ASSET INTEGRITY CASE DEVELOPMENT FOR NORMALLY UNATTENDED OFFSHORE INSTALLATIONS

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ABSTRACT

This thesis proposes the initial stages of the development of a NUI – Asset Integrity Case (Normally Unattended Installation). An NUI – Asset Integrity Case will enable the user to determine the impact of deficiencies in asset integrity and demonstrate that integrity is being managed. A key driver for improved asset integrity monitoring is centred on the level of accurate reporting of incidents. This stems from incidents to key offshore systems and areas. For example, gas turbine driven generators where 22% of fuel gas leaks were undetected with 60% of these 22% having been found to have ignited.

Accordingly, there is a need for dynamic risk assessment and improved asset integrity monitoring. The immediate objective of this research is to investigate how a dynamic risk model can be developed for an offshore system. Subsequently, two dynamic risk assessment models were developed for an offshore gas turbine driven electrical power generation system. Bayesian Networks provided the base theory and algorithms to develop the models. The first model focuses on the consequences of one component failure. While the second model focuses on the consequences of a fuel gas release with escalated fire and explosion, based upon several initiating failures. This research also provides a Multiple Attribute Decision Analysis (MADA) to determine the most suitable Wireless Sensor Network (WSN) configuration for asset integrity monitoring. The WSN is applied to the same gas turbine system as in the dynamic risk assessment models.

In the future, this work can be expanded to other systems and industries by applying the developed Asset Integrity Case framework and methodology. The framework outlines the steps to develop a dynamic risk assessment model along with MADA for the most suitable remote sensing and detection methods.

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I would first and foremost like to thank my director of studies, Prof. Jin Wang for his encouragement, wise words and time throughout the entire duration of this research project. Prof. Wang has provided countless hours in supporting me through the whole research project. His selfless support and effort has ensured that I have adhered to the requirement of completing my work within 3 years. I doubt that my experiences in this time would have been as fulfilling or enjoyable without his continued support and input. Further thanks must go to my second and third supervisors, Dr. Ben Matellini and Dr. Trung Thanh Nguyen for their valued time and effort in contributing with the supervision of the project. Similarly, thanks are extended to Dr. Zaili Yang for his continued advisement and support.

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BN	Bayesian Network
CI	Consistency Index
CPD	Conditional Probability Distribution
CPT	Conditional Probability Table
CR	Consistency Ratio
DAG	Directed Acyclic Graph
DM	Decision-Making
DNV GL	Det Norske Veritas Germanischer Lloyd
ER	Evidential Reasoning
FSA	Formal Safety Assessment
HP	High Pressure
HSE	Health and Safety Executive
IoT	Internet of Things
LLX	Late Life Extension strategy
LOC	Loss of Containment
LP	Low Pressure
MADA	Multi-Attribute Decision Analysis
MAIB	Marine Accident Investigation Branch
NUI	Normally Unattended Installation
OGP	Oil and Gas Producers
OREDA	Offshore and onshore Reliability Data
PC	Pairwise Comparison

QRA	Quantified Risk Assessment
rpm	Revolutions per Minute
RI	Saaty’s Random Index
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations
RMRI	Risk Management Research Institute
SA	Sensitivity Analysis
TCS	Turbine Control System
UKCS	United Kingdom Continental Shelf
USD	United States Dollars
WOAD	World Offshore Accident Databank
WSN	Wireless Sensor network

CHAPTER 1:

INTRODUCTION

Summary

This chapter first introduces the key definition used in this research. The research aim and objectives are then defined, followed by the background. The objectives and hypotheses of this thesis will serve to set out a logical structure of this thesis which is aimed at addressing the inherent problems outlined.

1.1 Project Background and Rationale

The idea of an Asset Integrity Case was proposed by RMRI Plc. in 2011 and will enable the user to determine the impact of deficiencies in asset integrity on the potential loss of life and demonstrate that integrity is being managed to ensure safe operations. The Integrity Case is an extended Safety Case. Where safety cases demonstrate that safety procedures are in place, the Integrity Case shall ensure that the safety procedures are properly implemented. The Integrity Case can be applicable to operations for any large-scale asset, and in the case of this research project the large asset for which the Integrity Case shall be developed is an offshore installation (RMRI Plc., 2011).

By expanding on this Integrity Case proposal, it is intended that an Integrity Case be developed for a Normally Unattended Installation (NUI) in conjunction with a dynamic risk assessment model to maintain a live representation of an offshore installations integrity. Furthermore, it is proposed that the NUI-Integrity Case initially be developed utilising a manned installation, but modelling failure and risks without human presence on board. This is due to a much larger range of failure data being available regarding manned installations as opposed to unmanned installations. Similarly, should a risk assessment model be feasible for various hazardous zones of an installation, and the dynamic model demonstrates effective operation in the detection of failures and mapping of consequences, it may be possible to reduce the number of personnel on board manned offshore installations. To develop the initial stages of the NUI-Integrity Case, certain systems must be analysed utilising dynamic risk assessment. For the purpose of this research project, the electrical generation equipment shall be the focus, specifically, the gas turbine driven generators in an offshore electrical generation module.

Gas turbines are used for a variety of purposes on offshore installations, such as: power generation, compression pumping and water injection, most often in remote locations. Gas turbines are most commonly duel fuelled. They have the ability to run on fuel taken from the production process under normal operations, known as fuel gas. They can also run on diesel fuel in emergency circumstances. Typically, offshore gas turbines run from 1 to 50 MW and may well be modified from aero-engines or industrial engines. The most often used gas turbines are Aeroderivative, particularly for the gas generator. It is known that relatively little information is contained within safety cases regarding the operation and safety of gas turbines. What is contained is the model, manufacture, ISO power rating (in Mega Watts (MW)), the fuel types and the location of the turbine shown on the respective installations drawings. Information in reference to integrity management and maintenance can also be limited (HSE, 2006c). This information provides sound reasoning to produce dynamic risk assessment models regarding the integrity and safety of gas turbines.

Industrial power plants are critical systems on board offshore platforms as they supply electrical power to safety critical systems, such as: refrigeration systems, HVAC (Heating, Ventilation and Air Conditioning), detection systems and fire suppression systems.. These safety critical systems not only provide safe working for crew and other personnel, they also protect the integrity of the offshore platforms systems and structures. All of this protection stems from power supplied by the electrical generation systems, which is why offshore platforms and marine vessels ensure they have back-up generators in the event that one or two generators fail to operate (Perera, *et al*., 2015).

Ideally on offshore platforms, there are three generators, two in the same module for main power generation and one in an upper module as the emergency generator. There are many safety precautions that protect offshore generators and their locations, however, failures do occur. The most common failures within a gas turbine generator occur due to components under heavy stress fracturing and affecting the balance and rotation of the turbine and alternator, Similarly, these component failures also cause fuel gas releases, which in turn can develop into fuel gas fires and explosions (HSE, 2006c) (HSE, 2012) (HSE, 2014). A number of incidents, scenarios and failure statistics are outlined in detail in Chapter 2.

It is situations such as those described that increase the requirement for a dynamic risk assessment model to accurately monitor the consequences of failures within gas driven generators as they are critical in the survival of crew members as well as the integrity of the respective offshore installation. Similarly, the information regarding gas turbines and the reporting of incidents is invaluable as it demonstrates that, in terms of gas turbine failures, offshore platforms in the UKCS are not completely equipped to be unmanned. A system must be developed to detect these failures and releases given that there is no human presence on board. This moves the focus to the Internet of Things (IoT) and Wireless Sensor Networks (WSNs).

In the present world smart homes, smart water networks, and intelligent transportation, are infrastructure systems that connect the world together more than was thought possible. This common vision of interrelating systems is associated with a common concept, the IoT, where, through the use of sensors, an entire physical infrastructure is paired with information and communication technology. Intelligent monitoring and management can be achieved through the application of network embedded devices. In these sophisticated and dynamic systems, devices are interconnected to transmit useful information regarding measurements and control instructions through distributed sensor networks (IEC, 2014).

Furthermore, a WSN is a network formed by several sensor nodes, where each node is equipped with a sensor to detect physical phenomena such as: heat, light, sound and pressure. WSNs are considered a revolutionary information harvesting method in the building of information and communication systems which will greatly improve the systems efficiency and reliability. WSNs feature easy deployment and vast flexibility of devices, and with the rapid growth in today's development of sensor technology, WSNs are becoming the key technology for IoT (IEC, 2014) (Fischione, 2014).

1.2 Research Aims and Objectives

The overall aim of the research is *to investigate how a dynamic risk assessment model for an NUI - Integrity Case can be developed to facilitate safety assessment for the duty holder, the regulatory body and other various parties involved in the oil and gas industry*. A key part of the study is that it is the development of a logical and consistent risk assessment model, by applying Bayesian Network techniques to a specific system of an offshore installation. Furthermore, the issue of detecting incident on NUIs given that there is not a human presence on board. The objectives of this study are as follows:

i. Identify a key offshore system that can be utilised as a base study for the Asset Integrity Case.
ii. Develop a substantial research methodology and Asset Integrity Case framework for producing a dynamic risk assessment model utilising risk assessment and decision-making modelling methods.
iii. Develop flexible risk assessment and decision-making models for modelling offshore risk under uncertainty. As well as developing a number of viable methods that allows for the detecting and monitoring of asset integrity without a human presence on board an offshore installation.
iv. Provide validation of the risk assessment and decision-making models, through the use of case studies, to demonstrate a reasonable level of confidence in the results.
v. Discuss the results and provide hypotheses for further development of the NUI-Asset Integrity Case.

1.3 Scope and Limitations of the Research

It is important to highlight that there are limitations in regards to what the presented research can achieve. The project may not completely encompass all possible failure incidents and scenarios that can occur regarding gas turbines and offshore power generation. Nor will it cover the software aspect of WSNs even though an outline of the cyber-security is conducted in Chapter 2. There are a number of specific limitations that are identified that clarify the scope of the research and its applicability. These points are as follows:

- The research is focused around developing dynamic risk assessment models and WSN designs for one key area of an offshore installation. This area is the electrical generation module of a fixed steel offshore platform in the North Sea.
- The BN models are built for the situation where the offshore platform contains no crew and hence does not consider fatalities. There are two key reasons for this; the first is that the BN models are to be for an NUI (Normally Unattended Installation) Integrity Case, where humans are not present on the platform for large periods of time, and are monitored from other platforms or onshore. Secondly, the BN is part of the development of an Integrity Case which shall focus on maintaining the integrity of the equipment as a priority, as well as the effects of incidents on the environment. Hence fatalities are not part of the consequences for the models.
- The scope of the BN models is primarily within the power generation module of a large fixed offshore platform. Therefore, the section of the models assigned to the probability of equipment damage confined to the equipment and machinery located only within the stated module, unless stated otherwise. Further limitations of BNs are outlined in Chapter 2.
- Within the limitations of the scope of the research there are limitations within the methodology and application of the modelling and mathematical techniques. This can be stated as all techniques are not ideal for all applications but some are ideal for certain applications. The Limitations of BNs has been outlined in chapter 2 along with the justification. AHP is used within Chapters 4 and 6 for the purpose of determining weights from subjective expert judgement. Yet AHP does have its limitations. With AHP one of the main limitations is that the decision problem is

decomposed into a number of subsystems, within which and between which a substantial number of pairwise comparisons need to be completed. This approach has the disadvantage that the number of pairwise comparisons to be made, may become very large and thus analysis can become a lengthy task (Macharis, *et al.*, 2004). However, the pairwise comparisons in this research are developed to reduce the complexity and ask fewer questions of the experts. Hence, the issue of substantial evaluation of pairwise comparisons can be addressed.

- There are many gas turbine component failures that can have an effect on the outcomes of the BN models, however, the models presented are part of a development. Hence, the cause and effects of a specific number of failures is analysed.
- It is important that some remarks are made regarding the uniformity of the data within the models. Statistics exist in a number of formats and originate from many sources. When formulating a model as specific and confined as the one being created, it is almost impossible to gather data sets from the same consistent sources.
- When considering the design of WSNs, only the hardware and the topology are considered not any software aspects. This due to the increased levels of complexity that including a software aspect would bring to the research. In terms of what the scope of the research is, a decision is made based upon how a WSN would fit into asset integrity monitoring.

These are generic limitations regarding the whole research project. Each technical chapter (Chapters 4, 5 and 6) contains their own specific limitations relating to both the domain of operation and the issue of data gathering and analysis.

1.4 Thesis Structure

The thesis is divided into 8 chapters which are supported by a number of appendices. Following the introductory chapter, a comprehensive literature review is conducted examining offshore safety assessment and trends of regulations with the reporting of offshore incidents, as well as justification of BNs and WSNs. Chapter 3 focuses on the research methodology, while Chapters 4, 5 and 6 present the main focus of the projects research and results. These chapters are presented in accordance with the aims and objectives as well as the research methodology. Finally, the thesis is concluded in Chapters 7 and 8 where a final discussion and conclusions are presented. The following explanations summarise what is contained within each chapter.

Chapter 1: Introduction.

This chapter provides the background, justification, and aims and objectives of the project, and an outline of the thesis is provided.

Chapter 2: Literature Review.

The literature review is vital for organising and planning research appropriately. It allows the researcher to learn from, progress and expand from previous academic / industrial achievements. More importantly it should ensure that the research is novel and meaningful. The literature review commences by examining the beginnings of offshore safety cases and the potential introduction of the asset integrity case to operate in conjunction. Similarly, the reasoning for the expansion of safety cases is outlined. Statistics regarding the gas turbine incidents are outlined and examined, with emphasis on the reliance of manual fuel; gas detection and reporting. Furthermore, an investigation of ship to platform collision incident and accidents is outlined to demonstrate that other areas of the offshore industry are following a trend of reporting or under reporting of incidents with the updating of safety case regulations. Finally, a review of WSN technology is presented, with an outline of the applications on offshore platforms that are heavily applicable to asset integrity monitoring.

Chapter 3: Research Methodology.

The research methodology aims at delivering a risk-based research methodology framework to establish the guidelines for developing the dynamic risk assessment and the remote detection methods for the NUI-Asset Integrity Case. The Bayesian Network elements of the framework shall be capable of dealing with dynamic risk assessment by accommodating the ability to continually update the conditional probability data. Furthermore, the remote sensing and detection methods along with the decision-making methodology shall allow for the determination of a suitable method for detecting and identifying asset integrity on an offshore platform. The chapter also includes the individual dynamic risk assessment and decision-making methodologies, along with the applied research techniques.

Chapter 4: Initial BN model for a single gas turbine failure.

This chapter focuses on the development of an Initial Bayesian Network (BN) model for modelling system and component failures on an offshore installation. The intention is to model a sequence of events following a specific component failure, under certain conditions and assumptions. This should provide a base with which to expand the BN model to facilitate the requirement of having a dynamic risk assessment model within an NUI (Normally Unattended Installation) - Integrity Case.

Chapter 5: Expanded BN model for several failures and fuel gas release.

This chapter focuses on the development of a Bayesian Network (BN) model for modelling control system and physical failures of a gas turbine utilised in offshore electrical generation. The intention is to model a sequence of events following several component failures, under certain conditions and assumptions. These initial failures are defined in two categories; control system failures and physical or structural failures. This should provide a base with which to expand the BN model to facilitate the requirement of having a dynamic risk assessment model that allows for accurate representation of the hazards and consequences associated with gas turbine fuel gas releases.

Chapter 6: Development of WSN for offshore asset integrity monitoring.

This chapter focuses on the development of a Wireless Sensor Network (WSN) for and offshore system. The system in question is the electrical generation units. The intention is to design the structure of a number of WSNs within the electrical generation system with varying connection types and methods of relaying data. The research is concerned only with the design of the WSNs, i.e. the hardware and orientation of the sensor nodes and not the software, programming or data protection. This should provide a good base, once an ideal WSN design is determined, to expand the network further incorporating more attributes and develop the necessary software to complete the WSN. Sensitivity Analysis and validation is provided for the analysis.

Chapter 7: Discussion and further Research.

The way the research was developed and its applicability are discussed. The limitations of the work are outlined and examined. Future research ideas are proposed including some which deal with these limitations

Chapter 8: Conclusion.

The contributions to knowledge and research conclusions are presented.

1.5 Conclusion

The background of the project and the NUI-Asset Integrity Case have been introduced, with the development to be centred on offshore power generation. Hence, an outline of the importance of the gas turbine generator on board offshore installations has been outlined with a brief, initial outline of gas turbine incidents. From this the aims and objectives of the project have been outlined. Some additional information is presented regarding the scope of the project. The introduction has then been finalised by presenting the outline of the thesis.

1.6 Publications Generated from the Research

During the course of the research, three publications were produced. These are outlined as follows:

- S. Loughney, J. Wang, D. Lau, D. Minty, "Integrity Case Development for Normally Unattended Offshore Installations - Initial Bayesian Network Modelling", Risk, Reliability and Safety: Innovating Theory and Practice – Walls, Revie & Bedford (Eds). 2017 Taylor & Francis Group, London, ISBN 978-1-138-02997-2. ESREL 2016. Sep 13, 2016.
- S. Loughney, J. Wang, "Bayesian network modelling of an offshore electrical generation system for applications within an asset integrity case for normally unattended offshore installations", Proc IMechE Part M: J Engineering for the Maritime Environment, 1–19, online: May 12, 2017.
- S. Loughney, J. Wang, P. Davies, "Bayesian network modelling for offshore installations: Gas turbine fuel gas release with potential fire and explosion

consequences", Safety and Reliability. Theory and Applications – Cepin & Bris Hardback (Eds). 2017 Taylor & Francis Group, London, ISBN 978-1-138-62937-0. ESREL 2017. May 25, 2017.

These publications can be found in Appendices A, B and C

CHAPTER 2:

LITERATURE REVIEW

Summary

In this chapter, the important literature influencing the current study is reviewed. It includes the examination of the beginnings of offshore safety cases and the potential introduction of the asset integrity case to operate in conjunction. Similarly, the reasoning for the expansion of safety cases is outlined. Statistics regarding the gas turbine incidents are outlined and examined, with emphasis on the reliance of manual fuel gas detection and reporting. Furthermore, an investigation of ship to platform collision incident and accidents is outlined to demonstrate that other areas of the offshore industry are following a trend of reporting or under reporting of incidents with the updating of safety case regulations. Finally, a review of WSN technology is presented, with an outline of the applications on offshore platforms that are heavily applicable to asset integrity monitoring.

2.1 Offshore Safety Assessment

2.1.1 Outline of Safety Cases and ALARP

Following the public inquiry into the Piper Alpha disaster, the responsibilities for offshore safety regulations were transferred from the Department of Energy to the Health and Safety Commission (HSC) through the Health and Safety Executive (HSE) as the singular regulatory body for safety in the offshore industry (Wang, 2002) (Department of Energy, 1990). In response to this the HSE launched a review of all safety legislation and subsequently implemented changes. The propositions sought to replace the legislations that were seen as prescriptive to a more “goal setting” approach. Several regulations were produced, with the mainstay being the Health and Safety at Work Act (HSE, 1992). Under this a draft of the offshore installations safety case regulations was produced. The regulations required operational safety cases to be prepared for all offshore installations, both fixed and mobile. Within this all new fixed installations require a design safety case and for mobile installations, the duty holder is the owner (Wang, 2002).

Offshore operators must submit operational safety cases (SC) for all existing and new offshore installations to the Health and Safety Executive’s (HSE) Offshore Safety Division for acceptance, and it is an offence to operate without an approved SC (HSE, 2006b). The SC must show that it identifies the hazards with potential to produce a serious accident and that these hazards are below a tolerability limit and have been reduced to the ALARP Level (As Low As Reasonably Practicable) (Wang, 2002). The HSE framework for decisions on the tolerability of risk is shown in Figure 2-1.

Safety and risk assessment for offshore installations is vigorous and requires demonstration from duty holders that all hazards with potential to cause major accident are identified, all major risks have been evaluated, and measure have been or will be taken to control the major accident risks to ensure compliance with the statutory provisions (HSE, 2006a).

This is vitally important as accidents in the offshore industry lead to devastating consequences, such as the explosion on board the Deepwater Horizon rig in the Gulf of Mexico which was caused by the failure of a subsea blowout preventer (BOP), with some failures thought to have occurred before the blowout. This solidifies the use of quantitative risk and reliability analysis, with recent emphasis on Bayesian networks, as the model can perform predictive analysis and diagnostic analysis (Cai, *et al*., 2013).

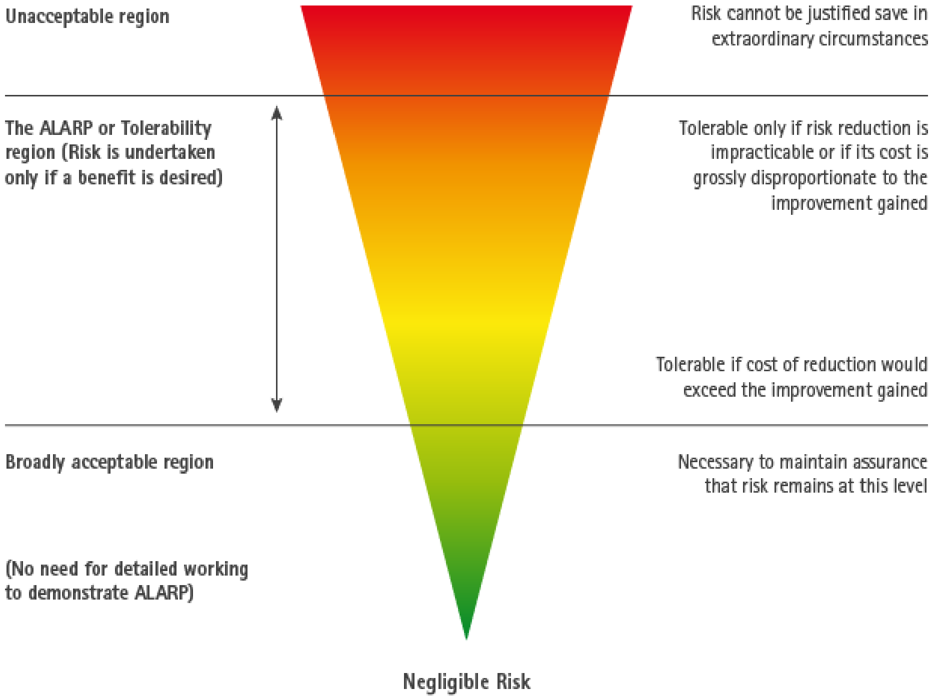

Figure 2-1: HSE Framework for decisions on the tolerability of risk

After many years of employing the safety case approach in the UK offshore industry, the regulations were expanded in 1996 to include verification of safety critical elements. Also, the offshore installations and wells regulations were introduced to deal with various stages of the life cycle of the installation. Safety Critical Elements (SCE) are parts of an installation and its plant, including computer programs or any part whose failure could cause or contribute substantially to or whose purpose of which is to prevent or limit the effect of a major accident (Wang, 2002) (HSE, 1996).

2.1.2 Safety Case Expansion, Dynamic Risk Assessment and Integrity Case

Recently, however, it is felt that an expansion on Safety Cases is necessary, especially in the offshore and marine industry, as they are static documents that are produced at the inception of offshore installations and contains a structured argument demonstrating that the evidence contained therein is sufficient to show that the system is safe (Auld, 2013). That is the extent of the Safety Case, it involves very little updating unless an operational or facility change is made. It can be difficult to navigate through a safety case; they can be difficult for project teams and regulators to understand, as well as often being monolithic (Risktec, 2013).

This is where the e-Safety Case comes into play. They are html web-based electronic Safety Cases. They are much easier to navigate and have clear concise information about the safety of the facility they are provided for. However, the QRA data (Quantified Risk Assessment) is only updated with the release of updated regulations (Cockram & Lockwood, 2003).

The Integrity Case, an idea proposed by RMRI Plc. (Risk Management Research Institute), can be said to be dynamic as it shall be continually updated with the QRA data for an installation as the QRA data is recorded. This allows for the integrity of the various systems and components of a large asset, such as an offshore installation, to be continually monitored. This continual updating of the assets QRA data allows for the users to have a clearer understanding of the current status of an asset, identify the impact of any deviation from specified performance standards, facilitate more efficient identification of appropriate risk reduction measures, identify key trends within assets (i.e. failures, failure modes), reporting to regulators would improve greatly and it would provide a historical audit trail for the asset. Furthermore, the integrity of an asset is maintained so that potential loss of life is kept ALARP. This means that an asset may continue safe operations under circumstances that may have instigated precautionary shutdown, resulting in considerable cost saving for the owner and operator (RMRI Plc., 2011).

2.2 Offshore Gas Turbines

Gas turbines are used for a variety of purposes on offshore installations, such as: power generation, compression pumping and water injection, most often in remote locations. Gas turbines are most commonly duel fuelled. They have the ability to run on fuel taken from the production process under normal operations, known as fuel gas. They can also run on diesel fuel in emergency circumstances. Typically, offshore gas turbines run from 1 to 50 MW and may well be modified from aero-engines or industrial engines. The most often used gas turbines are Aeroderivative, particularly for the gas generator. It is known that relatively little information is contained within safety cases regarding the operation and safety of gas turbines. What is contained is the model, manufacture, ISO power rating (in Mega Watts (MW)), the fuel types and the location of the turbine shown on the respective installations drawings. Additional information can be found on occasion, such as: text regarding the power generation package or back-up generators. However, information in reference to integrity management and maintenance can be very limited (HSE, 2006c). This information, or lack of, provides sound reasoning to produce dynamic risk assessment models regarding the integrity and safety of gas turbines.

2.2.1 Offshore Gas Turbine Incidents and Incomplete Incident Data

Industrial power plants are critical systems on board offshore platforms as they supply electrical power to safety critical systems, such as: refrigeration systems, HVAC (Heating, Ventilation and Air Conditioning), detection systems, and fire suppression systems. These safety critical systems not only provide safe working for crew and other personnel, they also protect the integrity of the offshore platforms systems and structures. All of this protection stems from power supplied by the electrical generation systems, which is why offshore platforms and marine vessels ensure they have back-up generators in the event that one or two generators fail to operate (Perera, *et al.*, 2015). Usually, on offshore platforms, there are three electrical generation systems, with two in the same module and the third in a separate module on a higher level which usually acts as the emergency generator. Despite the safety precautions behind the number of generators and their locations, there is still the possibility of all generators failing to operate (Ramakrishnan, 2007). A situation, similar to the one described, had the potential to occur on board the Thistle Alpha platform in the North Sea, off the coast of Scotland. In this particular event in 2009, the platform was running off one generator, known as Unit B. Units A and C were out of commission due to damages and repair. It is possible for one gas driven generator to supply a large fixed platform of over 200 crew members, like Thistle Alpha, with power when running at full capacity. In this event Unit C was the emergency generator on a in a different module to A and B. During maintenance, it was found that all generators had cause for failure due to a single component. The components in question, the rotor retaining ring, were highly susceptible to fracture and fragmentation, hence it was of vital importance that they were replaced. Should they have failure within generator B, the offshore platform would have been temporarily without power, with the exception of the Temporary Refuge which has its own power supply in the form of batteries, separate from the rest of the platform (RMRI Plc., 2009). Continually, it is these single component failure that can lead to situations were fuel gas can be released from the gas turbine system. It is also possible for external factors to begin a series of events that can cause a fuel gas release such as: control system errors, operational errors and corrosion.

Furthermore, in recent years there has been a marked increase in fires associated with fuel gas leaks with offshore gas turbines. A detailed review of offshore gas turbines incidents conducted in 2005 showed that there were 307 hazardous events over 13 year period, from 1991 to 2004. The review concerned itself with over 550 gas turbine machines. The analysis concluded that the majority of incidents (approximately 40%) occurred during normal operations, with approximately 20% during start-up, another 20% during or after maintenance and the remaining 10% of fuel gas leaks occur during fuel changeover. With the majority of incidents occurring during normal operations, the fuel gas detection is heavily reliant on either turbine fuel detectors and/or fire and gas system detectors. This is due to the modules containing the electrical power generators being almost totally unmanned during normal operation. It was also found that based upon the review conducted on machines in the stated 13 year period, shows that approximately 22% of gas leaks remained undetected. Subsequently, 60% of those undetected leaks were found to have ignited (HSE, 2008b).

It is situations such as those described that increase the requirement for a dynamic risk assessment model to accurately monitor the consequences of failures within gas driven generators as they are critical in the survival of crew members as well as the integrity of the respective offshore installation.

2.3 Ship/Platform Collisions

As stated previously in Section 1, the research presented in this thesis focuses on the development of dynamic risk assessment model and WSNs for use on board an offshore installation. The emphasis is on the electrical power generation systems, for Asset Integrity Case development for NUIs. Furthermore, it has been stated that there have been gas turbine incidents over the past 20 years that have been detected by humans with little reporting of the incidents. This is key as the Asset Integrity Case proposes to maintain the status of asset integrity using dynamic risk assessment model and WSNs while operating alongside safety case regulations. It is known that the rate at which safety case regulations are updated is slow, making safety cases monolithic. However, due to under reporting and the availability of data, it is difficult to demonstrate the trend of gas turbine incidents with the updating of offshore regulations.

On the other hand, it is possible to demonstrate the effect that slow updating and enforcement of regulations, as well as under reporting, has on incidents on-board offshore platforms. A key area that can be assessed is the issue of ship to platform collisions. The current database of ship to platform collisions provided by the HSE is out dated as it was last published in 2001, similarly the OGP produced a document in 2010 of worldwide collision statistics (HSE, 2003). However, the OGP document provides only the frequency of collisions of incidents over key offshore and shipping areas around the world. Neither is sufficient enough to demonstrate the trend between offshore collision incidents and offshore regulations. Therefore, a statistical analysis is conducted for ship to platform collisions from 1971 – 2014 across the UK Continental Shelf (UKCS) and the North Sea. Information is provided by the HSE's RIDDOR database, the World Offshore Accident Databank (WOAD) from DNV GL and the Marine Accident Investigation Branch (MAIB). The aim of this analysis is to demonstrate that there is a trend between key offshore regulations and ship to platform collision incidents.

2.3.1 Key Offshore Regulations and Events 1975 - 2015

Before any data is presented, it is important to understand the timeline of key offshore regulations and incidents that have shaped the modern-day safety case regulations. Table 2-1 shows the timeline of incidents that have built the current safety case regulations.

Similarly, Figure 2-2 shows the number of ship to platform collision incidents from 1971 – 2014 as well as the key regulations and incidents from Table 2-1.

Table 2-1: Time line of key regulations and events that have shaped the modern offshore safety case

Year	Name	Description
1974	Health & Safety at Work Act (HSWA)	The HSWA adopted a holistic approach to the health, safety and welfare of workers. The Act focuses on the concept that any situations that may give rise to harm need to be recognised and suitable measures put in place to eliminate or reduce the potential for harm. It set up two new organisations to oversee its implementation: The Health and Safety Commission (HSC) and the Health and Safety Executive (HSE). The HSE is the executive organisation that enforces the provisions of the HSWA. However, in April 2008 the HSC was dissolved and merged with the HSE. The HSC used to protect health and safety at work in the UK by conducting research, training and providing advice and information. The Commission also used to propose new regulations and approved codes of practice under the authority of the Act. This is all now conducted by the HSE (Inge, 2007) (The Stationary Office, 1974).
1988	Piper Alpha Disaster	Piper Alpha was an oil production platform in the North Sea off the coast of Aberdeen, Scotland. The platform began production in 1976, initially as an oil platform but was later converted to accommodate gas production. Oil & Gas fires and explosions destroyed Piper Alpha on 6 July 1988, killing 167 people, including two crewmen of a rescue vessel and 61 workers aboard survived. Thirty bodies were never recovered. The total insured loss was about £1.7 billion ($3.4 billion), making it one of the costliest manmade catastrophes ever. At the time of the disaster, the platform accounted for

		approximately ten per cent of North Sea oil and gas production. The Cullen Inquiry was set up in November 1988 to establish the cause of the disaster, chaired by Judge William Cullen. After 180 days of proceedings, the "Public Inquiry into the Piper Alpha Disaster" or "Cullen Report" was released in November 1990. It concluded that the initial condensate leak was the result of maintenance work being carried out simultaneously on a pump and related safety valve. The report was critical of Piper Alpha's operator, which was found guilty of having inadequate maintenance and safety procedures (Inge, 2007) (Oil & Gas UK, 2008).
1989	Offshore Installations (Safety Representatives & Safety Committee) Regulations	The document provides information on interpretation and enforcement of the Offshore Installations (Safety Representatives and Safety Committees) Regulations 1989. These regulations were made under the Mineral Workings (Offshore Installations) Act 1971. They allow the workforce on an offshore installation to elect safety representatives from among themselves, and confers on those functions and powers in relation to the health and safety of the workforce. They also provide for time off with pay for safety representatives so they can perform these functions and undergo relevant training (The Stationery Office, 1989).
1990	The Cullen Report	The Cullen Inquiry was set up in November 1988 to establish the cause of the disaster, chaired by Judge William Cullen. After 180 days of proceedings, the "Public Inquiry into the Piper Alpha Disaster" or "Cullen Report" was released in November 1990. It concluded that the initial condensate leak was the result of maintenance work being carried out simultaneously on a pump and related safety valve. The report critical of Piper Alpha's operator, which was found guilty of having inadequate maintenance and safety

		procedures. 106 recommendations were made calling for, amongst many matters, the requirement of a SCs, the transference of the discharge of offshore regulation from the Department of Energy to a discrete division of the HSE. The responsibility of implementing the recommendations was spread across the regulators and the industry with, the HSE overseeing 57, the operators were responsible for 40, the offshore industry were given 8 to progress and the final one was for the Standby Ship Owners Association. The industry acted urgently to carry out the 48 recommendations that operators were directly responsible for. The HSE developed and implemented Lord Cullen's key recommendation: the introduction of safety regulations requiring the operator/owner of every fixed and mobile installation operating in UK waters to submit to the HSE, for their acceptance, a SC (Inge, 2007).
1992	Safety Case Regulations	The Offshore Installations (Safety Case) Regulations came into force in 1992. By November 1993 a safety case for every installation had been submitted to the HSE and by November 1995 all had had their safety case accepted by the HSE. The Safety Case Regulations require the owner/operator/duty holder of every fixed and mobile installation operating in UK waters to submit to the HSE, for their acceptance, a safety case. The safety case must give full details of the arrangements for managing health and safety and controlling major accident hazards on the installation. It must demonstrate, for example, that the company has safety management systems in place, has identified risks and reduced them to as low as reasonably practicable, has introduced management controls, provided a temporary safe refuge on the installation and has made provisions for safe evacuation and rescue (Inge, 2007) (HSE, 2005).

1995	Offshore Installations Prevention of Fire and Explosion, and Emergency Response (PFEER)	PFEER deals primarily with fire and explosion events but it also deals with any event which may require emergency response and includes systems that may rely on radar on a standby vessel or responsible staff on the installation monitoring incoming vessels. The Regulations, ACOP and guidance deal with: (a) preventing fires and explosions, and protecting people from the effects of any which do occur; (b) securing effective response to emergencies affecting people on the installation or engaged in activities in connection with it, and which have the potential to require evacuation, escape and rescue (Amended in 2005 and 2015) (HSE, 2015).
1996	Offshore Installation (Design & Construction) Regulations	DCR Requires the installation to possess integrity at all times, as is reasonably practicable. It requires the design of the installation to withstand such forces that are reasonably foreseeable and in the event of foreseeable damage it will retain sufficient integrity to enable action to be taken to safeguard the health and safety of persons on or near it. The duty holder also has to record the appropriate limits within which it is to be operated. Further duties can be found in the Offshore Installations and Wells (Design and Construction, *etc*.) Regulations 1996.(HSE, 2008a).

2005	Offshore Installations (Safety Case) Regulations (April 2006)	The Offshore Installations (Safety Case) Regulations 2005 came into force on 6 April 2006. They replace the previous 1992 Regulations. The primary aim of the Regulations is to reduce the risks from major accident hazards to the health and safety of the workforce employed on offshore installations or in connected activities. The Regulations implement the central recommendation of Lord Cullen's report on the public inquiry into the Piper Alpha disaster. This was that the operator or owner of every offshore installation should be required to prepare a safety case and submit it to HSE for acceptance (HSE, 2005). These SC regulations have been replaced by the 2015 regulations.
2008	Safety Zones around Oil & Gas Installations in Waters around the UK (HSE)	While this document is not a regulation, it explains the purpose and significance of safety zones around offshore oil and gas installations and their effect on marine activities, particularly relating to fishing vessels. A safety zone is an area extending 500 m from any part of offshore oil and gas installations and is established automatically around all installations which project above the sea at any state of the tide. Subsea installations may also have safety zones, created by statutory instrument, to protect them. These safety zones are a 500m radius from a central point. Vessels of all nations are required to respect them. It is an offence (under section 23 of the Petroleum Act 1987) to enter a safety zone except under the special circumstances. (HSE, 2008c).
2015	Offshore Installations (Offshore Safety Directive) (Safety Cases	The Offshore Installations (Offshore Safety Directive) (Safety Case *etc*.) Regulations 2015 came into force on 19 July 2015. They apply to oil and gas operations in external waters, that is, the territorial sea adjacent to Great Britain and any designated area within the United Kingdom Continental Shelf (UKCS). They replace the Offshore Installations

etc.) regulations (July 2015)	(Safety Case) Regulations 2005 in these waters, subject to certain transitional arrangements (HSE, 2015a).

