these figures can be obtained for the System 2B pipeline. However, there are no details of the distribution of the size of the damage; as a result, there is no precise cost based on the size of the pipeline damage. This analysis will, therefore, take the average cost per damage as an indication of the direct economic cost per failure. Table 6-13 shows the number of System 2B pipeline failures for a decade up to 2015. The average annual cases of pipeline failure, the cost of repair, the product loss and the estimated economic cost are shown in Table 6-14.

Table 6-14: System 2B Average Annual Damage and Economic Costs (Ekwo, 2011)

System	Number of Pipeline Damage(/yr)	Product Loss ('000 mt/yr)	Economic Cost (Total/yr)	Cost per Damage (Average)
2B	652	196	$ 51,865,983	$ 79,943

Note that this figure is of a very high level and only includes the actual repair cost and the cost of product loss due to spillage. The figure may not include the cost of lost revenue due to shut-in or third-party liabilities which could be an order of magnitude higher.

6.5.3 Environmental Damage and Restoration Cost

The cost associated with oil spills is traditionally divided into two: the cost to clean up the spill and the cost to make good the damage made by the spill in terms of its social, environmental and resource-based damages. This section only looks at the cost of cleaning the environment post-spill.

Various derivations of the oil spill clean-up cost have been developed, including work carried out by Etkin (2000; 1999) and Kontovas *et al*., (2011b; 2011a). The work of Kontovas *et al*., (2011b; 2011a) has subsequently been adopted in the IMO Formal Safety Assessment guidelines (IMO, 2018). The two works derived their data primarily for spills on water, but the Kontovas *et al*., (2011b; 2011a) approach has been used in studies of pipelines, including onshore pipeline spills (Eglington *et al.*, 2012; Gunton & Broadbent, 2015).

Using the dataset from the International Oil Pollution Compensation Fund (IOPCF) for the period between 1979 and 2006, Kontovas *et al*., (2011b; 2011a) used a linear regression analysis to come up with a fitted model which calculates both the clean-up cost and a total cost of oil spills as a function of spill volume. The fitted curve for the total cost as adopted by the IMO is used here, as shown in Table 6-15. This assessment analyses the two spill datasets and compares it with the anecdotal evidence of suggested payments for spill clean-up in Nigeria (NNPC, 2012) to decide which is more appropriate for use.

Table 6-15: Spill Clean-Up Cost Models

Cost	Dataset	Equation
Total cost	All spills	$67275\ V^{0.5893}$
	V>0.1 tonnes	$42301\ V^{0.7233}$

V is the spill volume in metric tonnes. The difference between the 'all spills' and spills with volumes greater than 0.1 tonnes equations is as a result of the datasets used, the IOPCF and the OSLTF (US Oil Spill Liability Trust Fund), with one overestimating the volumetric total clean-up cost compared to the other.

Using the derivations and adjusting for inflation (US inflation figures to 2015 prices), the annual oil spill volume of 196,000 metric tonnes for the System 2B pipeline gives a total cost of $107 million using the 'all spills' dataset. If the dataset that excludes small spills is used, the cost increases to $345 million, as shown in Table 6-16. The costs are adjusted from 2005 prices to 2015 prices so that they align with the life safety and economic costs which are set at 2015 prices. This assessment discounts the cost-increase trend over time, as highlighted by Etkin (1999).

Anecdotal evidence and discussion with field operatives indicate that the most appropriate equation to use is the total costs equation for spills greater than 0.1

tonnes. This is also in line with the types of spills encountered, as the spills are in the order of hundreds or thousands of tonnes.

Table 6-16: Total Spill Cost.

	Spill Volume (mt)	Formula	2005 prices	2015 Prices
Total Cost (all spills)	196,000	$67275\ V^{0.5893}$	$88,426,047	$107,306,570
Total Cost (V>0.1t)	196,000	$42301\ V^{0.7233}$	$284,602,985	$345,370,750

6.5.4 Total Failure Cost

The estimated failure cost of pipeline 2B includes the cost of human losses, the direct economic cost and the environmental damage and restoration cost, which have all been outlined in Sections 6.5.1, 6.5.2 and 6.5.3. The failure cost in Section 6.5.1 has been estimated using VSL assessment and the FMEA. The failure cost in Section 6.5.2 has been obtained directly from the system 2B infrastructure operator, whilst the cost in Section 6.5.3 is estimated using the IMO derivation.

The direct economic cost is calculated as an average of the losses over 10 years to 2015 and is estimated at $51.9 million. The environmental cost is estimated as $345.4 million at 2015 prices. The cost associated with life safety, in equivalent fatalities, is estimated as $315.3 million, also at 2015 prices. The total cost of the three components is, therefore, $712.6 million.

6.5.5 Cost of Risk Reduction and Control Measures

An assessment has been carried out to determine the financial costs required to implement the identified risk reduction and control measures. Based on the ER aggregation results shown in Section 6.4, some measures are more effective than others. However, for this assessment, it is assumed that all measures may be implemented. The cost of each RCO varies and so does its effectiveness. First, the failure likelihood of the baseline intervention options needs to be established. This is achieved by using the failure likelihood derived for intentional third-party damage from Figure 5-3, which is 0.30, and the belief degrees provided by the experts, which is represented as the weightings in Table 6-1. The two values are then used to estimate the failure likelihood for the inadequate provision of the basic attributes. For example, to obtain the failure likelihood estimates relating to inadequate surveillance the following are used: the intentional third-party damage failure likelihood of 0.300, the detection general attribute weight of 0.290, from Table 6-1, and the surveillance basic attribute weight of 0.298, also from Table 6-1. This gives inadequate surveillance a failure likelihood of 0.0263, that is, *0.300* x *0.290* x *0.298.* The failure likelihood of the rest of the attributes is shown in Table 6-17. The total of the entirety of Table 6-17 should be equal to 0.3, which is the likelihood of failure due to intentional third-party damage estimated in Chapter 5.

Table 6-17: Failure Likelihood for Baseline Studies - System Without any RCO

S/N	Lack of or Inadequate Provision the Basic Attributes	Failure Likelihood (/yr)
1	Lack of or Inadequate Surveillance	0.0263
2	Leak Detection	0.0313
3	SCADA/Staffing Measures	0.0186
4	Patrol	0.0120
5	Pipeline Cover	0.0215
6	Burial Depth	0.0287
7	Public Education	0.0233
8	Barrier	0.0606
9	Right of Way Control	0.0277
10	Spill Response	0.0112
11	Industry Cooperation	0.0111
12	Intelligence	0.0121
13	Security Forces	0.0038
14	Punishment	0.0043
15	Community Partnering	0.0073

To obtain the estimated cost of intervention, two levels of risk reduction options for each of the attributes have been identified: the basic RCOs and advanced RCOs. The “as-installed” provisions are cost-neutral because they are already installed and therefore do not require any additional budgetary expenditure. These "as-installed" provisions are included only for completeness. The basic RCO provisions are the options that minimise expenditure whilst providing an improvement on the existing provisions. The advanced RCO provisions are the detailed provisions that aim to reduce the likelihood of a threat being realised to significantly low levels. The downside of advanced RCO provisions is the high level of expenditure associated with their provision. Note that the majority of RCO provisions aim to reduce the likelihood of a failure event happening. Some RCOs, such as patrols, could reduce the failure likelihood as well as the eventual consequences when a failure event happens. However, as consequence analysis has not been carried out as part of this research, assessment of the consequence reduction potential of the RCOs have not been investigated.

Table 6-18 shows the RCOs and their estimated cost in dollars (set at 2015 prices) for each of the intervention provisions. There are three cost options for each RCO. The first is for the operator to do nothing, the second is for a basic implementation of the RCO and the last involves advanced RCO provisions. The majority of the estimated costs are obtained from literature which looks at similar interventions and in some cases is adjusted to reflect the Nigerian environment. Where no information is available in the literature or there is no unpublished in-house data from the pipeline operator, expert opinion has been elicited. Where information has been obtained or adapted from a source, a reference has been provided in Table 6-18, against the relevant RCO cost estimate.

The assigned value for reduction in failure likelihood is subjectively assessed with the support of experts based on the perceived effectiveness of each RCO and the level of the intervention. For example, advanced RCOs have been assumed to be capable of reducing the failure likelihood by more than 99%.

The estimated cost (total) includes the initial purchase of the equipment, its maintenance, spare parts and repairs. In order to arrive at the present value, these cost components have been calculated and added to the final figure. The present value of the maintenance and spares cost is calculated using the net present value formula $NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$ where i is the discount rate or the interest rate, R_t is the outlay cost and t is the number of years.

For example, the costs for a real-time transient leak detection facility includes a purchase cost of $1,000,000, annual maintenance costs of $2,000 per year and repairs/spare parts cost of $500 per year for an expected service lifetime of 25 years. The cost of the capital or interest rate is assumed to be 10%.

The cost components will be:

1. Purchase cost = $1,000,000

2. PV(maintenance) = $\sum_{t=1}^{25} \left(\frac{2{,}000}{(1+10\%^{25})}\right) = 2{,}000 \times \left(\frac{(1+10\%)^{25}-1}{10\%\ x\ (1+10\%)^{25}}\right) = \$18{,}154.08$

3. PV(spares) = $\sum_{t=1}^{25} \left(\frac{500}{(1+10\%^{25})}\right) = 500 \times \left(\frac{(1+10\%)^{25}-1}{10\%\ x\ (1+10\%)^{25}}\right) = \$4{,}538.52$

The total cost is therefore $1,022,693. Table 6-18 provides the estimated costs for implementing each of the RCOs. As outlined earlier, the assigned values for the reduction in failure likelihood is subjectively assessed with the support of experts based on the perceived effectiveness of each RCO.