Figure 2-2 demonstrates the number of ship to platform collision incidents between 1971 and 2014. The incidents are incidents have been compiled from WOAD, HSE and MAIB. All incidents presented have resulted in some form of damage to the platform, either, insignificant, minor, severe and in one case total loss. The graph is a depiction of 582 reported incidents in the 43-year period (GL, 2017) (HSE, 2016) (MAIB, 2016).

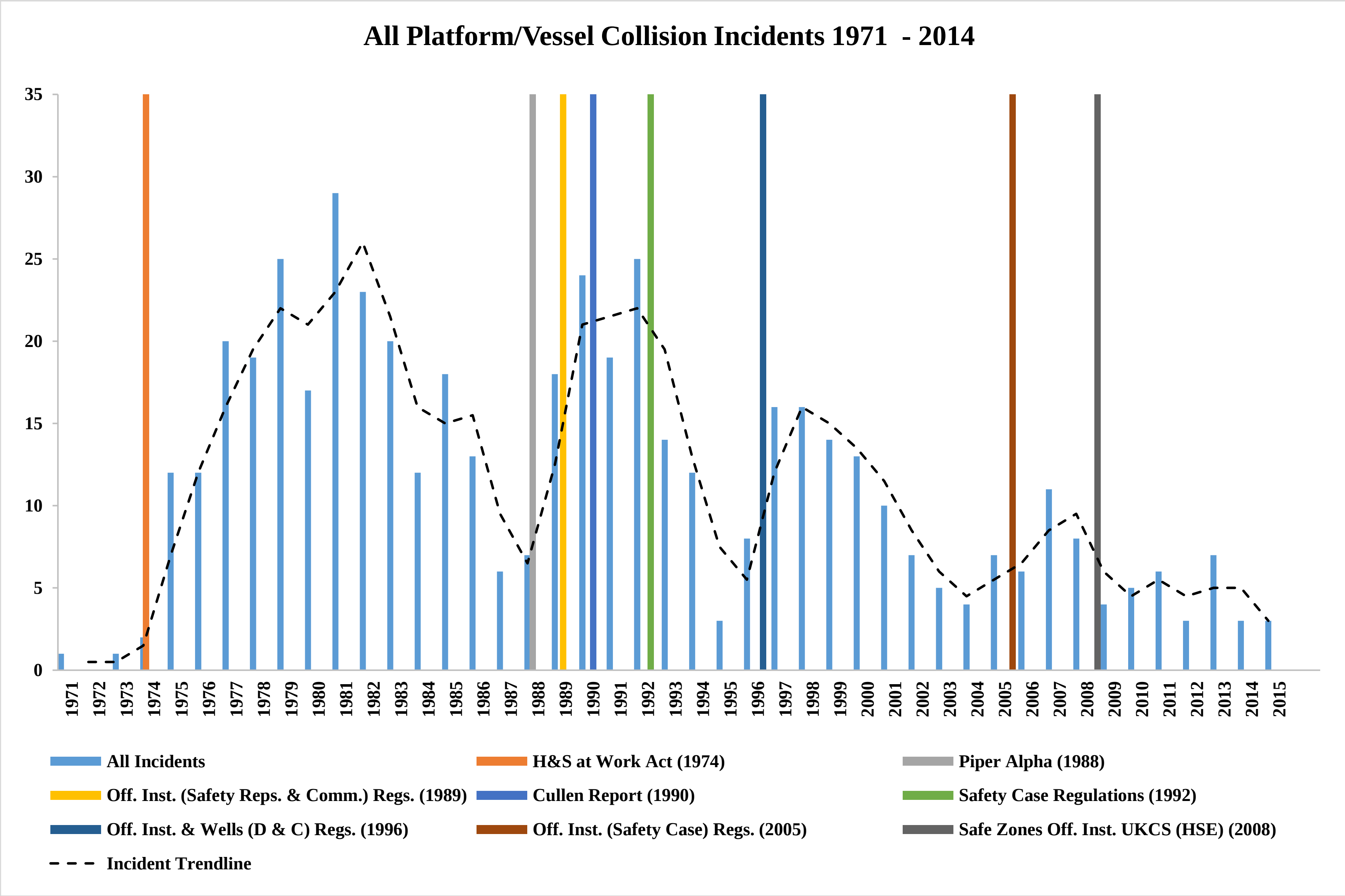

Figure 2-2: Graph demonstrating the number of ship to platform collision incident s per year, as well as the key regulations and events that formed the modern safety case

2.3.2 Analysis of Incidents and Regulations Timeline

It can be seen from Figure 2-2 that the number of ship to platform collision incidents from 1971 to 2014 is very turbulent, as more clearly demonstrated by the average trend line. At a first glance, this trend seems to be rather erratic, following no clear pattern. However, when the milestones in the safety case regulation timeline are taken into consideration, patterns begin to emerge in the number of incidents each year in UKCS and the North Sea.

2.3.2.1 HSE and the Health and Safety at Work Act, 1971 - 1981

Initially, from 1971 to 1973 the number of incidents is very low at one per year. A possible reason for this is that the data entries for 1971 to 1973 are from WOAD only, as the HSE began their ship to platform collision recordings from 1975. However, from 1975 onwards the number of incidents per year greatly increases until 1981 from 12 to 32 respectively. There are a number of possibilities that can cause this rapid increase. Firstly, the HSWA is enforced from 1974 hence, the recognition of dangerous incidents that can cause harm to personnel is increased. Secondly, as more and more dangerous incidents are being recognised, the need to report said incidents also increases. Therefore, it is safe to say that an increased awareness of dangerous situations coupled with the need to report these incidents gives rise to a dramatic increase in the number of collision incidents. Thirdly, according to the HSE, the average number of installations operating in the UKCS alone increases from 88 in 1975 to 120 in 1981. The increase in the number of operating platforms would statistically increase the number of collisions at that time.

2.3.2.2 Pre-Piper Alpha and Cullen Report, 1981 - 1987

From 1981, however, the number of incidents per year begins to decrease until 1987, from 32 to 7. This decrease is much greater that the increase in incidents from 1975 to 1981. It is possible that the enforcement of the HSWA had a large effect on the safety procedures on offshore platforms in the North Sea. This hypothesis would also be consistent with the average number of platforms operating in the UKCS which increases from 120 in 1981 to 174 in 1987. This contradicts the previous statement that the number of incidents would increase with the number of platforms in operation. However, in the 6-year period between 1981 and 1987 this is not the case. This further backs up the idea that the regulations form 1974 have been increasingly enforced and have reduced the number of incidents. However, it is also possible to state that the level of reporting of the collision incidents has decreased. This is a much more difficult claim to validate as there isn't any possible way to determine whether an incident has happened and hasn't been reported. This is part of the reasoning behind the Asset Integrity Case, as the only way wireless sensor will not detect and log any information is if it is faulty. On the other hand a human has the ability to choose not to carry out an action. Hence it is difficult to accurately determine the level of underreporting that would have taken place between 1981 and 1987.

2.3.2.3 Piper Alpha and Offshore Installations Regulations, 1988 - 1989

Continually, the time period between 1988 and 1994, in terms of collision incidents, is very interesting. The year 1988 is well known in the offshore industry and indeed the world as the year of the Piper Alpha disaster in which 167 crew members lost their lives in the July of that year. When one examines the collision incidents that were reported in 1988, more than 60% were reported after the loss of Piper Alpha on 6th July (See Appendix D). This may suggest that a large-scale disaster, such as Piper Alpha, triggered an increase in the level of incident reporting. However, the number of collision incidents in 1988 alone are not enough to state this with any conviction. What is interesting however, is that the number of collision incidents increase in 1989 to 21, from 8 in 1988.

This is a drastic increase in terms of the number of reported incidents in the North Sea, after a large-scale offshore disaster. Furthermore, in 1989 the Offshore Installations (Safety Representatives & Safety Committee) Regulations were published. This stated that the workforce could elect safety representatives from amongst themselves. This may have increased the level of reporting of collision incidents in 1989. However, it appears to be too much of a drastic increase from the previous year to conclusively state that the new regulations in 1989 resulted in a considerable number of reported incidents. It seems much more likely that a combination of the Piper Alpha disaster and the release of the Offshore Installations (Safety Representatives & Safety Committee) Regulations contributed to the vast increase in reported collision incidents.

2.3.2.4 Cullen Report and Inception of Safety Case Regulations, 1990 - 1995

Continually, in 1990, the Cullen Report was published which was public enquiry into the Piper Alpha disaster. The report was heavily critical of the platform operators. Lord Cullen made a total of 106 recommendations within his report, all of which were accepted by industry. The responsibility of implementing them was spread across the regulators and the industry with, the HSE overseeing 57, the operators were responsible for 40, the offshore industry were given 8 to progress and the final one was for the Standby Ship Owners Association. The industry acted urgently to carry out the 48 recommendations that operators were directly responsible for. By 1993 all had been acted upon and substantially implemented. Furthermore, the HSE developed and implemented Lord Cullen's key recommendation: the introduction of safety regulations requiring the operator/owner of every fixed and mobile installation operating in UK waters to submit to the HSE, for their acceptance, a safety case. Hence, in 1992 the Offshore Installations (Safety Case) Regulations came into force. By November 1993 a safety case for every installation had been submitted to the HSE and by November 1995 all had had their safety case accepted by the HSE.

2.3.2.5 PFEER and Further Safety Case Regulations, 1996 - 2004

If the number of collision incidents is examined from the Cullen Report in 1990 to all installation Safety Cases being accepted in 1995, it can be seen that the number of incidents per year decreases rapidly from 27 to 3 respectively. This again a massive fluctuation in the number of incidents following a series of key regulations being enforced. Its shows that the release of new regulations prompts the level of incidents to decrease as the regulations are enforced. However, as 1995 is a number of years after the Cullen Report and the introduction of Safety Cases it is possible that an element of complacency in terms of reporting may occur. This can be seen from the number of incidents between 1995 and 2004. The number of collision incidents increases from 3 in 1995, to a peak in 1999 of 22, then to a new low of 5 in 2004. This fluctuation could be attributed to jus the number of incidents increasing after 1995 due to the increase of the average number of installations operating in the UKCS from 289 to 319 in 1999. However, the increase in installations does not correlate well with the increase in incidents.

What appears to be more likely is at the low point of 3 collisions in 1995, a new set of regulations are introduced and enforced, the Offshore Installations Prevention of Fire and Explosion, and Emergency Response (PFEER) along with the Offshore Installation (Design & Construction) Regulations in 1996. At that point, the number of incidents increases and peaks in 1999. It is likely is that the increase of new regulations prompts a more proactive response in the accuracy of incident reporting.

2.3.2.6 Amended Safety Case Regulations and Attention to 500m Safety Zones, 2005 - 2015

This trend can be seen yet again from 2004 to 2012, were the number of collision incidents per year increases from 5 in 2004 to 12 in 2007 then decreases to 4 in 2012. This could be attributed to the Offshore Installations (Safety Case) Regulations 2005 being enforced in 2006. As with the regulations in 1995 and 1996 the number of incident increases and begins to decrease. However, the number of collision incidents becomes much steadier and doesn't fluctuate as much as previous years, as an increase from 5 to 12 is not a huge increase, but it is an increase none the less. Furthermore, in 2008 the document entitled Safety Zones around Oil & Gas Installations in Waters around the UK is introduced by the HSE. This specifically targets the area of offshore collisions and near misses. Therefore, it makes sense to state that this introduction has maintained a steady level of incidents between 2008, with 9, and 2015, with 3.

From the information presented in Figure 2-2 and Appendix D it can be seen that the offshore industry can be said to be reactive in its approach to reporting incidents, especially in the area of ship to platform collisions. What is also apparent is that the fluctuation has become gradually smaller in more recent times. This shows that the effect of introducing and amending regulations over time has a positive effect on the overall trend of collision incidents. While this study identifies trends in ship to platform collisions, it would still be valid to state that the offshore industry would profit greatly from have a dynamic risk monitoring tool to aid with the continual enforcement of regulations across all areas of an offshore platform. In the near future, the Asset Integrity Case could be the answer to this problem.

2.4 Dynamic Risk Assessment in the Offshore Industry

Improving offshore safety is a large objective for various offshore companies such as the HSE and DNV GL (Det Norske Veritas) (Germanischer Lloyd). In order to help achieve this improvement in offshore safety risk assessment, analysis models need to become more efficient and dynamic. Hence, in this section, the justification of the development of a potential dynamic risk assessment model utilising BN methods is presented. (Matellini, 2012).

2.4.1 Comparison of Dynamic Risk Assessment Techniques

Over the past 10 years it has been stated that a dynamic risk assessment model is required within the offshore and process industries. Khakzad, *et al.,* (2013) proposed to apply BN to Bow-Tie (BT) analysis. They postulated that the addition of BN to BT would help to overcome the static limitations of BT and show that the combination could be a substantial dynamic risk assessment tool. Similarly, in the oil, gas & process industry (Yang & Mannan, 2010) proposed a methodology of Dynamic Operational Risk Assessment (DORA). This starts from a conceptual framework design to mathematical modelling and to decision making based on cost-benefit analysis. Furthermore, Eleye-Datubo, *et al.* (2006) proposes an offshore decision-support solution, through BN techniques, to demonstrate that it is necessary to model the assessment domain such that the probabilistic measure of each event becomes more reliable in light of new evidence being received. As opposed to obtaining data incrementally, causing uncertainty from imperfect understanding and incomplete knowledge of the domain being analysed.

Furthermore, dynamic risk assessment has been developed through the use of BT alone. Abimdola *et al.*, (2014) present a dynamic risk assessment model utilising the BT approach. The work outlines a predictive failure probabilistic model which is determining failure probabilities of basic components of during drilling operations. The dynamic model is capable of updating the failure probabilities of the components of the bow-tie, thus, overcoming the static nature of common risk assessment techniques (Abimdola, *et al.*, 2014). Other research has developed algorithms tailored to specific incidents and events. For example, Liu *et al.*, (2016) developed a system specific, novel methodology coupling the reservoir/wellbore model with distribution of uncertainties of a number of independent variables to obtain a risk picture of possible uncontrolled wellbore flow events. They state that industry could implement this methodology with minor modification as a benchmark to evaluate the onshore/offshore blowout risk (Liu, *et al.*, 2016).

2.4.2 Bayesian Networks in Dynamic Risk Assessment

The risk of hazards and failures offshore is determined by a huge array of factors due to the innumerable possible scenarios in which incidents and accidents can develop. This makes establishing risk both qualitatively and quantitatively an intimidating task. There are many techniques which can aid risk analysis, yet in this report the focus is to be around BNs, and a large number of studies have been conducted for marine, offshore and process industries. Most studies usually associate themselves around a particular area. For example, BNs have been utilised by (Cai, *et al.*, 2013) to conduct quantitative risk assessment of operations in the offshore oil and gas industry. Their method involves translating a flow chart of operations into the BN directly. They then validate their model through the use of a case study involving Subsea Blowout Preventer Operations, in light of the Deepwater Horizon sinking in 2010, whose cause was the failure of subsea blowout preventer (Jones, 2010). In another instance, Eleye-Datubo, *et al.* (2006) apply BN to produce a marine and offshore decision support tool to realistically deal with random uncertainties, while at the same time making risk assessments easier to build and to check (Fenton & Neil, 2013). Continually, Wu *et al.* (2016) further apply the use of Bayesian Networks for prediction and diagnosis of offshore drilling given certain geological conditions. Their work also applies the use of the BT approach to develop the BN and apply a case study (Wu, *et al*., 2016). This application of merging the BT approach with the BN approach is not uncommon which can be clearly seen in the outlined literature.

There are several advantages of using BNs over alternate approaches, for example, in BNs diverse data, expert judgement and empirical data can all be combined. This is very useful in situations where there is incomplete data or a complete absence of data, and thus other forms of data and information can be incorporated into the network (Bolstad, 2007). The advantageous nature of BNs over other methods is outlined by (Khakzad, *et al*., 2011), who presented a journal paper with the exclusive nature of comparing BNs and Fault Tree Analysis (FTA) in safety analysis within the process industry. It was concluded by Khakzad, *et al*., (2011) that a BN is a superior technique in safety analysis due to its flexible structure, which allows for it to fit a wide variety of accident scenarios. These views are also supported by Wu *et al.* (2016) and Yeo *et al.*, (2016).

In conjunction to this, BNs provide a clear visual representation of what they are representing and can be a very powerful tool for formulating ideas and expanding the model in itself (Fenton & Neil, 2013). This trait is shared by other risk modelling techniques; however, BNs are particularly adaptable method. BNs also facilitate inference and the ability to update predictions through the insertion of new evidence or observations into its parameters. This makes them a very useful tool when dealing with uncertainty.

2.4.3 Limitations of Bayesian Networks

The BN methodology provides a substantial way in which the modelling of relationships between variables, within a given domain, through the assignment and linking of nodes. The method also allows for clear graphical representation of a scenario resulting from a series of events. The uncertainty between multiple dependencies of nodes is captured through the assignment of conditional probabilities (Neapolitan, 2004). It is worth noting that BNs are not without their critics. Bayesianism is analysed by (Wang, 2004) and discusses some of the limitations of BNs. He addresses in particular that the Bayesian approach cannot combine conflicting beliefs that are based on different implicit conditions and cannot carry out inference when the premises are based on different implicit conditions (Fenton & Neil, 2013). The key disadvantage of BNs is the computational complexity which can be generated. This is because the number of permutations in the CPTs grow exponentially with the number of parent nodes. (Matellini, 2012). This can be combated by the application of the Symmetric Method assesses large CPTs as being linear and not exponential (the method is outlined further in Chapter 3). In terms of the research presented throughout this thesis, the BN should be thought of as a probabilistic approach to risk analysis which considers factors and chains of potential events, which can result in an undesired situation or conditions and is therefore ideal for this research.

2.5 Wireless Sensor Networks

2.5.1 Brief history of Wireless Sensor Networks

The initial development of WSNs was motivated by military applications, such as: surveillance in conflict zones. In the modern world, they consist of independent devices using sensors to monitor physical conditions with applications across industrial infrastructure, automation, health and consumer areas. These sensor devices are usually spread over areas of varying size. The sensor nodes are usually transceivers scattered within the sensor field where they can detect and transfer information to the gateway or sinkhole for use by the end user (IEC, 2014) (Fischione, 2014).

The beginnings of the research into WSNs initiated in the 1980's where the United States Defence Advanced Research Projects Agency (DARPA) conducted the Distributed Sensor Networks (DSNs) programme for the military. DSNs had a number of distributed, low-cost sensor nodes connecting to each other autonomously, with the information being sent to the node that could best utilise the information. Despite early interpretations of sensor networks had the DSN idea as a base, the technology was not readily available. More specifically, the first sensor nodes were much larger than the modern sensor nodes that are known today. These sensor nodes were roughly the size of a standard shoe box or bigger, with the number of practical applications being very limited. The earliest DSNs were not associated with wireless connectivity (Chong & Kumar, 2003) (IEC, 2014).

However, recent advancements in the fields of communication and micro-electromechanical technology have resulted in a significant movement in WSN research. The increasing research of WSNs has put its focus in networked information processing and networking technology for application in highly dynamic environments. Similarly, sensor nodes have become increasingly smaller in size with greater output potential and a reduction in cost, hence many applications in the civilian world have emerged, such as: vehicle sensor networks, environment monitoring and body sensor networks. Currently WSNs are viewed as the most important technologies of the 21st Century, with countries like China incorporating WSNs in their national strategic programmes (Ni, 2008). This has resulted in a massive acceleration in the commercialisation of WSNs and many more technology companies are emerging (IEC, 2014).

Industrial automation is one of the key areas of WSN applications. The Freedonia Group state that the global market share of sensors for industrial use is approximately $11 billion USD, with the cost of installation, including cabling costs, and usage is up to $100 billion USD. It is this cost hindering the further development of industrial communication technology. WSNs can improve the whole industrial process by securing the important parameters that are unavailable through online monitoring due to the costs stated by the Freedonia Group.

Furthermore, according to the ON world, the number of wireless networking devices installed in industry will have increased 553% between 2011 – 2016, with 24 million wireless sensors, actuators or sensing points deployed worldwide. It is stated that 39% of these sensors will be applied to new applications which are only made possible by the development of WSNs. Figure 2-3 shows the global installed industrial wireless sensing

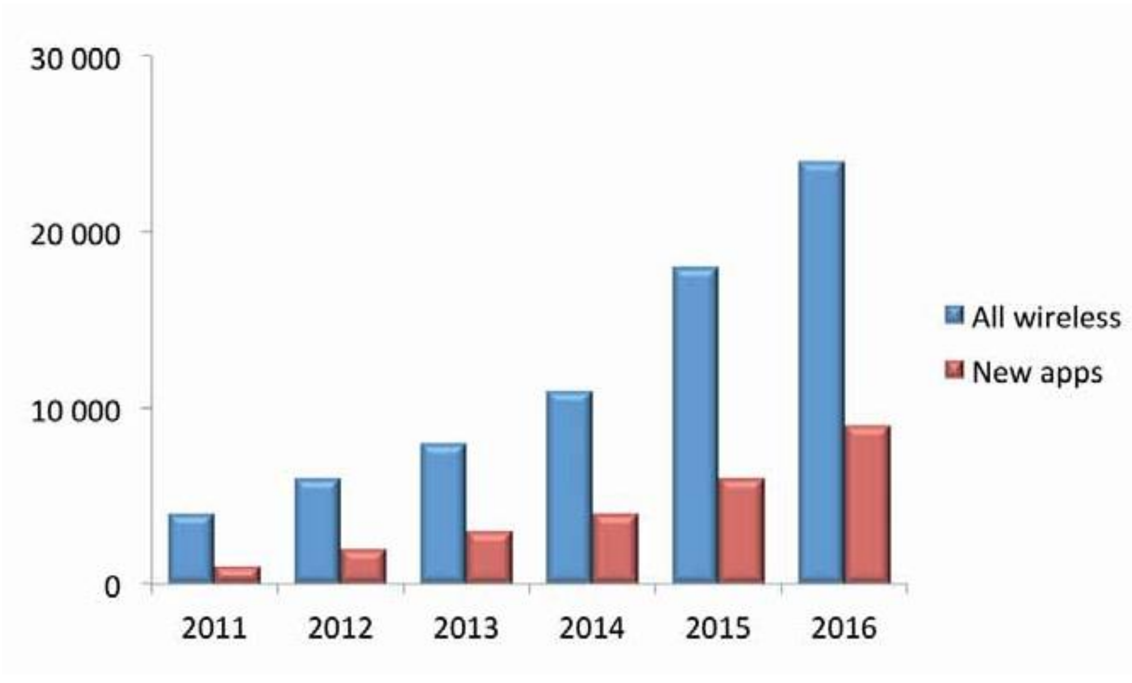

Figure 2-3: Increase of global industrial wireless sensing points, in thousands (IEC, 2014) *(Halter, et al., 2012)*

points, courtesy of (IEC, 2014) and (Halter, *et al.*, 2012). At the present time, 75% of industrial WSN income arises from the process industry, with Oil and Gas being the fastest growing sectors. For example, PetroChina is conducting Internet of Things (IoT) projects across its oil fields, with the focus on the reconstruction of more than 200, 000 oil wells. The WSN technology applied in the oil wells will provide the ability to monitor the oil well production and the integrity of the oil well systems to ensure safe production (IEC, 2014).

2.5.2 Wireless Sensor Network Technology

A WSN is composed of a number of sensor nodes which are densely deployed either inside or very close to a physical phenomenon. The sensors cooperatively detect and control events and anomalies within the environment, enabling interaction between persons or computers and the environment. WSNs consist of a grouping of sensor nodes in a sensor field, cluster heads (in some cases), a sink or gateway and clients, as shown in Figure 2-4. The sensor nodes are usually transceivers scattered in the sensor field where each has the capability to collect data and route it back to the sink/gateway. They apply specific processing capabilities to conduct simple computations and transmit only the required and partially processed data. During the transmission, several nodes may handle the monitored data on route to the gateway. This is known as multi-hop routing. The data finally reaches the client or management node through the internet or via satellite. The end user configures and manages the WSN through the management node (Fischione, 2014).

The sensor node is one of the main parts of a WSN. The hardware of a sensor node contains five key components: the power supply, the transceiver, the microcontroller, the sensor and possible memory storage capabilities. Figure 2-5 demonstrates these five components. Each one of these components is determinant in the design of a WSN. The microcontroller runs the different tasks such as: data processing and control of the other components. All other components are managed through the microcontroller. It is possible that there is a data storage capability associated with the controller, subject to

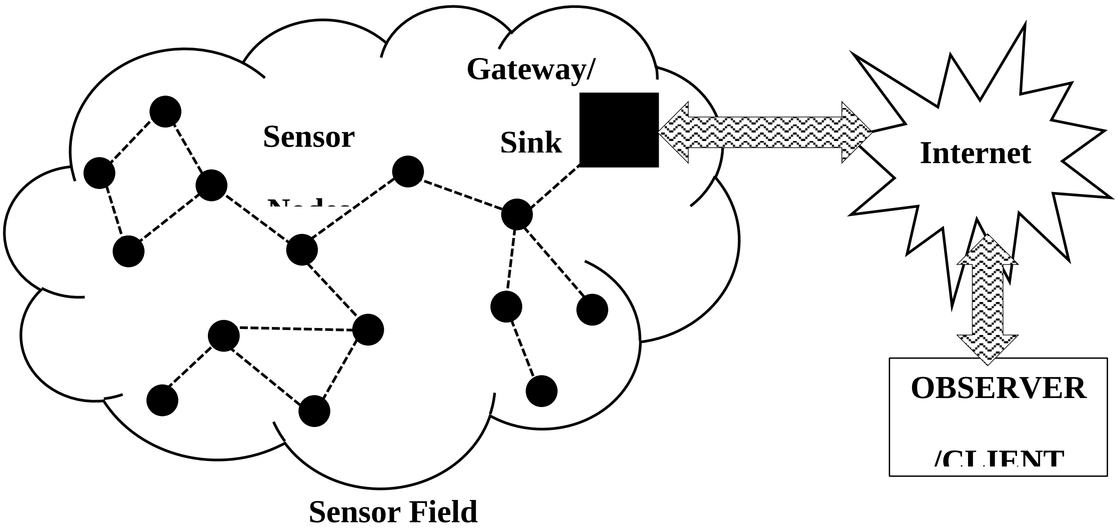

Figure 2-4: Generic wireless sensor networks

the WSN design requirements. However, it is also viable to have a small storage unit integrated into the embedded board (Fischione, 2014).

The sensor node is the key component of the node, and may consist of a number of sensing units. Each sensor unit is responsible for gathering and collecting certain types of data and information such as: temperature, moisture content or light. Most sensing units are comprised of two subunits: the sensor and an analogue-digital converter (ADC). The ADC converts the analogue signals detected by the sensor, given an observed phenomenon, to digital signals. These signals are then fed to the processing unit and transceiver. The transceiver transfers the data collected by the sensing unit by performing communications with other nodes and parts of the WSN. It is the unit that consumes the most power. The memory unit is purely for temporary storage of the collected data and can being the form of RAM, flash or even external storage, such as USB devices (Chhaya, *et al.*, 2017).

The most critical part of the sensor node is the power unit or power supply. It is most common to power the sensor node via batteries, either rechargeable or not. It is possible to utilise natural sources for extra power or for recharging capabilities, such as: solar

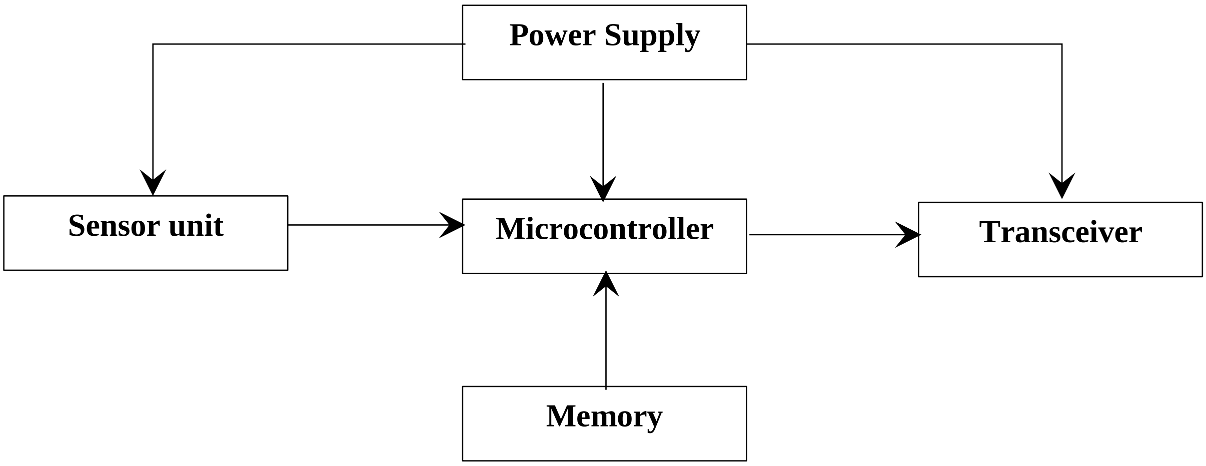

Figure 2-5: Components and hardware structure of a typical sensor node

power through photovoltaic cells. It is important that the design of all the parts of the WSN nodes consider key features, such as: the increasingly small sizes that WSN nodes have become and the levels and limits of the power supply.

2.5.3 Topology Data Aggregation and Battery Power

Generally, as previously stated, a WSN consists of a number of sensor nodes and a gateway for connection to the internet. The general deployment of WSNs follows a number of steps and is shown by Figure 2-6. Firstly, the sensor nodes will broadcast their status to the surrounding environment as well as receiving information regarding the status of other nodes in the sensor radius. Secondly, the nodes are organised into a connected network dependant on the given topology (single-hop, multi-hop). The final stage is determining the most efficient routes for the information to be transmitted through (IEC, 2014) (Mhatre & Rosenberg, 2004).

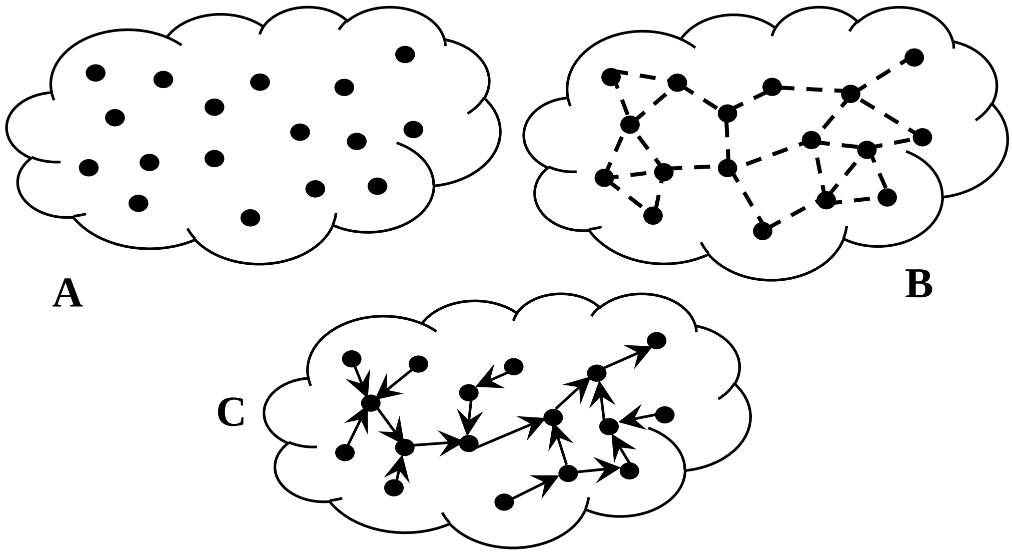

Figure 2-6: Organisation and transmission process of a WSN. A) Waking and detecting, B) Connecting as a network & C) Routing through multi-hop topology (assuming data routing from left to right)

As the power for sensor nodes is usually provided through the use of batteries, their sensory range can be quite short. The optimal ranges are between 800 – 1,000 meters given that the nodes are in free space with a clear line of sight to one another. However, this is not always the case. Given that the sensor nodes are in a sheltered environment or within machinery, such as a gas turbine, the sensory range reduces rapidly to no more than a few meters (IEC, 2014). As power is a key factor in the operation of a sensor node, it is possible to put transceivers into an idle state, i.e. they are ready to receive information but are not doing so. Where some utilities can be powered down and reduce energy consumption. Figure 2-7 demonstrates a breakdown of the power consumption of a typical WSN node. Figure 2-7 shows that a transceiver consumes almost the same energy when transmitting/receiving as when it is idle. Furthermore, a large amount of energy can be saved if the transceiver is put in the sleep state, effectively turning it off when the node does not need to send or receive information. While in the 'sleep state' certain parts of the transceiver are switched off, and nodes cannot immediately relay information. This results in a significant allocation of battery power for start-up and recovery time to leave the sleep state (Fischione, 2014) (Mhatre & Rosenberg, 2004).

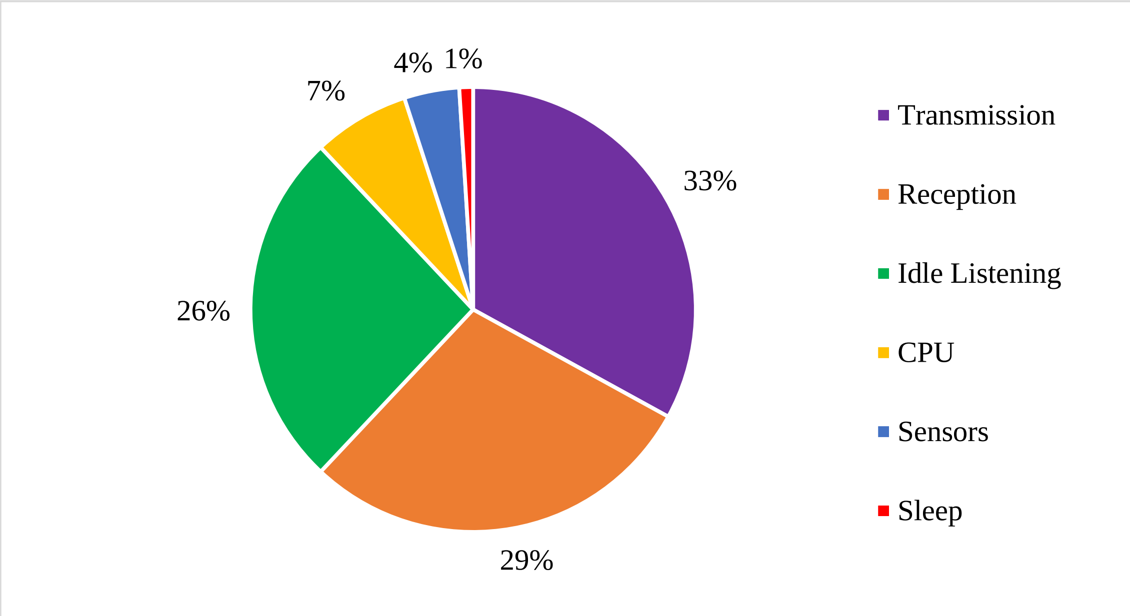

Figure 2-7: Power consumption of a generic sensor node to receive and transmit information *(Fischione, 2014)*

2.5.3.1 Single-hop Transmission

When the transmission ranges of the sensor nodes are large enough or the radius of the sensor cloud is less than that of the transmission radius of the sensor nodes, the nodes can transmit their information directly to the centralised gateway. They form what's known as a star topology with single-hop communications, as shown by Figure 2-8. When sensors utilise single-hop communication, there is no relaying of packets of information. Since the communication is directly between the sensor node and the gateway, each node should transmit their data in sequence, i.e. one at a time. In this instance, the lifetime of the network is determined by the node with the shortest life span. In a single-hop network, this is the node furthest away from the gateway as it must expend the most energy to transmit information (Chhaya, *et al.*, 2017) (Gupta & Kumar, 1998). If it is assumed that within the sensor network that all sensor nodes are alike, it is possible to dimension the battery given the worst-case scenario. Similarly, the battery power is also heavily related to the environment, this is known as the propagation loss exponent, usually referred to as a k value. An example value of k would be when the WSN is in free space, resulting in k being equal to 2. This value is dependent on the environment surrounding the sensor

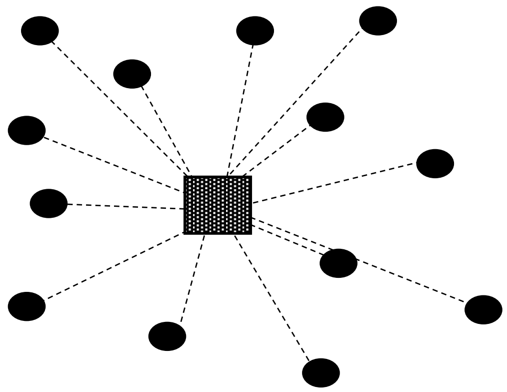

Figure 2-8: Star topology with single-hop communication

nodes. For example within buildings, factories, machinery spaces and dense vegetation, the value of k increase to approximately 3 – 5.

2.5.3.2 Multi-hop Transmission

It is more common for the transmission ranges of the sensor nodes to be less than the radius of the sensor cloud, in which case the transmission range of the sensor nodes is kept at a minimum to conserve battery life. In this instance, nodes relay information from one another, utilising the shortest possible route to the gateway. Here the nodes form a mesh topology using multi-hop communications. In this topology not only do nodes have to capture and process their own data, but they must collaborate to propagate sensor data towards the gateway (Fischione, 2014). Figure 2-9 shows an example of multi-hop routing. When a node serves as a relay for multiple routes, it has the opportunity to analyse and pre-process data in the network, which can lead to the elimination of redundant information or aggregation of data that can be smaller than the original data set. Furthermore, when considering multi-hop communication, each sensor has a communication range *R*, as shown in Figure 2-9, and *R* must be sufficiently large to maintain connectivity across the network. Gupta & Kumar (1998) developed a lower bound on the communication radius, *R*, in order to ensure connectivity of the nodes with a high probability when *n* nodes are distributed uniformly or randomly

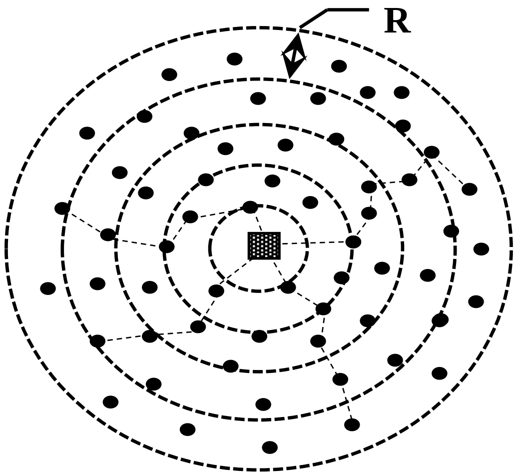

Figure 2-9: Multi-hop wireless network with indicated sensor communication radiuses, R

Mhatre & Rosenberg, (2004) also state that in order to determine the worst-case energy drain in the network, the sensor cloud is divided into a number of concentric circles of thickness *R*. In multi-hop connections of radius, *R*, where a packet of information is generated in the n^{th} ring, the packet must travel through the inner rings to reach the gateway. For each data gathering cycle it is possible to determine the mean energy expenditure of a node in the n^{th} ring. The ring, *n*, can vary given that the total number of rings is a/R. When *R* is at maximum, it corresponds to single-hop transmission ($a = R$). However, in the event that $k > 2$ the propagation loss term scales as μR^k, whereas the average number of packets scales at $1/R^k$. Therefore, the choice of whether to use multi-hop or single-hop transmission depends on other factors when $k > 2$, such as energy spent in the transceiver electronics, the propagation loss, antenna gains, the radius of the sensor cloud and the propagation loss exponent. (Gupta & Kumar, 1998) (Mhatre & Rosenberg, 2004).

2.5.4 Cyber Security

As WSNs become larger and increasingly complex, creating more and more intricate autonomous systems from industrial to civilian applications, the level of security for an operator or individual exponentially increases, with the weakest link or point in the network defining the overall level of security. While the research contained within this report is focused on the physical design and layout of a WSN and not the software, it is important to give an overview of cyber security and cyber-attacks (Chhaya, *et al*., 2017) (Radmand, *et al*., 2010).

The security issues related to the confidentiality, availability, authentication, integrity, authorization and freshness. Confidentiality deals with the secrecy of data communication. Authentication is necessary for the prevention of fake data from malicious nodes. Availability means the consistency in service is upheld in the presence of attacks. Integrity implies that the data, information or messages are received, unaffected at the destination. Authorisation means that only authorised sensor nodes can communicate to each other, and unauthorised access of data must be prevented. Freshness of data is important to ensure that the attackers do not replay old data to hinder the security of the WSN (Chhaya, *et al*., 2017) .

WSNs must implement strict encryption, transmitter availability and consistent data validation with constraints on power, memory, computation and bandwidth. The following defines the typical attacks that can affect WSNs. Generally, WSNs are susceptible to a multitude of cyber-attacks and security issues. In such sensitive commercial, industrial and civilian applications it imperative that the security of WSNs is assured from generic attacks (Radmand, *et al*., 2010) (Alajmi, 2014).

WSNs are generating a more significant interest as industrial and civilian system move further into the wireless domain. Such technology is beneficial, by eliminating the use of cables, for example, can reduce operating cost and installation time. A security risk level, however, must be accepted with WSNs. The key is to producing effective WSNs is to ensure that addressable security issues are dealt with and others managed and accepted. In this case many WSN devices and nodes would be for redundancy purposes as they cannot be relied on for critical tasks (Radmand, *et al*., 2010). As this research is concerned with the physical design of WSNs, the issue of cyber-security shall not be discussed in more detail. However, more information can be found in (Alajmi, 2014) (Chhaya, *et al*., 2017) (Dini & Tiloca, 2012) (Radmand, *et al*., 2010) (Singh, *et al*., 2010).

2.5.5 WSNs in Offshore Industry

The requirement to collect measurements relating to temperature, flow, pressure and vibration, in often remote and unsafe locations is common and vital in the offshore oil and gas industry. The offshore industry is continually expanding and progressing, particularly technological advances. This growth in industry and technology is also driving the need to measure, record and transmit data in real time. Wireless sensor networking is the way to do this without the need for cables and the associated problems that come with unsafe and inaccessible locations (Akhondi, *et al*., 2010).

Offshore platforms house an abundance of remote and unsafe locations associated with a variety of systems. Wired sensors and equipment require power, cables and conduit to reach devices in remote locations. This is costly, inconvenient, time consuming and in some cases impossible. Other factors include the man power associated with the installation, as well as the monitoring recording and data processing. This leave a lot of room for human error, which is a big concern when operating in high risk and extreme offshore conditions. (Lajoie, 2010)

WSNs can eliminate the expensive and inconvenient conduit and cables of wired networks. Measurement data can be collected accurately and in real time for faster response and decision making, with limited loss in the system integrity and availability. Similarly, a WSN can minimalize the personal required to perform manual duties where there is a high-risk level (Lajoie, 2010). This is key in the development of the Asset Integrity case outlined in Chapter 1.

The offshore industry includes processes for exploration, extraction, refining, transporting and marketing of products. As the demand for fossil fuels increases, so does the need for offshore companies to develop and employ new technologies. As well as improve operations to increase productivity, reduces injury and fatality and maintain system integrity. WSNs can quickly be organised and continually adapted to monitor and control a surrounding environmental conditions and machinery. There are a number of reasons as to why WSNs are vital to the progression of the offshore industry. Some are outlined as follows:

- Numerous remote and hazardous location (as stated previously).
- The difficulties and inflated cost of installing wired devices on and near pipelines.
- The requirement for temporary sensory equipment.
- Evolution of control solutions that require more and improved sensors.
- The continual demand for increased and optimized production.

- The demand for improved safety.
- The increased demand to more accurately and remotely monitor the integrity of systems.
- The increasing number and size of normally unattended installations.

As wireless technologies are being developed, there is an increase in the use of wireless sensors being deployed on older, end of life platforms in order to gain new insights and to attempt to optimise the platforms production (Carlsen, *et al*., 2008). There are many challenges associated with the deployment of WSNs on offshore platforms. Akhondi, *et al.*, (2010) have outlined some key difficulties and properties of offshore WSNs. These are outlined as follows:

- Restricted size, shape, construction and certification.
- Operators must accommodate for limited processing power, memory storage and battery consumption.
- Devices should generate their own power where possible, or contain battery packs with extended battery life of many months or years to reduce maintenance requirements.
- Sensors must operate in difficult wireless environments, both in terms of radio noise and obstructions, as well as areas where there are restrictions on the use of radio devices, such as areas with hydrocarbon containment or a flammable risk.
- Must operate in harsh environmental and platform conditions.
- Contribute in a simple Ad hoc and multi-hop network.
- Integrate with the existing IT solutions.
- Provide services in a dynamic and changing environment.

- Exhibit some level of fault tolerance and recovery.
- Operate in the unlicensed sections of the frequency spectrum.
- Clearly defined operational reliability and availability on the WSN in the operational environment.

Studies have shown that required changes in plant work processes may be the largest hindrance on the introduction of WSNs into the oil and gas industry. It was noted by Petersen, *et al.* (2008) that problems are typically experienced when human factors are ignored in the adoption of new technology (Petersen, 2008).

2.5.5.1 Applications in Offshore Oil & Gas

WSNs are a key investment across the whole offshore oil and gas industry, including pipelines, exploration, production and transportation. By providing secure and reliable wireless communications, WSNs enable automation and control solutions that are not feasible with wired networks. It is a multidisciplinary research area which requires good collaboration between users, hardware designers and engineers and software developers (Akhondi, *et al*., 2010).

There are four main application areas where WSNs would be extremely useful on board offshore platforms:

i. **Remote monitoring:** WSN solutions provide remote monitoring capabilities or the offshore industry to adhere to new technology, regulatory and productivity demands. Below are some examples of where WSNs can be applied for remote monitoring purposes (Petersen, 2008).

    - Pipeline Integrity monitoring.
    - On-board system integrity monitoring.

- Tank Level monitoring.
- Wellhead Automation and monitoring.

ii. **Condition monitoring and maintenance:** The overall aim of fault diagnostics is the estimation of the status of a component through sensor measurements and the monitoring of system components. Equipment diagnostics tries to determine the root cause of a component failure whereas system diagnostics is performed on a system of components. Utilising sensor measurements preventative and almost predictive maintenance can be performed, and subsequently post-fault diagnostics is improved. The predictive maintenance methodologies require that the system be monitored in real time. Sensors may detect vibration, temperature, power consumption, gases, performance and electromagnetic properties, when combined with other sensors in a network, these continuous signals can demonstrate clear and significant information about the status and integrity of a component or system. This allows for the detection, or even prediction, of potential upcoming failures (Ferreira & Alves da Silva, 2007).

iii. **Toxic substance monitoring:** During the exploration and extraction of oil and gas, many types of toxic gases are produced as a product or by-product of the production processes. The largest concern, with all toxic substances, is the potential for leaks. Not only is this damaging to people and the environment, any leak in a transport pipeline required a shutdown of the process. Leakages can be caused by any number of faults, such as: corrosion, earthquakes, general wear and tear, material flaws and even sabotage (Akhondi, *et al*., 2010) (Xiaojuan, *et al*., 2009).

Due to the extensive installation and maintenance costs, a stationary, wired sensing system may not cover the whole containment and transport system. Hence, each crew member must carry a portable sensor device as a safety precaution. The application of a WSN here would potentially give a cross section of any leaks for a more extensive analysis. Existing sensing systems do not correlate data, sensors produce information independently, and so determining the nature of the leak can be difficult and time-consuming (Xiaojuan, *et al.*, 2009).

iv. **Production performance:** Given the relevant level and amount of data, from a number of performance aspects of an offshore platform facilitated by WSNs, an unsupervised self-organising map can prioritise key sensor values and classify operational performance. This can show when a plant is operating normally or abnormally. This type of WSN is often used in conjunction with supervised methods. Whereby the unsupervised network will perform pre-processing of data and the supervised system will conduct the analysis and estimate the associated parameters (Akhondi, *et al*., 2010).

2.5.6 Decision-Making for WSNs and ER Justification

There is increased demand for diverse applications within the communication services industry, within which WSNs gain increasingly more attention. WSN development and deployment has been and is continually being enhanced in terms of autonomously supporting a variety of potential applications as well as providing more adept solutions. However, decisions lie within the appropriate selection of key WSN features such as, topology, the number of sensors, and the most efficient pathway for data transfer. This has given rise to the application of MADA techniques to determine the best or most suitable aspects of WSNs for specific deployment scenarios. One such example is the work presented by Tang *et al.*, (2014) in which an algorithm is developed based upon multiple criteria decision making to determine the most energy efficient routing within a WSN. Their research takes into account key factors affecting the network lifetime, and a chaos genetic algorithm to determine the next most energy efficient hop in the data route (Tang, *et al*., 2015). Similarly, a fuzzy decision model has been applied to the selection of wireless technology by Jiang, *et al.*, (2012). This work develops n evaluation hierarchy with six major criteria and a set of sub-criteria in order to determine the most suitable WSN technology for the tracking of construction materials. The work concluded that a Wi-Fi device was the best alternative, as opposed to RFID, GPS, ZigBee and UWD devices (Jiang, *et al.*, 2012). Finally, Gao, *et al.*, (2010) propose a novel MADA approach to cluster head selection within WSNs. The approach combines fuzzy-AHP and hierarchical fuzzy integral in order to analyse the optimum criteria that can influence energy efficiency to determine the selection of cluster head nodes in the WSN *(Gao, et al.*, 2010).

Numerous decision-making problems in management and engineering involve a several attributes of both a qualitative and quantitative nature. A comprehensive decision cannot be made with taking into account all attributes in question. It is the normal handling of qualitative attributes along with uncertain or incomplete information that causes complexity in multiple attribute assessments. There has been an increase in the development of theoretically sound methods and tools which deal with Multiple Attribute Decision Analysis (MADA) problems in a coherent, rational, reliable and repeatable manner (Chen, et al., 2015) (Yang & Xu, 2002) (Yang, 2001). In more recent times, the ER approach has been applied to decision-making problems in engineering, design and safety and risk assessment and supplier assessment. For example, motorcycle assessment, cargo ship design (Yang & Xu, 2002) and maritime safety analysis and risk assessment (Ren, *et al*., 2005) (Zhang, *et al*., 2016). Hence, the evidential reasoning algorithm was selected as a viable and accurate decision-making tool.

The ER algorithm is not without its limitations in terms of its application to belief decision matrices. The main limitation of the ER approach in belief decision matrices is that it can be seen as highly complex when compared to conventional decision matrices. This issue is more apparent when dealing with purely quantitative MADA problems. However, the application of IDS software and modern computer power assist with the computational complexity (Ruan, *et al.*, 2008). Furthermore, in this research the belief decision matrix is not highly complex, hence limiting the complexity of the ER algorithm and its respective calculations. Similarly, the IDS software is not applied here. Instead the ER algorithm is entered using the formula functions in EXCEL spreadsheets as the computing power can more than handle the level of complexity within the calculation.

2.6 Conclusion

The fundamentals of offshore safety assessment have been outlined along with the introduction of safety cases in the offshore industry. Similarly, the advantages and disadvantages of safety cases has been demonstrated with areas that could be improved with the addition of live dynamic risk assessment via the Asset Integrity Case. Furthermore, statistics regarding offshore gas turbine incidents have been outlined and examined. The emphasis on these incidents is to outline the significant role that human fuel gas detection and incident reporting has on the management of gas turbine fuel gas releases. This in turn showed that there is consistent under reporting or submission of incomplete data where human detection is concerned. In addition to this, an in depth statistical analysis of ship to platform collisions is conducted to demonstrate the reporting of incidents could potentially be heavily influenced by the periodic release of regulations. This analysis further adds to the claim that offshore safety assessment and safety case regulations would be much improved by the inclusion of a coherent real-time dynamic risk assessment approach. The justification of utilising Bayesian Networks as a viable risk assessment tool to develop a dynamic risk assessment model has also been outlined. Finally, an overview of the current status of WSNs is presented with key areas that can benefit the offshore industry as well as specific areas that would benefit greatly from the inclusion of WSNs as an asset integrity monitoring tool.

CHAPTER 3:

RESEARCH METHODOLOGY AND TECHNIQUES

Summary

This chapter aims at delivering a risk-based research methodology framework to establish the guidelines for developing the dynamic risk assessment and the remote detection methods for the NUI-Asset Integrity Case. The Bayesian Network elements of the framework shall be capable of dealing with dynamic risk assessment by accommodating the ability to continually update the conditional probability data. Furthermore, the remote sensing and detection methods along with the decision-making methodology shall allow for the determination of a suitable method for detecting and identifying asset integrity on an offshore platform. The chapter also includes the individual dynamic risk assessment and decision-making methodologies, along with the applied research techniques.

3.1 Research Framework

Conducting and operating any project or organisation of any size without a proper framework in place is a difficult task. It is hard to control the steps within a project if there aren't clear, established aims and objectives. The effectiveness and success of the project depends greatly on a clear and coherent research or management framework.

Figure 3-1 demonstrates an illustrative view of a research framework proposed for the purpose of this research, from which the research methodology is directed.

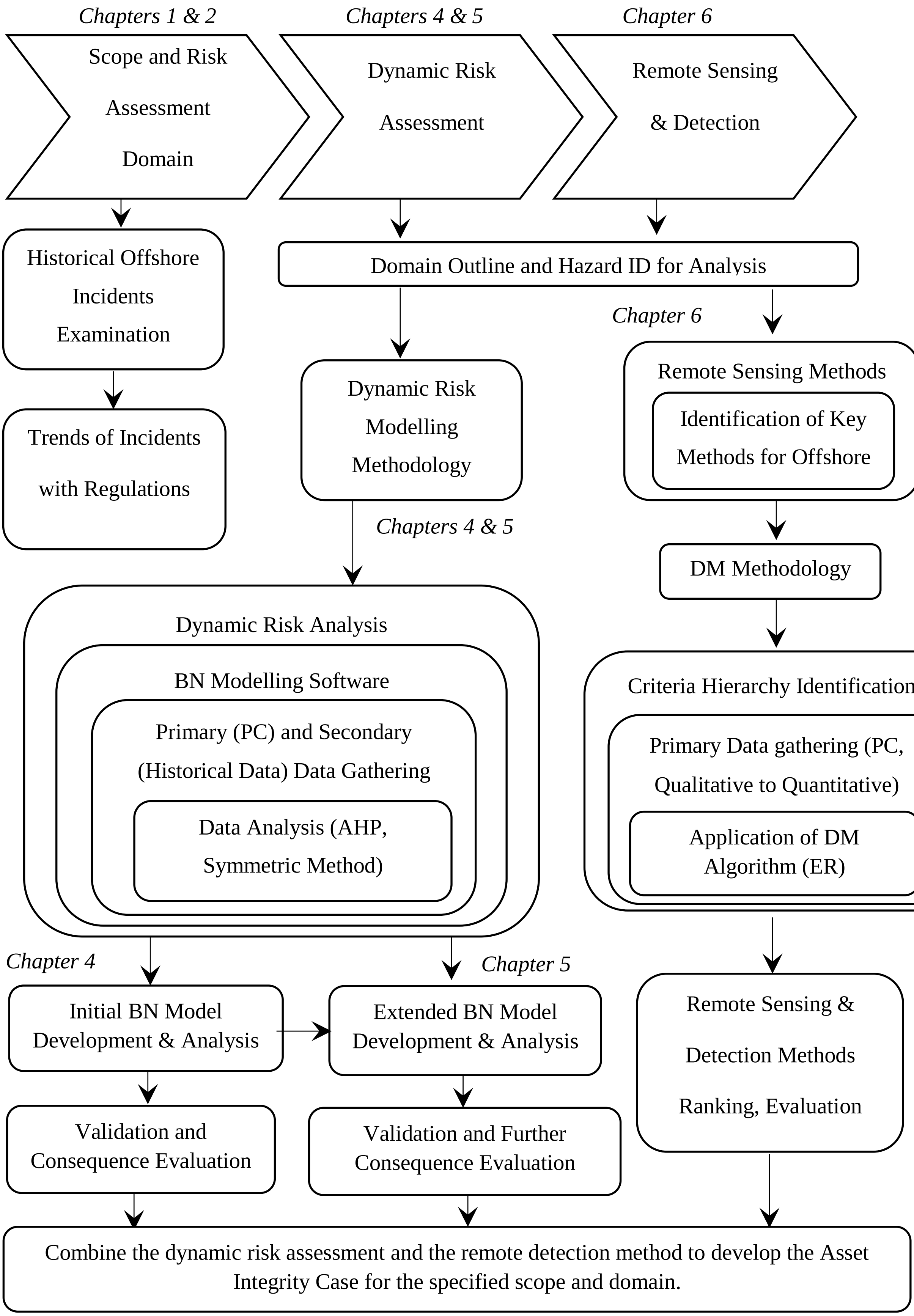

Figure 3-1: Proposed research framework for the initial development of a NUI-Asset Integrity Case

The research framework has been developed from a generic risk management framework and adapted to assist with the development a NUI-Asset Integrity Case. The framework breaks down the key elements required for the Asset Integrity Case, namely a coherent dynamic risk assessment model and the ability to sense and detect asset integrity on a NUI. As the Asset Integrity Case is a novel idea, a research management framework has never been presented and so it makes sense to adapt a risk management framework for use in this research.

Figure 3-1 outlines a number of key components and steps. These steps directly correlate to the technical research presented in Chapters 4, 5 and 6. Initially the framework requires the identification and outline of the scope and domain of the project. This is determined based upon the literature review in Chapter 2 as well as the project rationale in chapter 1. By analysing the literature regarding offshore incidents the domain for the research can be stated. In this situation, the domain to be utilised for developing the NUI-Asset Integrity Case is to be the electrical generation module. The reasoning for this is stated in Chapters 1 and 2. Briefly, the rationale is that there have been many incidents regarding gas turbine driven electrical generators over the past 20 years in the offshore industry, with the majority detected by human methods. There is a direct correlation between the number of under reported incidents and the number of incidents detected by human methods. Similarly, the scope and domain is also determined by the statistical analysis of other offshore areas, further solidifying the scope that a dynamic risk assessment model should be employed to aid with the enforcement of regulations.

Moving into the area of the dynamic risk assessment development, the domain must again be stated. This applies to the research in Chapters 4 and 5, where the dynamic risk assessment models are developed utilising BN modelling techniques. However, before the models can be constructed a separate methodology for formulating BNs must be determined. This methodology is outlined in Section 3.5. The BN formulation methodology is outlined here and not in Chapters 4 and 5 as the methodology is repeated for two BN models. Hence, demonstrating the methodology here avoids some elements of repetition. Furthermore, the framework is defined as risk-based, therefore a risk analysis is required. Hence the process of determining risk is essential to the framework and methodology. The proposed framework, in the long term, has the potential to result in more comprehensive application to offshore systems for asset integrity management with regard to the offshore regulations. As the dynamic modelling in the research is a risk assessment, key components of Formal Safety Assessment (FSA) are contained within the modelling process and structure. FSA was developed and introduced by the International Maritime Organization (IMO) in 1993, during the 62nd session of the IMO Marine Safety Committee (MSC) by the Maritime and Coastguard Agency (MCA) (DNV, 2002). The initiative was preceded by a number of marine incidents which brought into question the safety-related rules and regulations. The prior rules were derived as a reaction to an incident at sea in order to prevent accidents of a similar nature occurring in the future (Yang & Wang, 2008).

FSA is a systematic process for assessing the potential risks relating to maritime safety, the marine environment and cost and benefit analysis of these risks (Maistralis, 2007). The FSA consists of five steps, and the interaction between these steps is shown by Figure 3-2. There are repeated iterations between the steps which make the process effective, as it constantly checks for changes within the analysis. The execution and recording of each task is imperative as it enables the preceding steps to be carried out with ease. Similarly, for the process to be accurate the analyst appreciates and understands the objectives of each step, and carries them out without any half measures (Pillay & Wang, 2003).

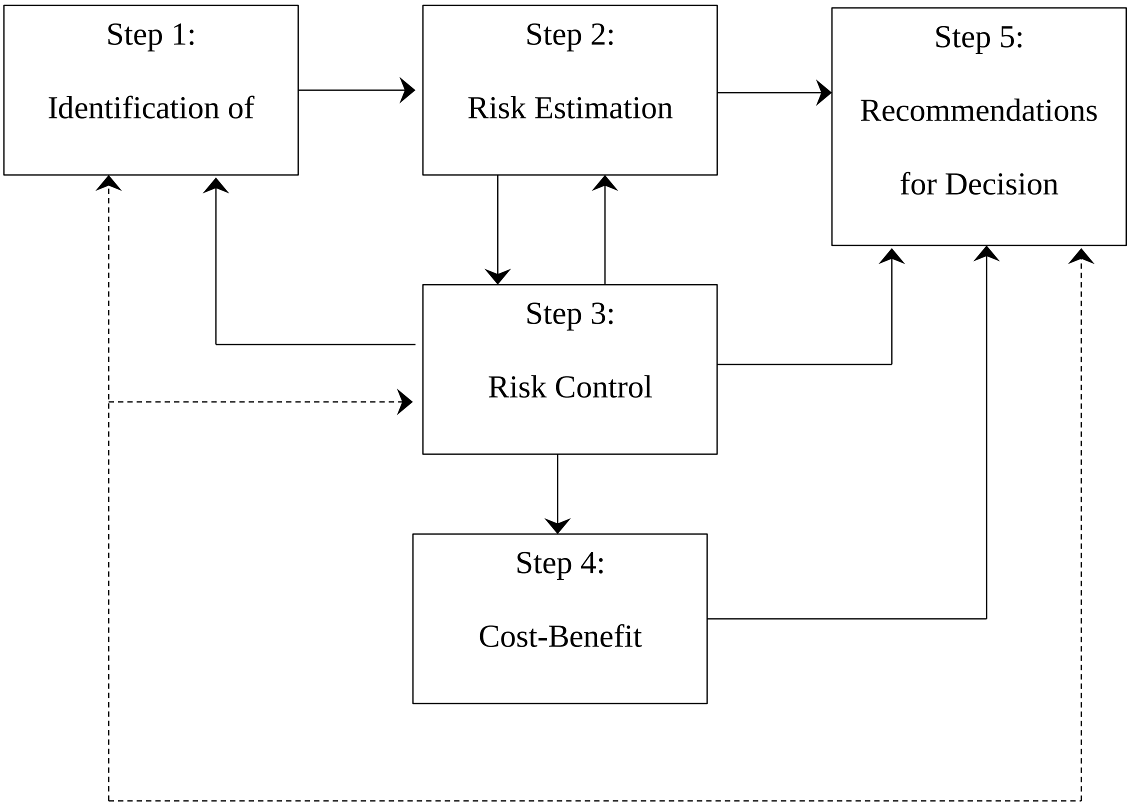

Figure 3-2: Flowchart of the five FSA Steps *(Pillay & Wang, 2003)*

The proposed dynamic risk assessment methodology and framework incorporates Steps 1, 2, 3 and 5 of FSA. Step 4, Cost Benefit Analysis is not considered at this stage of the Asset Integrity Case development. Similarly, the dynamic risk assessment methodology also incorporates the core steps of compete risk management. Figure 3-3 gives a demonstration of a risk management process. The components of the risk management diagram are contained within dynamic risk assessment section of the Asset Integrity Case framework. For example, the step *Analysis* from *Risk Assessment*, in Figure 3-3, is embedded in the framework stage of *Domain outline and Hazard ID*. Similarly, the components of *Evaluation* are contain within the *Dynamic Risk Analysis* and *Development & Analysis* steps of the framework Finally, areas of *Reduction and Control* are incorporated in *Consequence Evaluation.* Having this risk-based framework within the Asset Integrity Case methodology and framework provides a clear generic base that can potentially be applied to several offshore systems. This will allow for the further development and expansion of the Asset Integrity Case to other offshore areas and systems effectively.

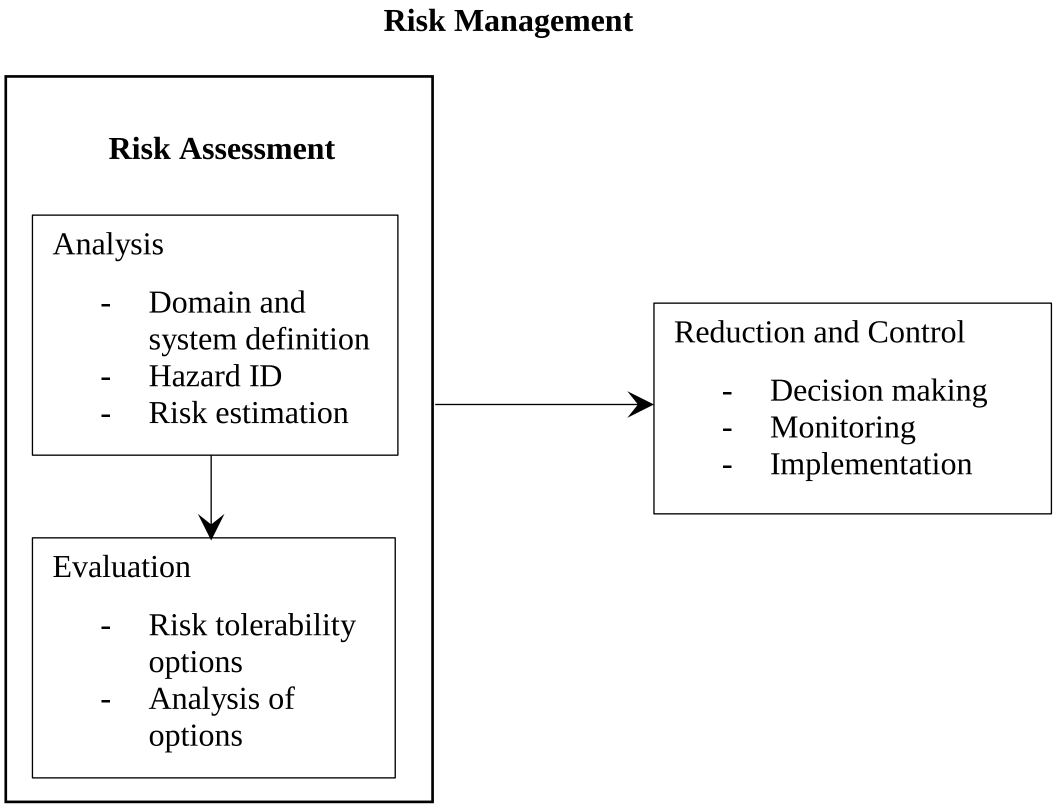

Figure 3-3: A risk management process, adapted from *(Matellini, 2012)*

The final section of the framework is concerned with the detection and remote sensing techniques. This incorporates areas and ideas that are key to developing system whereby asset integrity can be monitored without the use of manual methods. This includes both wired and wireless techniques. However, due to the remote and hazardous locations of some offshore equipment, wireless methods tend to be preferred. This methodology incorporates the design of a number of WSNs in a number of orientations regarding the hardware and most suitable forms of connectivity. Furthermore, the framework includes a methodology to determine the most suitable WSN design based upon a set evaluation hierarchy and criteria. This methodology can again be applied to a number of offshore areas where remote sensing of asset integrity would be of great importance, not only for the ability to continually monitor components and equipment in remote locations, but also to remove the hazards associated with using manual methods. In theory, this eliminates the risk to personnel who would normally be given the task of monitoring equipment in remote and hazardous locations.

Given that a dynamic risk assessment model has been developed, along with the remote monitoring and sensing method, the two can be combined to develop the Asset integrity Case for the specified domain. Further work is required in order to combine the two models and methods by incorporating the sensors into the dynamic risk assessment model. Furthermore, these sensors, once incorporated would transmit data to update the risk assessment model. This results in a live, dynamic risk assessment model for a given system.

Finally, all generic aspects of the analysis sections of the framework are outlined in the rest of this chapter. This includes an overview of the BN and probability techniques, as well as the BN methodology employed in Chapters 4 and 5. Similarly, the data analysis techniques applied across Chapters 4, 5 and 6 are outlined. This removes the need for any unnecessary repetition. The techniques are outlined in Chapter 3 while the numerical assessments are presented in Chapters 4, 5 and 6. The decision-making methodology applied in Chapter 6 is also outlined along with the decision-making techniques employed.

3.2 Overview of Bayesian Networks

Bayesian Networks (BNs) are a Directed Acyclic Graph (DAG) encoding Conditional Probability Distribution (CPD). There are two main components to BNs are the graphical structure which is the qualitative part and the probability distribution which is the quantitative part (Matellini, 2012).

3.2.1 The Graphical Representation

There are two key elements to the graphical structure of BNs, these are Nodes and Arcs:

- **Nodes:** Drawn as circles, represent random variables such as "*events*" that take values form the given domains. The relationship between nodes is expressed using a family notation. Influencing Nodes are "*Parents*", influenced nodes are "*Children*". If a node has no "*Parent*" it is Marginal or Unconditional. Nodes without Parents are "*Root*" nodes and nodes without children are *"leaf"* nodes.
- **Arcs:** Represent the direct probabilistic dependence relationship between variables.

The graphical structure is referred to as the DAG. The DAG contains a set of nodes each representing a random/chance variable which can take the form of an event, the presence

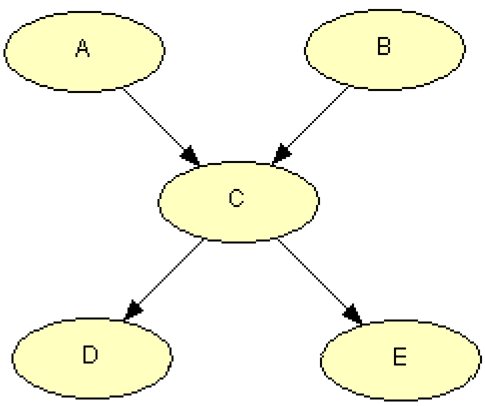

Figure 3-4: A simple BN

of something, a measurable parameter, a latent variable and an unknown parameter or hypothesis. Nodes are connected together by arcs in one-way directions. Arcs can also be referred to as directed edges, and they represent the direct probabilistic dependence relationship between variables. A simple example of a BN is shown in Figure 3-4. In this example, nodes *A* and *B* are the parents of node *C*. Node *C* is the parent of nodes *D* and *E* and the child of *A* and *B*. Nodes *D* and *E* are children of *C*. Following this logic, nodes *C*, *D*, and *E* are descendants of *A* and B. Nodes *A* and *B* are the root nodes, while nodes *D* and *E* are the leaf nodes (Fenton & Neil, 2013) (Bolstad, 2007).

3.2.2 Probability Distribution

Each node in the DAG has a number of possible states which must apply at any one time. Probability distribution indicate the strength of the belief in how the states of parent nodes can affect the states of their child nodes. Nodes can represent either discrete random variables with a finite number of states, i.e. 'Yes/No' and 'Low/Medium/High' or they can represent a continuous random variable with a normal density distribution, such as for temperature ranges or altitude. For root nodes a marginal probability table is defined. Non-root nodes are assigned conditional probability tables (CPTs) (Neapolitan, 2004). If the node is discrete then each cell in the CPT contains a conditional probability for the state of the node given the state of the parent node or combination nodes. When constructing a BN it is important to note that the number of permutations in the CPTs increases exponentially with the number of parent nodes and the number of states in the CPT. For example, if node a has 'x' parents with 'n' number of states, then there will be 'x^n' permutations in the CPT or node A. Similarly, the total number of cells in a CPT is equal to the product of the possible number of states in the node and the number of states in the parent nodes (Fenton & Neil, 2013).

3.3 Principles of Probability Theory

It is important to review the fundamentals of probability theory Bayes Theorem in order to further explore BNs, as the technique is built upon these principles. Assume that there are two events that exist in sample space 'S', these events are A and B.

$$S \supseteq A \text{ and } S \supseteq B$$

P(A) is assigned to measure the degree of uncertainty occurred by event A. The probability must adhere to four properties or axioms (Matellini, 2012).

Axiom 1: The probability of event A lies between 0 and 1.0, it cannot have a negative probability.

This is because if you divide a percentage probability by 100, the result lies between 0 and 1.0, as the percentage that expresses uncertainty cannot be more than 100. This also means that an event cannot have a negative probability (Fenton & Neil, 2013). Therefore, the following can be stated;

$$0 \leq P(A) \leq 1$$

Axiom 2: All possible outcomes are contained within the sample space 'S'.

For $S \supseteq A$ => The sum of the probabilities of A and its complement $\bar{A}$ must be equal to 1.0. The complement of *P(A)* is simply the Probability of the event being 'not' *A*.

$$P(S) = P(A) + P(\bar{A}) = 1 \qquad (3\text{-}1)$$

If $P(A) = 0.3$, then $P(\bar{A}) = 0.7$. In some cases the values of the probability are not given, words such as *'True & False'* or *'Yes & No'* may be used. In this case if *P(A)* is

True, then $P(\bar{A})$ is False. This can also be written as, $P(A) = 1$ and $P(\bar{A}) = 0$, should the values be needed for calculation purposes (Neapolitan, 2004) (Fenton & Neil, 2013).

Axiom 3: For mutually exclusive events, the probability of either event happening is the sum of the probabilities of the individual events.

This is the probability of either events A OR B occurring. The notation OR in probability is also known as the Union and is denoted by '∪'.

$$P(A \cup B) = P(A) + P(B) \;\; For\ S \supseteq A, S \supseteq B\ and\ P(A \cap B) = 0 \qquad \textit{(3-2)}$$

Two events are considered mutually exclusive if they have no elementary events in common. For example;

In a die rolling experiment, these two events are considered:

- E_1 - Roll a number greater than 4 (i.e.; the set of elementary events {5,6})
- E_2 - Roll a number less than 4 (i.e.; the set of elementary events {1,2,3})

Events E_1 and E_2 are mutually exclusive as there are no elementary events in common (Fenton & Neil, 2013).