Table 6-18: Costs for Implementing Risk Reduction Measures

General Attributes	Basic Attributes -Risk Reduction Options	Reduction in Failure Likelihood	Estimated Cost in $ (/yr.)	Reference
Surveillance	No surveillance	-	-	(PPMC, 2014)
	Weekly	0.2999	1,846,769	
	Daily	0.0001	5,207,272,727	
Leak Detection	Basic LDS (e.g., pressure/flow monitoring)	-	-	(Hill, 2011)
	Mid-range LDS (e.g., real time transient model)	0.1999	1,022,693	
	Advance LDS (e.g., fibre optics leak detection)	0.0001	14,548,750	

General Attributes	Basic Attributes -Risk Reduction Options	Reduction in Failure Likelihood	Estimated Cost in $ (/yr.)	Reference
SCADA/Staffing measures	No SCADA and minimal staff monitoring	-	-	(Oriental Consultants, 2011)
	Basic SCADA and limited staff monitoring	0.0999	487,085	
	Advanced SCADA and robust staff monitoring	0.0001	1,948,339	
Patrol	Irregular and ineffective patrol	-	473,388	(PPMC, 2014)
	Weekly	0.3332	1,420,591	
	Daily	0.0001	4,733,884,298	
Pipeline Cover	No cover	-	-	(Knoope, 2016)
	Reinforced concrete slab, etc., above the pipeline	0.0999	62,150,000	
	Reinforced concrete slab or high tensile netting plus visible warning above the pipeline	0.0001	62,274,300	
Burial Depth	≤ 0.4	-	-	(Knoope, 2016)
	≤ 1.0	0.4999	19,662,000	
	>1.6	0.0001	36,047,000	
Public Education	No public education	-	-	(USDT, 2012)
	Good, less effective public education	0.2999	500,000	
	Very good and effective public education	0.0001	2,000,000	
Barrier	No barrier	-	-	
	Basic physical barrier to the most vulnerable segment of the pipeline	0.0999	925,000	
	Fence, alarms and CCTV on all segments of pipeline subject to attack	0.0001	2,259,000	
Right of Way Control	No effective RoW enforcement	-		(Rui *et al.*, 2011)
	Less effective RoW control with pockets of incursions in some corridors	0.4999		
	Strick RoW control	0.0001	578,314	
Spill Response	No specified emergency spill response	-	-	(O&G UK & OPOL, 2012)
	Facility response plan in place but no coordination with outside entities	0.3157	101,376	
	Well planned emergency spill response including facility response plan, coordination and cooperation with nearby facilities and robust coordination	0.0001	126,720	

General Attributes	Basic Attributes -Risk Reduction Options	Reduction in Failure Likelihood	Estimated Cost in $ (/yr.)	Reference
	with public emergency planning authorities			
Industry Cooperation	No cooperation	-	-	
	Uncoordinated and informal cooperation	0.3477	250,000	
	Detailed coordination and cooperation with the rest of the industry and especially a formal coordinated approach to tackling asset threat	0.0001	1,000,000	
Intelligence	No intelligence gathering and sharing	-	-	(Amunwa, 2012)
	Some intelligence is gathered but actions are inconsistent.	0.1303	1,216,021	
	Optimum intelligence gathering and sharing with and between all relevant parties. Actions are taken based on intelligence.	0.0001	4,864,083	
Security Forces	Inconsistent and uncoordinated security provision	-	-	(Aghedo & Osumah, 2015)
	Less effective security provisions	0.3999	4,864,083	
	Robust, coordinated and effective security provisions by both the companies and govt	0.0001	19,456,333	
Punishment	No fear of punishment to serve as a deterrent	-	-	
	Some provision in place such that a fear exists of punishment if apprehended	0.2777	1,216,021	
	Robust provision in place such that absolute fear of the consequence of any pipeline vandalization or interference exists	0.0001	4,864,083	
Community Partnering	Bad relationship with the community and relevant interest groups	-	-	
	A somewhat good relationship but the community does not play an active role in pipeline security	0.2544	500,000	
	Excellent relationship with the community and interest groups within the community help in pipeline security	0.0001	2,000,000	

Assuming that all RCOs are to be implemented, basic provisions will cost about $96 million whilst advanced provisions are expected to cost about $10 billion. In reality, the limited budget and cost effectiveness imply that not all RCOs will be implemented. Therefore, the operator may decide to explore different options, such as assessing the cost effectiveness of implementing all basic provisions, for example, or only a selection of basic provisions. Table 6-19 shows the RCO provisions, the cost of the RCOs and the net benefit for each of the intervention combinations chosen. Other different combinations are possible, and each combination affords the user the opportunity to calculate the cost implication of their selection and the net benefit.

Table 6-19: Net Benefit of Different RCO Provisions

S/N	RCO Provisions	Failure Likelihood	Pipeline Losses	Cost of RCO	Net Benefit
1	Current provision - doing nothing	0.3000	$712,608,000	$ 0	$-712,608,000
2	Basic RCO provisions - implement all	0.076962	$182,812,456	$96,469,411	$433,326,133
3	Basic RCO provisions - implement the most effective	0.035200	$83,612,672	$68,329,445	$560,665,883
4	Advanced RCO provisions	0.000030	$71,261	$10,093,123,948	$-9,380,587,209

Note: only seven of the thirteen RCOs including surveillance, leak detection, SCADA, patrol, pipeline cover, public education and physical barriers are assumed to be implemented under item 3.

From Table 6-19, it can be seen that, although doing nothing costs the operator zero dollars in intervention expenditure, as they do not have to budget for any intervention, it results in estimated losses of $712.61 million annually, as calculated in Section 6.5.4. On the other extreme, implementing all the advanced RCO provisions would cost about $10.09 billion, but will reduce pipelines losses from $712.61 million per annum to $71,261 per annum. The net benefit of the intervention will be circa minus (loss of) $9.38 billion, due to the huge expenditure required. Clearly, this will not be effective either in terms of return on investment or in terms of effective utilisation of the available funds. The basic RCO provisions would seem to provide the best opportunity for cost-effective solutions. If all the basic provisions are implemented, this would cost about $96.47 million and will reduce the pipeline losses from $712.61 million per annum down to $182.81 million per annum. The net benefit of the interventions would be circa $433.33 million in the first year. On the other hand, if the available budget does not allow full implementation of the basic provisions, the operator may choose to implement those provisions that have the most impact on risk reduction. As an example, if the operator were to implement basic provisions of the seven out of the thirteen RCOs with the highest positive effect on reducing the failure likelihood, this would result in a net benefit of about $560.67 million in the first year. Specifically, the RCOs include surveillance, leak detection, SCADA, patrols, pipeline cover, public education and physical barriers.

Those effective RCOs fall largely within the technical solutions (surveillance, leak detection, pipeline cover, physical barriers) and management solutions (SCADA, patrol). This is consistent with the results of Table 6-6, which shows these solutions to be the most effective interventions – technical solutions first, followed by management solutions.

A sensitivity assessment investigates the impact of reduced or increased fatalities to the overall results in order to test how sensitive the results are to the assumptions made regarding the calculated number of fatalities. Implementing the basic RCO provisions or implementing the selected (most effective) basic RCOs gives a net positive cost-benefit, even if the costs due to loss of life are excluded from the assessment. The two options are still cost-beneficial if the assessment assumes a catastrophic consequence which results in 10 fatalities per incident, as opposed to one fatality per incident. Conversely, implementing advanced RCO provisions will still have a negative cost-benefit even if a catastrophic consequence is assumed. Advanced RCOs only become positively beneficial when 30 fatalities per pipeline failure are recorded, giving about 19,000 total fatalities per annum. These significant fatalities cannot be countenanced. In summary, the CBA criterion is met by implementing either all RCO provisions or only selected basic RCO provisions, even if the life safety aspect of the calculation is excluded from the analysis. Conversely, implementing the advanced RCO provisions will not be cost-beneficial, even if each of the more-than-six-hundred incidents are assumed to have caused ten fatalities.

6.6 Discussion

The analysis carried out in this chapter provides a set of tools that a pipeline operator may use to reduce their exposure to loss of containment as a result of intentional third-party damage. The model, employing ER, expert elicitation and CBA, identifies the most effective set of interventions that the pipeline operator could take to reduce the identified threat.

The expert elicitation used in this assessment, where the majority of the experts approached are operating within the Nigerian environment, led to some interesting results. The decision-making alternatives are grouped into control solutions: those that are expected to be provided for by the government and their agencies and those that the pipeline operator can provide through its management systems. The control solutions can also be achieved through technical solutions, which require the use of technology and/or physical features. The model divides the RCOs based on their main attributes, which are detection, prevention, mitigation and 'other measures'. Figure 6-1 shows the connections between the general attributes and their alternatives.

The failure factor analysed is intentional third-party damage, which is usually driven by political, economic and social factors. Therefore, it would have been expected that the government intervention alternative – via the use of security personnel to prevent and provide deterrence for criminal actions – is the most effective. However, the results indicate that such solutions are the least effective. The results instead identify the technical solutions alternative to be the most effective, followed by the operator's implementation of management systems. The technical solutions make it difficult for the saboteur to get to the pipeline in the first instance.

The results can be explained by local experience and the recent history of interventions by government agencies in regard to criminal activities around the pipeline in Nigeria, especially in the delta region. The government's intervention approach in the past several years has not resulted in a reduction of third-party damage losses (NNPC, 2016). Rather, it has emboldened criminals to be more daring (Aghedo & Osumah, 2015). It could be argued that government intervention was always badly planned and implemented, in addition to the occurrence of internal sabotage by means of leaking government plans to the criminal factions (Katsouris & Sayne, 2013).

The experts' belief that technical solutions are the most effective is perhaps based on the expectation that, once implemented, access to and damaging of the pipelines becomes difficult, thus eliminating the need for government and/or management solutions. In reality, one set of control solutions or alternatives alone will not address the challenge and a combination of control solutions are required. Identifying the most effective combination of solutions can be better appreciated by interrogating the basic attributes and their contribution to risk reduction and control measures. Interrogating the basic attributes indicates that the attribute with the most effective impact is the provision of a physical barrier to the exposed and the most vulnerable sections of the system, such as pumping stations and river crossings. The attribute which is least effective is the provision of security forces, which directly corroborates with the results that show government intervention solutions as being the least effective, as outlined earlier.

The resulting cost-benefit analysis of the possible interventions provides guidance on the net benefit of any one intervention or set of solutions. This allows the pipeline operator access to an easy and straightforward tool to decide on the interventions that are the most effective or the ones that the operator's current budget could allow. The assessment indicates that implementing advanced RCOs will have a significant budget outlay but will almost entirely put a stop to third-party damage. However, that intervention is not cost-effective, with a net benefit of minus $9.4 billion. Conversely, the basic RCO interventions are the most cost-effective, in that they require a lower financial outlay of $96 million, significantly less than the operator's estimated losses annually. The net benefit for basic RCOs is circa $433 million.

When the operator decides to implement only part of the basic RCO provisions, then selecting seven out of the eleven RCOs would cost about two-thirds ($68 million) of what the operator would spend when compared to the implementation of all the basic RCOs, which would cost $96.5 million with a net benefit of $560.7 million. The net benefit of implementing the seven most effective RCOs is higher than the $433.3 million worth of benefits for implementing all eleven basic RCOs. A sensitivity assessment has been carried out in Section 6.5.5, which shows that the CBA criterion has been met for the implementation of RCO provisions, or the selected basic RCO provisions, even if life safety aspects are discounted in the analysis. Conversely, implementing advanced RCO provisions will not be cost-beneficial, even if each of the more-than-six hundred incidents is assumed to have caused ten fatalities.

Although the assessment is detailed and complete, both the ER-based decision-making and CBA have a number of areas that can be improved upon. The most significant part is the dearth of directly applicable data for the geographical area under consideration and the subjectivity of the input from the subject matter experts.