Axiom 4: If events are not mutually exclusive then their conditional probability is subtracted from their union.

The conditional probability or Intersection is the probability of both events occurring simultaneously, and is denoted by '∩'. The intersection is the product of the events.

$$P(A \cap B) = P(A).P(B) \qquad \textit{(3-3)}$$

Therefore, the union of none mutually exclusive events is;

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)\ For\ S \supseteq A, S \supseteq B and\ P(A \cap B) \neq 0 \qquad (3\text{-}4)$$

The proof for Axiom 4 is demonstrated below, with Figure 3-5 being used as a visual representation for the interactions of events A and B. It is based on the idea of breaking the union of the two events down into events that are mutually exclusive. Figure 3-5 shows events represented by shaded areas (Fenton & Neil, 2013) (Neil, *et al*., 2000).

1. A∪B is the union of the mutually exclusive events $(A \cap B), (A \cap \bar{B}), (B \cap \bar{A})$.

2. A is the union of mutually exclusive events $(A \cap B), (A \cap \bar{B})$.

3. B is the union of mutually exclusive events $(A \cap B), (B \cap \bar{A})$.

4. $(A \cup B) = P(A \cap B)\ +\ P(A \cap \bar{B}\ )\ +\ P(B \cap \bar{A})$, by Axiom 3 applied to 1.

5. $(A)\ =\ P(A \cap B)\ +\ P(A \cap \bar{B}\ )$, by Axiom 3 applied to 2.

6. Therefore, $P(A \cap \bar{B})\ =\ P(A)\ -\ P(A \cap B)$, by rearranging 5.

7. $(B)\ =\ P(A \cap B)\ +\ P(B \cap \bar{A})$, by Axiom 3 applied to 3.

8. Therefore, $P(B \cap \bar{A})\ =\ P(B)\ -\ P(A \cap B)$ by rearranging 7.

9. $(A \cup B)\ =\ \ P(A \cap B)\ +\ P(A)\ -\ P(A \cap B)\ +\ P(B)\ -\ P(A \cap B)$, by substituting 6 and 8 into 4.

10. $P(A \cup B)\ =\ \ P(A)\ +\ P(B)\ -\ P(A \cap B)$, by simplifying 9.

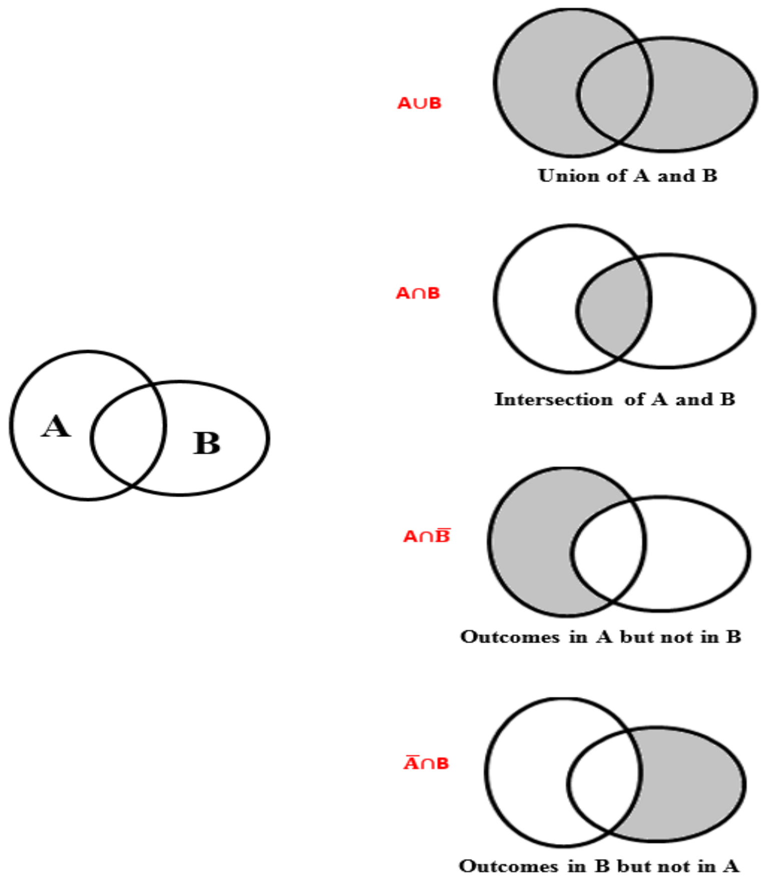

Figure 3-5: Visual representation of the interactions between events A and B, adapted from Fenton & Neil, (2013)

3.4 Conditional Probability

Conditional probabilities are essential to BNs. they can be expressed by statements such as "*B occurs given that A has already occurred*" and "*given event A, the probability of event B is 'p'*", which is denoted by $P(B|A) = p$. This specifically means that if event A occurs and everything else is unrelated to event *B* (except event *A*), then the probability of *B* is *'p'* (Fenton & Neil, 2013). Conditional probabilities are part of the joint probability of the intersection of *A* and *B*, *P(A∩B)*, and can be shown as;

$$P(A|B) = P(A \cap B)/P(A) \qquad (3\text{-}5)$$

For any two events A and B:

$$P(A \cap B) = P(B|A).P(B) = P(A|B).P(A) \tag{3-6}$$

It should be noted that if $P(A) = 0$ then A is an event with no possible outcomes. Therefore, it follows that $A \cap B$ also contains no possible outcomes and $P(A \cap B) = 0$. The independence of events can be shown by definition. Let *A* and *B* be any events with $P(A) \neq 0$. then *A* and *B* can be defined as independent if,

$$P(B) = P(B|A) \tag{3-7}$$

Thus, it follows from the previous definition, that;

$$P(A \cap B) = P(A).P(B) \tag{3-8}$$

3.4.1 Bayes Theorem

Bayes Theorem of probability theory is seen as a way of understanding how the probability that a theory is true, is affected by new evidence. For example, the probability of *A* can be updated if new evidence about event *B* is known (Matellini, 2012).

$$P(A|B) = \frac{P(B|A).P(A)}{P(B)} \tag{3-9}$$

It is very common for Bayes theorem to accommodate more than two events, for example if a second parent node, *C*, for child *A* is introduced then the equation becomes:

$$P(A|B,C) = \frac{P(B|A,C).P(A|C)}{P(B|C)} \tag{3-10}$$

3.4.2 BN Connections and d-separation

From very simple to very complex BNs the nodes contained within a network are always connected through one of the following three types of connections (Fenton & Neil, 2013) (Matellini, 2012):

1. *Serial connections (Casual and evidential trails)* feature nodes in which the first node influences the second, which in turn influences the third. An example of this is shown in Figure 3-6 where node *A* connects nodes *B* and *C*. In this case if new evidence is known about node *B*, then it shall influence node *C* through *A*, and this is true in reverse if new evidence is known about *C*. However, if the state of *A* is known then nodes *B* and *C* become independent of each other. Hence, nodes *B* and *C* are said to be *d-separated* given *A*.

If the relationships in the serial connection are casual, then it is known as a *causal trail*. If one is interested in reasoning from *C* to *B* then it is known as an *evidential trail*.

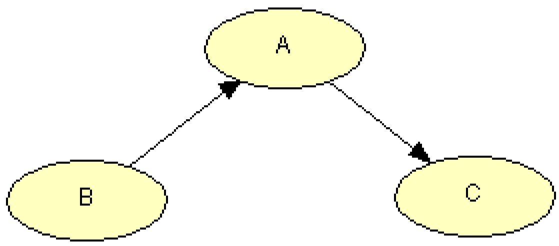

Figure 3-6: A Bayesian Network serial connection.

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2. *Converging connections (common effect)* feature two or more parents, *B* and *C*, which influence a child node, *A*, as shown in Figure 3-7. If no new evidence is available then parent nodes *B* and *C* are independent of each other, but if new evidence is known about child node *A*, then *B* and *C* are conditionally dependent on *A*. In other words, *B* and *C* are *d-connected* given *A*.

   If the relationships in the connection are casual then node *A* is a *common effect* as it is shared by more than one cause.

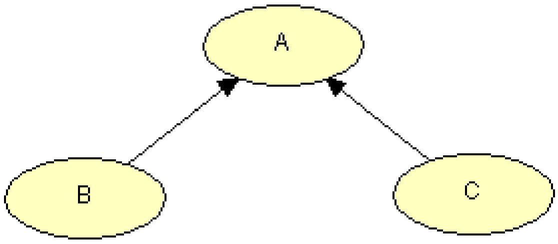


Figure 3-7: A Bayesian Network converging connection.

3. *Diverging connections (common cause)* feature a parent node, A, which influences at least two child nodes, *B* and *C*, as shown in Figure 3-8. All child nodes in this type of connection can influence each other, provided new evidence about A is unknown. However, if new evidence is known at *A*, then *B* and *C* are conditionally independent or equivalently, *B* and *C* are *d-separated* given *A*.

If the relationships in the connections are casual, then *A* is a *common cause* because it is the cause of more than one effect variable.

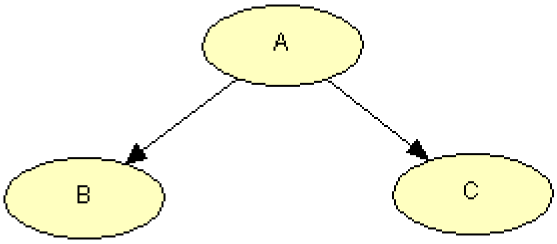


Figure 3-8: A Bayesian Network diverging connection.

3.5 Formulating a BN Model

When formulating a BN it is important to clearly outline the domain that it is to represent. Nodes and their subsequent states must be appropriately allocated, with much attention being paid to what each node shall symbolise and how they relate to one another. This is essential as to leave no area for misinterpretation. The fundamental part of building a BN with the ability to deliver meaningful results lies in its graphical structure and the input of data, hence the precise linking of nodes and the assignment of probability distributions is imperative (Fenton & Neil, 2013). With this in mind a BN has been produced to model the probabilities of failure within an electrical generation unit within one contained section of an installation. To ensure that a coherent model was constructed, knowledge was obtained through reviewing literature and speaking to members of RMRI Plc.

Attempting to build a model that incorporated several modules of an installation or an entire installation at this point in the research would be impractical. The focus is to determine whether it is possible to coherently model the cause and effect relationships of various components within a system to establish a base model for expansion further to other connected systems and an increased number of observed failures. From this some constraints and assumptions were made to ensure that the model remained simple yet clear and relevant to the research aims, these assumptions and limitations are outlined in Chapters 4 and 5 for each specific BN model.

3.5.1 BN Formulation and Analysis Methodology.

There are many step-by-step procedures in use that allow for construction of the various parts of the BN model. The procedures are useful as it allows for maintaining consistency throughout the process and offers an element of confident to the model. The procedures have varying parts depending on the context of the model and how much information is already available (Neapolitan, 2004) (Neil, *et al*., 2000). However, there are key elements which all the procedures follow, these are:

Step 1 - Establish the domain and project definition.

This involves putting boundaries in place for the model. It has already been stated that the model represents the series of events within a system where a specific component failure has been observed, within module 2 on the Thistle Alpha platform. The model begins with the initial failure and ends with major events occurring.

Step 2 - Identify the objective.

This involves stating what results are expected to be achieved from the model. For the initial model the focus is on the interaction of the components and their probability of occurrence.

Step 3 - Identify the set of variables relative to the problem.

This involves filtering possible parameters that are relevant to the description and objective. For the initial model the initial variables where devised utilising a sequence of events diagram. It is always necessary to keep the number of variables/nodes to a minimum to avoid over complication initially. For the initial model approximately twenty-one nodes where first outlined.

Step 4 - Create appropriate nodes corresponding to the variables identified.

From reviewing the risk assessment projects and relevant literature, the list of variable/nodes from step three is reduced to those that will be used in the model.

Step 5 - Creating arcs between nodes.

Once the relevant nodes are identified, they are input into a BN software package, HuginResearcher7.7, and connected. This entails referring to the sequence of events from the initial failure to determine the most effective way of connecting the nodes together. The network is reviewed to ensure there are no missing factors. HuginResearcher7.7 was selected as the BN software package for this research based upon testing comparisons with another BN package in Netica. These two were tested due to the availability of full software licences. It seemed much more prudent to utilise an existing software licence. After testing both packages, Hugin was selected due to the preferred interface and ease of use of its key features, such as, the Sensitivity Analysis Wizard.

Step 6 - Obtain data and construct probability tables.

The data is sought from various sources including; experts, industrial & academic publications, the RMRI Plc. risk assessment projects, as well as databases such as: OREDA, HSE & OGP. The data is then used to create the marginal or conditional probability tables.

Step 7 - Analyse BN model.

This is where the Hugin software is used to run the model and test for conflicts in data by inserting evidence in various nodes.

Step 8 - Validate the BN Model.

Validation is a key aspect of the methodology as it provides a reasonable amount of confidence to the results of the model. In current work and literature, there is a three axiom based validation procedure, which is used for partial validation of a proposed BN model. The three axioms to be satisfied are as follows (Jones, *et al*., 2010):

- *Axiom i.*

A small increase or decrease in the prior subjective probabilities of each parent node should certainly result in the effect of a relative increase or decrease of the posterior probabilities of the child node.

- *Axiom ii.*

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

- *Axiom iii.*

  The total influence magnitudes of the combination of the probability variations from "x" attributes (evidence) on the values should always be greater than that from the set of "x-y" ($y \in x$) attributes.

3.6 Data Acquisition and Analysis Methods

3.6.1 Developing Relative Weights through Pairwise Comparison and Analytical Hierarchy Process

The AHP approach is a structured technique for organising and analysing complex decisions. It is based on the well-defined mathematical structure of consistent matrices and their associated right eigenvector's ability to generate true or approximate weights (Merkin, 1979) (Saaty, 1980). Also, it enables comparison of criteria or alternatives with respect to a criterion in a nature of the pair-wise comparison mode. Such a comparison uses a fundamental scale of absolute numbers, for example, in this research the scale is as follows; "1 is equally important", "3 is a little important", "5 is important", "7 is very important", "9 is extremely important" and "2, 4, 6, and 8 are intermediate values of important". This fundamental scale has been shown to be a scale that captures individual preferences with respect to quantitative and qualitative attributes (Saaty, 1990) (Saaty, 1994).

To find the relative weight of each criterion, an AHP approach containing a pair-wise comparison matrix will be used. To conduct the pair-wise comparison matrix, at first, set up n criteria in the row and column of a $n \times n$ matrix. Then, perform the pair-wise comparison to all the criteria by applying a ratio scale assessment. The assessment scale is shown in Table 3-1 and each expert has to understand it before completing the pair-wise comparison. This table contains two parts which describe the numerical weighting together with the explanation of each number. The first part is on the left hand side which explains "IMPORTANT", while the right hand side is the second part of the table which describes "UNIMPORTANT" (Ahmed, *et al*., 2005) (Kou, *et al*., 2016).

Table 3-1: Weighting scale for the Pairwise 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 qualified judgements on pairs of attributes A_i and A_j are represented by a $n \times n$ matrix *A* as shown in Equation 3-11 (Koczkodaj & Szybowski, 2015).

$$A = (a_{ij}) = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a/a_{12} & 1 & \dots & a_{2n} \\ . & . & \dots & . \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \quad (3\text{-}11)$$

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

For a matrix of order *n*, $(n \times (n-1)/2)$ comparisons are required. According to Ahmed *et al.* (2005), the weight vector indicates the priority of each element in the pair-wise comparison matrix in terms of its overall contribution to the decision-making process (Tan & Promentilla, 2013). Such a weight value can be calculated using Equation 3-12.

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) \ (k = 1, 2, 3, \dots, n) \quad (3\text{-}12)$$

where a_{ij} stands for the entry of row *i* and column *j* in a comparison matrix of order *n*.

The weight values obtained in the pair-wise comparison matrix are checked for consistency purpose using a Consistency Ratio (*CR*). The *CR* value is computed using the following equations (Saaty, 1980):

$$CR = CI/RI \quad (3\text{-}13)$$

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (3\text{-}14)$$

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \tag{3-15}$$

where n equals the number of items being compared, λ_{max} stands for maximum weight value of the $n \times n$ comparison matrix, *RI* stands for average random index (Table 3-2) and *CI* stands for consistency index (Donegan & Dodd, 1991) (Saaty, 1980).

Table 3-2: Saaty's Random Index (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

CR is designed in such a way that a value greater than 0.10 indicates an inconsistency in pair-wise comparison. If *CR* is 0.10 or less, the consistency of the pair-wise comparisons is considered reasonable (Saaty, 1980).

3.6.2 Developing Relative Weights through Incomplete Data

When constructing a BN the prior probabilities are required to be assigned locally to the probability link, $P(Parent(A_i)) \rightarrow P(Child(B_i))$, as a conditional probability, $P(B_i|A_i)$. Where i is the number of possible states of the parent node and the child node. However, it is not always a straightforward process to obtain the relevant data. In principle, the majority of the data can be acquired through failure databases or experimentation. However, designing and conducting experiments can prove difficult and historical data does not always satisfy the scope of certain nodes and CPTs within a BN. Therefore, in practice, it is necessary to rely on subjective probabilities provided by expert judgement as an expression of an individual's degree of belief. However, since subjective probabilities are based on informed guesses, it is possible for deviation to occur when the data is expressed as precise numbers.

As the process of creating PC questionnaires, distributing them and waiting for feedback can be time consuming, this process to be amended by utilising hard data from risk assessment experimentation and historical data. This entails utilising hard data from the parent nodes and sections of the child node CPT to create relative weights for the parent nodes and apply those to the symmetric method algorithm.

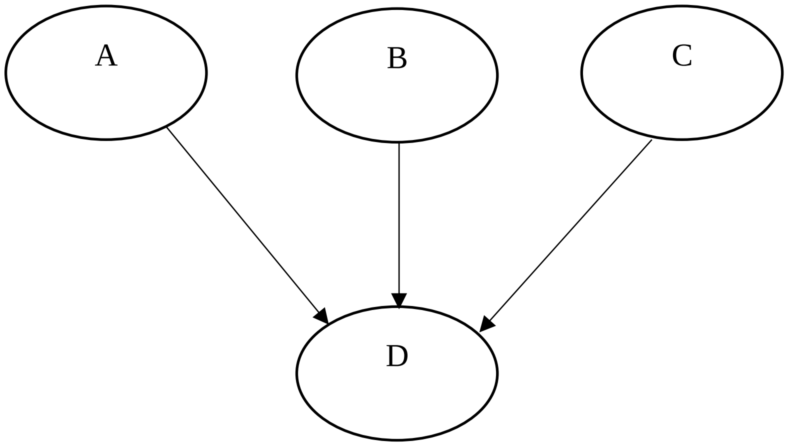


Figure 3-9: Sample BN representing 3 parents and 1 child

Figure 3-9 demonstrates a sample BN with three parents and one child, with the notation *A, B, C & D* respectively. While it is not possible to accurately obtain *P(D|A, B, C)* or even *P(D|A, B)* through historical or experimental data. It is possible to obtain the conditional probability of event *Z* give the individual parents. i.e.; *P(D|A)*, *P(D|B)* and *P(D|C)*. These conditional probabilities can be used to develop normalised weights for the parent nodes.

The individual local conditional probabilities of the parent to child can be distributed by relative importance for the associated child node, i.e. the normalised weight. Hence, in normal space and using the notation outlined in Figure 3-9, the probability of *D* being of state *"Yes"* given that the probability of *A* being in state *"Yes"* is equal to $\hat{X}_A$, where $\hat{X}_A$ is the relative importance of the parent node *A*. This is applied across all the parent nodes and is demonstrated by Equation 3-16 (Riahi, 2010).

$$P(D = \text{“}Yes\text{”}|A = \text{“}Yes\text{”}) = P(\hat{X}_A) = \frac{P(X_A)}{\sum_{m=A}^{n} P(X_m)} \qquad (m = A, B, \ldots . N)$$

$$\ldots \qquad (3\text{-}16)$$

$$P(D = \text{“}Yes\text{”}|n = \text{“}Yes\text{”}) = P(\hat{X}_n) = \frac{P(X_n)}{\sum_{m=a}^{n} P(X_m)}$$

where, $P(X_A)$ is the individual probability of A.

Therefore,

$$P(\hat{X}_A) + P(\hat{X}_B) + \cdots + P(\hat{X}_n) = 1$$

In normalised space, based on the influence of each parent node, the conditional probability of a binary child node "*D*" given each binary parent node, X_n , where n = A, B, ..., *n.*, can be estimated as follows.

$$P(D = \text{“}Yes\text{”}|A = \text{“}Yes\text{”}) = w_1$$

$$P(D = \text{“}Yes\text{”}|B = \text{“}Yes\text{”}) = w_2$$

$$\ldots \qquad (3\text{-}17)$$

$$P(D = \text{“}Yes\text{”}|n = \text{“}Yes\text{”}) = w_n$$

$$\sum_{n=1}^{n} w_n = 1$$

Following from Equations 3-16 and 3-17, it is possible to calculate the weights of the parents given the individual parent to child conditional probabilities (Riahi, 2010).

3.6.3 Symmetric Method

The symmetric method provides an input algorithm which consists of a set of relative weights that quantify the relative strengths of the influences of the parent-nodes on the child-node, and a set of probability distributions the number of which grows only linearly, as opposed to exponentially, with the number of associated parent-nodes. Yet the most common method of gathering the required data for the algorithm is to use expert judgements. It is also possible to utilise the symmetric method with historic data and experimentation. While it is very difficult or not possible to complete a large CPT in a BN using hard data, it is possible to obtain key conditional probabilities for a node.

To outline the symmetric method let us consider the network in Figure 3-9. In this example, node D has 2^3 different parental configurations, as there are three parents with two states each (Yes and No). Hence the CPT will consist of 2^3 probability distributions. The scale and scope of the CPT and node provides considerable difficulty when attempting to gather data to complete the CPT. Even if one were to utilise expert judgements to complete the CPT, it would demand a considerable amount of intensive effort on the part of the expert. An additional issue is that the CPT grows exponentially given the number of parents and states. A CPT quantifying the dependency on *n* parents would demand 2^n distributions in order to be functional. It is this exponential growth with the number of parents that constitutes the essential problem. This symmetry method simplifies the problem of exponentially large CPTs.

For calculation of the CPT for the child node “D”, assume that the number of distributions grows linearly as opposed to exponentially. i.e. with the network shown there are 2×3 distributions linearly as opposed to 2^3 exponentially. If the states of the parents have one-to-one capability correspondence (which is an equivalence relation) then the number of 'Questions' regarding the CPT for the child node is reduced (Das, 2008).

The parent nodes, A, B and C, in this instance, have the same number of states: $k_1 = k_2 = ... = k_n, = k$, where, k_n represents the number of states of the n^{th} node.

Suppose: $B = b^t$ is compatible with $A = a^t$, for $1 \leq t \leq k$.

$B = b^t$ is not compatible with $A = b^s$ whenever $t \neq s$ where t and s are the sets of n elements of the parents.

Let $\{comp(B = b^s)\}$ denote the C*ompatible Parent Configuration* where parent B is in the state y^s and the rest of the parents are in states compatible to $B = b^s$

Therefore, using the symbol '≡' to relate two identical sets, one has:

$$\{comp(A = a^s)\} \equiv \{comp(B = b^s)\} \equiv \{comp(C = c^s)\} \equiv \{A = a^s, B = b^s, C = c^s\}$$

Consider the network shown in Figure 3-9, Starting with parent A and interpreting the compatible parent configurations as follows in equation 3-18 (Das, 2008):

$$\{comp(A = s)\} \equiv \{comp(B = s)\} \equiv \{comp(C = s)\} \equiv \{A = s, B = s, C = s\} \qquad \textit{(3-18)}$$

where the set contains two states. $S = Yes, No$

Hence the probability distribution over the child node D will be:

$$P(D|\{comp(A = s)\}) = P(D \,|\, \{comp(B = s)\}) = P(D \,|\, \{comp(C = s)\}) \qquad \textit{(3-19)}$$

where the set contains two states. $s = Yes, No$

However, the CPT requires probability distributions for all possible parental configurations compatible or not. This leads to the concept of relative weights. The relative weights are calculated utilising the individual parent to child conditional probabilities (Das, 2008).

The Weighted Sum Algorithm

It is possible to apply the weighted sum algorithm as the following information has been identified:

i) The relative weights of the parent nodes $w_1, \ldots, w_n$, and,

ii) The $k_1 + \ldots + k_n$ probability distributions over event "*D*", of the linear type, for compatible parental configurations.

Given the information provided the following algorithm is used to produce an estimate, based information from historical data sources, of the $k_1 \times \ldots \times k_n$ distribution for child node "*D*" (Das, 2008).

$$P\left(x^l \mid y_1^{S_1}, y_2^{S_2}, \ldots, y_n^{S_n}\right) = \sum_{j=1}^{n} w_j \,.\, P\left(x^l \mid \{Comp(Y_j = y_j^{S_j})\}\right) \qquad (3\text{-}20)$$

where: $l = 0, 1, \ldots, m$ and $S_j = 1, 2, \ldots, k_j$.

This weighted sum algorithm is applied to the distribution over child node "*D*" for compatible parental configurations. The algorithm utilises the weights determined by the AHP method.

3.7 Decision-Making Formulation and Analysis Methodology

When developing a decision-making methodology it is important to clearly define the domain that it is to represent. The attributes must be appropriately allocated, which careful attention being paid to what each attribute shall represent and where they shall rank in the evaluation hierarchy. The fundamental part of developing a coherent decision-making method, with the ability to deliver coherent results, lies in its evaluation hierarchy and the allocation the belief degrees and weights. With this in mind, a decision-making method has been established to ascertain the most suitable WSN design for use in the asset integrity monitoring of an offshore electrical generation system. To ensure a coherent method was established knowledge was obtained through reviewing literature and conversing with industrial experts (Liu, *et al*., 2004).

There are a number of steps involved in the procedure for applying a decision-making algorithm to a problem. Having a number of steps is key for maintaining consistency throughout the process and offers and element of confidence to the final analysis (Liu, *et al*., 2004). There are key elements that the procedure must follow, these are outlined as follows:

1. Establish the domain and definition.

This involves putting boundaries in place in order to prevent the process from becoming too complex. A finite number of wireless sensor nodes will be established in key areas of the machinery.

2. Identify the objective.

This involves stating what results are to be expected to be achieved from the problem-solving process. For this procedure and analysis, the goal is to determine the most suitable WSN based upon a set of attributes related to the design of a WSN. Furthermore, the evidential reasoning approach shall be utilised for the decision-making process.

3. Identify a set of attributes relative to the problem.

This involves filtering possible attributes that are relative to the description and the objective. For this problem, the attributes were devised from literature studies based upon the key hardware attributes and criteria of a WSN. It is necessary to keep the attributes to a sensible number at this stage to avoid over complications when applying the decision-making algorithm.

4. Develop the evaluation hierarchy.

Once the attributes have been established, a hierarchy must be determined n order to coherently develop a solution to the problem. This hierarchy groups certain attributes under one general attribute. This allows for a smaller number of attributes to be aggregated gradually to reduce the calculation complexity of the decision-making algorithm.

5. Outline suitable evaluation grades.

This key for the process of data gathering for the decision-making algorithm. A sensible set of evaluation grades was established to maintain consistency throughout the problem-solving process. In the end, five grades were selected in order to accurately outline each WSNs suitability and to assist with the qualitative to quantitative assessment.

6. Obtain data develop the belief degrees and attribute weights.

The belief degrees are sought from expert judgement through the use of data questionnaires. Initially the weights of the attributes are assumed to be normalised, then weights determined from expert judgements through Pairwise Comparison and AHP are to be applied to the decision-making process. The Pairwise Comparison and AHP processes have been outlined in section 3.6.1. This allows for a good degree of comparison when establishing the final results and WSN performance rankings.

7. Attribute aggregation.

Once the weights and beliefs of the basic attributes are determined the ER algorithm can be applied to aggregate the attributes to determine the belief degrees for the general attributes. Similarly, once the beliefs for the general attributes are determined, they also can be aggregated to find the overall suitability belief degree for each WSN. The data aggregation for both the basic attributes and general attributes is conducted with both normalised weights and calculated weights.

8. Utility assessment and ranking.

Once the overall belief degrees of each WSN have been determined, then the WSNs can be ranked in terms of their suitability for offshore applications. A utility interval is determined for each WSN for both the normalised weights and the calculated weights. These utility intervals are then ranked from greatest to smallest. The WSN with the greatest value is the most suited for offshore application.

9. Analyse the results.

Each of the proposed WSNs are to be ranked based upon their performance in the decision-making analysis. The analysis includes the comparison of applying normalised weights and calculated weights. This is useful to test conflicts on the data and the potential accuracy of the belief degrees.

10. Sensitivity analysis.

A sensitivity analysis is conducted to determine how responsive the output of the analysis are to small variations in the input data. The sensitivity analysis provides a degree of confidence that the ER algorithm has been applied correctly and has functioned as intended.

11. Validate the decision-making process.

Validation is a key aspect to the methodology, as it provides a reasonable amount of confidence to the results. In current literature, there is an axiom based validation procedure, which is useful for partial validation of the process. The aggregation process may not be rational or meaningful if it does not follow certain axioms. The four axioms to be assessed are as follows (Yang & Xu, 2002) (Durnbachm, 2012):

- *Axiom 1 (Independence).*

  A general attribute must not be assessed to an evaluation grade, H_n, if none of the basic attributes in E are assessed to H_n.. This means that if $\beta_{n,i} = 0$ for $i = 1, \ldots, L$ then $\beta_{n,} = 0$ $(n = 1, \ldots, N, n \neq k)$.

- *Axiom 2 (Consensus).*

  The general attributes should be precisely assessed to a grade H_n, if all of the basic attributes in E are assessed to H_n. This means that if $\beta k_{,i} = 1$ and $\beta_{n,i} = 0$ and $n = 1, \ldots, N, n \neq k$, then $\beta_{k,} = 1$ and $\beta_{n,} = 0$.

- *Axiom 3 (Completeness).*

  If all basic attributes in E are completely assessed to a subset of evaluation grades, then the general attributes should be completely assessed to the same subset of grades.

- *Axiom 4 (Incompleteness).*

  If an assessment for any basic attribute in E is incomplete, then the assessment for the general attribute should be incomplete to a certain degree.

3.7.1 Evidential Reasoning

3.7.1.1 Background

Numerous decision-making problems in management and engineering involve a several attributes of both a qualitative and quantitative nature. A comprehensive decision cannot be made with taking into account all attributes in question. It is the normal handling of qualitative attributes along with uncertain or incomplete information that causes complexity in multiple attribute assessments. There has been an increase in the development of theoretically sound methods and tools which deal with Multiple Attribute Decision Analysis (MADA) problems in a coherent, rational, reliable and repeatable manner (Yang & Xu, 2002) (Chen, et al., 2013).

There has been considerable research conducted on integrating techniques from Artificial Intelligence to Operational Research for handling uncertain information. From this line of research, the Evidential Reasoning (ER) approach was developed for MADA. This method of decision-making is based on an evaluation analysis model and the Dempster-Schafer (D-S) theory of evidence. The ER approach has been applied to decision-making problems in engineering, design and safety and risk assessment and supplier assessment. For example, motorcycle assessment, cargo ship design (Yang & Xu, 2002) and marine system safety analysis (Ren, *et al*., 2005). The key component of the ER approach is an ER algorithm developed around a multi-attribute evaluation framework or hierarchy and the evidence combination rule of D-S theory (Yang & Xu, 2002) (Chen, *et al*., 2013).

This ER algorithm can be used to aggregate attribute in a multilevel structure, and a rational aggregation process needs to satisfy certain self-evident rules, commonly referred to as synthesis axioms. Suppose there are two levels of attributes with general attributes at the top and several basic attributes at the bottom level. Each basic attribute can be assessed against a given set of evaluation grades. An attribute may be assessed against an individual or a subset of the evaluation grades, with different degrees of belief (Yang & Xu, 2002) (Yang, *et al.*, 2003) (Zhang, et al., 2016).

In order to apply the ER algorithm, a set of variables and a hierarchical structure of general and basic attributes must first be defined. The variables and hierarchical structure are based the definition and scope of the given problem. Figure 3-10 shows an example of a general attribute with 3 basic attributes, taken from the full analysis presented in Chapter 6.

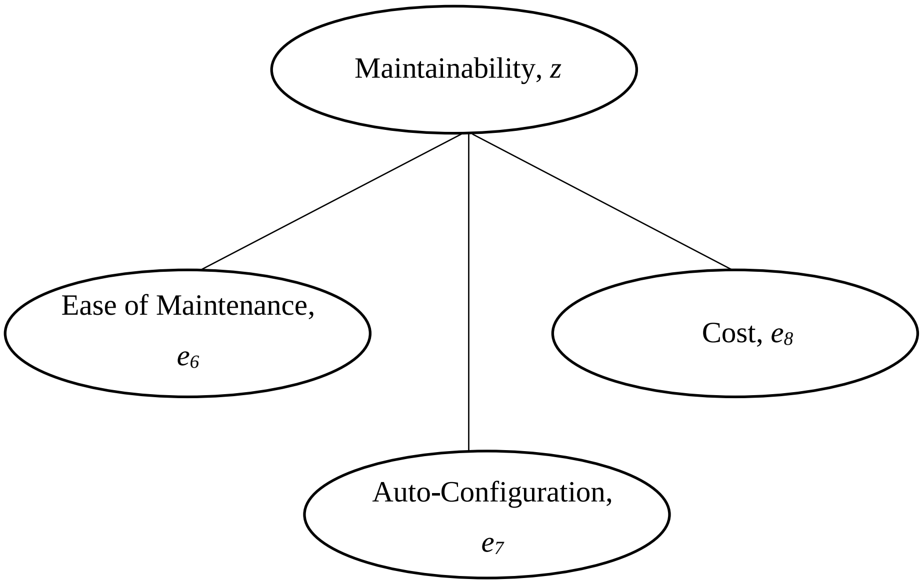


Figure 3-10: Evaluation hierarchy example

3.7.1.2 The Evidential Reasoning Algorithm

Subjective judgements may be used to distinguish one alternative from another in terms of qualitative attributes. For example, to evaluate the Maintainability of a WSN some typical judgements may be that "*the maintainability of the WSN is poor, average* or *good*". In this instance the terms *poor, average* and *good* denote clear, distinct evaluation grades. However, in terms of applying evidential reasoning, three evaluations grades are not sufficient. Therefore, five evaluation terms have been outlined, with H_n denoting the n^{th}

evaluation grade (Ren, *et al*., 2005) (Yang & Xu, 2002) . This is demonstrated by Equation 3-21:

$$H_n = \{Poor\ (H_1)\ \ Indifferent\ (H_2)\ \ Average\ (H_3)$$

$$Good\ (H_4)\ \ Excellent\ (H_5)\} \qquad \textit{(3-21)}$$

Maintainability is not an easy attribute assess directly, so it is defined by three basic attributes, as previously stated. It is possible to directly assess the basic attributes and hence the general attribute.

In hierarchical assessment, higher level attributes are assessed through lower level attributes, i.e. if the *Ease of Maintenance* (e_6), *Auto-Configuration* (e_7) and *cost* (e_8) are all deemed to be *Average* for a WSN. Then the *Maintainability (z)* is deemed to be *average*. In evaluation of the qualitative attributes, uncertain judgments can be used. It is important to note that in the analysis expert judgements are used for data collection and analysis. In this instance, the assessment of *maintainability (z)* may be as follows (Yang & Xu, 2002):

i. 50% sure that *Ease of Maintenance* (e_6) is *good* and 50% sure that it is *excellent.*
ii. 20% sure that the *Auto-configuration* (e_7) is *indifferent, average* and *good* and 40% sure that it is *excellent*.
iii. 20% sure that the *Cost* (e_8) is *poor* and *average* and 60% sure that it is *good.*

In the above assessment, the percentages are referred to as belief degrees, and sometimes used in decimal format (0.2, 0.4, 0.6 *etc.*). It should also be noted that all assessment grades sum to 1 for each attribute. This is key in the application of the ER algorithm and all beliefs in the future analysis shall sum to 1. It is possible to adapt the ER algorithm to deal with incomplete belief degrees. However, that shall not be outlined further. For further reading purposes, Yang & Xu (2002) outlines an ER algorithm for incomplete beliefs in great detail.

Continuing on, it is supposed that there is a simple two-level hierarchy, as outlined. Suppose there are L basic attributes e_i $(i = 1 \ldots L)$ *a*ssociated with general attribute z. the basic set of attributes are defined by Equation 3-22:

$$E = \{e_1 \quad e_2 \ldots e_i \ldots e_L\} \tag{3-22}$$

Suppose the weights of each attribute are given by Equation 3-23:

$$\omega = \{\omega_1 \quad \omega_2 \ldots \omega_i \ldots \omega_L\} \tag{3-23}$$

where, ω_i is the relative weight of the i^{th} basic attribute (e_i) with $0 \leq \omega_i \leq 1$. The relative weights play a vital role in the ER assessment. The relative weights may be estimated using simple rating methods or pairwise comparison methods (Li & Liao, 2007) (Ren, *et al*., 2005) (Yang & Xu, 2002).