In terms of the decision-making, a more refined aggregation and a higher number of evaluation grades than the five used could provide more granular results, which can be of better help to decision makers by providing visibility of the impact of a very small intervention to the overall aggregation results. However, the more evaluation grades or attributes are introduced, the more complex the analysis becomes. Also obtaining expert inputs via questionnaire becomes burdensome. Using a higher number of evaluation grades has been shown by Ren, *et al*. (2005) to provide better and more accurate basic attributes belief degrees.

The subjectivity of the initial utility estimation of the basic attributes obtained from the experts can also be reduced by introducing some probability analysis methods. This assessment has had to disqualify a number of expert judgements due to inconsistency. Perhaps if the grades were determined in a similar way as described in Yang and Xu (2002), a more robust utility estimation would have been derived. Yang and Xu (2002)'s study determines the lowest and highest utility grade in a similar way as is estimated in this study. However, the remaining three grades are attained by asking the experts to identify two extreme points and choose a value at which the probability of the worst and best performance is equidistant. This applies for each of the three grades. The experts then determine what value the probability holds at a given evaluation grade.
Additionally, a future research that look at the probability estimation of all the RCOs including probability of success of those interventions would provide more detailed tool to the operator not only to identify the most effective tool but also the one with the most likely success rate.

6.7 Conclusions

This chapter assesses the decision-making to be taken for a pipeline loss of containment threat as a result of third-party activities and the most effective RCOs available to reduce or eliminate the threat. The representative pipeline system in Nigeria is chosen as a case study consistent with the system chosen in the previous chapters. Four broad RCOs were identified, including detection, prevention, mitigation and other measures. These main RCOs are designated as general attributes. Each of the main RCOs has a number of sub-attributes and is further linked to solution groupings or alternatives, which include technical solutions, management solutions and government solutions. The number of attributes and their different hierarchies and assigned degrees of belief call for a complex decision-making algorithm that takes into account all the required attributes and their importance, eventually arriving at the most effective solutions. The ER algorithm has been applied to this problem, aggregating the attributes and hierarchies of each of the RCOs. The assessment results identify the most optimal alternative as being technical solutions in reducing the threat of a pipeline loss of containment due to a third party. The assessment results can also be investigated further to a sub-attribute level to find out the most effective basic attribute(s) that contribute more than others in reducing the loss of containment threat.

A CBA has also been carried out to estimate the current financial losses that are being encountered as a result of third-party damage to the pipeline system. The assessment relies on publicly available information from the operator, unpublished proprietary operator information, other available literature and calculations of the cost of the spill using IMO guidance. It has been estimated that the annual loss, based on data up to 2015, is circa $713 million. The CBA then calculated the expected expenditure required to implement the RCOs for different levels of details and the loss reduction that such RCOs would provide. The cost of implementing the RCOs varies from $68 million to $10 billion. The most cost-effective measure is not *a no-loss* scenario, which can be achieved if $10 billion is expended, but a reduced loss scenario such that the net benefit is at its maximum. That option entails implementing some of the RCOs under basic provisions, specifically, the following RCOs: surveillance, leak detection, SCADA, patrols, pipeline cover, public education and physical barriers. The net benefit of implementing these options is estimated to be circa $561 million.

The chapter will provide pipeline operators with easy-to-apply tools that will hopefully allow them to prioritise their investment in reducing the loss of containment threat. It will also give them a good idea of the relative effectiveness of the many RCOs available and their estimated costs. Due to limited directly applicable data, the CBA uses data from other countries, and where no relevant data is available, a number of assumptions were made. Therefore, the estimated cost may vary within a real-life assessment but the relative costs of one option compared to the other should be reasonably in line with the actual differences between the options. For decision-making processes, that relative difference may be the most important factor.

This chapter and the two preceding ones formed the main technical contribution towards the onshore cross-country pipeline risk assessment. The models and the framework developed ties in together for a holistic assessment. The results of each preceding chapter serve as an input into the next chapter. The results of the preliminary assessment chapter, Chapter 4, identified leak and rupture as the failure mode with the highest likelihood of causing loss of containment. Therefore, failure due to leak or rupture serves as the top event in the BN analysis chapter, Chapter 5. The BN assessed all the contributing failure factors and identified third party damage as having the most significant contribution to the failure likelihood. This chapter, Chapter 6, then assessed the main attributes contributing towards risk reduction of the failure due to third party damage and their cost benefit estimate.

Chapter 7. Conclusions

This chapter provided the conclusions of the work carried out in this thesis including the results, its implications, the envisaged contribution and limitations. It also highlights the need for the research, the research objectives and whether such objectives have been met. The contribution of this thesis to the body of knowledge and the challenges currently encountered by operators is outlined, including limitations to the application of this work in the field. This chapter also enumerates areas where this study would benefit from further research and investigation.

7.1 Main Conclusions of the Research

The likelihood of loss of containment, as a result of pipeline failure in general and for onshore cross-country products pipelines in particular, is reducing in most countries due to improvements in the technical, operational and risk management systems already in place. However, in certain countries, such as Nigeria, the frequency of such incidents has been on the increase, driven mainly by incidents relating to human intervention. The sparse available data from the pipeline operator (NNPC, 2016) indicates a fourfold increase in the 5-year moving average of pipeline failures from 2003 to 2016. The majority of the increase is as a result of third-party damages. The human, environmental and economic losses associated with these incidents are significant and so are the political consequences. The absence of reliable failure data, the lack of adequate maintenance and the lack of a risk management regime make it difficult for any appropriate tool to be put in place to reduce, control or mitigate the risks of such failures. There is, therefore, a need to develop models that will help with pipeline risk assessment, but which take into consideration the unreliability of the data in Nigeria and similar geographical areas.

Having identified the research needs, this thesis aimed to achieve the objectives that have been outlined in Section 1.3. All the objectives have been achieved as summarised in the paragraphs below.

The first objective has been achieved by carrying out an in-depth literature review and interviews with field staff working for the pipeline operator. The past and current trends of reported incidences, and the operational statistics regarding the integrity management of the European, American and Nigerian cross-country pipelines, have been reviewed, thus identifying the main drivers behind the increasing failure frequency of the pipelines, especially in Nigeria and similar geographical areas. Globally, the increase in the price of petroleum product is driving the rate of intentional pipeline damage for product theft as both Nigerian (NNPC, 2016; PPMC, 2014) and European data (Cech *et al.*, 2018) have shown. In 2015, 90% of all petroleum product pipeline-related failure was due to product theft in Europe. Depending on which data one reviews, Nigeria's share of petroleum product pipeline failure due to deliberate third-party activities range between 88% (PPMC, 2014) and 99% (NNPC, 2016) of all failures for the period between 2006 and 2013.

Another driver is uncontrolled development and encroachment onto pipeline corridors due to population growth: Nigeria's population has increased by more than 60 million in the decade leading up to 2017 (World Bank, 2017). Other drivers include lack of adequate maintenance and criminal collusion with pipeline operator staff to destroy the pipeline so that repair contracts can be awarded (Katsouris & Sayne, 2013).

The second objective has been achieved in Chapter 4 by developing a model for identifying and ranking failure modes by modifying the FMEA process to accommodate uncertainty due to inadequate data. The modified process uses the Fuzzy Rules Base and Grey Relations Theory. Similar to the FMEA, the modified process assesses the potential pipeline failures and qualitatively ranks them in terms of the likelihood of the failure to occur. It also assesses any detection in place to reveal the failure and the likely severity in terms of human safety, environmental damage and economic loss. Unlike FMEA, rather than using numerical values to rank the failures, the Fuzzy Rules Base and Grey Relations Theory use linguistic terms where the experts are asked whether, for example, the likelihood of an event happening is low or high. A membership function diagram is then used to generate the related linguistic terms and membership functions for each failure mode and an IF-THEN analysis is carried out to obtain the consequential linguistic terms and beliefs degree. The final linguistic expressions are then converted into a ranking using a utility value formula. Grey Relation Theory approach has also been used to rank the failure modes. This entails the calculation of the difference between the comparative series and the standards series, using Klein's expression to obtain the degree of relations, which is the ranking of the failure modes.

The rankings using the modified approaches and those using the traditional FMEA have been compared. It shows a number of agreements but with differences on certain failure modes. Since the aim of the modified approach is to address the identified weaknesses of the traditional FMEA model, such as the assumption that the three failure factors have the same weight and also that all the experts approached have the same level of experience, the difference in the rankings highlights the benefits of the new approach. All three approaches show that pipeline failure due to a leak or a rupture as the failure modes with the highest ranking. This forms the basis for addressing the next objective which is the identification of the likelihood of the failure mode with the highest risk ranking.

The model developed in Chapter 5 addressed the third objective, by using Bayesian Networks (BN) to develop the failure probability of the identified failure mode – pipeline failure due to a leak or rupture – under uncertainty. The uncertainty arises due to the lack of or inadequate data, which is the case in Nigeria's onshore cross-country pipeline. Nigeria's pipeline data obtained from the three different sources are disparate, conflicting and incomplete. The Bayesian Network approach is best suited for addressing this objective because, in addition to accommodating data uncertainty, it can also integrate expert knowledge. The model is especially good at updating uncertainty whenever new data becomes available.

Calculating the failure likelihood requires identification of the primary and secondary failure factors and determining their Conditional Probability Tables (CPTs). The CPTs are then inserted as marginal probabilities, helping to determine the pipeline leak and rupture probabilities. The marginal probabilities for the primary factors, which are the root events in the Bayesian Networks, have been obtained from the pipeline operator and the failure data of other operators where such data exists. Where the data is unavailable or inadequate, expert elicitation using AHP has been employed. Expert elicitation has also been used, together with the Symmetric method, to fill in the data for the child nodes.

The results indicate that the failure likelihood of pipeline leak and rupture for the case study pipeline system, in terms of marginal probabilities, is 14.72% and 7.51% respectively. The interrogation of the results indicates that the failure factor with the most impact on the results is third-party damage, contributing about 33.8% of the failure. Evidence propagation has been carried out to assess the likely impact of improvements to the marginal probability contribution of third-party damage to the pipeline failure likelihood. If both the government and the operator institute effective security and political intervention, for example, then that reduces the marginal probability of third-party damage happening from 33.8% to 7%. The overall failure likelihood of pipeline failure due to leaks and ruptures is then reduced from 14.7% and 7.5% to 3.9% and 3.3% respectively.

Chapter 6 demonstrates that the final two objectives, which includes risk-based decision-making and the cost-benefit analysis have been achieved. An Evidential Reasoning model has been developed to aid risk management decision-making, whilst cost-benefit calculations have been carried out that estimate the financial outlay required for each Risk Control Option (RCO), the benefit of implementing such options and the costs associated with pipeline failure.