Suppose there are N evaluation grades defined collectively to provide a full set of standards for the assessment of the attribute, as shown by Equation 3-24:

$$H = \{H_1 \quad H_2 \ldots H_i \ldots H_N\} \tag{3-24}$$

where, H_n is the n^{th} evaluation grade and it is assumed that H_{n+1} is preferred to H_n. The given assessment for e_i $(i = 1 \ldots L)$ an alternative can be represented by Equation 3-25:

$$S(e_i) = \{(H_n \beta_{n,i}), n = 1, \ldots, N\} i = 1, \ldots, L \tag{3-25}$$

where, $\beta_{n,i} \geq 0$, $\sum_{n=1}^{N} \beta_{n,i} \leq 1$ and denotes the belief degree of an attribute given a certain evaluation grade. In other words, the attribute e_i is assess to the grade H_n with a degree of belief of $\beta_{n,i}$, $n = 1 \ldots N$. the assessment of an attribute, $S(e_i)$ is complete if the sum of the belief degrees is equal to 1, i.e. $\sum_{n=1}^{N} \beta_{n,i} = 1$.

Let β_n be the belief degree that the general attribute z is assessed, to the grade H_n. the problem is to generate β_n $(n = 1, \ldots, N)$ by aggregating the assessments for all of the associated basic attributes. This is where the ER algorithm is applied.

The ER algorithm can now be outlined. Let $m_{n,i}$ be the probability mass representing the degree to which the i^{th} basic attribute, e_i, supports the hypothesis that the attribute z is assessed to the n^{-th} grade, H_n. Similarly, let $m_{H,i}$ be the remaining probability mass unassigned to any individual grade after all grades have been considered for the assessment of the general attribute (Li & Liao, 2007) (Yang & Xu, 2002) (Chen, *et al*., 2013). In terms of the basic attributes, e_i, the probability mass is calculated by Equation 3-26:

$$m_{n,i} = \omega_i \beta_{n,i} \quad n = 1, \ldots, N \tag{3-26}$$

Similarly, $m_{H,i}$ is given by Equation 3-27:

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i} \tag{3-27}$$

Also, $E_{I(i)}$ must be defined as the subset of the i basic attributes, as given by Equation 3-28:

$$E_{I(i)} = \{e_1 \quad e_2 \ldots \; e_i\} \tag{3-28}$$

Let $m_{n,I(i)}$ be the probability mass defined as the degree to which all i attributes in $E_{I(i)}$ support the hypothesis that z is assessed to the grade H_n. Similarly, $m_{H,I(i)}$ is the remaining probability mass which is unassigned to individual grades after all of the basic attributes in $E_{I(i)}$ have been assessed. The terms $m_{n,I(i)}$ and $m_{H,I(i)}$ can be determined by combining the basic probability masses $m_{n,j}$ and $m_{H,j}$ for all values of $n=1, \ldots, N, j=1, \ldots, i$. (Li & Liao, 2007) (Yang & Xu, 2002) (Chen, *et al*., 2013).

Given the definitions and terms outlined in the above paragraphs the ER algorithm can be demonstrates by Equations (3-29), (3-30) and (3-31):

$$m_{n,I(i+1)} = K_{I(i+1)} \begin{pmatrix} m_{n,I(i)}m_{n,i+1} + m_{n,I(i)}m_{H,i+1} \\ +m_{H,I(i)}m_{n,i+1} \end{pmatrix} \quad n = 1, \ldots, N \tag{3-29}$$

$$m_{H,I(i+1)} = K_{I(i+1)}m_{H,I(i)}m_{H,i+1} \tag{3-30}$$

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

$$i = 1, \ldots, L-1 \tag{3-31}$$

where $K_{I(i+1)}$ is a normalising factor so that $\sum_{n=1}^{N} m_{n,I(i+1)} + m_{H,I(i+1)} = 1$. It is important to note that $m_{n,I(1)} = m_{n,1}$ for $n=1 \ldots, N$ and $m_{H,I(1)} = m_{H,1}$. Continually, the basic attributes are numbered subjectively, meaning that the results in $m_{n,I(L)}$ and $m_{H,I(L)}$ are not the dependent on the order that the basic attributes are aggregated (Li & Liao, 2007) (Yang & Xu, 2002).

Furthermore, in the ER algorithm, the combined belief degree β_n must be found in order to finalise the decision –making process. This is calculated through Equation 3-32:

$$\beta_n = \frac{m_{n,I(L)}}{1 - m_{H,I(L)}}, \qquad n = 1, \ldots, N, \qquad i = 1, \ldots, L$$

$$\beta_H = 1 - \textstyle\sum_{n=1}^{N} \beta_n \tag{3-32}$$

where, 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 shows a degree of incompleteness in the assessment (Liu, *et al.*, 2004).

Finally, the attributes must be ranked based upon their aggregated belief degrees from the ER algorithm. This can be done through utility assessment. Suppose the utility of an evaluation grade, H_n, is denoted by $u(H_n)$. The utility of the evaluation grade must be determined beforehand, with $u(H_1) = 0$ and $u(H_5)=1$ assuming there are five evaluation grades (Yang, 2001). If there is not preference information available then the values of $u(H_n)$ can be assumed to be equidistant, as shown by Equation 3-33:

$$u(H_n) = \{u(H_1) = 0, u(H_2) = 0.25, u(H_3) = 0.5, u(H_4) = 0.75, u(H_5) = 1\} \quad (3\text{-}33)$$

The estimated utility for the general and basic attributes, $S(z(e_i))$, given the set of evaluation grades is given by Equation 3-34:

$$u\left(S\big(z(e_i)\big)\right) = \sum_{n=1}^{N} u(H_n)\beta_n\,(e_i) \quad (3\text{-}34)$$

In Equation 3-34 the term $\beta_{n,i}(e_i)$determines the lower bound of the likelihood that e_i is assessed to a grade H_n. the upper bound is given by $\beta_n(e_i) + \beta_H(e_i)$. This is given the assumption that there is an incomplete belief degree. In the event that $\sum_{n=1}^{N} \beta_n = 1$then this is the utility estimation and a rank for each attribute can be determined (Yang, 2001). A numerical assessment and example shall be conducted in Chapter 6.

3.8 Conclusion

A framework and methodology for the Asset Integrity Case has been proposed to assist with the initial development and decision making. A generic risk based framework has been used as the basis as the majority of the Asset Integrity Case development focuses on dynamic risk assessment. Hence it makes sense to primarily base the framework for development from a risk based framework. There are a number of components within the framework, split into three key areas. These three areas involve the scope and domain of the risk assessment, the dynamic risk assessment itself and the addition of remote monitoring and sensing. The framework is designed so that it can be employed to several offshore areas to further develop the Asset Integrity Case. This framework should be viewed as part of a process of continuous improvement.

Two key research methodologies are outlined; i) a BN formulation methodology which is applied in Chapters 4 and 5, and ii) a decision-making methodology which is applied in Chapter 6. Furthermore, the research techniques used throughout Chapters 4, 5 and 6 have been outlined to avoid continuous and unnecessary repletion within the thesis. All techniques are outlined in Chapter 3 and are applied to numerical analyses across Chapters 4, 5 and 6.

CHAPTER 4:

INITIAL BAYESIAN NETWORK MODELLING OF A SINGLE COMPONENT FAILURE IN AN OFFSHORE ELECTRICAL POWER GENERATOR

Summary

In this chapter, the proposed Bayesian Network methodology, outlined in Chapter 3, is demonstrated by applying it to a case study. The study undertakes the evaluation of the effects a rotor retaining ring failure has on an offshore electrical generation unit and key surrounding systems, within a module of a fixed steel offshore platform in the North Sea.

4.1 Introduction

The Thistle Alpha Platform, located in the North Sea, has three gas turbine driven electrical generators, (termed Unit A, Unit B & Unit C), each of which is capable of providing 100% of the platform power requirements. The platform is currently part of the Thistle Late Life Extension (LLX) strategy, which aims to recover over 35 million barrels of oil through to 2025 from the Thistle and Deveron oil fields. In order for the platform to be operable to 2025 and beyond, the LLX strategy incorporates a series of major initiatives to improve structural and topside integrity, upgrade safety and control systems, improve the oil production and water treatment process and provide reliable power. This provides an ideal scenario to identify possible areas of failure and what possible consequences could occur (Cresswell, 2010).

During the initial part of the LLX strategy, in 2009, the Unit A generator was no longer in operation due to a fire which occurred in 2007 and Unit C was providing all of the power as Unit B was under refurbishment. The alternator on each generator has two rotor retaining rings which ensure that the rotor windings, insulation and packing blocks are contained as they rotate at the operational speed of 3600 rpm. These rings are considered to be the most highly stressed components in the generator unit. There was a concern on the Thistle Alpha platform of the possibility of one or both of the rings failing due to stress corrosion cracking. This provided a sound basis with which to begin constructing an initial BN to show the cause and effect relationships on failure potentially has on the surrounding equipment and systems.

4.2 Location of Equipment

The potential damage scenarios from the failure of the retaining rings shall be assessed for the Unit B generator as it is contained within module 2 of the platform, which has significant hydrocarbon inventories adjacent to either side of the module, as shown by Figure 4-1. Hence the potential for damage to key hydrocarbon systems is present and provides an ideal position to model the cause and effect relationship of the retaining ring failure across various systems. Unit C on the other hand is located in module 21 (see Figure 4-2) with no hydrocarbon inventories adjacent or directly below (module 5 is redundant), and therefore the potential major events regarding hydrocarbon release is not considered for this area. Figure 4-3 shows the north elevation of the platform and locations of Units B and C for completeness. Figure 4-1, Figure 4-2 and Figure 4-3 are adapted from the plot plans for the Thistle Alpha platform in Appendix E.

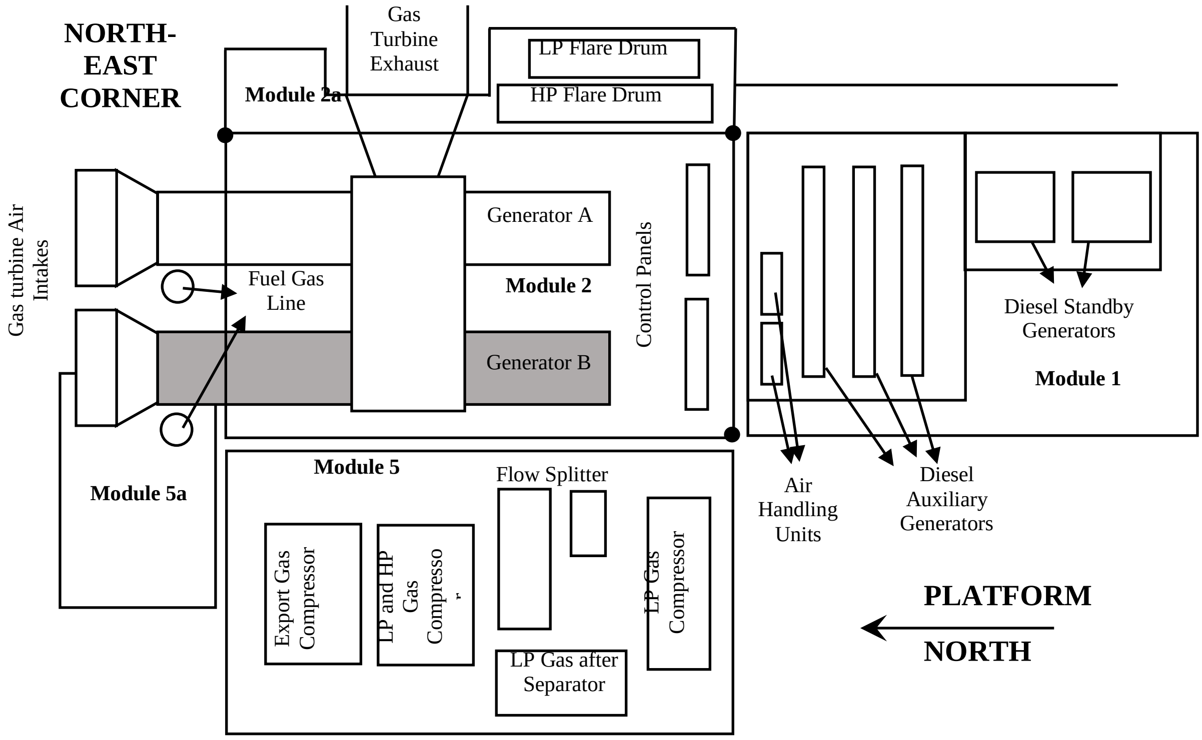


Figure 4-1: Plan view of the location of generator Unit B (adapted from Appendix E)

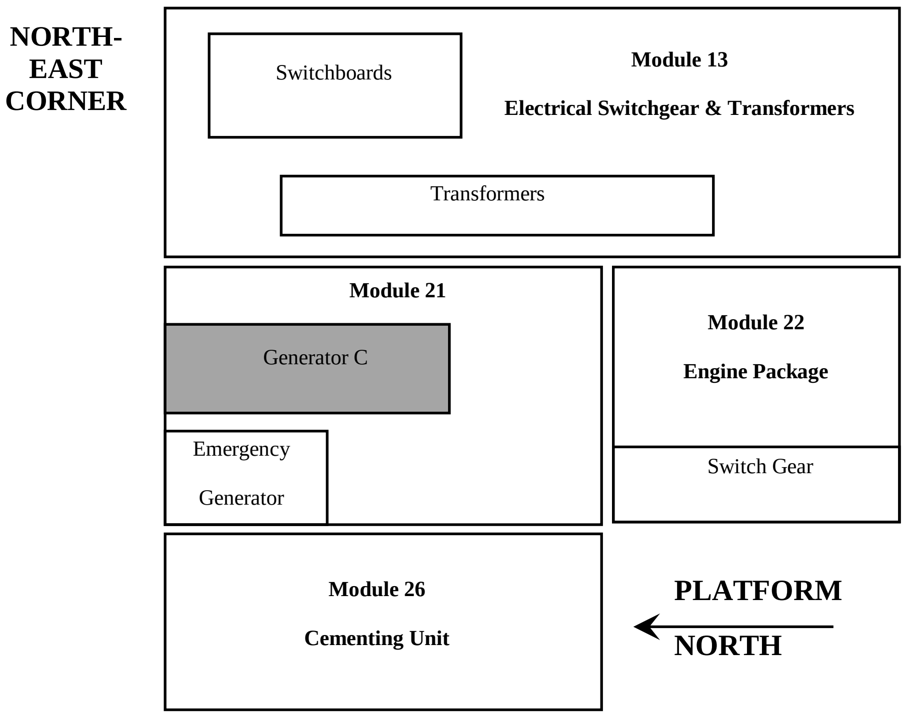


Figure 4-2: Plan view of the location of generator Unit C (adapted from Appendix E)

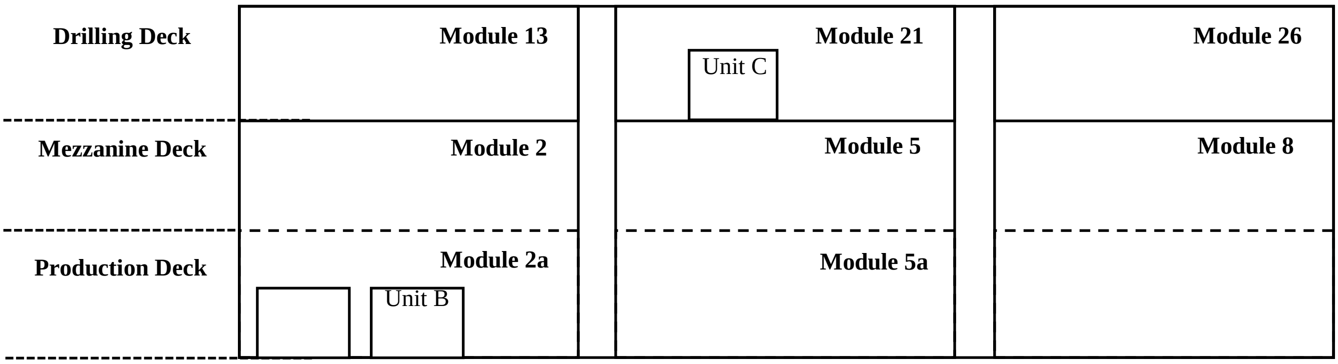


Figure 4-3: North elevation of Thistle Alpha (adapted from Appendix E)

4.3 Damage Scenarios

The turbine generator set consists of a primary alternator, driven by a gas turbine. Located after the alternator is an exciter, which generates the electromagnetic field in the stator coils of the alternator. The alternator rotor and shaft are forged in one piece with the exciter coupled onto one end. The opposite end of the shaft is coupled to the turbine drive shaft, which has an operating speed of 3600 rpm. The main shaft is supported by two main bearings, housed in large pedestals, on stools on the baseplate. The main bearings are situated in two places, between the turbine and the alternator and between the

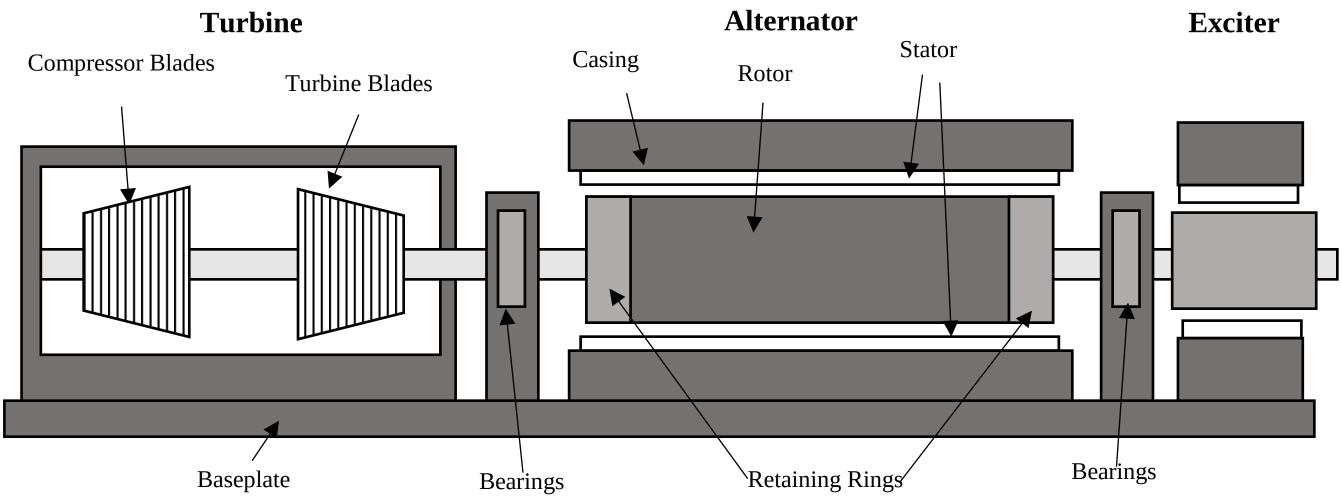


Figure 4-4: Schematic of a generator unit

alternator and the exciter. Figure 4-4 shows the generic layout of the generator set (McGeorge, 2002).

Should one of the retaining rings fail, the main shaft would become unbalanced causing potential fragmentation of the rings inside the alternator. Given the extreme tolerances' within the generator construction, the unbalanced shaft could also cause damage to other areas of the equipment, such as: the turbine blades and the exciter. Should the retaining ring fail within the alternator casing, and fragment, debris would be created within the casing. Furthermore with the machine operating at 3600rpm, an out of balance shaft would cause substantial vibrations, which could cause the main bearings to fail. Should the bearings fail, causing the shaft to become misaligned, it would result in increased damage to the turbine, alternator and exciter (RMRI Plc., 2009).

From this the most likely point of failure within the turbine is the turbine blades shearing. Multiple blade failure could lead to the turbine casing not fully containing the turbine blade debris. This would result in turbine blades being expelled through the turbine casing as high velocity projectiles. Continually, the violent shaft vibrations and misalignment could have a severe impact on the exciter and which may result in the exciter, weighing approximately one tonne, becoming detached from the main shaft. Some catastrophic failures have resulted in the exciter breaking up and some have had the exciter remain mostly intact (RMRI Plc., 2009). Should the bearings not fail, the alternator stator coils & casing, can provide enough resistance and are substantial enough to prevent the debris from the retaining ring penetrating the alternator casing. However, it is possible for the fragments to be expelled axially towards either the turbine or the exciter or both (U.S. Nuclear Regulatory Commission, 2008).

4.3.1 Physical Consequences

In the event of one or two rotor retaining ring failures, significant damage could occur within the alternator casing and fragments of the retaining ring could be expelled axially. Should the ring debris be expelled, it is assumed that it will travel in two possible direction; i) towards the turbine or ii) towards the exciter and out of the casing. Should the debris travel to the turbine there is potential for the fragments to impact the fuel gas line within the turbine. This then provides the escalation to a fire (given the location of the potential release, ignition is assumed). Should the debris travel out of the casing towards the exciter, it is considered by RMRI. Plc (2009) that while the axial velocity may be considerable, it is likely to be lower than the radial velocity that the debris would be expelled at were the casing and stator not there. Therefore, while it is possible for the ring debris to penetrate the casing, they would not have the required velocity to penetrate the module walls or deck. From this it is deemed that if retaining ring failure does not cause a bearing failure, then the consequence of the event is likely to be limited to the damages caused by the retaining ring (U.S. Nuclear Regulatory Commission, 2008).

However, should the main bearing fail, the potential consequences become much more severe. It has been stated by (RMRI Plc., 2009) that the significant damage caused by the bearing failure can potentially produce high velocity projectiles from the turbine blades being expelled and/or the exciter becoming detached. In these events, there is potential for the projectiles to impact the hydrocarbon containment around generator Unit B.

4.3.2 Areas of Escalation.

4.3.2.1 Escalation due to Turbine Blades

Based upon research conducted by the FAA (US Federal Aviation Agency) and RMRI Plc., there is a possibility of the gas turbine blades being expelled radially, through the casing as high velocity projectiles. However, it is considered not to be feasible for the projectiles to have enough energy to penetrate the module walls, nor will it be possible for the projectiles to penetrate the module decking/floor as the turbines are mounted on a substantial steel baseplate (Lundin, 2002) (RMRI Plc., 2009).

On the other hand, should the turbine blades be expelled axially out of the generator, there is potential for the blades to impact the gas import riser located in module 5a. It is important to note that should Loss of Containment (LOC) occur, due to the impact from projectiles, ignition is not assumed for the initial model. The escalation to gas riser loss of containment is taken as either Small (10mm Diameter), Medium (50mm Diameter), Full-bore and No LOC (Meher-Homji & Gabriles, 1998).

4.3.2.2 Escalation due Exciter

As stated in section 4.3, should the main bearings fail, it is considered that the exciter may become detached from the main rotor shaft and be expelled radially as a projectile. Should the exciter remain largely intact, the weight of the exciter coupled with the generator housing would prevent it from exiting the confines of the module. However, should the exciter fragment, the debris could be projected in several directions, but according to RMRI Plc. (2009), the likelihood of both the generator housing and the module wall being penetrated is reduced.

Based upon the layout of the modules, the location of the equipment and engineering judgement, it is considered possible for the exciter to impact the High Pressure (HP) Flare drum contained in module 2a, should the exciter become detached and be expelled from the housing. As stated in the instance with the gas import riser, ignition is not assumed in the event of LOC from the HP flare drum.

4.4 Possible Sequence of Events

Based upon the information stated in Sections 4.2 and 4.3 a possible sequence of events is outlined to demonstrate the initial variables identified, as shown by Figure 4-5.

As shown in Figure 4-5 if the retaining ring fails, there is a possibility that this will have an effect on the bearings, and potentially cause a failure with the bearings. This can result in one of two scenarios, violent shaft vibrations could be caused or only the bearing fail and shaft vibrations do no occur.

If violent vibrations do not occur, attention is drawn to the fragments of the failed retaining ring. These fragments potentially become projectiles within the alternator and are expelled in three possible direction; towards the gas turbine, towards the exciter or remaining in the alternator. Should the fragments of the ring fragments not become projectiles and remain within the alternator, this would provide no further escalation in terms progression of the fragments within the generator. However, should the fragments be expelled, they are assumed to move axially either to the turbine or towards the exciter. Should the fragments project towards the exciter they can potentially leave the generator unit but have no further impact on the surrounding equipment due to their low velocity (Meher-Homji & Gabriles, 1998). In the event that the fragments are expelled toward the turbine, they have the potential to impact the turbine's fuel gas line. This event can escalate to a fuel gas fire, as the conditions within the turbine are sufficient to ignite the gas, should a leak from the impact occur (RMRI Plc., 2009).

On the other hand, should violent vibrations occur following a bearing failure, attention is drawn to the possibility of turbine blades being expelled as projectiles or the exciter detaching from the shaft. If the turbine blades are not expelled and/or the exciter does not detach, that it is deemed that a major event has occurred regarding the failure of the bearing but the situation doesn't have enough potential to escalate. However, in the event that the turbine blades become projectiles, they have the potential to cause escalation in the form of possibly impacting a gas import riser located in module 5a. This event can cause escalation to the failure of the gas import riser, or should the gas riser not be impacted, a major event is deemed to occur without further escalation. Similarly, should the exciter become detached and become a projectile in any way, it is deemed to have the potential to impact the HP gas knockout flare drum. This event has the potential to escalate to failure of the HP gas flare drum, yet should the gas flare drum not be impacted, the situation is again deemed to be a major event without further escalation.

The sequence of events shown in Figure 4-5 are to form the basis of the BN by representing the possible variables outlined in step 3 of the BN methodology. The sequence of events diagram is created by analysing the situations highlighted in the potential damage scenarios and the possible physical consequences.

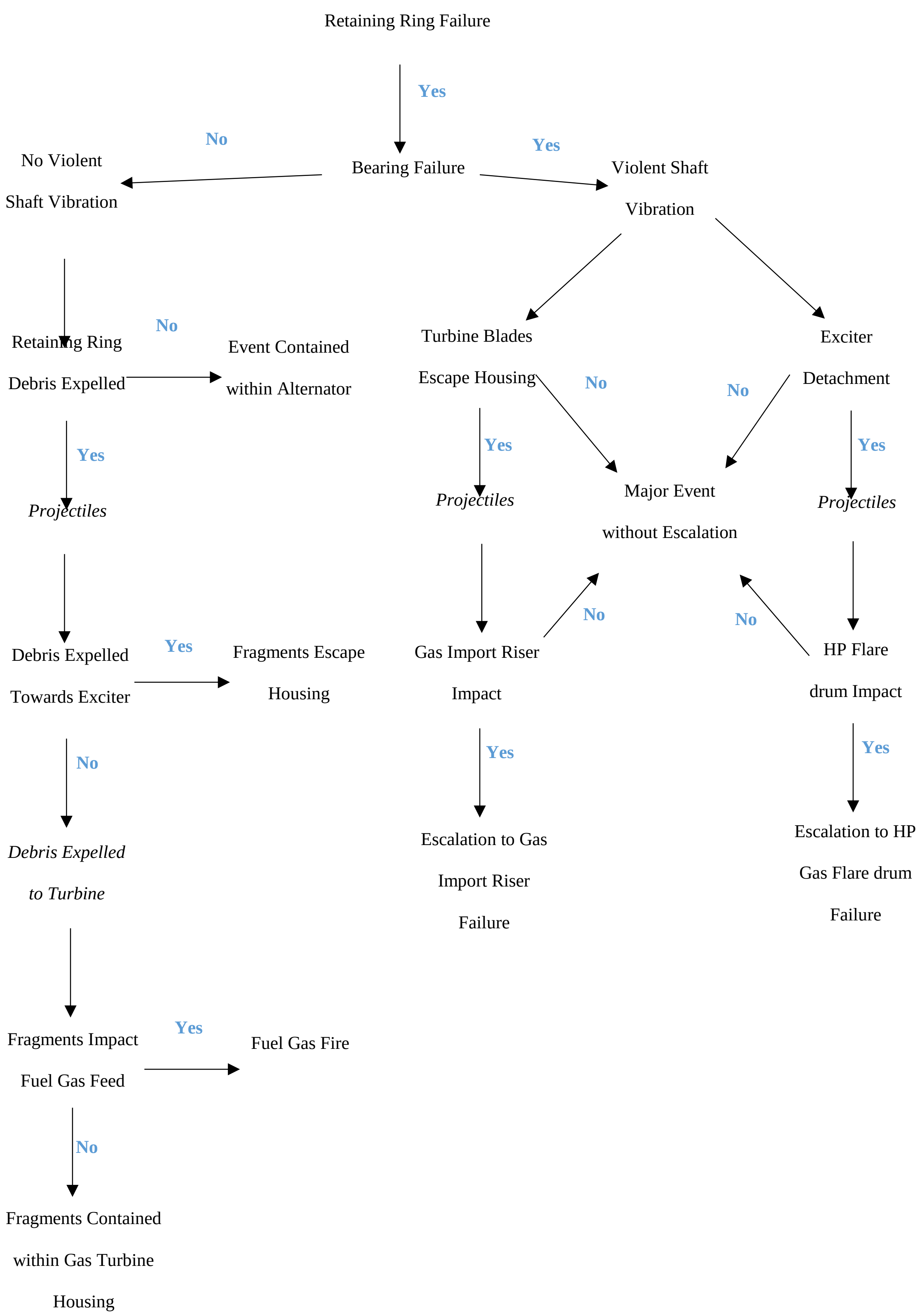


Figure 4-5: Possible sequence of events following a Retaining Ring failure within Unit B

4.5 The Initial BN Model

4.5.1 Assumptions and Limitations

There are some underlying assumptions within the model that must be explained for the model to valid and understood:

- The model has been built for the situation where the offshore platform contains no crew and hence does not consider fatalities, *i.e.* human injury and death. There are two key reasons for this; the first is that the BN model is to be for an NUI (Normally Unattended Installation) Integrity Case, where humans are not present on the platform for large periods of time, and are monitored from other platforms or onshore. Secondly, the BN is part of the development of an Integrity Case which shall focus on maintaining the integrity of the equipment as a priority, as well as the effects of incidents on the environment. Hence fatalities are not part of the initial model.
- The model is only an initial model in the development of a NUI-Integrity Case. Its purpose is to demonstrate that the cause and effect relationships between offshore failure modes, systems and components can be modelled effectively using the methodology stated in Chapter 3.
- There are many component failures that can have an effect on the outcomes of the stated events, however, the BN model presented is an initial model. Hence, the cause and effects of one component failure are analysed, to show that the model is valid before expansion to other related component failures.
- For "Fuel Gas Feed Impact & Failure" being of the state "Yes", ignition is assumed due to the nature of the environment where the fuel release is located. In

other words, the temperature within the turbine, during normal operations, is sufficient enough to ignite any fuel released from the fuel gas line.

- In contrast it is assumed that if “Gas Riser impact & Failure” and “HP Flare Drum Impact & Failure” are of the state “Yes”, then ignition is not assumed due to the area where the leaks would be located. This keeps the model from becoming too complicated by adding possible ignition sources to the analysis.

4.5.2 Nodes and Structure

The initial model is demonstrated in Figure 4-6 and is designed around the variable identified in the sequence of events shown in Figure 4-5, and is to represent the cause and effect of one initial component failure has on systems within the stated domain. The Initial BN model is not a direct representation of the sequence of events in terms of the section of the model where possible debris is expelled. Within the sequence of events if the debris is not expelled initially, it is assumed to remain in the alternator, yet if debris expelled, it is assumed to travel towards the exciter. Similarly, should the debris not be expelled to the exciter, it is assumed to be expelled towards the turbine. While this is all possible, it is more realistic to assume that if the debris is created from the retaining ring failure, it has the potential travel to the turbine and the exciter in the same instance. However, it is possible for debris to be expelled to the exciter and not to the gas turbine, whereby some debris would remain in the alternator. The way in which the BN model is created ensures that it contains all relevant possible outcomes.

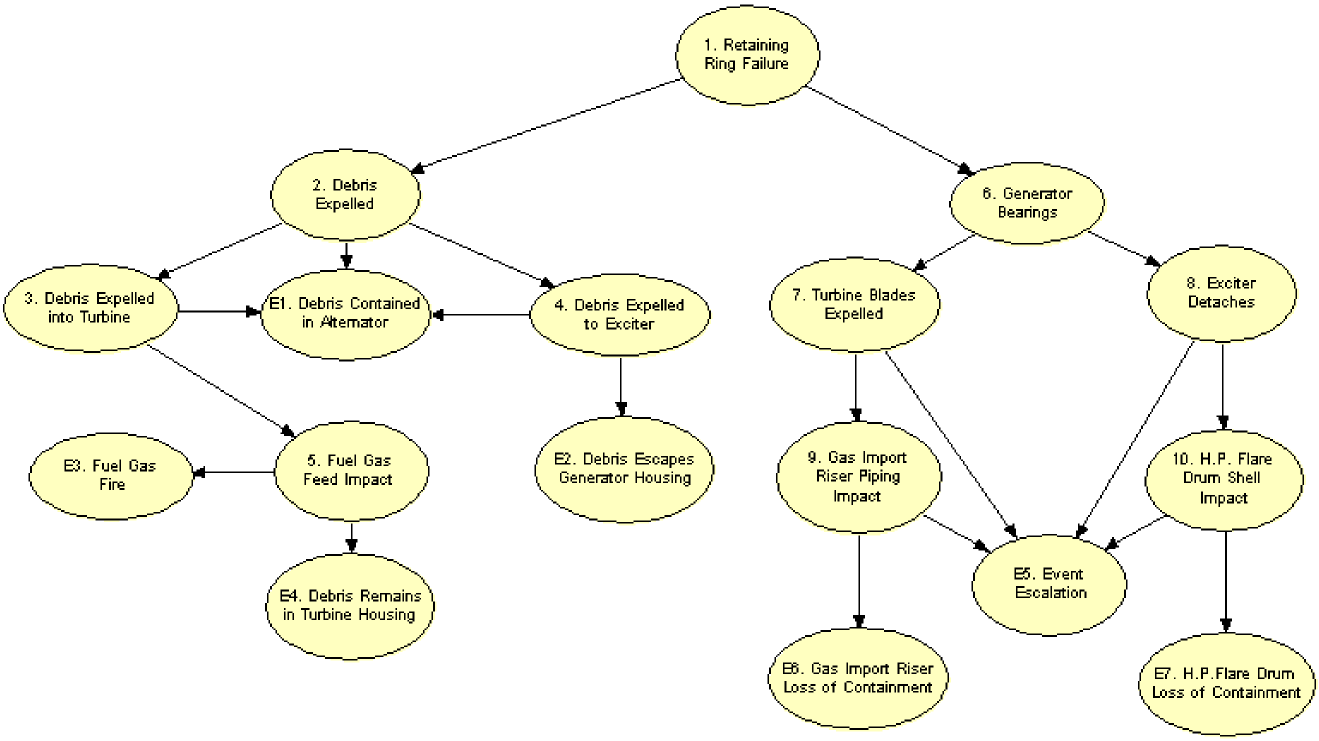


Figure 4-6: Initial BN Model representing Retaining Ring failure within an offshore generator.

In this case the analysis is conducted within module 2 of the Thistle Alpha Platform. The initial model is made up of seventeen chance nodes labelled 1 to 10 and E1 to E7. The latter nodes represent the possible events that can result from the initial mechanical failure. All nodes have two states except for event node E6 which has four. The nodes are described in the following paragraphs.

Initiating Circumstance.

1. Retaining Ring [States: Failure, No Failure] – This is a root node or parentless chance node which represents the initiating, observed component failure. The data within the node represents the frequency of either of the two retaining rings contained within the alternator failing.

Intermediate Events.

2. Debris Expelled [States Yes, No] – This chance node represents the probability of debris being created from fragments of the retaining ring and being expelled. Its conditional probabilities are set based upon the states of its parent node 1.
3. Debris Expelled into Turbine [States: Yes, No] – This chance node represents the probability of the retaining ring debris being expelled towards the turbine. Its conditional probabilities are based upon the states of its parent node 2.
4. Debris Expelled towards Exciter [States: Yes, No] – This chance node represents the probability of the debris created by the retaining ring being expelled towards the exciter. Its conditional probabilities are based upon the sates of its parent node 2.
5. Fuel Gas Feed Impact [States: Yes, No] – This node describes whether the debris from the retaining ring impacts the fuel gas feed within the gas turbine. Its conditional probabilities are based upon the states of its parent node 3.
6. Generator Bearings [States: Failure, No Failure] – This chance node represents the generator bearings failing or not failing. The conditional probabilities of this node are based upon the states of its parent node 1.
7. Turbine Blades Expelled [States: Yes, no] – This chance node represents turbine blades being expelled axially out of the turbine casing, due to the generator bearings failing and causing violent vibrations. Its conditional probabilities are based upon the states of its parent node 6.
8. Exciter Detaches [States: Yes, no] – This chance node represents the exciter being detached and acting as a projectile due to the generator bearings failing causing violent vibrations. Its conditional probabilities are based on the states of its parent node 6.