The BN analysis has identified third-party damage as one of the major failure factors, the Evidential Reasoning algorithm has been used to assess risk control solutions or options that will reduce the likelihood of pipeline failure due to third-party damage, especially intentional third-party damage. The risk control solutions include technical, government and management solutions, which in the ER algorithm are labelled as the alternatives, have been compared with each other to identify and rank their effectiveness. The risk control measures, which are the general attributes in the ER algorithm, include detection, prevention, mitigation and 'other measures'. The ER process evaluates the general attributes and ranks the alternatives by means of an evaluation grade $u(H_n)$ using a predetermined number of ratings.

The results of the different attributes and alternatives indicate that overall the technical or technological solutions as an alternative have more likelihood of being the most effective intervention. This is followed by management intervention alternative and, lastly, government intervention alternative, which is deemed to be the least effective.

A cost and benefit estimate has also been carried out to provide insight into financial losses relating to third-party damage to the pipeline, based on life safety consequences, environmental damage and direct economic losses.

7.2 Research Contribution

The main contributions of this research include the following:

i. Identification of the parameters and the reasoning behind the high failure incidents of cross-country pipelines in Nigeria and elsewhere.

ii. Development of a model that identifies, assesses and ranks pipeline failure hazards under uncertainty by using linguistic terms and belief degrees. The use of modified FMEA, incorporating the Fuzzy Set and Grey Relations Theory, ensures that some of the weaknesses of the traditional FMEA are addressed. This also ensures that field staff experience is captured in the assessment and makes the overall assessment accessible to the field operatives that may struggle with numerical analysis.
iii. A framework for estimating the failure likelihood using a Bayesian Network model, which enumerates the cause-and-effect relationship that can be established between failure factors and the pipeline failure condition for pipeline systems with inadequate or unreliable data. The Bayesian Network provides an intuitive visual representation that allows modelling of pipeline damages with a rigorous mathematical basis in Bayesian probability, outlining the cause-and-effect relationship between and among factors. The Bayesian Network model is easier to update, allowing for new predictions when fresh data becomes available. This feature is important, as the model needs continuous improvement when new knowledge becomes available. The model is capable of combining diverse data, expert knowledge and empirical data for parameter estimation.
iv. A decision-making framework for a pipeline loss of containment threat as a result of third-party activities using Evidential Reasoning and the most effective RCOs in reducing or eliminating the threat.
v. A cost-benefit estimates model for the financial losses encountered as a result of the assessed third-party damage to the pipeline system, as well as the cost of various Risk Control Options and which option is the most cost-effective.

7.3 Limitations

This research has some limitations, which can be summarised as follows:

1. Although the modified FMEA approach improves on the traditional FMEA model, the high level of reliance placed by the model on subjective input from experts limits the model's ability to produce comparable results for the same case study if a different set of experts were asked to assess the pipeline. For regulatory compliance purposes, regulators often want to know that any approach adopted is repeatable and can provide the same or very similar results.
2. The BN model developed in Chapter 5 incorporated only two states for most of the nodes, either 'yes' or 'no'. This became necessary in order to reduce the complexity of the CPTs within the nodes and due to the lack of data required to fill in complex CPTs. This approach limits the model in many ways and also limits the validation and verification process so that only a partial validation has been possible. However, the complexity of inference associated with the model grows beyond tractability when more states are added, and more effective algorithms may very well be needed.
3. The ER decision-making approach could not use a more refined aggregation and a higher number of evaluation grades than the five used. This limits the granularity of the results and limits further interrogation in obtaining greater insight. Obtaining expert inputs via the questionnaire also becomes burdensome. Using a higher number of evaluation grades has been shown by Ren *et al.* (2005) to provide better and more accurate basic attributes belief degrees.
4. The CBA model has had to use a high level of subjective judgement and assumptions due to the lack of public data on the compensations due to people who have been affected by pipeline accidents in Nigeria. In most cases, the compensation is treated as confidential, including those settled in

the courts. Therefore, the cost calculated is representative and may not be the exact figure for the losses estimated for the case study pipeline.

7.4 Future Research

This thesis has developed tools and models that will help the operators of onshore cross-country oil and gas pipelines in Nigeria and similar countries to identify and assess the driving factors behind loss of containment, especially when historic data is not available or unreliable. The thesis identified research questions and objectives and addressed those adequately. However, during the course of this research, more questions have arisen, and these could benefit from further study to build upon the work already carried out. These include:

1. Modelling the consequence of pipeline failure due to failure factors prevalent in developing countries. The work presented in this thesis did not include consequence modelling and therefore, the work could be more useful as a complete risk assessment tool with consequence assessment included. Carrying out a consequence analysis of onshore cross-country pipeline failure as a result of third-party damage will provide a better understanding of the pipeline failure.
2. The models for the failure likelihood, decision-making and cost-benefit analyses have focused on pipeline failure due to third-party interference. Analysing other failure factors, such as operational damage, corrosion and mechanical damage, would help in providing a better picture of the overall threat.
3. The BN model developed in Chapter 5 required CPT construction, which in this analysis used AHP and the symmetric method in the absence of hard data. The symmetric method is one of several methods that could be used to construct the CPTs. It may be worthwhile using the other technique – Noisy-OR – to build the CPTs, such as was applied by Matellini (2013), to compare which approach yields better results.

4. The main factor in carrying out a risk assessment in geographical areas similar to Nigeria is the lack of data or the high level of data uncertainty. This necessitates the use of assumptions, subjective judgements and opinions in the reasoning process. For the hazard identification process, the approximate reasoning approach is used to address the uncertainty in the process. Future research can carry out the hazard identification process using other approaches that are capable of addressing uncertainty, combining it with expert judgement and empirical data. This can then be compared with approximate reasoning, which will further validate this approach and provide the pipeline operator with further optional tools they could use.
5. The ER-based risk management decision-making support model and the CBA has been carried out with the operator in mind. Future research that accommodates the regulator's requirements at the same time as that of the operators is a strong starting point, since their objectives and expectations are often different. Regulators are often preoccupied with minimising risks; operators may be preoccupied with trying to maximise profit. The MCDM approach that accommodates all these objectives and results in a ranking that is satisfactory to both will be of great benefit to the industry.
6. The models developed have been applied to a case study pipeline in Nigeria. It would be desirable if the models could be tested on pipelines located in other similar geographical areas where a high level of third-party related pipeline damage is being encountered. The models could also be applied to offshore pipelines where data is scarce or unreliable.
7. As part of the ER decision-making approach, the initial utility estimation of the basic attributes had to rely on the subjective judgement of the experts. This can be improved upon by introducing probability analysis methods that calculate the utilities of the evaluation grades. This can be carried out by determining the lowest and highest utility grade in a similar way as it is

estimated in this work. However, when determining the intervening three grades, experts can then be asked to identify two extreme points and choose a value at which the probability of the worst and best performance is equidistant for each of the three grades. The experts would then determine what value the probability holds at a given evaluation grade.

8. A future research that look at the probability estimation of all the RCOs including probability of success of those interventions would provide more detailed tool to the operator not only to identify the most effective intervention but also the one with the most likely success rate.

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Appendix A 125 IF-THEN Rules

The 125 IF-THEN rule, originally developed by (Wang, 1997), has been updated for this research to include belief structure such that the consequent risk linguistic terms include belief degree.

The original IF-THEN rule, for instance, does not distinguish the consequent risk of the first two combinations of the likelihood, detection and severity of "very low, highly likely, negligible" and "very low, likely, marginal" respectively. They all have "very low, low" as the consequent risk. However, using the belief structure, the consequent risks become "1 very low, 0 low" and "0.57 very low, 0.43 low" respectively. This is arrived at first by allocating numerical value to the linguistic variables of likelihood, detection and severity such that very low is allocated value 1, and low the value of 2, etc. The full numerical values are given in Table A1.1.

Table A1.1: Numerical Ranking of the Variables

Likelihood		Detection		Severity	
very low	1	highly likely	1	negligible	1
low	2	likely	2	marginal	2
average	3	reasonably likely	3	moderate	3
high	4	unlikely	4	critical	4
very high	5	highly unlikely	5	catastrophic	5

For consequent risks, the lowest risk linguistic term is "very low" which is the product of "very low" likelihood, "highly likely" detection and "negligible" severity and the corresponding belief is therefore $1 \times 1 \times 1 = 1$. Conversely, the highest linguistic terms in terms of risk is "very high" and it is the product of "very high" likelihood, "highly unlikely" detection and "catastrophic" severity, with the corresponding belief of $5 \times 5 \times 5 = 125$. All other combinations of the three variables and the consequent risks lie in between these two ends. The aim of the belief structure is to situate any consequent risk in relation to its position within this numerical value spectrum. For example, the combination of "very low" likelihood, "likely" detection and "marginal" severity produces $1 \times 2 \times 2 = 4$ numerical value. This situates the consequent risk to be between "very low" with $1 \times 1 \times 1 = 1$ value and "low" with $2 \times 2 \times 2 = 8$. This places it at ((4-1)/ (8-1)) = 0.43 to the "low" end and hence 0.57 (i.e., 1-0.43) to the "very low" end; thus, the consequent risk with the belief structure is "0.57 very low, 0.43 low". Table A1.2 below shows the complete 125 IF-THEN and the consequent risks with belief structure as used in the research.

Table A1.2: 125 IF-THEN Rules with Belief Structure

S/N	Likelihood	Detection	Severity	Risk with Belief Structure
1	very low	highly likely	negligible	1 very low, 0 low
2	very low	likely	marginal	0.57 very low, 0.43 low
3	very low	reasonably likely	moderate	0.95 low, 0.05 moderate
4	very low	unlikely	critical	0.58 low, 0.42 moderate
5	very low	highly unlikely	catastrophic	0.89 moderate, 0.11 low
6	low	highly likely	negligible	0.86 very low, 0.14 low
7	low	likely	marginal	1 low, 0 moderate
8	low	reasonably likely	moderate	0.53 moderate, 0.47 low
9	low	unlikely	critical	0.86 moderate, 0.14 high
10	low	highly unlikely	catastrophic	0.62 high, 0.38 moderate
11	average	highly likely	negligible	0.71 very low, 0.29 low
12	average	likely	marginal	0.79 low, 0.21 moderate
13	average	reasonably likely	moderate	1 moderate, 0 high
14	average	unlikely	critical	0.57 high, 0.43 moderate
15	average	highly unlikely	catastrophic	0.82 high, 0.18 very high
16	high	highly likely	negligible	0.57 very low, 0.43 low
17	high	likely	marginal	0.58 low, 0.42 moderate
18	high	reasonably likely	moderate	0.76 moderate, 0.24 high
19	high	unlikely	critical	1 high, 0 very high
20	high	highly unlikely	catastrophic	0.59 very high, 0.41 high
21	very high	highly likely	negligible	0.57 low, 0.43 very low
22	very high	likely	marginal	0.63 moderate, 0.37 low
23	very high	reasonably likely	moderate	0.51 moderate, 0.49 high
24	very high	unlikely	critical	0.74 high, 0.26 very high
25	very high	highly unlikely	catastrophic	1 very high, 0 high
26	very low	highly likely	marginal	0.86 very low, 0.14 low
27	very low	likely	moderate	0.71 low, 0.29 very low
28	very low	reasonably likely	critical	0.79 low, 0.21 moderate
29	very low	unlikely	catastrophic	0.63 moderate, 0.37 low
30	very low	highly unlikely	negligible	0.57 low, 0.43 very low
31	low	highly likely	marginal	0.57 very low, 0.43 low
32	low	likely	moderate	0.79 low, 0.21 moderate
33	low	reasonably likely	critical	0.84 moderate, 0.16 low
34	low	unlikely	catastrophic	0.65 moderate, 0.35 high
35	low	highly unlikely	negligible	0.89 low, 0.11 moderate
36	average	highly likely	marginal	0.71 low, 0.29 very low
37	average	likely	moderate	0.53 moderate, 0.47 low
38	average	reasonably likely	critical	0.76 moderate, 0.24 high

S/N	Likelihood	Detection	Severity	Risk with Belief Structure
39	average	unlikely	catastrophic	0.89 high, 0.11 moderate
40	average	highly unlikely	negligible	0.63 low, 0.37 moderate
41	high	highly likely	marginal	1 low, 0 moderate
42	high	likely	moderate	0.84 moderate, 0.16 low
43	high	reasonably likely	critical	0.57 high, 0.43 moderate
44	high	unlikely	catastrophic	0.74 high, 0.26 very high
45	high	highly unlikely	negligible	0.63 moderate, 0.37 low
46	very high	highly likely	marginal	0.89 low, 0.11 moderate
47	very high	likely	moderate	0.92 moderate, 0.08 high
48	very high	reasonably likely	critical	0.89 high, 0.11 moderate
49	very high	unlikely	catastrophic	0.59 very high, 0.41 high
50	very high	highly unlikely	negligible	0.89 moderate, 0.11 low
51	very low	highly likely	moderate	0.71 very low, 0.29 low
52	very low	likely	critical	1 low, 0 moderate
53	very low	reasonably likely	catastrophic	0.63 low, 0.37 moderate
54	very low	unlikely	negligible	0.57 very low, 0.43 low
55	very low	highly unlikely	marginal	0.89 low, 0.11 moderate
56	low	highly likely	moderate	0.71 low, 0.29 very low
57	low	likely	critical	0.58 low, 0.42 moderate
58	low	reasonably likely	catastrophic	0.92 moderate, 0.08 high
59	low	unlikely	negligible	1 low, 0 moderate
60	low	highly unlikely	marginal	0.63 moderate, 0.37 low
61	average	highly likely	moderate	0.95 low, 0.05 moderate
62	average	likely	critical	0.84 moderate, 0.16 low
63	average	reasonably likely	catastrophic	0.51 moderate, 0.49 high
64	average	unlikely	negligible	0.79 low, 0.21 moderate
65	average	highly unlikely	marginal	0.92 moderate, 0.08 high
66	high	highly likely	moderate	0.79 low, 0.21 moderate
67	high	likely	critical	0.86 moderate, 0.14 high
68	high	reasonably likely	catastrophic	0.89 high, 0.11 moderate
69	high	unlikely	negligible	0.58 low, 0.42 moderate
70	high	highly unlikely	marginal	0.65 moderate, 0.35 high
71	very high	highly likely	moderate	0.63 low, 0.37 moderate
72	very high	likely	critical	0.65 moderate, 0.35 high
73	very high	reasonably likely	catastrophic	0.82 high, 0.18 very high
74	very high	unlikely	negligible	0.63 moderate, 0.37 low
75	very high	highly unlikely	marginal	0.62 high, 0.38 moderate
76	very low	highly likely	critical	0.57 very low, 0.43 low
77	very low	likely	catastrophic	0.89 low, 0.11 moderate
78	very low	reasonably likely	negligible	0.71 very low, 0.29 low
79	very low	unlikely	marginal	1 low, 0 moderate
80	very low	highly unlikely	moderate	0.63 low, 0.37 moderate
81	low	highly likely	critical	1 low, 0 moderate
82	low	likely	catastrophic	0.63 moderate, 0.37 low

S/N	Likelihood	Detection	Severity	Risk with Belief Structure
83	low	reasonably likely	negligible	0.71 low, 0.29 very low
84	low	unlikely	marginal	0.58 low, 0.42 moderate
85	low	highly unlikely	moderate	0.92 moderate, 0.08 high
86	average	highly likely	critical	0.79 low, 0.21 moderate
87	average	likely	catastrophic	0.92 moderate, 0.08 high
88	average	reasonably likely	negligible	0.95 low, 0.05 moderate
89	average	unlikely	marginal	0.84 moderate, 0.16 low
90	average	highly unlikely	moderate	0.51 moderate, 0.49 high
91	high	highly likely	critical	0.58 low, 0.42 moderate
92	high	likely	catastrophic	0.65 moderate, 0.35 high
93	high	reasonably likely	negligible	0.79 low, 0.21 moderate
94	high	unlikely	marginal	0.86 moderate, 0.14 high
95	high	highly unlikely	moderate	0.89 high, 0.11 moderate
96	very high	highly likely	critical	0.63 moderate, 0.37 low
97	very high	likely	catastrophic	0.62 high, 0.38 moderate
98	very high	reasonably likely	negligible	0.63 low, 0.37 moderate
99	very high	unlikely	marginal	0.65 moderate, 0.35 high
100	very high	highly unlikely	moderate	0.82 high, 0.18 very high
101	very low	highly likely	catastrophic	0.57 low, 0.43 very low
102	very low	likely	negligible	0.86 very low, 0.14 low
103	very low	reasonably likely	marginal	0.71 low, 0.29 very low
104	very low	unlikely	moderate	0.79 low, 0.21 moderate
105	very low	highly unlikely	critical	0.63 moderate, 0.37 low
106	low	highly likely	catastrophic	0.89 low, 0.11 moderate
107	low	likely	negligible	0.57 very low, 0.43 low
108	low	reasonably likely	marginal	0.79 low, 0.21 moderate
109	low	unlikely	moderate	0.84 moderate, 0.16 low
110	low	highly unlikely	critical	0.65 moderate, 0.35 high
111	average	highly likely	catastrophic	0.63 low, 0.37 moderate
112	average	likely	negligible	0.71 low, 0.29 very low
113	average	reasonably likely	marginal	0.53 moderate, 0.47 low
114	average	unlikely	moderate	0.76 moderate, 0.24 high
115	average	highly unlikely	critical	0.89 high, 0.11 moderate
116	high	highly likely	catastrophic	0.63 moderate, 0.37 low
117	high	likely	negligible	1 low, 0 moderate
118	high	reasonably likely	marginal	0.84 moderate, 0.16 low
119	high	unlikely	moderate	0.57 high, 0.43 moderate
120	high	highly unlikely	critical	0.74 high, 0.26 very high
121	very high	highly likely	catastrophic	0.89 moderate, 0.11 low
122	very high	likely	negligible	0.89 low, 0.11 moderate
123	very high	reasonably likely	marginal	0.92 moderate, 0.08 high
124	very high	unlikely	moderate	0.89 high, 0.11 moderate
125	very high	highly unlikely	critical	0.59 very high, 0.41 high

Appendix B Traditional FMEA Description and Results

S/N	System	Item	Event	Equipment	Failure Mode	Cause	Detectability / Revealed	Effects - Local	Effects - System	Safeguards
1	2B	1	1	Oil Pipeline	Product Leak/Rupture	External leakage from pinhole, flange or following impact, welding failure, etc.	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Pipeline leak detection system, buried pipeline with impact protection at crossings, increased inspection.
2	2B	1	2	Oil Pipeline	Product Leak/Rupture	Deliberate - pipeline interdiction for product theft or vandalism	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Pipeline leak detection system, theft and vandalism prevention, e.g., by deep burying of pipeline with impact protection, regular patrols and adoption of technology aim at deterring the threat.
3	2B	1	3	Oil Pipeline	Product Leak/rupture	Pipeline failure due to - corrosion - structural weakness	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Pipeline leak detection system, buried pipeline, providing adequate support where pipelines are exposed, regular inspection to monitor corrosion and identify and prevent failures.
4	2B	1	4	Oil Pipeline	Blockage	Line restricted by partial or complete blockage.	Pressure alarms, flow alarms	Reduced or no hydrocarbon flow in pipeline	Unable to operate pipeline or part of it or operation at reduced capacity.	Pressure alarms, flow alarms
5	2B	2	1	Pipeline Manifold/Block Valve	Product Leak/Rupture	External leakage from pinhole, flange or following impact, welding failure, etc.	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Leak detection system, regular inspection
6	2B	2	2	Pipeline Manifold/Block Valve	Product Leak/Rupture	Deliberate - interdiction for product theft or vandalism	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Leak detection system, theft and vandalism prevention, e.g., by deep burying of pipeline with impact protection, regular patrols and adoption of technology aim at deterring the threat.
7	2B	2	3	Pipeline Manifold/Block Valve	Product Leak/Rupture	Pipeline failure due to - corrosion - structural weakness	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline leading to supply disruption, fires and or explosion that may take the system out of action for a long time.	Leak detection system, buried pipeline, providing adequate support where pipelines are exposed, regular inspection to monitor corrosion and identify and prevent failures.
8	2B	2	4	Pipeline Manifold/Block Valve	Blockage	Line restricted by partial or complete blockage.	Pressure alarms, flow alarms	Reduced or no hydrocarbon flow in pipeline	Unable to operate the intended pipeline, could lead to the system being shutdown resulting in product supply disruption	Pressure & flow alarms
9	2B	2	5	Pipeline Manifold/Block Valve	Line Valve Failure	Actuated valve fails shut	Pressure alarms, flow alarms	No flow to the intended pipeline system	Supply disruption, may lead to pipeline failure resulting in fires and or explosion	Pressure & flow alarms
10	2B	2	6	Pipeline Manifold/Block Valve	Line Valve Failure	Actuated valve fails open	Pressure alarms, flow alarms	Hydrocarbon flow misdirected to an unintended part of the system	Supply disruption, may divert supplies resulting in unintended consequences	Pressure & flow alarms
11	2B	2	7	Pipeline Manifold/Block Valve	Line Valve Failure	Actuated valve fails partly open	Pressure alarms, flow alarms	Hydrocarbon flow may be misdirected to an unintended part of the system	Unable to operate the intended pipeline at required capacity, could lead to fluid being diverted to other pipeline systems	Pressure & flow alarms