9. Gas import Riser Impact [States: Yes, No] - This chance node represents the gas import riser being impacted due to turbine blades being expelled. Its conditional probabilities are based upon the states of its parent node 7.
10. HP Flare Drum Impact [States: Yes, No] – This chance node represents the HP flare drum being impacted due to the exciter detaching and acting as a projectile. Its conditional probabilities are based upon the states of its parent node 8.

Final Events.

E1. Debris contained in Alternator [States: Yes, No] – This chance node represents the debris being contained within the alternator following debris being expelled and debris not being expelled into the turbine and/or towards the exciter. Its conditional probabilities are based upon the states of its parent nodes, 2, 3 and 4.

E2. Debris Escapes Generator Housing [States: Yes, No] – This chance node represents the retaining ring debris leaving the generator unit following its expulsion towards the exciter. Its conditional probabilities are based upon the states of its parent node 4.

E3. Fuel Gas Fire [States: Yes, No] – This chance node represents a fuel gas fire occurring within the turbine following the retaining ring fragments impacting the fuel gas line within the gas turbine. Its conditional probabilities are based upon the states of its parent node 5.

E4. Debris Remains in Turbine Housing [States: Yes, No] – This chance node represents the retaining ring debris remaining within the gas turbine in the event that there is not a fuel gas feed impact. Its conditional probabilities are based upon the states of its parent node 5.

E5. Event Escalation [States: No, Yes] – This chance node represents the probability of there being no further escalation to “Gas import Riser LOC” or “H.P. Flare Drum

LOC”. Its conditional probabilities are based upon the states of its parent nodes 7, 8, 9, and 10.

E6. Gas Import Riser Loss of Containment [States: Small (10mm Dia.), Medium (50mm Dia.), Full-bore, None] – This chance node describes key loss of containment levels in terms of the size of the hole in the gas import riser, from impact by turbine blade projectiles. Its conditional probabilities are based upon the states of its parent node 9.

E7. H.P. Flare Drum Loss of Containment [States: Yes, No] – This chance node represents escalation to the release from the high pressure flare knockout drum, located in module 2a (see Figure 4-1), following impact from the detached exciter. Its conditional probabilities are based upon the states of its parent node 10.

4.6 Data for the Initial BN Model

It is important to note that the numerical results of the model are not significant in terms of being absolute, but rather to serve to demonstrate the practicability of the model. Once a full set of verified data is fed into the model, the confidence level associated with planning and decision making under uncertainty will improve.

Data for the initial model was compiled from various sources and is by no means a fully complete representative of each possible variable. Some problems were encountered in terms of data being scarce or non-existent, data being based on small samples or data based within a given time and not up to date, such as: failures for components occurring between 1991 and 2004. It has been previously mentioned that the initial BN model presented here is purely to demonstrate a valuable method of modelling cause and effect relationships of components and systems based upon one specific initial component failure or no failure. Work involving improving deficiencies in data and the accuracy of the model can be dealt with in later research. Data and information that is fed into the BN model in the form of marginal and conditional probabilities has originated mostly from risk assessment projects conducted for the Thistle Alpha Platform, academic papers, risk assessment databases and expert judgement.

To complete the CPTs within a BN, certain data and knowledge is required regarding each specific node. For some nodes data is limited or not available. For cases where there is an absence of hard data, CPTs must be completed through subjective reasoning or the application of expert judgement. This process can be demonstrated by looking at the node "Event Escalation". This node represents the chance of escalation following key component failures. The parents of this node are: "Turbine Blades Expelled", "Exciter Detaches", Gas Import Riser Piping Impact" and "HP Flare Drum Shell Impact". In order to put together an appropriate estimate, experts must judge the situation and provide their opinions. This data acquisition can be either qualitative or quantitative in nature. However, the child node "Event Escalation" has a CPT which is too large for an expert to simply fill with their own judgements and opinions. Therefore, an effective way to gather information, to fill these large CPTs, from experts is to apply the use of a Pairwise Comparison technique in questionnaires and make use of AHP to analyse the results, combined with the symmetric method algorithm to fill the large CPTs (Zhang, *et al*., 2014).

The AHP will produce a weighting for each parent criterion in the Pairwise Comparison matrix. These weighting are applied to the symmetric method which is utilised to fill large CPTs. The symmetric method provides an input algorithm which consists of a set of relative weights that quantify the relative strengths of the influences of the parent-nodes on the child-node, and a set of probability distributions the number of which grows only linearly, as opposed to exponentially, with the number of associated parent-nodes (Lin & Kou, 2015) (Saaty, 1980).

Table 4-1 summarises the origins of the data for each node in the initial BN model. There were several sources of literature and it is not practical to list them all. For example; node 1 was determined from historical data sources, such as (U.S. Nuclear Regulatory Commission, 2008) and (Sherlock & Jirinec, 1993), whilst, in comparison, data for node 9 is from (Atkins, 2008) and (RMRI Plc., 2009).

Table 4-1 also contains the number of states for each node and the number of permutations to demonstrate an idea of how data had to be broken down before being inserted into the corresponding CPT. Since the purpose of this study is to produce a functional BN model data collection for the Initial BN model was halted at this point. However, further in depth data acquisition and analysis is to be conducted once the model is expanded in Chapter 5.

Table 4-1: Details of each node and their data origins

Node	Node Name	States	Parents	Permutations in CPT	Data Sources
1	Retaining Ring Failure	2	0	2	Literature (HD[1])
2	Debris Expelled	2	1	4	Literature (Db[2] & RAP[3])
3	Debris Expelled into Turbine	2	1	4	Literature (Db[2] & RAP[3])
4	Debris Expelled towards Exciter	2	1	4	Literature (Db[2] & RAP[3])
5	Fuel Gas Feed Impact	2	1	4	Literature (Db[2] & RAP[3])
6	Generator Bearings	2	1	4	Literature (Db[2] & RAP[3])
7	Turbine Blades Expelled	2	1	4	Literature (Db[2] & RAP[3])
8	Exciter Detaches	2	1	4	Literature (Db[2] & RAP[3])
9	Gas Import Riser Piping Impact	2	1	4	Literature (Db[2] & RAP[3])
10	HP Flare Drum Shell Impact	2	1	4	Literature (Db[2] & RAP[3])
E1	Debris Contained in Alternator	2	3	16	Literature (Db[2] & RAP[3])
E2	Debris Escapes Generator Housing	2	1	4	Literature (Db[2] & RAP[3])
E3	Fuel Gas Fire	2	1	4	Literature (Db[2] & RAP[3])
E4	Debris Remains in Turbine Housing	2	1	4	Expert Opinion
E5	Event Escalation	2	4	32	Expert Opinion
E6	Gas Import Riser LOC	4	1	4	Literature (RAP)
E7	HP Flare Drum LOC	2	1	4	Literature (HD & RAP)

[1]Historical Data (HD), [2]Databases (Db)such as: OREDA, HSE, OGP, [3]Risk Assessment Projects (RAP) for Thistle

4.6.1 Application of Pairwise Comparison Technique and AHP

In order to obtain data for nodes in the BN where historical data is not available, a pair-wise comparison technique was utilised in the form of questionnaires to gather data from experts in the offshore industry. Pairwise comparison is required as the experts cannot simply analyse the individual nodes and provide their judgements. A specific criterion is required in order for the experts to understand the situation and provide the relevant information. Furthermore, the BN contains some nodes which are at component level and some nodes which are at system level. For example, "Turbine Blades Expelled" refers to a specific component, whereas "Gas Import Riser Piping Impact" refers to a gas riser system. The pairwise comparison provides a hierarchy for comparisons so the experts can see the breakdown of the situation and compare areas that are system related and those that are component related (see Appendix F for the data collection questionnaire) (Lin & Kou, 2015). Similarly, the Pairwise Comparison and AHP techniques are outlined in Chapter 3.

A set of questionnaires was sent to selected experts in the offshore industry for their evaluation. The feedback is investigated according to their judgements on the criteria under discussion. The back grounds of the five experts, who shall remain anonymous, is as follows:

Expert 1 is a current member of a national regulatory organisation with over 20 years of experience in the offshore industry. This person current holds chartered engineer status.

Expert 2 is currently in the employment of a leading classification society and holds a university qualification at the MSc. Level. This person has 8 years of experience at sea and more than 5 years as an offshore safety manager.

Expert 3 is currently in the employment of a leading classification society and holds a university degree at PhD level. This person has more than 10 years' experience of working in the offshore industry.

Experts 4 and 5 are both currently colleagues in the employment of a multinational energy corporation and have university degrees to MSc level. Both also have more than 10 years' experience in the offshore industry.

Referring to the system level criteria in part A of the questionnaire as an example of the AHP method, a 3×3 pairwise comparison matrix is constructed to obtain the weights of these criteria. Table 4-3 is a Pairwise Comparison matrix expressing the qualified judgement with regard to the relative priority of GIR, HPD and EG. An explanation of the abbreviations is given in Table 4-2.

Table 4-2: Criteria required for comparison at system level

System Failures	
Electrical Generator failure	EG
Gas Import Riser failure	GIR
High Pressure gas flare Drum failure	HPD

Table 4-3: Pairwise Comparison matrix for system level criteria

	GIR	HPD	EG
GIR	1	3.4	6.33
HPD	0.29	1	5
EG	0.16	0.20	1
SUM	1.45	4.61	12.26

A standardised matrix is calculated to show the performance ratio of the system level criteria. This is done by dividing the importance rating in each cell by the sum of its column. From here the relative weights of the criteria can be calculated by averaging the rows in the standardised matrix. A measure to know if the data is performing correctly is that all of the columns in the standardised matrix must sum to 1.0. The standardised matrix with calculated relative weights for the system level criteria is shown in Table 4-4. These step by step calculations as a whole represent Equation 3-12.

Table 4-4: Standardised matrix of system criteria along with their relative weights.

				Weight
GIR	0.69	0.74	0.52	**64.88%**
HPD	0.20	0.22	0.40	**27.31%**
EG	0.11	0.04	0.08	**7.81%**
SUM	1	1	1	**100.00%**

The next phase of AHP is the consistency ratio calculation. Each value in the columns of Table 4-3 is multiplied by the weight value of each criterion in Table 4-4. For example each value in the column *GIR* of Table 4-3 is multiplied by the weight of the *GIR* row in Table 4-4. Once these figures have been calculated, they are to be summarised by row, as shown in Table 4-5. A Sum Weight is then calculated by dividing the summarised row of Table 4-5 by the corresponding weight in Table 4-4. For example ‘Sum Row’ *GIR* is divided by the weight in row *GIR* in Table 4-4. The full results are shown in Table 4-5.

Table 4-5: The product of the Pairwise Comparison matrix values and the calculated weights (columns 2- 4). Along with the sum of each row and the sum weight of each criteria.

				Sum Row	Sum Weight
GIR	0.65	0.93	0.50	2.07	3.20
HPD	0.19	0.27	0.38	0.85	3.10
EG	0.10	0.06	0.08	0.24	3.02

The λ_{max} value is then calculated by dividing the sum of the 'Sum Weights' by the number of criteria, *n* in the Pairwise Comparison, which in this case is 3. This calculation utilises Equation 3-15. Hence, λ_{max} is calculated as:

$$\lambda_{\text{max}} = \frac{3.2 + 3.1 + 3.02}{3} = 3.11$$

Next the CI is computed using Equation 3-14, as follows:

$$CI = \frac{3.11 - 3}{3 - 1} = 0.05$$

Subsequently the consistency ratio (CR) is calculated using Equation 3-13. There are 3 criteria in this pairwise comparison under evaluation, so the corresponding Random Index (RI) is 0.58, as shown in Table 3-2. The CR of the system level criteria can now be calculated as follows:

$$CR = \frac{0.05}{0.58} = 0.09$$

The CR value of the system level criteria is 0.09. This means that the degree of consistency within the pairwise comparison is acceptable as the CR value is less than 0.10.

Similar calculations were conducted for the other criteria in the pairwise comparison with one other CR being calculated as 0.00. This again is acceptable as it is less than 0.10. The full pairwise comparison and AHP results are shown in Appendix G. CR calculations are not possible for matrices of less than 2×2 as the Saaty RI values for 2×2 matrices is zero.

4.6.2 Application of Symmetric Method

To outline the symmetry method outlined in Chapter 3, let us consider part of the initial BN model consisting of nodes 7, 8, 9, 10 and E5. as shown in Figure 4-7.

Also, for ease of explanation, Table 4-6 shows a simple notation for each parent node.

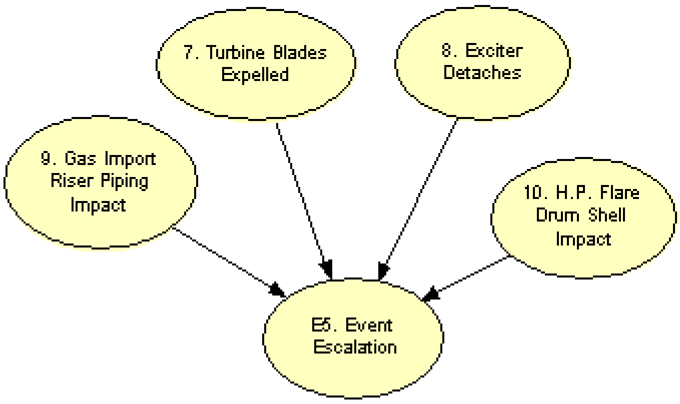


Figure 4-7: Small BN taken from the initial BN model

Table 4-6: Notation for parent nodes in Figure 4-2

Parent Nodes (from left to right in figure 4-2)	**Notation**
Gas Import Riser Piping Impact	W
Turbine Blades Expelled	X
Exciter Detaches	Y
HP flare Drum Shell Impact	Z

In this example the child node E5 has 2^4 different parental configurations, as there are four parents each with two states (Yes and No). Hence, the CPT will consist of 2^4

probability distributions. This large number of distributions demands a considerable amount of intensive effort on the part of an expert to generate the CPT. The vexing part is that it is not just large but exponentially large. A CPT quantifying the dependency on *n* parents would demand 2^n distributions in order to be functional. It is this exponential growth with the number of parents that constitutes the essential problem. This symmetric method simplifies the problem of exponentially large CPTs.

For calculation of the CPT for the Child Node (Event E5), assume that the number of distributions grows linearly as opposed to exponentially. i.e. with the network shown there are 2x4 distributions linearly as opposed to 2^4 exponentially. If the states of the parents have one-to-one capability correspondence (which is an equivalence relation) then the number of 'Questions' regarding the CPT for the child node is reduced (Das, 2008). The symmetric method demonstrated in Chapter 3 is utilised to complete the CPT and so the theory is altered to accommodate four parent nodes instead of three. Hence the compatible parent configuration for is demonstrated by Equation 4-1

$$\{comp(Y = y^s)\} \equiv \{comp(W = w^s)\} \equiv \{comp(X = x^s)\} \equiv \{comp(Z = z^s)\} \equiv$$

$$\{W = w^s, X = x^s, Y = y^s, Z = z^s\} \tag{4-1}$$

Consider the network shown in Figure 4-7 where the 2×4 linear probability distribution has been assigned. Starting with parent W and interpreting the compatible parent configurations as follows in equation 4-2 (Das, 2008):

$$\{comp(W = s)\} \equiv \{comp(X = s)\} \equiv \{comp(Y = s)\} \equiv$$

$$\{comp(Z = s)\} \equiv \{W = s, X = s, Y = s, Z = s\} \tag{4-2}$$

where the set contains two states. s = *Yes, No*

Hence the probability distribution over the child node *E5* will be:

$$P(E5|\{comp(W = s)\}) = P(E5|\{comp(X = s)\}) =$$

$$P(E5 \,|\, \{comp(Y = s)\}) = P(E5 \,|\, \{comp(Z = s)\}) \qquad \textit{(4-3)}$$

where the set contains two states *s* = *Yes*, *No.*

Given the network in Figure 4-7 it is possible to assign the relative weights (w_1, ..., w_n), demonstrated in Table 4-4 and Appendix G, to the parents *W*, *X*, *Y*, *Z* respectively, to quantify the relative strengths of their influences on child node *E5*.

The weights are positive and should be in a normalised form, i.e. $0 \leq w_i \leq 1$, for $i=1, ..., n$, and $w_1 + ... + w_n = 1$.

The Weighted Sum Algorithm

If all the information that the expert is willing to give is:

i) The relative weights w_1 , ... , w_n , and,

ii) The $k_1 + ... + k_n$ probability distributions over *E5*, of the linear type, for compatible parental configurations.

Given the information provided the following algorithm is used to produce an estimate, based upon expert judgements, of the $k_1 \times ... \times k_n$ distribution for child node *E5* (Das, 2008).

$$P\left(x^l | \, y_1^{S_1}, \, y_2^{S_2}, \, \ldots, \, y_n^{S_n}\right) = \sum_{j=1}^{n} w_j \, . \, P\left(x^l \, | \, \{Comp(Y_j = \, y_j^{S_j})\}\right) \qquad \textit{(4-4)}$$

where: $l = 0, 1, ..., m$ and $S_j = 1, 2, ..., k_j$.

This weighted sum algorithm is applied to the distribution over *E5* for compatible parental configurations. Table 4-7 shows the compatible distributions over child node *E5*, with data obtained from expert judgement through pairwise comparison and AHP.

Table 4-7: Distribution over E5 for compatible parental configurations {Comp (W = s)}

Probability Distribution over E5	**s = Yes**	**s = No**
P(E5 = Yes|{Comp(W = s)})	0.23	0.77
P(E5 = No|{Comp(W = s)})	0.77	0.23

In addition, Table 4-8 shows the relative weights for the parents of event E5, which were obtained from expert judgment through pair-wise comparison and AHP.

Table 4-8: Relative weights of parent nodes of Event E5

Parent Node	**Weighting Notation**	**Relative Weights**
Gas Import Riser Piping Impact (W)	W_1	0.65
Turbine Blades Expelled (X)	W_2	0.05
Exciter Detaches (Y)	W_3	0.03
HP flare Drum Shell Impact (Z)	W_4	0.27
	Total	1.00

Utilising the data shown in Table 4-7 and Table 4-8, it is possible to calculate all of the 2^4 parental distributions required to populate the CPT for event *E5*. Consider an example to demonstrate the algorithm for a specific parental distribution, where the probability of E5=Yes is required. One possible distribution is shown in Table 4-9.

Table 4-9: Possible parental configuration for parents of Event E5

Parent Node	**State: Yes or No**
Gas Import Riser Piping Impact (W)	No
Turbine Blades Expelled (X)	Yes
Exciter Detaches (Y)	No
HP flare Drum Shell Impact (Z)	Yes

Given the states of the parents in Table 4-9, the distribution over *E5* is to be:

$$P(E5 = Yes|W = No, X = Yes, Y = No, Z = Yes) \tag{4-5}$$

Once all of the relevant data is known, according to Equation 4-4, the following computation is required:

$$P(E5 = Yes\ |W = No, X = Yes, Y = No, Z = Yes) = w_1.P(E = Yes\ |\{comp(W = No)\}) + w_2.P(E = Yes\ |\{comp(X = Yes)\}) + w_3.P(E = Yes\ |\{comp(Y = No)\}) + w_4.P(E = Yes\ |\{comp(Z = Yes)\}) \tag{4-6}$$

From Equation 4-6 it can be deduced that for the parental configuration shown in Table 4-9, when the correct compatible probabilities and weights are substituted in, the probability of event *E5* being in the state "Yes" is to be:

$$P(E5 = Yes|W = No, X = Yes, Y = No, Z = Yes) = 0.6 \tag{4-7}$$

Subsequently, according to Axiom 2 shown in Section 3.3, the complement of 4-7 [P($E5 = No$)] is to be:

$$P(E5 = No|W = No, X = Yes, Y = No, Z = Yes) =$$

$$1 - P(E5 = Yes|W = No, X = Yes, Y = No, Z = Yes) = 0.4 \tag{4-8}$$

The relative weight algorithm is applied to all cells within the relevant CPT table to obtain the full conditional probability distribution. This process was completed using the formula function in Microsoft Excel, which also saves time for calculations. The completed CPTs for the Initial BN Model can be found in Appendix H.

4.7 Model Validation

Prior to generating the results for the Initial BN model, a series of test were carried out to demonstrate that the network operates as intended. This involves examining several different combinations and scenarios of events taking place, such as 100% probability of failure. This process serves to highlight potential problematic areas that could require closer scrutiny and should a certain event occur. Furthermore, the set of axioms outlined in Section 3.5.1 should be satisfied by the model. A sensitivity analysis is also carried out to demonstrate how responsive or "sensitive" the output of the model is to variations in its inputs (Jones, *et al*., 2010) (Cai, *et al*., 2013).

4.7.1 Propagation of Evidence

4.7.1.1 Retaining Ring Failure

The propagation of evidence, as previously stated, examines combinations and scenarios of events occurring. With regard to this case study the focus of the first analysis shall be on the seven final event nodes (*E1* to *E7*) when evidence is inserted to the parent Node "Retaining Ring Failure".

From the scenario, illustrated by Figure 4-8, a failure of a retaining ring (100% probability of State "Failure") results in changes in the probabilities of the final event nodes. This shows that the nodes closer to the initial event (Retaining Ring Failure) display larger changes than nodes further away in the network. The same can be said for evidence inserted in the other state of node 1, "No Failure", as shown by Figure 4-9. However, the changes are very small as the prior probability for "No Failure" of a Retaining Ring was already very high. Figure 4-10 shows three scenarios: From left to right, A) The Marginalized prior probabilities of node 1 and Nodes *E1 - E7*, B) The posterior probabilities of nodes *E1 – E7*, given that the retaining ring fails, and C) The posterior probabilities of nodes *E1 – E7*, given that the retaining ring doesn't fail.

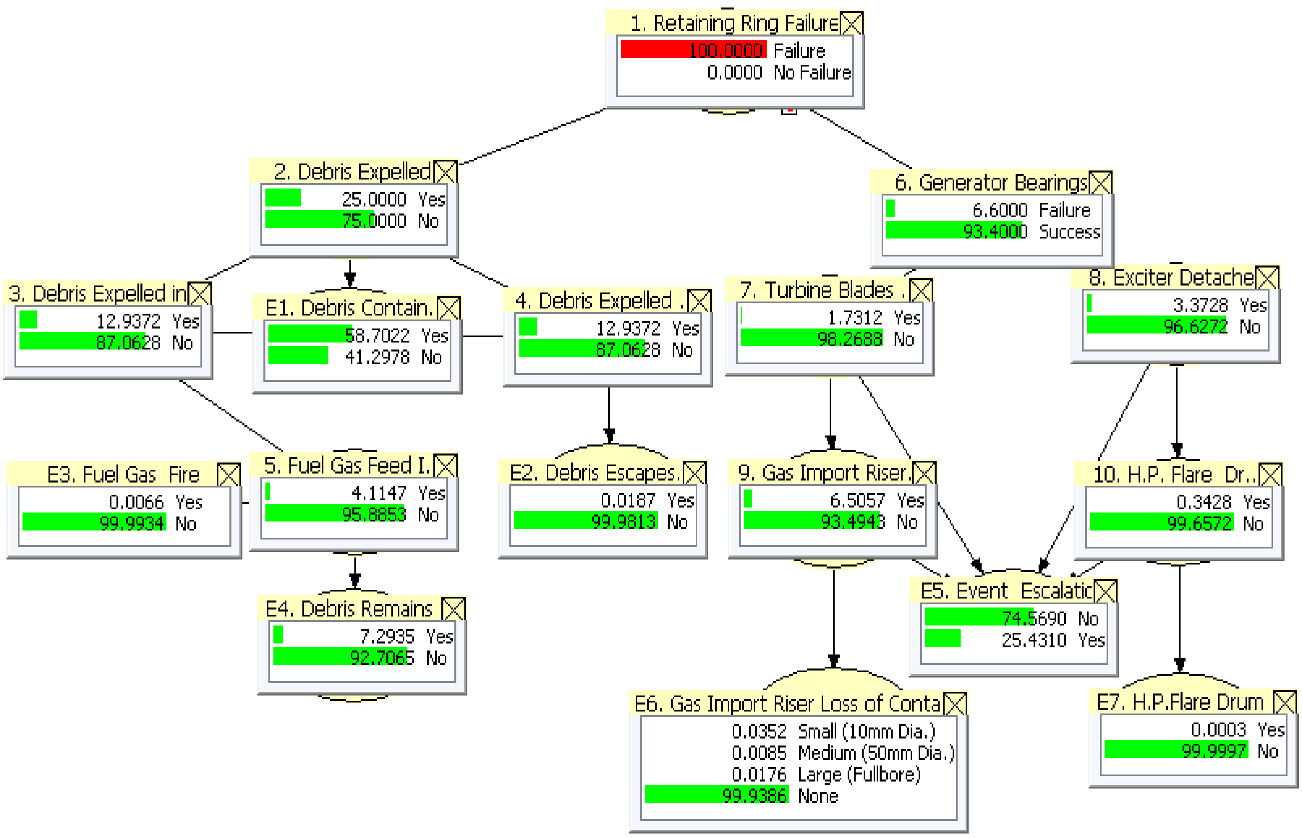


Figure 4-8: Scenario showing the effect of evidence in the form of 100% failure of a Retaining Ring

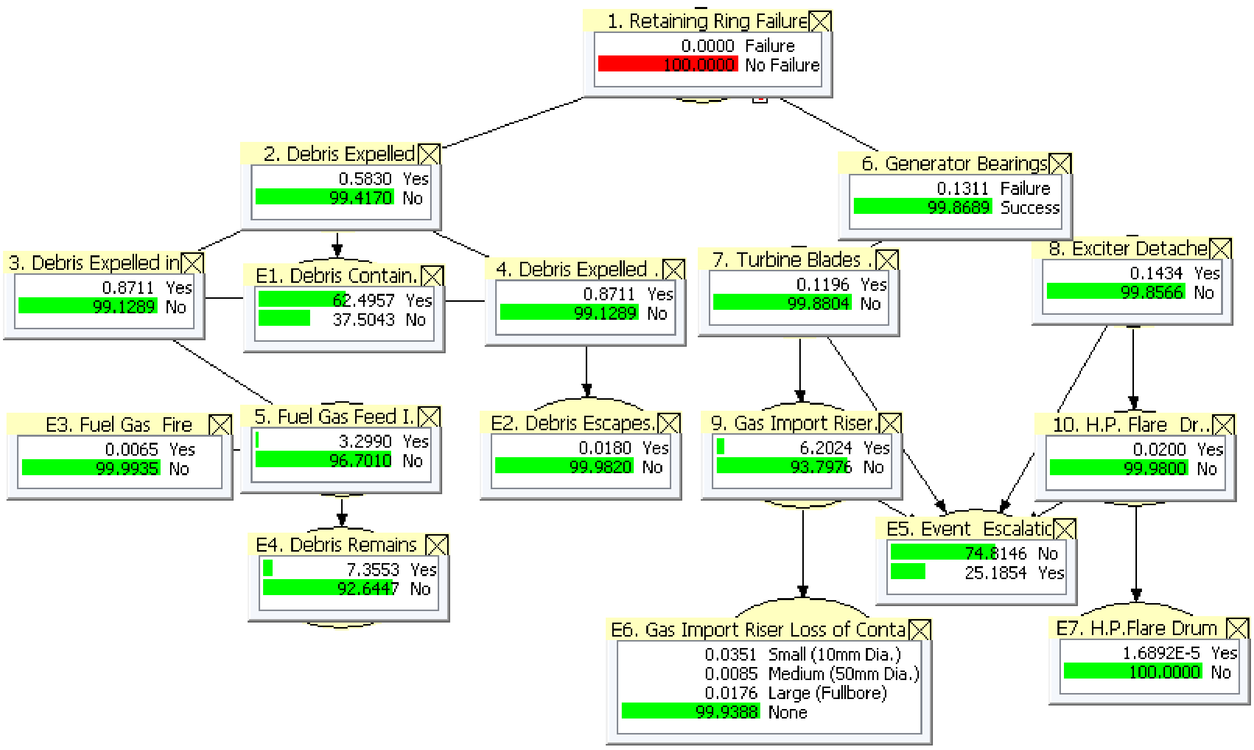


Figure 4-9: Scenario showing the effect of evidence in the form of 100% no failure of a Retaining Ring

Figure 4-10 demonstrates that when evidence is presented in node 1, representing the initial component failure, this will have an effect on all of the presented final events. It can also be seen that individual node react in the way they would be expected, for example, should the retaining ring fail, the likelihood of the being “E5. Event Escalation” increases from 25.19% to 25.43%. Similarly, in the same situation the probability of “E1. Debris being contained within the Alternator” decreases from 62.49% to 58.70%. This is due to the corresponding effects the initial failure has on the parents of event E1, and the likelihood of the debris being expelled towards the turbine or towards the exciter are increased, as shown by Figure 4-8.

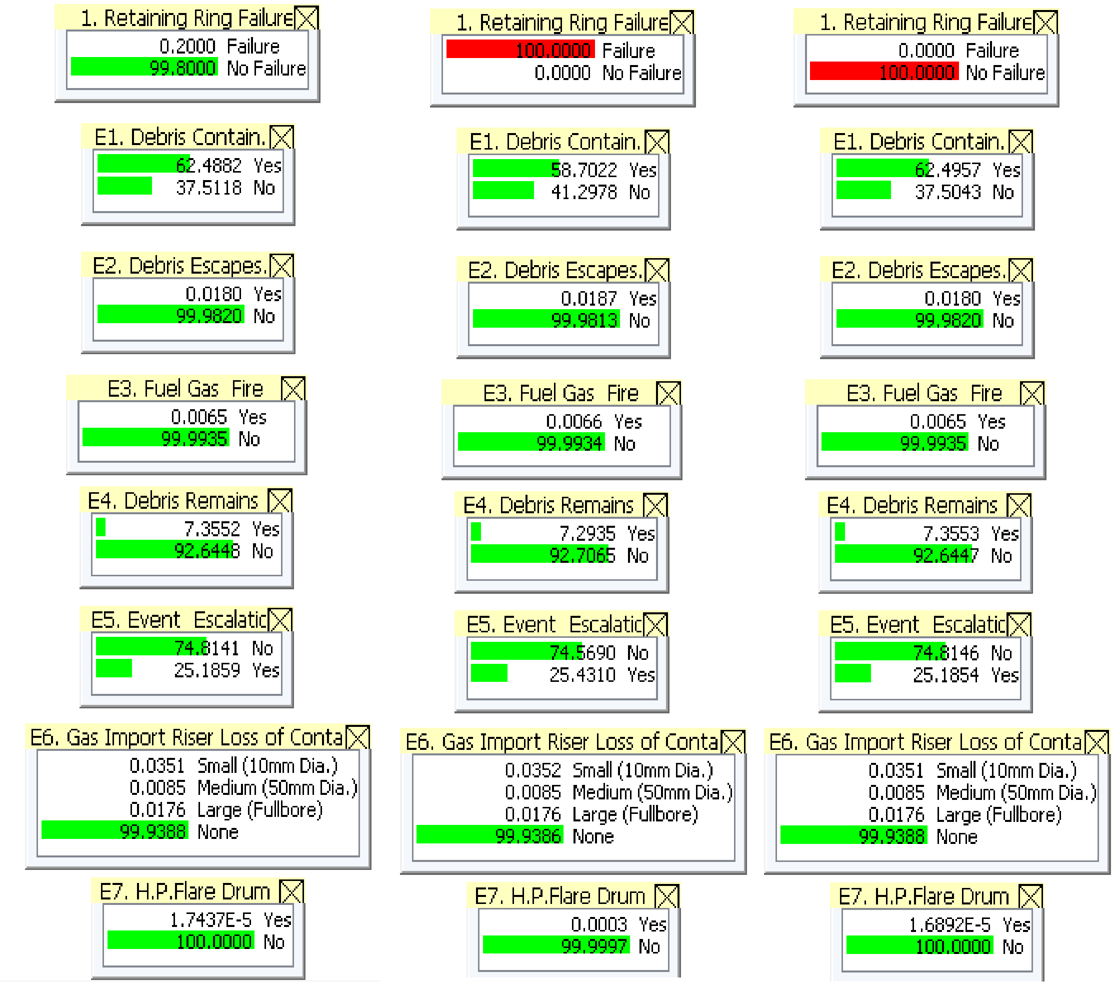


Figure 4-10: A) Prior probabilities B) Posterior probabilities after 100% failure of retaining ring C) Posterior probabilities after 100% no failure of Retaining Ring

4.7.1.2 Event Escalation

Further analysis is carried out on a specific section of the Initial BN model, shown in Figure 4-11, this time concerning the event “E5. Event Escalation” and its parents. This analysis involved systematically inserting evidence into each of the parent nodes and finally the child node. In addition, nodes 7 and 8 have a parent node “Generator Bearings” which has no evidence inserted, and there is no evidence inserted anywhere else within the model. However, in this section of the BN model Nodes 7 and 8 are parents of nodes 9 and 10 respectively, and therefore will alter the posterior probabilities of these nodes when evidence is inserted. This relationship has been left in the analysis to give an accurate representation of the posterior probabilities of the event *E5*, which is the focus node in this analysis.

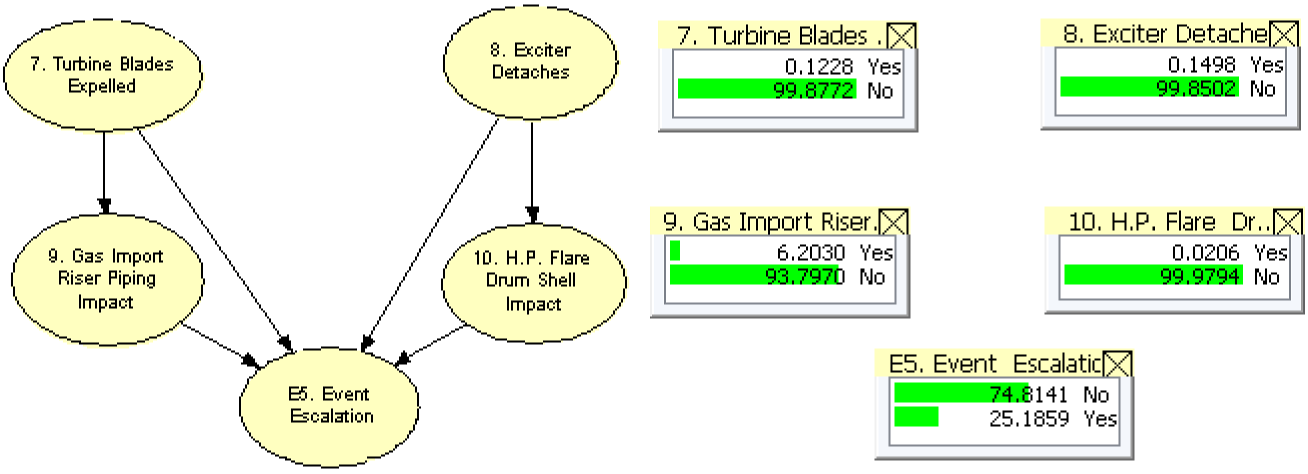


Figure 4-11: A) Specific section of BN to be analysed. B) Prior probabilities for Event E5 and its parent nodes.

The scenario shown in Figure 4-12 illustrates the gas turbine blades being expelled as projectiles from the generator housing. This increases the probability of the events escalating from 25.19% to 35.09%. This increase would involve some concern as a

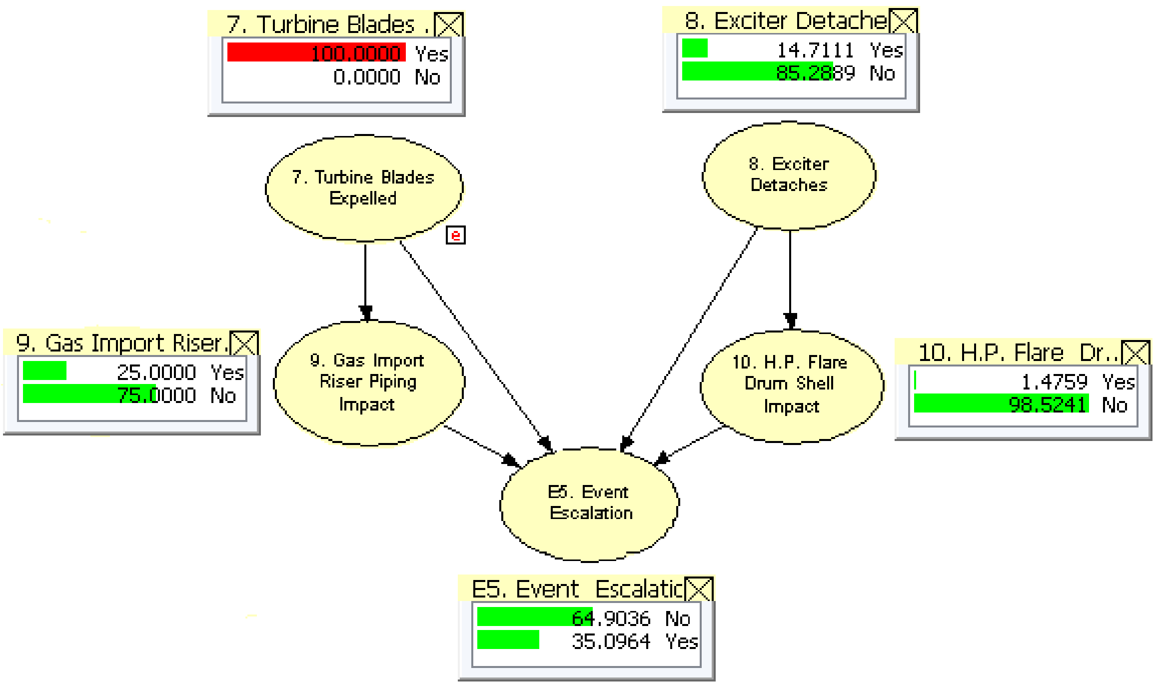


Figure 4-12: Probability of "Event Escalation" given Turbine Blades are expelled

potential escalation from this is the impact of the turbine blades on the Gas Import Riser. This can also be seen in Figure 4-12 where the probability of there being a gas import riser impact increases from 6.2% to 25%.