S/N	System	Item	Event	Equipment	Failure Mode	Cause	Detectability / Revealed	Effects - Local	Effects - System	Safeguards
12	2B	3	1	Pumps	Product Leak	External leakage from pinhole, flange, seals, following impact or sabotage	Pressure alarms, flow alarms, inspection, surveillance.	Flammable hydrocarbon leak and or a pool	Unable to operate pipeline, may affect other connected pipelines	Regular inspection, seal leak detection
13	2B	3	2	Pumps	Pump Fault	Pump reduced performance due to bearing or impeller problem or partial blockage	Pressure alarms, flow alarms	Reduced hydrocarbon flow in pipeline	Reduced supply – may be addressed with standby pumps	Pump pressure and flow monitoring, following manufacturers/industry standard maintenance requirements, standby pump
14	2B	3	3	Pumps	Pump Failure	Pump stops due to power loss or shaft breakage, etc.	Pump pressure and flow monitoring, control unit alarm	No hydrocarbon flow in pipeline	Supply disruption – may be addressed with standby pumps	Pump pressure and flow monitoring, following manufacturers/industry standard maintenance requirements, keeping spares, standby pump
15	2B	3	4	Pumps	Pump Failure	Pump stops due to loss of common power supply	Pump pressure and flow monitoring, control unit alarm	No hydrocarbon flow in pipeline	Supply disruption – may be addressed with standby pumps	Pump pressure and flow monitoring, motor control unit alarms, standby pump
16	2B	3	5	Pumps	Pump Failure	Standby pump fails to start on demand when duty pump fails	Pump pressure and flow monitoring, control unit alarm	No hydrocarbon flow in pipeline	Supply disruption - no pumps available, no flow	Pump pressure and flow monitoring, motor control unit alarms
17	2B	4	1	Utility	Loss of supply	Loss of utility or power	Monitoring	Key equipment unable to function	Unable to operate pipeline	Monitoring, system to be designed to shutdown safely
18	2B	4	2	Utility	Reduced supply	Restriction in supply due to faulty instrument, valve, controller or pump	Monitoring	Key equipment unable to function effectively	May affect the ability to operate pipeline at required capacity	Monitoring and inspection, regular maintenance
19	2B	4	3	Utility	Electrical over supply	High supply due to power surge	Monitoring	Damage to electrical equipment	Unable to operate pipeline	Electrical protection, e.g., circuit breakers
20	2B	5	1	Metering Package	Instrumentatio n Fault	Flow mismatch or inaccurate reading	Pressure alarms, flow alarm, operator check	Unreliable flow metering, wrong volume flow	Could be a safety trigger if more product is being delivered than it is recorded	Metering self-checking, QA between injection and delivery stations to reconcile product volume
21	2B	5	2	Metering Package	Product Leak	Leakage from pinhole, flange, following impact or sabotage	Pressure alarms, flow alarm, operator check	Hydrocarbon leak	Unable to operate pipeline	Leak detection system, regular inspection and checks
22	2B	5	3	Metering Package	Blockage	Line restricted by partial or complete blockage. e.g. stuck sphere	Pressure alarms, flow alarm, operator check	Reduced or no hydrocarbon flow in pipeline	Unable to operate pipeline at required capacity or completely	Pressure alarms, flow alarms
23	2B	6	1	Pig Launcher/ Receiver	Product Leak/Rupture	Leakage from pinhole, flange, following impact or sabotage	Pressure alarms, Operators present	Flammable hydrocarbon leak and or a pool	Unable to pig pipeline and operate the pipeline.	Personnel present during pigging, pig unit isolated/ empty at all other times
24	2B	6	2	Pig Launcher/ Receiver	Blockage	Line restricted blockage. e.g. stuck sphere across main isolation valve	Pressure alarms, Operators present	Unable to isolate pig launcher/receiver from pipeline	Unable to operate pipeline at required capacity, interrupting supply.	Pressure alarm, following established operator procedure
25	2B	6	3	Pig Launcher/ Receiver	Valve Failure / Problems with Valve Sequencing	Unable to isolate pig unit due to jammed, passing or failed valve	Pressure alarms, operators present, valve position indication	Unable to isolate pig launcher/receiver from pipeline	Unable to operate pipeline at required capacity, interrupting supply.	Pressure alarm, following established operator procedure
26	2B	6	4	Pig Launcher/ Receiver	Door Failure	Unable to seal pig unit due to jammed or failed door mechanism	Pressure alarms, Operators present	Unable to isolate pig launcher/receiver from pipeline	Unable to pig pipeline	Pressure alarm, following established operator procedure
27	2B	7	1	Future Tie-in Connection	Product Leak/Rupture	External leakage from pinhole, flange, following impact or sabotage.	Pressure alarms, flow alarms, surveillance, third party reporting.	Flammable hydrocarbon leak	Unable to operate pipeline	Double isolation standard

Appendix C AHP Questionnaire for the BN Analysis

Introduction

The goal of this study is to determine which factors have a greater influence on Nigeria's cross-country pipeline system – System 2b – in the pipeline failure/loss of containment.

The risk criteria focus on five general attributes:

i) third party damage,
ii) operational factor,
iii) material defect,
iv) corrosion and
v) natural hazard

These are the parameters to be evaluated utilizing the pair-wise comparison technique.

To proceed with the *Pair-wise Comparison* technique, one should first understand the weighting measurement used in the study. Table 1 contains two weighting scales for "Important" and "Unimportant", along with an explanation of what each weighting denotes.

Table 1: Weighting Scale for the Pair-Wise Comparison

IMPORTANT		UNIMPORTANT	
Numerical Weighting	**Explanation**	**Numerical Weighting**	**Explanation**
1	Equally important	1	Equally important
3	A little important	1/3	A little unimportant
5	Important	1/5	Unimportant
7	Very important	1/7	Very unimportant
9	Extremely important	1/9	Extremely unimportant
2, 4, 6, 8	Intermediate important values	1/2, 1/4, 1/6, 1/8	Intermediate unimportant values

Using Table 1 as a reference, it is required that possible judgement to all questions is to be given based upon one's expertise and experience in the Pipeline Risk and Integrity Management. The judgement provided should be focused on the objectives presented for each section, and to do this please 'mark' (*) the importance weighting of each general attribute or intermediate hazard event in the presented column. The following is a brief example of how to apply Table 1.

Objective: To select the most important elements of a car.

1) The Steering Wheel																	
	Unimportant								**Equally Important**	**Important**							
	1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
To achieve the stated objective, how important is a Steering Wheel, compared to the Radio/Sound System?																	*
To achieve the stated objective, how important is a Steering Wheel, compared to a Rear View Mirror?											*						
To achieve the stated objective, how important is a Steering Wheel, compared to the Engine?	*																

Explanation of the example:

- The Steering Wheel is 9 times more *Important* that the Radio/Sound System. This is because it is still possible to operate the car if the Radio/Sound System is not functioning.
- The Steering Wheel is 3 times more *Important* than the Rear View Mirror. This is because, while it is harder to operate a car without the rearview mirror, one can still navigate with the side mirrors and moving one's head to see traffic.

The Steering Wheel is 1/9 times more *Unimportant* that the Engine. This is because, without the engine, the car would not function

Questionnaire

Material Defect

Objective: To select the most important factor resulting into pipeline failure

1. Material Defect	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is a design failure, compared to the construction failure?																	
To achieve the stated objective, how important is a design failure, compared to the failure due to material quality?																	
To achieve the stated objective, how important is a construction failure, compared to the failure due to material quality?																	

2. Corrosion	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is an external corrosion, compared to the internal corrosion?																	
To achieve the stated objective, how important is an external corrosion, compared to the stress cracking?																	
To achieve the stated objective, how important is an internal corrosion, compared to the stress cracking?																	

3. Third-Party Damage	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is an accidental damage, compared to the incidental damage?																	
To achieve the stated objective, how important is an accidental damage, compared to the intentional damage?																	
To achieve the stated objective, how important is an incidental damage, compared to the intentional damage?																	

4. Operational damage	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is a system malfunction, compared to the human error?																	

5. Natural Hazards	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is a ground movement, compared to other forms of natural hazards?																	

6. **Human Intervention**	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is an operational failure, compared to 3rd party damage?																	

7. **Mechanical failure**	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is a material defect, compared to corrosion?																	

8. **Failed Pipeline**	Unimportant								Equally Important	Important							
	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is a human intervention, compared to the mechanical damage?																	
To achieve the stated objective, how important is a human intervention, compared to the natural hazards?																	
To achieve the stated objective, how important is a mechanical damage, compared to the natural hazards?																	

Appendix D AHP Questionnaire for ER Decision Making

Pipeline 3rd Party Damage Risk Reduction/Control Decision: Questionnaire

1- Introduction

The goal of this study is to determine which of the risk reduction and control factors as it affect intentional 3rd party damage have greater influence on Nigeria's and other developing countries' cross-country pipeline system with respect to the pipeline failure and loss of containment.

The risk reduction/control criteria focus on four general attributes each with their basic attributes as below:

General Attributes	Basic Attributes
1.Detection	Surveillance
	Leak Detection
	SCADA/Staffing measures
	Patrol
2. Prevention	Pipeline Cover
	Burial Depth
	Public Education
	Barrier
3. Mitigation	Right of Way Control
	Spill Response
	Industry Cooperation
4. Other Measures	Intelligence
	Security Forces
	Punishment
	Community Partnering

These are the parameters to be evaluated, utilizing the pair-wise comparison and ranking techniques.

To proceed with the pair-wise comparison technique, one should first understand the weighting measurement used in the study. Table 1 contains two weighting scales for "Important" and "Unimportant", along with an explanation of what each weighting denotes.

Using Table 1 as a reference, it is required that possible judgement to all questions is to be given based upon one's expertise and experience in the Pipeline Risk and Integrity Management. The judgement provided should be focused on the objectives presented for each section, and to do this please tick the importance weighting of each general and basic attribute or intermediate hazard event in the presented column.

1. **Email address** *

Table 1: Weighting Scale for the Pair-Wise Comparison

IMPORTANT		UNIMPORTANT	
Numerical Weighting	**Explanation**	**Numerical Weighting**	**Explanation**
1	Equally important	1	Equally important
3	A little important	1/3	A little unimportant
5	Important	1/5	Unimportant
7	Very important	1/7	Very unimportant
9	Extremely important	1/9	Extremely unimportant
2, 4, 6, 8	Intermediate important values	1/2, 1/4, 1/6, 1/8,	Intermediate unimportant values

The following is a brief example of how to apply Table 1

Objective - To select the most important elements of a car - Steering Wheel

Response - page 1 of 2

	9 - Extremely important	8	7 - Very important	6	5 - Important	4	3 - A little important	2
To achieve the stated objective, how important is a Steering Wheel, compared to the Radio/Sound System	☑	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is a Steering Wheel, compared to a Rear View Mirror	☐	☐	☐	☐	☐	☐	☑	☐
To achieve the stated objective, how important is a Steering	☐	☐	☐	☐	☐	☐	☐	☐

Response - page 2 of 2

	1/3 - A little unimportant	1/4	1/5 - Unimportant	1/6	1/7 - Very unimportant	1/8	1/9 - Extremely unimportant
To achieve the stated objective, how important is a Steering Wheel, compared to the Radio/Sound System	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is a Steering Wheel, compared to a Rear View Mirror	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is a Steering Wheel, compared to the Engine	☐	☐	☐	☐	☐	☐	☑

Explanation of the example

- The Steering Wheel is 9 times more IMPORTANT that the Radio/Sound System. This is because it is still possible to operate the car if the Radio/Sound System is not functioning.

- The Steering Wheel is 3 times more IMPORTANT than the Rear View Mirror. This is because, while it is harder to operate a car without the rear view mirror, one can still navigate with the side mirrors and moving ones head to see traffic.

- The Steering Wheel is 1/9 times more UNIMPORTANT that the Engine. This is because without the engine, the car would not function.

2 - Pair-wise Comparison

Note: to access all the available weighting choices, one need to scroll to the right

2. **1. Objective: To select the most important factor for risk reduction and control of 3rd party damage pipeline failure - General Attributes**
Tick all that apply.

	9 - Extremely important	8	7 - Very important	6	5 - Important	4	3 - A little important	2	1- Equally important	1/2	1/3 - A little unimportant	1/4	1/5 - Unimportant	1/6	1/7 - Very unimportant	1/8	1/9 - Extremely unimportan
To achieve the stated objective, how important is the Detection compared to the Prevention?																	
To achieve the stated objective, how important is the Detection compared to the Mitigation?																	
To achieve the stated objective, how important is the Detection compared to the Other Measures?																	
To achieve the stated objective, how important is the Prevention compared to the Mitigation?																	
To achieve the stated objective, how important is the Prevention compared to the Other Measures?																	
To achieve the stated objective, how important is the Mitigation compared to the Other Measures?																	

3. **2. Objective: To select the most important factor for risk reduction and control of 3rd party damage pipeline failure - Detection Attributes**
Tick all that apply.

	9 - Extremely important	8	7 - Very important	6	5 - Important	4	3 - A little important	2	1- Equally important	1/2	1/3 - A little unimportant	1/4	1/5 - Unimportant	1/6	1/7 - Very unimportant	1/8	1/9 - Extremely unimportan
To achieve the stated objective, how important is the Surveillance compared to the Leak Detection?																	
To achieve the stated objective, how important is the Surveillance compared to the SCADA/Staffing measures?																	
To achieve the stated objective, how important is the Surveillance compared to the Patrol?																	
To achieve the stated objective, how important is the Leak Detection compared to the SCADA/Staffing measures?																	
To achieve the stated objective, how important is the Leak Detection compared to the Patrol?																	
To achieve the stated objective, how important is the SCADA/Staffing measures compared to the Patrol?																	

4. **3. Objective: To select the most important factor for risk reduction and control of 3rd party damage pipeline failure - Prevention Attributes**
Tick all that apply.

	9 - Extremely important	8	7 - Very important	6	5 - Important	4	3 - A little important	2	1- Equally important	1/2	1/3 - A little unimportant	1/4	1/5 - Unimportant	1/6	1/7 - Very unimportant	1/8	1/9 - Extremely unimportan
To achieve the stated objective, how important is the Pipeline Cover compared to the Burial Depth?																	
To achieve the stated objective, how important is the Pipeline Cover compared to the Public Education?																	
To achieve the stated objective, how important is the Pipeline Cover compared to the Barrier?																	
To achieve the stated objective, how important is the Burial Depth compared to the Public Education?																	
To achieve the stated objective, how important is the Burial Depth compared to the Barrier?																	
To achieve the stated objective, how important is the Public Education compared to the Barrier?																	

5. **4. Objective: To select the most important factor for risk reduction and control of 3rd party damage pipeline failure - Mitigation Attributes**
Tick all that apply.

	9 - Extremely important	8	7 - Very important	6	5 - Important	4	3 - A little important	2	1- Equally important	1/2	1/3 - A little unimportant	1/4	1/5 - Unimportant	1/6	1/7 - Very unimportant	1/8	1/9 - Extremely unimportan
To achieve the stated objective, how important is the Right of Way Control compared to the Spill Response?																	
To achieve the stated objective, how important is the Right of Way Control compared to the Industry Cooperation ?																	
To achieve the stated objective, how important is the Spill Response compared to the Industry Cooperation ?																	

6. **5. Objective: To select the most important factor for risk reduction and control of 3rd party damage pipeline failure - Other measures Attributes**
Tick all that apply.

	9 - Extremely important	8	7 - Very important	6	5 - Important	4	3 - A little important	2	1- Equally important	1/2	1/3 - A little unimportant	1/4	1/5 - Unimportant	1/6	1/7 - Very unimportant	1/8	1/9 - Extremely unimportan
To achieve the stated objective, how important is the Intelligence compared to the Security Forces?	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is the Intelligence compared to the Punishment?	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is the Intelligence compared to the Community Partnering?	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is the Security Forces compared to the Punishment?	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is the Security Forces compared to the Community Partnering?	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
To achieve the stated objective, how important is the Punishment compared to the Community Partnering?	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

3 - Ranking Assessment

This section solicits your opinion on the relevance of the various criteria outlined in the previous section as regards their effectiveness to the risk reduction and control measures for 3rd party pipeline damage. The relevance ranking is for the basic attributes of the four general attributes of Detection, Prevention, Mitigation and Other Measures outlined in section 2.
The ranking is defined as:
1. Very Low (VL) - this means the selected general or basic attribute's contribution to the risk reduction measure has the lowest impact when compared with other attributes
2. Low (L) - this means the selected general or basic attribute's contribution to the risk reduction measure is low when compared with other attributes
3. Medium (M) - this means the selected general or basic attribute's contribution to the risk reduction measure is in the middle when compared with other attributes.
4. High (H) – this means the selected general or basic attribute's contribution to the risk reduction measure has a second-best impact when compared with other attributes Very High
5. (VH) – this means the selected general or basic attribute's contribution to the risk reduction measure has the highest impact when compared with the other attributes.

7. **For the Detection main attribute, please rank the basic attributes by the impact they have to the risk reduction and control measures to 3rd party pipeline damage using the ranking options provided.**
Mark only one oval per row.

	1. Very Low	2. Low	3. Medium	4. High	5. Very High
Survellance	◯	◯	◯	◯	◯
Leak Detection	◯	◯	◯	◯	◯
SCADA/Staffing Measures	◯	◯	◯	◯	◯
Patrol	◯	◯	◯	◯	◯

8. **For the Prevention main attribute,please rank the basic attributes by the impact they have to the risk reduction and control measures to 3rd party pipeline damage using the ranking options provided.**
Mark only one oval per row.

	1. Very Low	2. Low	3. Medium	4. High	5. Very High
Pipeline Cover	◯	◯	◯	◯	◯
Burial Depth	◯	◯	◯	◯	◯
Public Education	◯	◯	◯	◯	◯
Barrier	◯	◯	◯	◯	◯

9. **For the Mitigation main attribute, please rank the basic attributes by the impact they have to the risk reduction and control measures to 3rd party pipeline damage using the ranking options provided.**
Mark only one oval per row.

	1. Very Low	2. Low	3. Medium	4. High	5. Very High
Right of Way Control	◯	◯	◯	◯	◯
Spill Response	◯	◯	◯	◯	◯
Industry Cooperation	◯	◯	◯	◯	◯

10. **For the Other Measures main attribute, please rank the basic attributes by the impact they have to the risk reduction and control measures to 3rd party pipeline damage using the ranking options provided.**
Mark only one oval per row.

	1. Very Low	2. Low	3. Medium	4. High	5. Very High
Intelligence	◯	◯	◯	◯	◯
Security Forces	◯	◯	◯	◯	◯
Punishment	◯	◯	◯	◯	◯
Community Partnering	◯	◯	◯	◯	◯

About you

Please choose below one of the best that describe you and your expertise

11. **What best described your area of expertise**
Mark only one oval.

◯ Pipeline Safety
◯ Pipeline Integrity
◯ Pipeline Design
◯ Pipeline Project management
◯ Pipeline Operation/Maintenance
◯ Consultant
◯ Other

12. **Which best described your employer**
Mark only one oval.

◯ Pipeline Infrastructure Operating Company
◯ Pipeline Design Company
◯ Pipeline Contracting Company
◯ Pipeline Project Management Company
◯ Pipeline Repair and Maintenance Company
◯ Consultant
◯ Other

13. **Which best described your years of experience**
Mark only one oval.

◯ 1-5 years
◯ 6-10 years
◯ 11-20 years
◯ 21 and above

Appendix D1: AHP Results for ER Decision Making

General Attributes

Attributes	Abbreviation
Detection	D
Prevention	P
Mitigation	M
Other Measures	Others

Pairwise comparison for General Attributes				
	D	P	M	Others
D	1.00	0.80	2.08	2.50
P	1.25	1.00	4.25	4.25
M	0.48	0.24	1.00	3.00
Others	0.40	0.24	0.33	1.00
Total	3.13	2.27	7.67	10.75

Relative weight table					
					Weight
D	0.32	0.35	0.27	0.23	0.29
P	0.40	0.44	0.55	0.40	0.45
M	0.15	0.10	0.13	0.28	0.17
Others	0.13	0.10	0.04	0.09	0.09
Total	1	1	1	1	100%

Consistency check						
	D	P	M	Others	Sum row	Sum weight
D	0.29	0.36	0.35	0.23	1.23	4.18
P	0.37	0.45	0.71	0.39	1.91	4.28
M	0.14	0.11	0.17	0.28	0.69	4.13
Others	0.12	0.11	0.06	0.09	0.37	4.03

lamda max = total sum weight/number of matrix	
=	4.15
Consistency Index = lamda max-4/4-1	
=	0.05
Consistency ratio = CI/0.9	
=	0.06

Basic Attributes

1. Detection

Attributes	Abbreviation
Surveillance	S
Leak Detection	LD
SCADA/Staffing Measures	SCADA
Patrol	Patrol

Pairwise comparison for Detection Attributes				
	S	LD	SCADA	Patrol
S	1.00	0.88	2.00	1.55
LD	1.14	1.00	2.08	2.50
SCADA	0.50	0.48	1.00	2.55
Patrol	0.65	0.40	0.39	1.00
Total	3.29	2.76	5.48	7.60