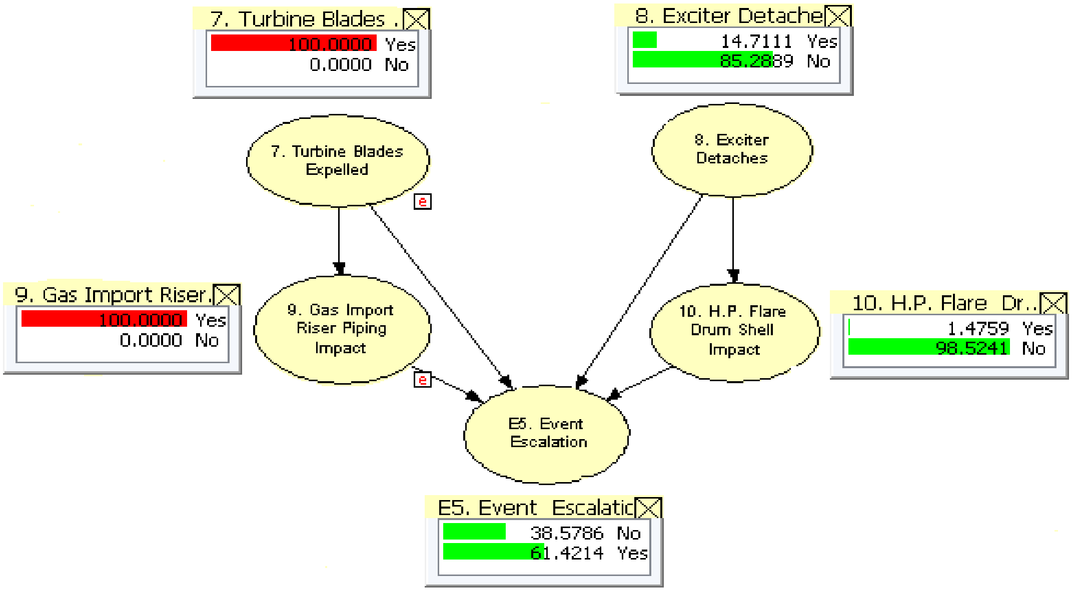


Figure 4-13: Probability of "Event Escalation" given both Turbine Blades Expelled and Gas Import Riser Impact

Furthermore, as shown in Figure 4-13, the expulsion of the turbine blades coupled with a gas riser impact, the probability of their being escalation increases from 35.09% to 61.42%. This is a very large increase as the impact of a gas riser is the largest threat to escalation, due to the loss of containment of the gas, this hypothesis was also confirmed by expert opinion. It can also be noted that in both Figure 4-12 and Figure 4-13 when evidence is inserted into nodes 7 and 9, there is no effect on nodes 8 and 10, which is to be expected as they should be independent from each other. Should this scenario have the potential to occur, immediate action should be taken to prevent a major accident in the form of LOC of hydrocarbons and potential explosion & fire.

Figure 4-14 further demonstrates the potential for escalation by showing that the generator's exciter detaches, along with turbine blades expelled and gas riser impact. It shows that again the potential for escalation increases from 61.42% to 63.86%. This scenario also increases the probability of the HP flare drum being impacted from 1.47% to 10% as would be expected.

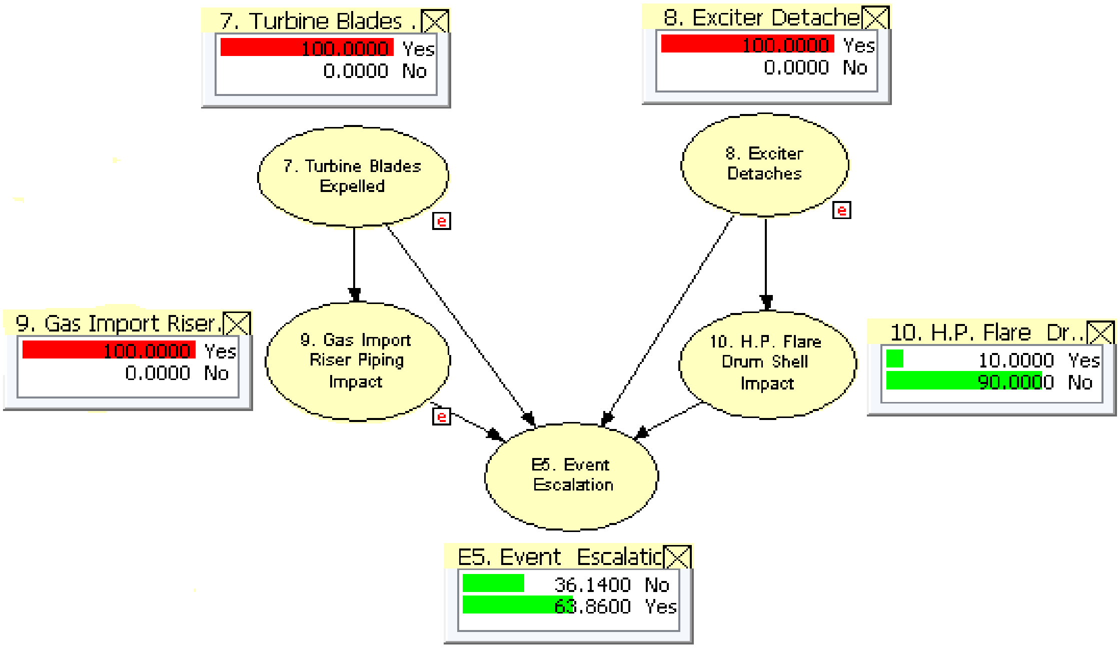


Figure 4-14: Probability of "Event Escalation" given Turbine Blades Expelled and Gas Import Riser Impact, together with the Exciter Detaching.

Figure 4-15 demonstrates the final influencing factor on the possibility of event escalation, whereby the HP flare drum is impacted. This increases the potential for escalation from 63.86% to 77%.

The final scenario, shown in Figure 4-16, demonstrates the effect of there being an escalated event, for example, observing an explosion or a fire within the area of the platform containing the electrical generator, and the effect this has on the influencing parameters. This serves to obtain areas that would require closer inspection. This scenario has given insight to the possible causes of the event escalation, based upon the data presented, here the main influencing factors are: "Turbine Blades Expelled" – Yes, increases from 0.12% to 0.17%; “Exciter Detaches” –Yes, increases from 0.15% to 0.17%; “Gas Import Riser Piping Impact” – Yes, increases from 6.2% to 14.31%; and “HP Flare Drum Shell Impact” – Yes, increasing from 0.02% to 0.03%.

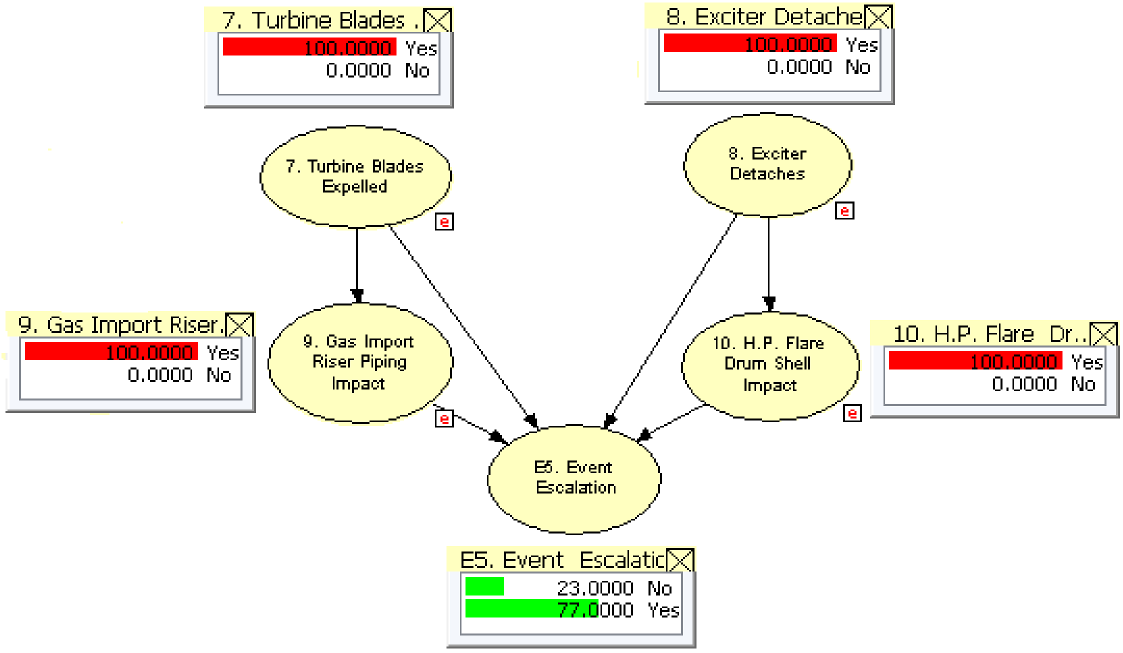


Figure 4-15: Probability of "Event Escalation" given that all influencing factors take place

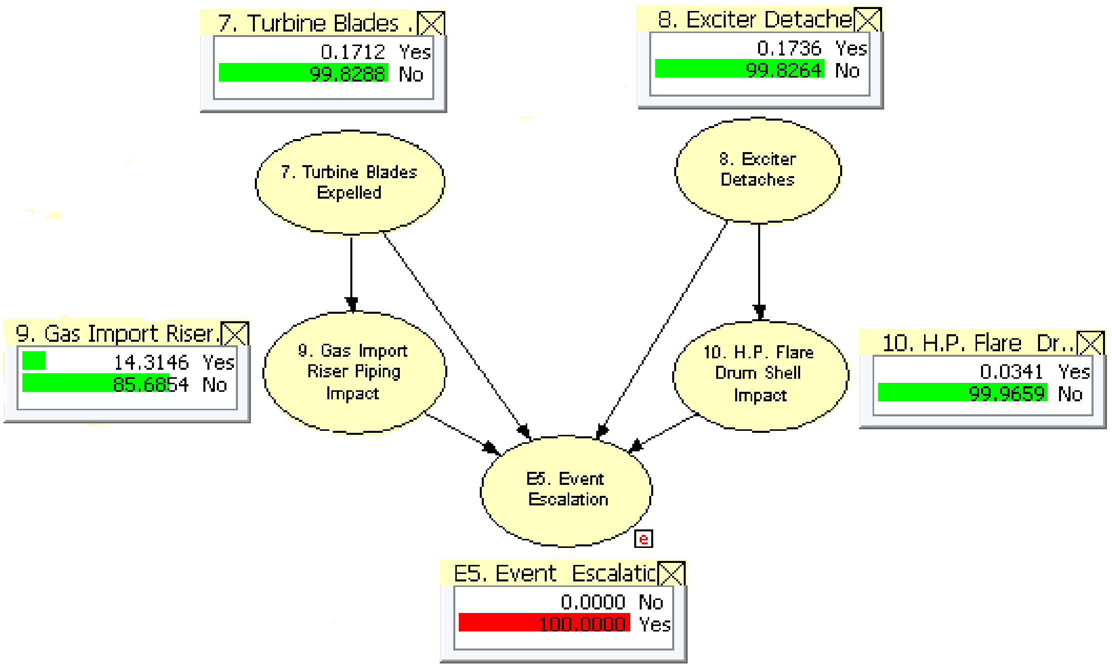


Figure 4-16: BN Model illustrating when "Event Escalation" takes place.

4.7.2 Validation

In order for the model to be validated, it should satisfy the three axioms stated in Section 3.5.1. Examination of the model in Figure 4-8, Figure 4-9 & Figure 4-10 shows that when evidence is inserted in the form of the initiating component failing or not failing, the posterior probabilities for the final events decrease or increase depending on the node in question. This analysis also demonstrates that nodes closer to the focus node, in this case node 1, will display a larger influence than those which are further away. This can be shown as node *E1* demonstrates a larger change, 62.49% to 58.70%, when the retaining ring fails, as opposed to event *E5* which has a small change from 25.19% to 25.43%, as it is further from the focus node than event *E1*.

Furthermore, examination of a specific part of the model, in Figure 4-12, reveals when “turbine Blades Expelled” is set to 100% ‘Yes’, this produces a revised increase in probability for “Event Escalation” occurring from 25.19% to 35.09%. Figure 4-13 shows both the change in Figure 4-12 and “Gas Import Riser Piping Impact” set at 100% ‘Yes’. This resulted in a further increase in the potential for “Event Escalation” occurring. Figure 4-14 shows the changes in Figure 4-13 plus the “Exciter Detaches” being set to 100% ‘Yes’, again resulting in an increase for the potential for “Event Escalation” being of the state ‘Yes’. Finally, Figure 4-15 shows all of the influencing factors on “Event Escalation” being set to 100% ‘Yes’, resulting in yet another increase in the probability of “Event Escalation” occurring from 63.86% to 77.00%.

This exercise of increasing each of the influencing nodes as well as the changes displayed when increasing or decreasing the probability of the initial event occurring satisfies the three axioms states in the BN methodology, thus giving validation to the BN model.

4.7.3 Sensitivity Analysis

Sensitivity Analysis (SA) is essentially a measure of how responsive or sensitive the output of the model is when subject to variations from its inputs. Having the understanding of how a model responds to changes in its parameters is important when trying to maximise its potential and ensuring correct use of the model. SA provides a degree of confidence that the BN model has been built correctly and is working as intended. In the context of this research, SA will be used as a demonstration to determine how responsive an event node is to variations in other nodes. Knowing the most influential nodes can assist in the experimentation and further expansion of the model. Similarly, nodes which have very little influence can be altered or discarded (Matellini, 2012).

The SA conducted for the Initial BN model focuses on the event *E5* and its parent nodes, shown in Figure 4-11, to further validate the claims in Section 4.7.2. However, the analysis will be conducted using smaller increases and decreases in the probabilities of the parent nodes as opposed to inserting 100% occurrence probability into the input node CPTs.

A possible way of undertaking this is to manually insert evidence into the input nodes, one by one, and subsequently analyse the effect on the output node via its posterior probability. When doing this the input nodes are increased or decreased by equal percentages, individually. This allows for clear comparison of their impact upon the output node. However, this manual method was not applied to this analysis. Instead a parameter sensitivity wizard within the Hugin BN software was used. In this program wizard the input node is individually paired with the output node in its desired state. In this case that was “E5. Event Escalation” in the state ‘Yes’. A state for each of the input nodes was purposely selected. It should be noted that in this analysis, node 6, “Generator bearings” has had evidence input at state – ‘Failure’ to 100%. This input of evidence allows for nodes 7, 8, 9 & 10 to remain independent from each other, which allows for the values analysed in the sensitivity analysis to remain consistent. Following this the four input nodes (Nodes 7, 8, 9 & 10) are all set to state – ‘No’ in the parameter sensitivity wizard. In this way a sensitivity value from Hugin was obtained for each input node and using Microsoft Excel a graph was constructed to show the results.

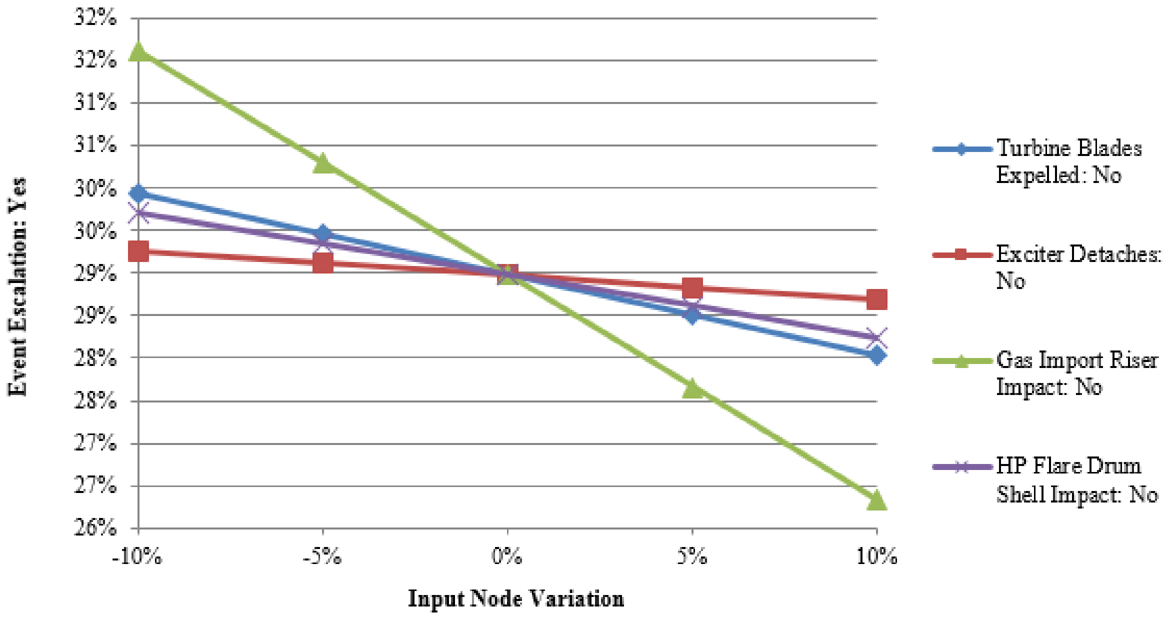


Figure 4-17: Sensitivity functions for the four input nodes for event "E5. Event Escalation"

From the graph in Figure 4-17 it can be seen that the most influential factor on “Event Escalation” is “Gas import Riser Impact”, whilst the least influential is “Exciter Detaches”. If the probability of State - ‘No’, “Gas Riser Impact” increases by 10%, then the probability of “Event Escalation” decreases by 2.63%. Whereas, if the probability of State - ‘No’, “Exciter Detaches” increases by 10%, then the probability of “Event Escalation” only decreases by 0.29%. From the graph it is also apparent that the sensitivity function is a straight line which further add to the model validation. The sensitivity values computed within Hugin are shown in Table 4-10.

Table 4-10: Sensitivity values for the four input nodes acting upon event "E5. Event Escalation"

Input Node	**Sensitivity Value**
7. Turbine Blades Expelled: No	-0.095
8. Exciter Detaches: No	-0.029
9. Gas Import Riser Impact: No	-0.263
10. HP Flare Drum Shell Impact: No	-0.073

It should be noted that the sensitivity values in Table 4-10 are negative as in their current states of ‘No’, they have a negative effect on the outcome of “Event Escalation” – ‘Yes’. For example; with the probability of “Turbine Blades Expelled” increasingly being ‘No’, it is less likely that “Event Escalation” – ‘Yes’ occurs.

4.8 Further Development of the Initial BN Model

The initial BN model could be further developed to investigate, in more specific detail, addition component failures and their subsequent events within module 2 of the Thistle Alpha platform. This allows for a more comprehensive dynamic risk assessment model to be included as part of an NUI-Integrity Case.

One interesting modification is to expand on the area around the event of “Fuel Gas Fire” and “Event Escalation” by including possible “Gas Release within Module”, as shown by Figure 4-18. The reasoning behind this is to incorporate additional initiating failures to the model and explore other causes of the current final events stated in the Initial BN model. The reasoning behind the addition of the node “A. Gas Release in Module” is that not all fuel fires, or hydrocarbon fires for that matter, are caused my immediate ignition.

Therefore, by working back from the node “Fuel Gas Fire”, one can establish other causes other than impact of the fuel gas line within the turbine, such as an external gas leak. Following the node “Gas Released in Module”, it is important to know where the leak has been detected or not. Should the leak be detected, the Turbine Control System (TCS) has the potential to shut off the fuel gas supply to prevent further release. Continually, should a gas release occur, it is possible for the gas to ignite. The probability of whether the fuel gas would ignite is commonly spread between three main states; “Instant”, “Delayed” or “None”. Should the leak instantly ignite, a fuel gas fire would occur. If the ignition is “delayed”, possibly by the oxygen to gas ratio in the atmosphere not being at it optimum for ignition, the gas can continuously release, if not detected. This causes a build-up of fuel gas within the confined area and until the optimal gas to oxygen ratio is achieved. Ignition at this point could cause an explosion of varying magnitude, and severely damage the module and other areas of the offshore platform. If there is no ignition of any kind, the gas is either shut off or continuously released into the atmosphere.

Another possible modification to the model is the addition of instances that induce mechanical failures. In a similar way that a retaining ring within an alternator can cause damage and failures of an electrical generator, the turbine running overspeed can has a similar effect. Figure 4-19 shows the addition of the parent node “Overspeed Excursion” to the Initial BN model. A turbine running overspeed has many of its own causes, such as loss of load and control system failure, and are not shown here as these are hypotheses that can be expanded on.

“Overspeed Excursion” would potentially have an effect on the mechanical equipment related to the rotor on the generator. This is demonstrated in Figure 4-19 as the node could potentially have an effect on the retaining ring, the generator bearings, the turbine blades and the exciter, by increasing the stresses on these components that have small mechanical tolerances. From the “Overspeed Excursion” it is possible that “Overspeed Detection” could occur and potentially shut down the turbine and eliminate the possibility of event escalation.

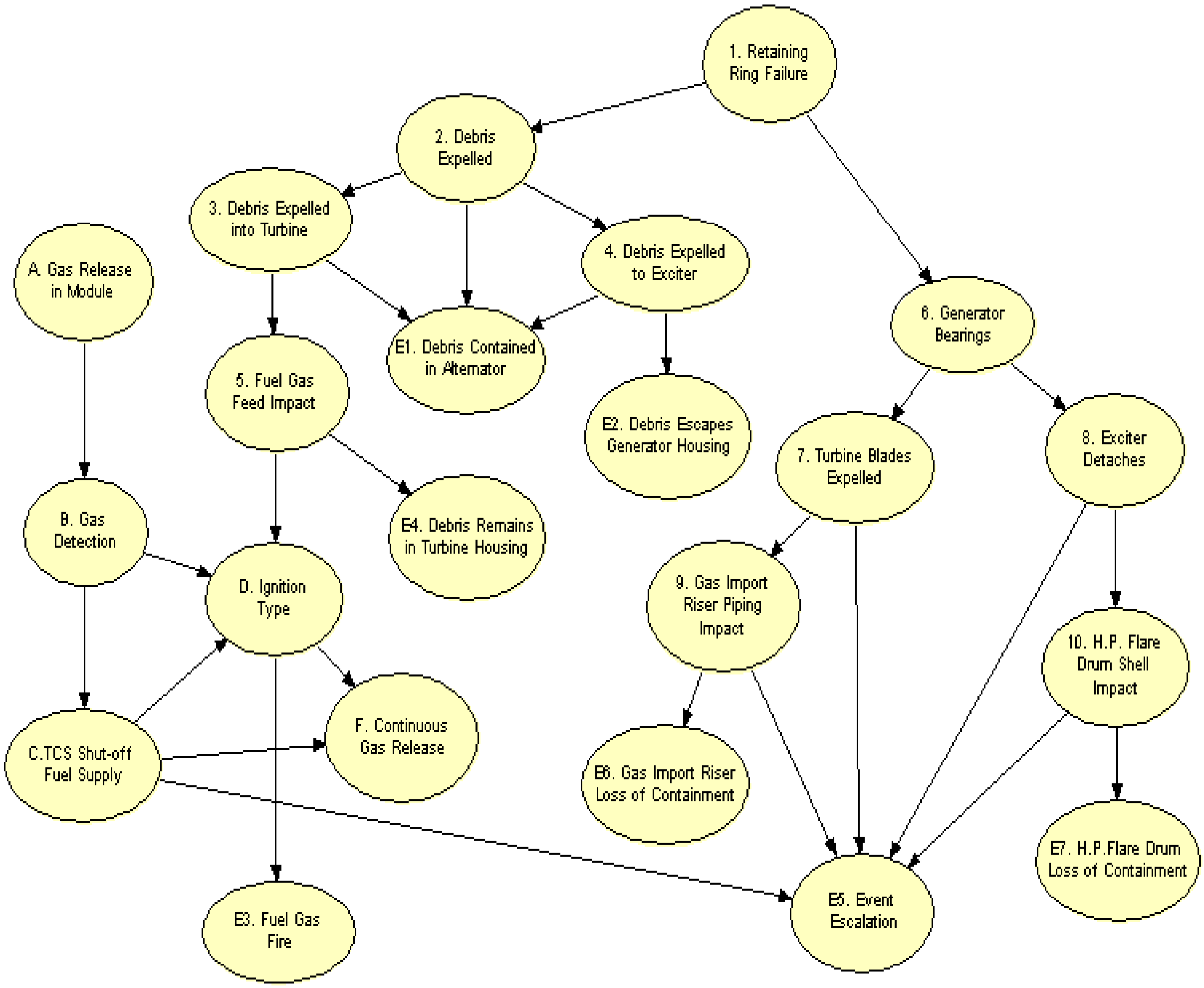


Figure 4-18: Modified version of the initial BN model, featuring the addition of "Gas Release in Module", "Gas Detection", "TCS Shut-off Fuel Supply" and "ignition Type"

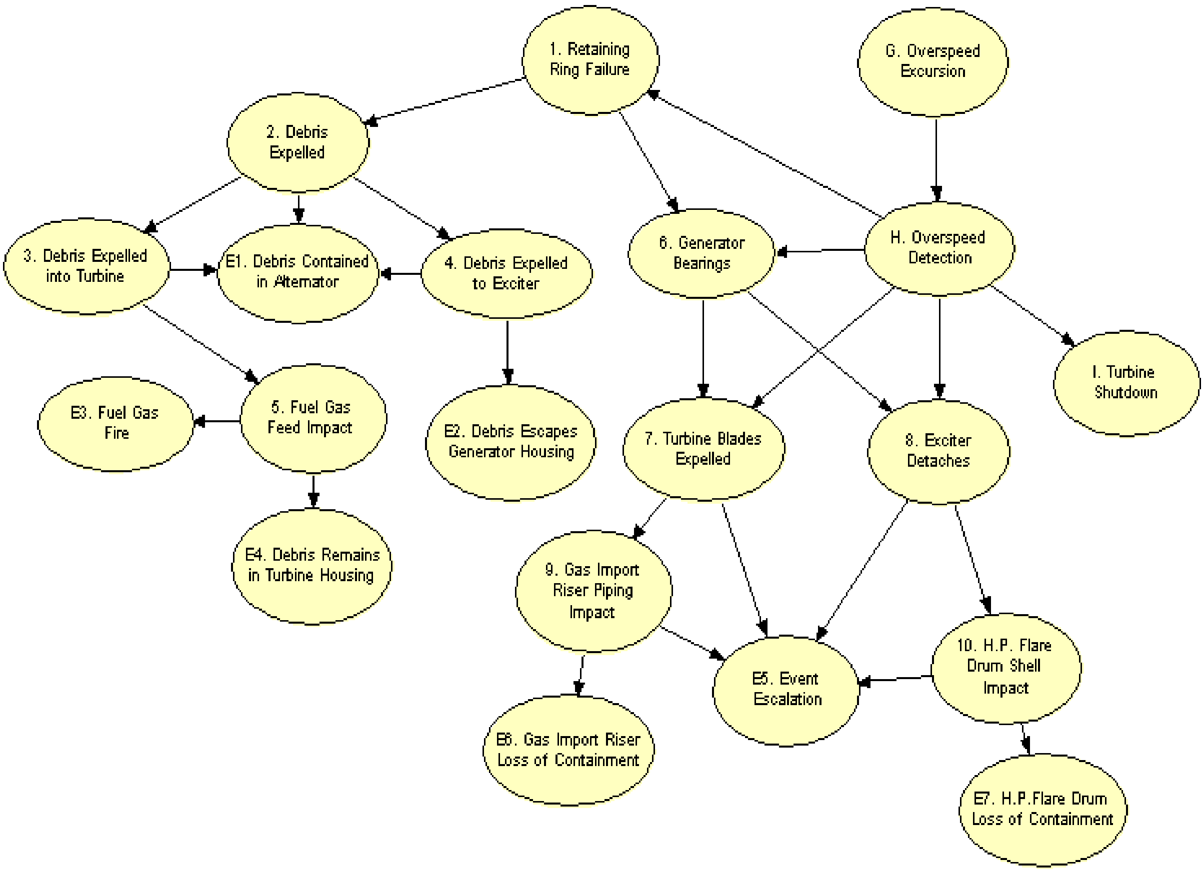


Figure 4-19: Modified version of the initial BN model featuring the addition of "Overspeed Excursion", "Overspeed Detection" and "Turbine Shutdown"

Further modifications are possible in other aspects. For example, the model is part of research into the development of dynamic risk assessment modelling of a NUI. As NUI's have very limited physical human presence, the way in which failures and hazards are observed becomes different. In this instance, it would be feasible for future research to take into account addition detection methods within the model, whereby, an observer onshore, monitoring a section of the installation, can observe failures as though one where on board. These future developments are key to the creation of the dynamic risk assessment models for an NUI-Integrity case.

4.9 Discussion and Conclusion

This chapter has outlined the Bayesian Network technique that has been used to model the cause and effect relationship of a specific component failure within a module of an offshore platform. It has been stated that offshore systems can be very complex and when coupled with the volume of data required to model failures within these systems, it makes BNs a challenge to model effectively. As well as in some cases a lack of reliable data means that some risk assessment models cannot always be applied. With this in mind, the Initial BN model, which deals with a single component failure within module 2 of the Thistle Alpha Platform, demonstrates that BNs can provide an effective and applicable method of determining the likelihood of various events under uncertainty. The model can be used to investigate various scenarios around the systems and components outlined and to show the beginnings of establishing where attention should be focused within the objective of preventing offshore incidents, as well as having a clear representation of specifically where these accidents can originate from. This method of modelling offshore risk assessment is to be improved upon in future research to potential model larger areas with several systems and their components to gain a wider understanding of how offshore systems interrelate.

Continuing with the initial BN model, a number of tests were generated to validate the hypotheses of model by applying the methodology to a case study (Section 4.7). The BN model demonstrated the effect a possible retaining ring failure would have on the electrical generation system, and surround area, of an offshore platform. The levels of fatalities have been omitted from the analysis as the objective of the research was to determine whether it is possible to accurately model equipment failures using BN. This is because the BN model is part of the development of NUI-Integrity Cases, whereby there is very limited physical human presence on board. Furthermore, the BN was constructed utilising equipment on a manned installation as a further objective of the research is to demonstrate whether it is possible to create a dynamic risk assessment model that will allow for humans to not be continuously present on a large installation, such as the Thistle Alpha platform, but monitor its operations from onshore. Hence, the Initial BN model presented in this Chapter provides a base to expand the research and the BN model to achieve this goal.

In relation to the validation of the model a sensitivity analysis was carried out to determine how responsive the output of the model is to various modifications in the inputs and subsequently validate that the model works as expected. This exercise is vital as it provides an indication to what the most important variables. In addition, inputs can be ranked or weighted in terms of their importance upon the output or final consequences. For example, in the Initial BN model "Gas Import Riser piping Impact" had a much larger effect on the possibility of "Event Escalation". The more advantageous element of conducting SA in BNs is that they take into consideration the chain of events below the input node leading to the output node, which presents a closer approximation to reality.

Finally, the section entitled "Further Development of the Initial BN model" shows how additional hypotheses could be incorporated into the modelling process and what purposes they would serve. There are several interesting and relevant possibilities that can be considered and explored with relative ease now that the core structure of an initial model has been constructed. However, before expanding the model it is vital to maintain that it must remain practical and close to reality from the perspective of gathering data and generating results. Continually too many variables which display vague information or increasingly irrelevant effects can diminish the quality of results and findings. The further development of the model should add further insight to this.

CHAPTER 5:

BAYESIAN NETWORK MODELING OF FUEL GAS RELEASE WITH POTENTIAL FIRE AND EXPLOSION CONSEQUENCES

Summary

In this chapter, the proposed BN methodology, outlined in Chapter 3, is demonstrated by applying it to a case study by focusing on the development of a BN model for modelling control system and physical failures of a gas turbine utilised in offshore electrical generation. The intention is to model a sequence of events following several component failures, under certain conditions and assumptions. These initial failures are defined in two categories; control system failures and physical or structural failures. The BN is subject to a series of test cases to demonstrate its validity. A sensitivity analysis is also applied to a section of the BN.

5.1 Introduction

This chapter focuses on the development of a BN model for modelling control system and physical failures of a gas turbine utilised in offshore electrical generation. The intention is to model a sequence of events following several component failures, under certain conditions and assumptions. These initial failures are defined in two categories; control system failures and physical or structural failures. This should provide a base with which to expand the BN model to facilitate the requirement of having a dynamic risk assessment model that allows for accurate representation of the hazards and consequences associated with gas turbine fuel gas releases.

The research presented within this chapter is an expansion of previous research conducted for an electrical generation system of an offshore installation in Chapter 4. The initial research focused on creating a dynamic risk assessment model for an electrical generation system, based upon one initial component failure in the form of a Rotor Retaining ring failure. From the initial research a sequence of events and a BN was produced to demonstrate the cause and effect relationships between the safety critical elements of the generator. The BN demonstrated a number of potential consequences, such as: Gas Import Riser failure, High Pressure Gas Flare Drum failure and Fuel Gas Release & fire. These final consequences were not expanded or demonstrated in great detail to keep the initial model as less complex as possible while achieving valid results. This is where the research presented in this chapter comes into play. The model to be presented here is an expansion of the previous model, focused on the consequence Fuel Gas release and Fire. In the initial BN this scenario this was represented as one node in the network, this research expands by constructing an entire new network to demonstrate the consequence of Fuel Gas release in much more detail.

The underlying theory of BN is provided in Chapter 3, similarly the step by step procedure used to construct the BN model is also described in Chapter 3. The model representing the potential for fuel gas release from an offshore gas turbine, along with the further consequences of fire and explosion, begins at the point of several initiating events. These events are the beginning of the sequence of events and continues through the point of potential gas release, the barriers involved in preventing the release and the potential consequences should these barriers fail. The sequence of events method was outlined in Chapter 4. The same method was applied to construct the fuel gas release BN model.

5.2 Model Assumptions and Limitations

There are some underlying assumptions and limitations within the model that must be explained for the model to be valid and understood. These limitations are split into two groups: space & domain and model data.

5.2.1 Space and Domain Limitations

The purpose of the model is to show what the effects of several component failures have on a gas turbine which can lead to a fuel gas release. Hence, the consequences of said fuel release are analysed, and in order to do this, the boundaries of the model need to be defined. These boundaries are concerned with the affected area, the detail of the consequences and the ignition types & sources. The outlined assumptions and limitations concerned with the model domain are as follows:

- The model has been built for the situation where the offshore platform does not house any crew and hence does not consider fatalities. There are two key reasons for this: The first is that the BN model is to be for an NUI (Normally Unattended Installation) Integrity Case, where humans are not present on the platform for large periods of time, and are monitored from other platforms or onshore. Secondly, the BN is part of continual development of an Integrity Case which shall focus on maintaining the integrity of the equipment as a priority, as well as the effects of incidents on the environment. Hence fatalities are not part of the BN model consequences.

- The model is designed to demonstrate the hazards and consequences associated with the fuel gas release from an offshore gas turbine. Hence, the consequences regarding fire and explosion are not concerned with the probability of other hydrocarbon releases contributing to fires and explosions.
- The scope of the model is primarily within the power generation module of a large fixed offshore platform. Therefore, the section of the model assigned to the probability of equipment damage due to fire and explosion is confined to the equipment and machinery located only within the stated module.
- The model is representative of fuel gas being released into the module and not within the gas turbine itself. This is due to the fact that should there be a gas release the turbine, it is assumed that the combustion chamber is of sufficient temperature to ignite the fuel. However, the presence of an ignition source within the confines of the module is not a total certainty. The node "Ignition Source" represents this uncertainty and possibility of a source being present.
- While the level of consequence is confined to the module, and the presence of an ignition source is not certain, it is still possible for the gas levels to reach dangerous levels. These dangerous levels do not represent a direct threat to human personnel as it has been stated that humans are not present in the module. The dangerous levels relate to the potential environmental impact of harmful substances being released into the atmosphere. This is in conjunction with the revised requirement of safety cases for offshore installations to contain precautions for potential environmental impact of offshore incidents and accidents (HSE, 2015).