Relative weight table					
					Weight
S	0.30	0.32	0.37	0.20	0.30
LD	0.35	0.36	0.38	0.33	0.35
SCADA	0.15	0.17	0.18	0.34	0.21
Patrol	0.20	0.15	0.07	0.13	0.14
Total	1.00	1.00	1.00	1.00	100%

	S	LD	SCADA	Patrol	sum row	sum weight
S	0.30	0.31	0.42	0.21	1.24	4.17
LD	0.34	0.35	0.44	0.34	1.48	4.16
SCADA	0.15	0.21	0.21	0.35	0.92	4.37
Patrol	0.19	0.18	0.08	0.14	0.59	4.33

lamda max = total sum weight/number of matrix	
=	4.26
Consistency Index = lamda max-3/3-1	
=	0.09
Consistency ratio = CI/0.9	
=	0.10

2. Prevention

Attributes	Abbreviation
Pipeline Cover	PC
Burial Depth	BD
Barrier	Barrier
Public Education	PE

Pairwise comparison for Prevention Attributes				
	PC	BD	Barrier	PE
PC	1.00	1.18	0.71	0.26
BD	0.85	1.00	1.38	0.63
Barrier	1.41	0.73	1.00	0.36
PE	3.78	1.60	2.75	1.00
Total	7.04	4.50	5.83	2.25

Relative weight table					
					Weight
PC	0.14	0.26	0.12	0.12	0.16
BD	0.12	0.22	0.24	0.28	0.21
Barrier	0.20	0.16	0.17	0.16	0.17
PE	0.54	0.36	0.47	0.44	0.45
Total	1.00	1.00	1.00	1.00	100%

	PC	BD	Barrier	PE	sum row	sum weight
PC	0.16	0.25	0.12	0.12	0.65	4.08
BD	0.14	0.21	0.24	0.28	0.87	4.07
Barrier	0.23	0.13	0.21	0.16	0.73	4.21
PE	0.61	0.28	0.48	0.45	1.81	4.01

lamda max = total sum weight/number of matrix	
=	4.09
Consistency Index = lamda max-4/4-1	
=	0.03
Consistency ratio = CI/0.9	
=	0.03

3. Mitigation

Attributes	Abbreviation
Right of Way Control	RoW
Spill Response	SR
Industry Cooperation	IC

Pairwise comparison for Mitigation Attributes			
	RoW	SR	IC
RoW	1.00	2.75	2.25
SR	0.36	1.00	1.13
IC	0.44	0.89	1.00
Total	1.81	4.64	4.38

Relative weight table					
					Weight
RoW	0.55	0.59	0.51		0.55
SR	0.20	0.22	0.26		0.22
IC	0.25	0.19	0.23		0.22
Total	1.00	1.00	1.00		100%

	RoW	SR	IC	sum row	sum weight
RoW	0.55	0.62	0.50	1.67	3.02
SR	0.20	0.22	0.25	0.68	3.01
IC	0.25	0.20	0.22	0.67	3.01

lamda max = total sum weight/number of matrix	
=	3.01
Consistency Index = lamda max-3/3-1	
=	0.00564

4. Other Measures

Attributes	Abbreviation
Intelligence	I
Security Forces	SF
Community partnering	CP
Punishment	P

Pairwise comparison for Other Measures Attribute				
	I	SF	P	CP
I	1.00	4.00	4.25	1.00
SF	0.25	1.00	1.43	0.49
P	0.24	0.70	1.00	1.11
CP	1.00	2.05	0.90	1.00
Total	2.49	7.75	7.58	3.60

Relative weight table					
					Weight
I	0.40	0.52	0.56	0.28	0.44
SF	0.10	0.13	0.19	0.14	0.14
P	0.09	0.09	0.13	0.31	0.16
CP	0.40	0.26	0.12	0.28	0.27
Total	1.00	1.00	1.00	1.00	100%

	I	SF	P	CP	sum row	sum weight
I	0.44	0.55	0.67	0.27	1.92	4.38
SF	0.11	0.14	0.22	0.13	0.60	4.34
P	0.10	0.10	0.16	0.30	0.65	4.17
CP	0.44	0.28	0.14	0.27	1.13	4.25

lamda max = total sum weight/number of matrix	
=	4.28
Consistency Index = lamda max-3/3-1	
=	0.09
Consistency ratio = CI/0.9	
=	0.106

Appendix E Nigerian Cross-country Products Pipeline and Fluid Characteristics

PIPELINE SYSTEMS	SECTION		DIAMETER (INC)	WALL THICKNESS (INCH)	LENGTH (KM)	FLUID TYPE	DESIGN FLOW RATE		CURRENT FLOW RATE		PIPELINE CATEGORY	DESIGN PRESSURE(Psi)	Max ALLOWABLE OPERATING PRESSURE (Psi)	DESIGN LIFE	INTERNAL CORROSION MONITORING	PIPELINE GRADE	CATHODIC PROTECTION	SOIL COVERING (m)	INSTALLA TION DATE
	Originating	Terminating					MIN	MAX	MIN	MAX									
2A	Warri	Benin	15"	See foot note	88.9	PMS/AGO/DPK	320	350	270	330	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Benin	Ore	14"	"	109.8	PMS/AGO/DPK	300	350	270	330	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Ore	Mosimi	12"	"	151.3	PMS/AGO/DPK	280	350	270	330	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
					350														
2B	Atlas Cove	Mosimi	16"	"	72.8	PMS/AGO/DPK	??	815	400	500	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	SPM	Atlas Coce	20"	0.25"	5.6	PMS/AGO/DPK	**	1200	**	1000	Off Shore	450	360	>25yrs	None	API 5L Gr B(ERW)	Ground bed,Sacrificial Anode	0.9-1	1998
	Mosimi	Satelite(Lagos)	12" and 10"	See foot note	45.7	PMS	175	160	145	150	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Mosimi	Ibadan	12"	"	79.1	PMS/AGO/DPK	285	300	270	300	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Ibadan	Ilorin	6"	"	168.9	PMS/AGO/DPK	70	75	60	65	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
					372.1														
2C	Warri	Abudu	16"	"	89.6	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Abudu	Auchi	16"	"	89.5	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Auchi	Lokoja	16"	"	103.9	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Lokoja	Abaji	16"	"	100.2	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Abaji	Izom	16"	"	81.5	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Izom	Sakin Pawa	16"	"	90.8	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Sarkin Pawa	Kaduna	16"	"	58	CRUDE OIL	360	640	320	600	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Escravos IBP	EscravosTerminal	26"	"	27.7	CRUDE OIL	**	1200	**	1000	Off Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Escravos	Warri	24"	"	60	CRUDE OIL	3000	3250	2500	2603	On Shore	1450	1160	>25yrs	None	API X52 Gr B (ERW)	Ground bed,Sacrificial Anode	0.9-1	1978/80
					701.2														
2CX	Auchi	Suleja	12"	"	280	PMS/AGO/DPK	230	300	200	240	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
	Suleja	Kaduna	12"	"	150	PMS/AGO/DPK	230	300	200	240	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
	Suleja	Minna	8"	"	80	PMS/AGO/DPK	75	86	65	70	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
					510														
2D	Kaduna	Jos	10 and 12"	"	164.8	PMS/AGO/DPK	120	160	110	145	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Jos to Gombe	Gombe	6"	"	265	PMS/AGO/DPK	50	70	50	65	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Gombe	Biu Pump Station 13	6"	"	124.8	PMS/AGO/DPK	50	70	50	65	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Biu Pump Station 13	Maiduguri	6"	"	175.8	PMS/AGO/DPK	50	70	50	65	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Kaduna	Zaria	10"	"	83.7	PMS/AGO/DPK	40	50	33	45	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Zaria	Kano	10"	"	141	PMS/AGO/DPK	140	160	110	120	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Zaria	Gusau	6"	"	177.7	PMS/AGO/DPK	30	40	30	45	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
					1132.8														
2DX	jos	Gombe	8"	"	265	PMS/AGO/DPK	85	90	65	72	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
2E	Port Harcourt	Aba	12"	"	53.9	PMS/AGO/DPK	300	324	250	260	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Aba	Enugu	12"	"	156.4	PMS/AGO/DPK	300	324	250	260	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
	Enugu	Makurdi	6"	"	180	PMS/AGO/DPK	64	70	60	56	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1978/80
					390.3														
2EX WEST	Port Harcourt	Enugu	12"	"	210.3	PMS/AGO/DPK	317	342	300	330	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
	Enugu	Auchi	12"	"	169	PMS/AGO/DPK	377	394	300	315	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
	Auchi	Benin	12"	"	107	PMS/AGO/DPK	377	394	300	315	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
2EX EAST	Enugu	Makurdi	8"	"	180	PMS/AGO/DPK	95	112	80	90	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
	Makurdi	Yola	8"	"	470	PMS/AGO/DPK	75	86	65	70	On Shore	1450	1160	>25yrs	None	API X42 Gr B Seamless	Ground bed,Sacrificial Anode	0.9-1	1995
					1136.3														

The wall thickness vary along the routeaccording to the type of spoil and problem encouraged

a)Normal	0.25"(6.35mm)
b)Crossing:rail,road,Seasonal Swa	0.281"(7.14mm)
c)Bored Crossing river and Permar	0.375"(9.52mm)

Appendix F Published Conference Proceedings

Hassan, S., Wang, J., Bashir, M. and Kontovas, C. (2019). Application of Bayesian Model for Third Party Damage Assessment of Cross-Country Oil Pipeline under Uncertainty. In: M. Beer and E. Zio, eds., *Proceedings of the 29th European Safety and Reliability Conference 2019*. [Online] Hannover, Germany: European Safety and Reliability Association. Available at: http://itekcmsonline.com/rps2prod/esrel2019/e-proceedings/index.html [Accessed 30 Jan. 2020].

Hassan, S., Wang, J., Muhammad, CA. (2019). Cross Country Pipeline Risk-Based Failure Prediction using Hybrid Fuzzy Rule and Grey Theory in FMEA – A Case Study. In: *Proceedings of the 14th Pipeline Technology Conference 2019*. [Online] Berlin, Germany. Available at: https://www.pipeline-conference.com/abstracts/cross-country-pipeline-risk-based-failure-prediction-using-hybrid-fuzzy-rule-and-grey [Accessed 30 Jan. 2020].

Hassan, S., (2018). Cross Country Pipeline Risk-Based Failure Prediction Using Hybrid Fuzzy Approximate Reasoning in FMEA. In: *Proceedings of the 19th International HSE Biennial Conference on the Oil and Gas Industry in Nigeria*, 26 – 28 Nov 2018, Lagos Nigeria.