5.2.2 Model Data Limitations

It is important that some remarks are made regarding the uniformity of the data within the model. Statistics exist in a number of formats and originate from many sources. When formulating a model as specific and confined as the one being created, it is almost impossible to gather data sets from the same consistent sources.

It is important to understand that many statistics are not fully representative of reality. For instance, there are cases where the full extent of an incident is not reported, such as a fuel gas release. For example, from 1992 to 2014, 40% of fuel gas and power turbine gas releases were not detected by an automatic sensor, but were detected by human detection. The human detection includes smell, visual and a portable detector. In the instances of human detection, the recording of information is scarce, with 56% of fuel gas release incidents having little to no information regarding the location and cause of the release and in some cases, the extent of the dispersion. Furthermore, the majority of the 56% of releases with incomplete information and data were regarded as “Significant”, in terms of their severity level (HSE, 2014). It is inconsistencies within the data, such as this, that provide sound reasoning to limit data to automatic detection and shut down barriers.

There are some differences in terms of data relating the type of installation operating the same type of gas turbine generator. However, the location of the installations is restricted to the UKCS (United Kingdom Continental Shelf) and the North Sea. Much of the data represented in the model is adapted from gas turbines operating on fixed platforms, yet it is not feasible to obtain data from all sources relating to fixed installations. This limitation with the data goes back to either the absence of data or the lack of appropriate data recording. Hence, data is from fixed installations and FPSOs (Floating, Production, Storage and Offloading) which make use of very similar gas turbine machines.

There are also differences with the age of the data and the data sources used in the Fuel Gas Release model. All data utilised is taken from sources post 2002. Most of the data close to 2002 has been obtained from OREDA-2002 as full access to the database at this time was available. On the other hand most of the conditional data used to complete the CPTs for the nodes, in the BN, has come from risk assessment projects conducted on offshore installation for gas turbines, with the main focus of the projects being hydrocarbon and fuel gas release. These risk projects were conducted post-2009 by RMRI Plc., Petrofac and Maersk.

Finally, most of the nodes are based upon hard evidence statistics, while two of the nodes incorporate subjective judgement by utilising a symmetric algorithm from hard evidence. By combining information in this way it allows for situations that have little to no information to be overcome. This process does not compromise the validation and analysis of the model however it is important to take note of this when interpreting the information presented in the results.

5.3 Structure of the Model and Nodes

The fuel gas release model (shown in Figure 2.1) is primarily designed to represent key initial events of gas turbine failure, in two main areas: the turbine control system and the physical structure. Following the initial events and failures the BN model is designed to show the possible progression of these failures into fuel gas release and the potential fire & explosion consequences that can occur. There are a number of more intimate functions that the model provides. Firstly, the initial stages of the model demonstrate which initial event or hazard demonstrates the greater probability for potential gas release, as well as whether the greatest threat originates from the turbine control system or the physical structure. Secondly, the cause and effect relationships between the barriers is demonstrated in terms of the probability of whether a certain barrier operates as expected, based upon the operation of the previous barriers. Thirdly, the type of consequence that can occur following a fuel gas release. These consequences can be; none, a gas leak only, fire, explosion and resulting equipment damage from a fire and/or an explosion.

There is one transfer node within the fuel gas release BN which links the initial BN demonstrated in Chapter 4. This node is “Fuel Gas Feed Impact”. Through this node any updates from the initial BN model shall result in updates to the posterior probabilities of the fuel gas release BN. The model contains nineteen chance nodes with either two or three states.

To understand how the model operates and the reasoning behind why it has been constructed in the way it has, it is necessary to explain the logic behind each node. It is also necessary to explain what each state means (this is mostly applicable to the nodes “Immediate/Delayed Ignition” and “Consequences”), the more specific assumptions for each node, how the data for the different CPTs has been built, and the relationships of each node with their respective parents and child nodes. The nineteen nodes have been arranged into five categories; “Initial events/Roots”, “Categorized Initial Events”, “Barriers”, “Incidents/Accidents” and “Consequences”. Each node is arranged in the following descriptions by category.

Initial Events/Roots

1. Exceed System Capability [States: Yes, No] – This is a root node or parentless chance node which represents an initiating event whereby the turbine control system incurs a failure and operates outside the system’s capabilities. For example, in the event there

is a failure within the control system that controls the speed of the turbine, the turbine could run at overspeed hence exceeding the 3600 rpm capacity. This would be considered as the turbine exceeding the system's capacity. This node is utilised as a collective of a number of failures. More specific failures, such as overspeed or power surges are to be conducted in further BN models.

2. Operational Error [States: Yes, No] – This parentless chance node represents the operational errors incurred by the turbine control system. The operational errors outlined in this node pertain to pressure, temperature and other electronic sensors and detectors. However, it does not include the Gas Detector as this sensor is applicable after the potential gas leak. Whereas, the pressure and temperature sensors can fail to cause a potential fuel gas release.
3. System Defects [States: Yes, No] – This parentless chance node represents the possibility of there being inherent system defects within the turbine control system. The system defects are defined as an error, flaw, failure or fault in the turbines computer program and/or control system that causes it to produce an incorrect or unexpected result, or to behave in an unintended way.
4. Structural Support Failure [States: Yes, No] – This parentless chance node represents the probability of the main structural supports for the gas turbine experiencing a fault or failure. This can result in an unbalanced rotor shaft and turbine blades, which in turn has the potential to damage fuel gas feed lines, pumps and valves, hence leading to a fuel gas release.
5. Corrosion [States: Yes, No] – This parentless chance node represents the possibility of corrosion being a factor in a potential fuel gas release. Corrosion is a huge factor when considering possible failures on board an offshore installation due to the level

of salt water in the atmosphere. Most modules on an offshore platform are not closed off to the elements, for example, many of the decking sections are steel grating to primarily prevent the pooling of hydrocarbons. This prevents pool fires and slipping hazards for the crew. As the modules are mostly open and much of the offshore equipment is made from steel alloys, corrosion is an ever-present concern unless the steel is coated to prevent corrosion. (Roberge, 2000).

14. Ignition Source [States: Yes, No] – This parentless chance node represents the probability of there being an ignition source sufficient enough to cause ignition of the fuel gas release. While this node is not an initiating failure, it is a root node. The node is a demonstration as to whether the ignition source is present to ignite the fuel gas within the electrical generation module. This does not include combustion within the turbine itself as the stated scenario of “Normal Operation” dictates that the temperature of some of the equipment within the turbine is sufficient enough it ignite the fuel gas, should the gas to oxygen mixture is ideal.. It is also important to note that the fuel gas has a much higher Auto Ignition Temperature (AIT) than diesel, which is approximately 530^{o}C as opposed to 240^{o}C for diesel. Furthermore, it can be deemed unlikely that the exterior of the combustion chamber will cause the gas to auto ignite as the external temperature of the gas turbine combustion chamber can reach approximately 200 – 400^{o}C (HSE, 2008b).

Categorized Initial Events

6. Control System Failures [States: Yes, No] – This chance node represents the probability of there being an overall failure due to the turbine control system given the states of its three parents; “Exceed System Capability”, “Operational Error” and “System Defects”. The purpose of producing a child node form the three relevant

parent nodes is to ease the complexity of the model. Grouping the initial event nodes (nodes 1, 2 & 3) together into an intermediate node, the data acquisition becomes less challenging and the model, in theory, becomes less complex in terms of the complexity levels of some of the CPTs.

7. Physical/Structural Failures [States: Yes, No] – This chance node represents the probability of there being an overall failure due to a physical and/or structural failure given the states of its three parents. These parents are the two root nodes "Structural Support Failure" and "Corrosion" as well as the instance node "Fuel Gas Feed Impact". The reasoning behind this node is the same the "Control System Failures" chance node, outlined in the above paragraph.

Barriers

9. Gas Detection [States: Yes, No] – This chance node represents the probability of a potential gas release. The majority of gas turbine enclosures and/or modules have both gas and oil mist detection in the exhaust ducting (HSE, 2008b). The data within the node focuses on the fire and gas detectors within the electrical generation module. While this node can represent the probability of the gas being detected given that fuel gas was release, it can also show the probability of the detectors showing the presence of gas without a gas release. This can demonstrate the probability that the gas detector within the module has malfunctioned.
10. TCS Shut Off Fuel [States: Yes, No] – This chance node represents the probability that the Turbine Control System (TCS) will shut off the gas given fuel gas detection. The process for the fuel shutting off is split into two nodes as there are two separate fail safe systems concerned with the module and the equipment. One is the F&G system (outlined as node 11 below) and the other TCS. This node focuses on the

TCS’s fuel shut off. This shut off system usually consists of electrical and pneumatic shut-off valves within the turbine for fuel shutdown and isolation in the event of a detected release (HSE, 2008b).

11. F&G System Shut Off Fuel [States: Yes, No] – This chance node represents the probability of the second fuel shut off system operating in the event of a fuel gas detection within the electrical generation module. When the turbine in question is gas driven, not diesel driven, a venting system removes excess fuel gas and routes to the platforms flare system. Diesel is normally routed to a dump tank or hazardous drains. Furthermore, the F&G system applies the use of fuel isolation valves as well as venting systems, to minimise the risk of fire and explosions (HSE, 2008b).
13. Fuel Supply Off [States: Yes, No] – This chance node represents the probability of either of the fuel shut off systems preventing the supply of fuel gas to the turbine, or both systems operating or neither system operating. This node acts much like nodes 6 and 7 whereby it reduces the complexity of the model by reducing the CPTs of three nodes; “Continuous Gas Release”, “Immediate/Delayed Ignition” and “Consequences”. The CPTs are reduced in complexity as the number of parent nodes are reduced without compromising the integrity and purpose of the model.

Incidents/Accidents

8. Fuel Gas Release [States: Yes, No] – This node represents the probability of fuel gas being released given that there is either a TCS failure or a structural failure or both combined. This node is driven by the chance nodes “TCS Failure” and “Physical/Structural Failures”. This node is a way of reducing the size of the “Fuel Gas Release” node as there are five initial root nodes representing individual failures that can occur within a gas turbine. The purpose of this node is to demonstrate a

potential fuel gas leak of sufficient volume to trigger a gas detector and potentially cause a fire within the electrical generation module.

12. Continuous Gas Release [States: Yes, No] – This chance node represents the probability of the gas continuing to be released given that the success of the fuel shut off systems in the event of a gas detection. In the event both systems operate as expected and shut off the fuel, the gas is assumed to not continue to be released. This is also true in the opposing scenario. If both systems fail to operate, then the gas is assumed to continuously be released. However, as one system operates within the turbine and the other within the offshore module, the probability of gas continuously being released will vary depending on whether only one system operates when both are need or whether the gas release is location specific. For example; should the gas leak be detected in the module and not the turbine, it makes sense that the modules F&G system is responsible for the fuel shut off and not the TCS and vice versa.

15. Immediate/Delayed Ignition [States: Yes - Immediate, Yes – Delayed, None] – This chance node represents the probability of the fuel gas within the module being ignited. The ignition of the gas is dependent on a couple of key points: i) there must be an ignition source present and ii) the oxygen to flammable gas mixture must be at an ideal mixture. This leads to three possible states of possible ignition. The first of these is “none”, representing the absence of either an ignition source, ideal mixture or both. The second is “Yes – Immediate”, which is the probability that there is an ignition source present and the gas to oxygen mixture is ideal igniting the gas at the point of release. The third and final state is “Yes – Delayed” whereby an ignition source is not present at the moment the gas is released and the volume of gas within the module is

able to increase. The gas builds to a large volume in the module and given an ignition source, along with the ideal gas to oxygen mixture, delayed ignition can occur.

16. Fire [States: Yes, No] – This chance node represents the probability of a fire occurring within the electrical generation module. The probabilities of the node are determined by three prior nodes: "Fuel Supply off", "Ignition Source" and "immediate/Delayed Ignition". All outcomes from the three prior nodes have an impact on the occurrence probability of a fire in the module.. In this instance it is assumed that given any situation that results in a fire, the fire type is deemed to be a jet fire due to the hydrocarbon in question being fuel gas (OGP, 2010) (Lloyd's Register, 2008).
17. Explosion [States: Yes, No] – This chance node represents the probability of an explosion occurring due to fuel gas release. The probabilities of this node are determined by the "Fuel Supply off", "Ignition Source" and "immediate/Delayed Ignition" nodes. Based upon testing and previous incidents on offshore installations, it is concluded that an immediate ignition has a very unlikely chance to produce an explosion. Delayed ignition is the result of the build-up of a flammable vapour cloud which is assumed to result in explosions (OGP, 2010).

Consequences

18. Consequences [States: Yes – Ignition, Yes – Gas Leak, None] – This chance node generically represents the consequences that can experienced from a fuel gas leak. This node is primarily influenced by two parent nodes; "Immediate/Delayed Ignition" and "Fuel Supply Off". The occurrence probability of the states within this "Consequence" node are determined by the probabilities of the states within the parent nodes. Firstly, the state "Yes – Ignition" is heavily influenced by the "Immediate" and "Delayed" states of the ignition node and the "No" state of the "Fuel Supply Off"

node. This arrangement is due to the fact that if the fuel is shut off, there would be a very unlikely chance that ignition would occur. Secondly, the “Yes – Gas Leak” state is more influenced by the “Fuel Supply Off” node and the state “None” in the “Immediate/Delayed Ignition” node. Finally, the consequence state “None” is dependent on the Fuel supply being shut off and their being no ignition.

19. Damage due to Fire and Explosion [States: Yes, No] – This chance node represents the probability of machinery and equipment being damaged by possible fires and/or explosions within the electrical generation module. The machinery and equipment in question are the two, gas turbine driven electrical generators, the exhausts for the generators and the control panels for the generators. It is assumed that the fire/explosion has the potential to damage the generators and surrounding equipment (RMRI Plc., 2009).
20. Damage to Adjacent Areas [States: Yes, No] – This chance node represents the probability that in the event of an explosion occurring, it has the potential to affect adjacent modules to the electrical generation module. In this event, it is assumed that the walls of the module are that of H60 rating due to the hydrocarbon inventories located adjacent to the electrical generation module. The H60 rating ensures the wall can maintain integrity for 60 minutes and insulation for 30 minutes in the event of a jet fire. Hence a fire is unlikely affect an adjacent module. However, there is the possibility that an explosion has the potential to damage the H60 wall enough to then damage equipment in an adjacent area. The probability of the escalation to adjacent areas is based upon the likelihood of an explosion being of more than 1 bar overpressure (HSE, 2012).

The BN model for a potential fuel gas release is demonstrated by Figure 5-1. The graphical structure of the model is designed to keep the nodes that fall under the same group together and organised in a “top down” manner. The five root nodes and the inference node (node located within the square) are close together at the top. Then the categorised nodes are next in the top down sequence. The Inference node is the input connection from the BN outlined in Chapter 4, with the node outlined in grey representing the output node from the inference node. Continuing from the failures there is a potential

Figure 5-1: BN model demonstrating the cause and effect of a potential fuel gas leak from a gas driven electrical generation system.

incident, which then leads to the barrier nodes. Pending the probability of success or failure of the barriers there is potentially another incident ("Continuous Gas Release"). Following from the barriers there are further incidents, accidents and consequence nodes which are systematically introduced. One node does remain slightly anomalous from this organisation. The "ignition Source" node is grouped along with the incidents, accidents and consequences as it directly affect one of the incidents.

Furthermore, there are certain parameters that have been excluded from the model. These parameters have been excluded to prevent the model from becoming overly complex. An example of one such parameter is the level ventilation in the offshore module and the subsequent gas dispersion. This issue of ventilation and dispersion would bring in further parameters such as: automated ventilation systems, i.e. HVAC (Heating Ventilation and Air Conditioning) and natural ventilation and dispersion, i.e. varying types of weather (i.e., wind, rain). As well as the time taken for the gas to disperse which is dependent on the volume of gas released.

These parameters would allow the model to be much more intricate and complete. However, there are many specific parameters that are time based or rely on further specific parameters which exponentially increases the complexity of the model. This in turn can hinder the accuracy of the model due to the large amount of subjective data required. Hence, the initial parameters selected for the BN and the analysis are all internal failures within the gas turbine that can be measured accurately in terms of their reliability and integrity.

5.4 Data for the Fuel Gas Release Model

The BN model for fuel gas release has been kept as simple as possible while still maintaining a coherent, accurate and logical pathway from the initial root nodes to the final consequences. This level of complexity has allowed CPTs to be manageable when it comes to gathering data. While the majority of the connections in the model are simple converging and diverging connections, consisting mostly of two arc connections in each connection type, there are two node which are the result of triple converging connections. In terms of the size of the CPTs, this is not a huge issue. However, due to the subject of these nodes ("Control System Failure" and "Physical/Structural Failures") there is little to no hard data available to complete their CPTs. It is possible to compile data for the rest of the nodes based upon current literature, databases (primarily for the root nodes) and actual risk assessment project data.

As it is not possible to utilise hard data sources to complete the CPTs of nodes 6 and 7 while still maintaining a high degree of accuracy, other techniques must be used. In this case a variation of the Symmetric Method (outlined in Chapter 3 and demonstrated in Chapter 4) shall be applied to the CPTs of nodes 6 and 7.

5.4.1 Establishing the Conditional Probabilities

When constructing a BN the prior probabilities are required to be assigned locally to the probability link, $P(Parent(A_i)) \rightarrow P(Child(B_i))$, as a conditional probability, $P(B_i|A_i)$. Where i is the number of possible states of the parent node and the child node. However, it is not always a straightforward process to obtain the relevant data. In principle, the majority of the data can be acquired through failure databases or experimentation. However, designing and conducting experiments can prove difficult and historical data does not always satisfy the scope of certain nodes and CPTs within a BN. Therefore, in practice, it is necessary to rely on subjective probabilities provided by expert judgement as an expression of an individual's degree of belief. However, since subjective probabilities are based on informed guesses, it is possible for deviation to occur when the data is expressed as precise numbers.

It can be seen in Chapter 4 that a fully subjective approach has been applied to construct certain CPTs in the BN. This involved experts providing their judgement through a Pairwise Comparison (PC) method. The data from the PC is further analysed using AHP and relative importance weights were determined from this for each parent node in question. These weights are then applied to an algorithm that allows a large child CPT to be constructed cell by cell. This method of compiling data for large CPTs proved simple to implement and produced accurate results for the BN. However, it was found that a time consuming part was the gathering of data from experts through PC in questionnaires.

As the process of creating PC questionnaires, distributing them and waiting for feedback can be time consuming, this process to be amended by utilising hard data from risk assessment experimentation and historical data. This entails utilising hard data from the parent nodes and sections of the child node CPT to create relative weights for the parent nodes and apply those to the symmetric method algorithm.

5.4.2 Symmetric Method utilising hard data

The symmetric method (outlined in Chapter 3 and demonstrated in Chapter 4) provides an input algorithm which consists of a set of relative weights that quantify the relative strengths of the influences of the parent-nodes on the child-node, and a set of probability distributions the number of which grows only linearly, as opposed to exponentially, with the number of associated parent-nodes. Yet the most common method of gathering the required data for the algorithm is to use expert judgements. This method has been applied in Chapter 4. However, it is also possible to utilise the symmetric method with historic data and experimentation. This method is outlined in Chapter 3, specifically Section 3.6.2. While it is very difficult or not possible to complete a large CPT in a BN using hard data, it is possible to obtain key conditional probabilities for a node. For example, node 6, the chance node representing "Control System Failure", has three parent nodes each with two states. This produces a parental distribution in the order of 2^3. While this does not seem a large CPT, the nature of the node's scope limits the level of available data, and hence cannot be completed fully with hard data. However, it is possible to obtain key conditional probabilities and apply them to the symmetric method to complete the CPT.

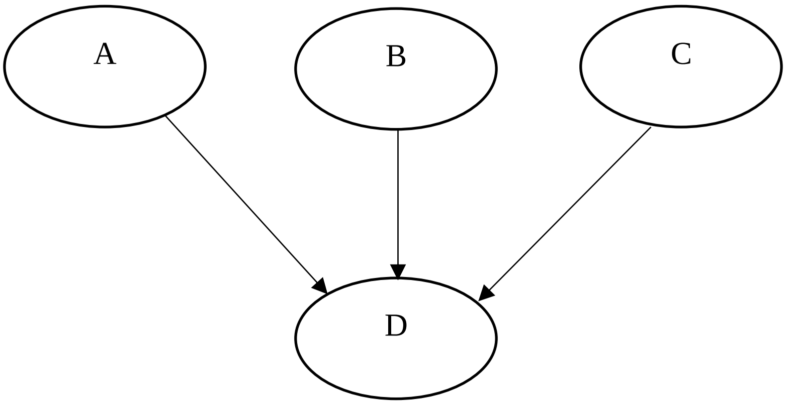


Figure 5-2**:** Sample BN representing 3 parents and 1 child

Figure 3-9 and Figure 5-2 demonstrate the situation in the BN of nodes 1, 2, 3 & 6 (see Figure 5-1) with the notation *A, B, C & D* respectively. While it is not possible to accurately obtain $P(D|A, B, C)$ or even $P(D|A, B)$ through historical or experimental data. It is possible to obtain the conditional probability of event *Z* given the individual parents.

i.e.; *P(D|A)*, *P(D|B)* and *P(D|C)*. These conditional probabilities can be used to develop normalised weights for the parent nodes.

5.4.2.1 Demonstration of Symmetric Method utilising hard data

To outline the symmetric method using hard data, let us consider part of the fuel gas release BN model consisting of nodes 1, 2, 3 & 6 (see Figure 5-1) as shown in Figure 5-3.

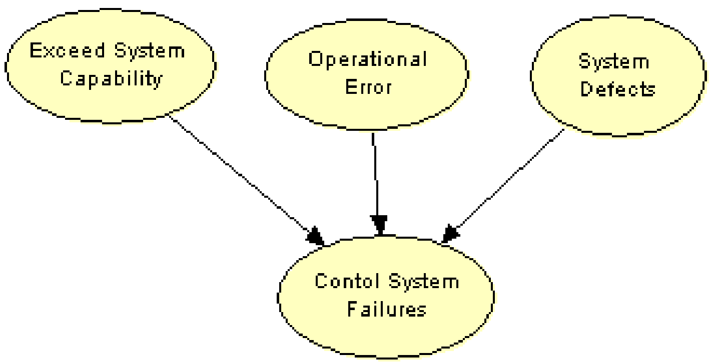


Figure 5-3: Small section of the Fuel Gas Release BN

Also for ease of explanation, the notation applied in Figure 3-9 shall be applied to the section of the BN in Figure 5-3, as shown by Table 5-1.

Table 5-1: Notation for nodes in Figure 3-2

Parent Nodes shown in Figure 3-2	Notation
Exceed System Capability	A
Operational Error	B
System Defects	C
Control System Failure	D

In this example, node D has 2^3 different parental configurations, as there are three parents with two states each (Yes and No). Hence the CPT will consist of 2^3 probability distributions. The scale and scope of the CPT and node provides considerable difficulty when attempting to gather data to complete the CPT. Even if one were to utilise expert judgements to complete the CPT, it would demand a considerable amount of intensive effort on the part of the expert. An additional issue is that the CPT grows exponentially given the number of parents and states. A CPT quantifying the dependency on *n* parents would demand 2^n distributions in order to be functional. It is this exponential growth with the number of parents that constitutes the essential problem. This symmetry method simplifies the problem of exponentially large CPTs.

Calculating the relative weights

As mentioned previously, in the symmetric model the individual local conditional probabilities of the parent to child can be distributed by relative importance for the associated child node, i.e. the normalised weight.

In order to demonstrate the calculation of relative weights, for parent nodes *A*, *B* and *C*, in the network shown in Figure 5-3 shall be used as an example. Table 5-2 shows the local conditional probabilities for the child node "Control System Failure" given each individual child node. The notation outlined in Table 5-1 is also applied for simplicity.

Table 5-2: Individual conditional probabilities for Control System failure

Control System Failure	**Exceed System Capability**	**Operational Error**	**System Defects**	**Sum**
D	**A**	**B**	**C**	
	Yes	Yes	Yes	
Yes	0.0584	0.0610	0.1330	0.2524

The information presented in Table 5-2 can be represented as follows:

$$P(D = \text{“}Yes\text{”}|A = \text{“}Yes\text{”}) = 0.0584 = P(X_A)$$

$$P(D = \text{“}Yes\text{”}|B = \text{“}Yes\text{”}) = 0.0610 = P(X_B)$$

$$P(D = \text{“}Yes\text{”}|C = \text{“}Yes\text{”}) = 0.1330 = P(X_C)$$

$$\sum_{n=A}^{n} P(X_n) = 0.2524$$

Hence, with the individual conditional probabilities, the relative weights of the parent nodes can be calculated utilising Equation 3-16.

$$P(\hat{X}_A) = \frac{P(X_A)}{\sum_{n=A}^{n} P(X_n)} = \frac{0.0584}{0.2524} = 0.2314 = w_1$$

$$P(\hat{X}_B) = \frac{P(X_B)}{\sum_{n=A}^{n} P(X_n)} = \frac{0.0610}{0.2524} = 0.2417 = w_2$$

$$P(\hat{X}_C) = \frac{P(X_C)}{\sum_{n=A}^{n} P(X_n)} = \frac{0.1330}{0.2524} = 0.5269 = w_3$$

Following from this, Equation 3-17 shows that the summation of the relative weights should be equal to 1, as follows:

$$\sum_{n=1}^{n} w_n = w_1 + w_2 + w_3 = 0.2314 + 0.2417 + 0.5269 = 1$$

As the relative weights for parent nodes *A*, *B* and *C* have been calculated and assigned accordingly, they can be applied to the weighted sum algorithm. Along with the linear compatible parental configuration to produce complete the CPT.

The Weighted Sum Algorithm

It is possible to apply the weighted sum algorithm as the following information has been identified:

iii) The relative weights of the parent nodes w_1 , ... , w_n , and,

iv) The k_1+ ... +k_n probability distributions over event "*D*", of the linear type, for compatible parental configurations.

Given the information provided Equation 3-20 is used to produce an estimate, based information from historical data sources, of the $k_1 \times ... \times k_n$ distribution for child node "*D*" (Das, 2008).

$$P\left(x^l \mid y_1^{S_1},\, y_2^{S_2},\, \dots,\, y_n^{S_n}\right) = \sum_{j=1}^{n} w_j \,.\, P\left(x^l \mid \{Comp(Y_j = y_j^{S_j})\}\right) \quad \textit{(3-20)}$$

where: $l = 0, 1, ..., m$ and $S_j = 1, 2, ..., k_j$.

This weighted sum algorithm is applied to the distribution over child node "*D*" for compatible parental configurations. Table 5-3 demonstrates the compatible distributions over child node "*D*" ("Control System Failure"), with data obtained from historical databases and offshore risk assessment projects.

Table 5-3: Distribution over *D* for compatible parental configurations {Comp(A = s)}

Probability Distribution over "D"	**s = Yes**	**s = No**
P(D = Yes|{Comp(A = s)})	0.936	0.064
P(D = No|{Comp(A = s)})	0.064	0.936

In addition, Table 5-4 shows the relative weights for the parents of event *"D"*, which were obtained from Equations 3-4 and 3-5 as well as historical data and risk assessment projects.

Table 5-4: Relative weight for the parent nodes of child node "D" (Control System failure)

Parent Node	**Weighting Notation**	**Relative Weights**
Exceed System Capability (A)	W_1	0.2314
Operational Error (B)	W_2	0.2417
System Defects (C)	W_3	0.5269
	Total	1.00

Utilising the data shown in Table 5-3 and Table 5-4, it is possible to calculate all of the 2^3 parental distributions required to populate the CPT for event "D". Consider an example to demonstrate the algorithm for a specific parental distribution, where *P(D="Yes")* is required. One possible distribution is shown in Table 5-5.

Table 5-5: Possible parental distribution for parents of child "D"

Parent Node	**State: Yes or No**
Exceed System Capability (A)	Yes
Operational Error (B)	No
System Defects (C)	Yes

Given the states of the parents in Table 5-5, the distribution over *"D"* is to be:

$$P(D = Yes|A = Yes, B = No, C = Yes) \qquad \textit{(5-1)}$$

Once all of the relevant data is known, according to Equation 5-1, the following computation is required:

$$P(D = Yes\ |A = Yes, B = No, C = Yes) = w_1.P(D = Yes\ |\{comp(A = Yes)\}) +$$
$$w_2.P(D = Yes\ |\{comp(B = No)\}) + w_3.P(D = Yes\ |\{comp(C = Yes)\}) \qquad \textit{(5-2)}$$

From Equation 5-2 it can be deduced that for the parental configuration shown in Table 5-5, when the correct compatible probabilities and weights are substituted in, the probability of event *"D"* being in the state "Yes" is to be:

$$P(D = Yes|A = Yes, B = No, C = Yes) = 0.725 \qquad \textit{(5-3)}$$

Subsequently, the complement of Equation 5-3 is to be:

$$P(D = No|A = Yes, B = No, C = Yes) =$$
$$1 - P(D = Yes|A = Yes, B = No, C = Yes) = 0.275 \qquad \textit{(5-4)}$$

The relative weight algorithm is applied to all cells within the relevant CPT table to obtain the full conditional probability distribution. This process was completed using the formula function in Microsoft Excel, which also saves time for calculations. The completed CPTs for the Fuel Gas Release model in Figure 5-1 can be found in Appendix I.

Continuing on from the data acquisition and analysis process which consists of gathering data from historical failure databases, risk assessment projects and experiments as well as utilising the symmetric method to complete larger CPTs. It is possible to complete the

BN by completing the CPTs and ascertaining the marginal probabilities for the nodes and conduct several test cases to validate the BN model.

Table 5-6 summarises the origins of the data for each node in the initial BN model. There were several sources of literature. For example, node 10 was determined from historical data sources, such as (OREDA 2002) and the HSE databases. Whilst, in comparison, data for node 17 is from (Atkins, 2008), (RMRI Plc. 2009) and (Lloyd's Register, 2008). Table 5-6 also contains the number of states for each node and the number of permutations to demonstrate an idea of how data had to be broken down before being inserted into the corresponding CPT. Similarly, Figure 5-4 shows the marginal probabilities for each node in the BN.

Table 5-6: Details of each nodes CPT and their data sources.

Node	Node Name	States	Parents	Permutations in probability table	Data Sources
			Transfer node from Initial BN		
0	Fuel Gas Feed Impact	2	1	4	Literature
			Initial Events/Roots		
1	Exceed System Capability	2	0	2	Literature (DB[1] & HD[2])
2	Operational Error	2	0	2	Literature (DB[1] & HD[2])
3	System Defects	2	0	2	Literature (DB[1] & HD[2])
4	Structural Support Failure	2	0	2	Literature (DB[1] & HD[2])
5	Corrosion	2	0	2	Literature (DB[1] & HD[2])
14	Ignition Source	2	0	2	Literature (DB[1] & HD[2])
			Categorized Initial Events		
6	Control System Failure	2	3	16	Literature with subjective analysis
7	Physical/Structural Failures	2	3	16	Literature with subjective analysis
			Barriers		
9	Gas Detection	2	2	8	Literature (HD[2] & RA[3])
10	TCS Shut Off Fuel	2	1	4	Literature (HD[2] & RA[3])
11	F&G System Shut Off Fuel	2	1	4	Literature (HD[2] & RA[3])
13	Fuel Supply Off	2	2	8	Literature (HD[2] & RA[3])
			Incidents/Accidents		
8	Fuel Gas Release	2	2	8	Literature (HD[2])
12	Continuous Gas Release	2	2	8	Literature (HD[2])
15	Immediate/Delayed ignition	3	2	12	Literature (HD[2] & RA[3])
16	Fire	2	1	4	Literature (HD[2] & RA[3])
17	Explosion	2	1	4	Literature (HD[2] & RA[3])
			Consequences		
18	Consequences	3	2	18	Literature (HD[2])
19	Damage due to Fire & Explosion	2	2	8	Literature (HD[2] & RA[3])
20	Damage to Adjacent areas	2	1	4	Literature (HD[2] & RA[3])

[1]DB: Data has been utilised form Failure Databases, such as OREDA and OGP.
[2]HD: Data has been utilised from Historical Data in literature, such as: Journals, and HSE reports,.
[3]RA: Data has been utilised from Risk Assessment projects conducted by RMRI Plc., Petrofac, Maersk, and Lloyd's Register.

5.5 Fuel Gas Release Model Test Cases and Sensitivity Analysis

As demonstrated in Appendices F and G, case studies are important for showing how research can be put into practice. The Fuel Gas Release model is now used to analyse a series of possible real-world scenarios. All variables from external BNs, i.e. the transfer node "Fuel Gas Feed Impact", are to remain unchanged and only those directly linked to the study for Fuel Gas Release shall be altered using the Hugin software. The Hugin software allows for evidence to be inserted to all nodes within the network in its "*Run*

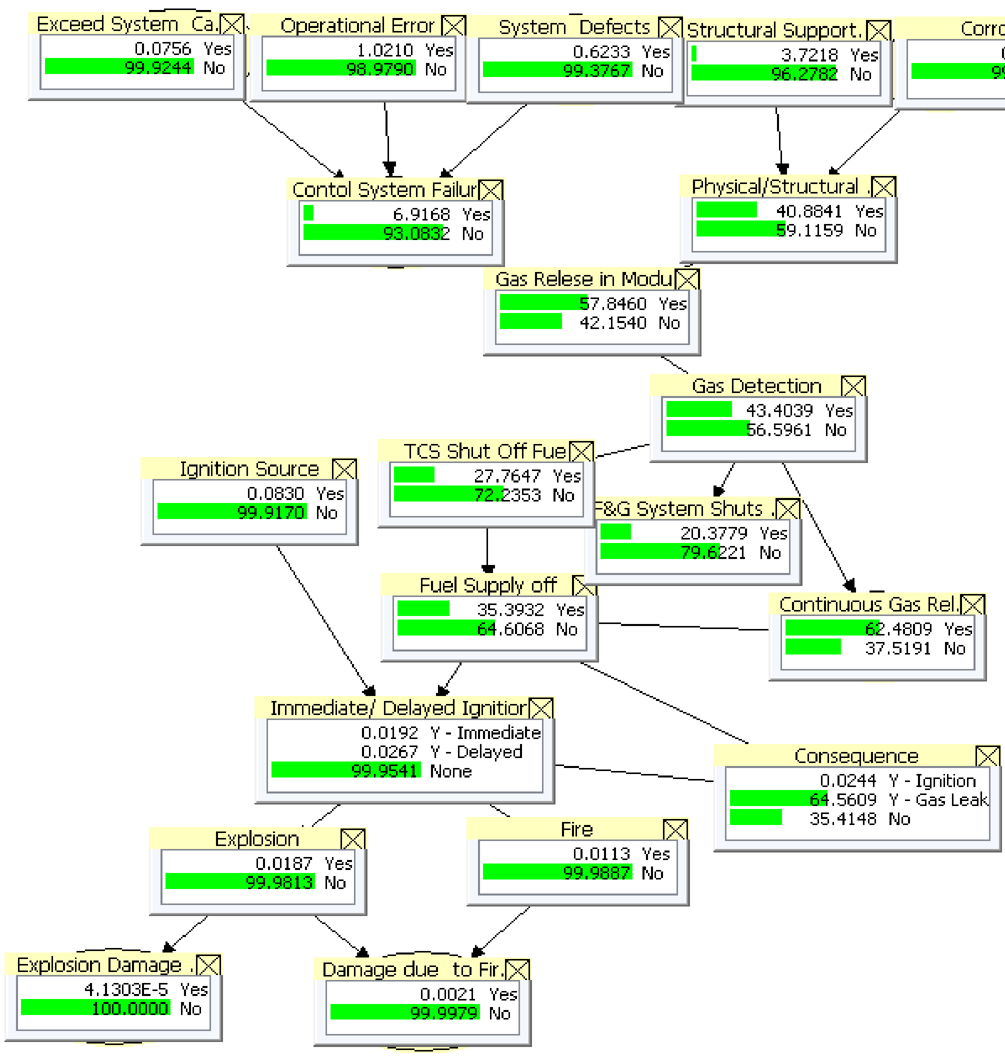


Figure 5-4: Marginal probabilities for each node within the Fuel Gas Release BN

Mode" function. This evidence is to the degree of 100% in a given state of a node. It is the posterior probabilities that are of interest and are computed given particular evidence of specific nodes.

The focus of the Fuel Gas Release model is on the effects of the initial failures on the likelihood of a gas release. As well as the possible performance of the barriers designed to mitigate against the escalation of a release to further, more severe incidents. Furthermore, the model analysis shall demonstrate the probability of possible consequences that may arise given that these barriers do not perform their required function. As well as the potential further escalation given other external factors, such as the presence of an ignition source. The model also allows for the comparison of combined effects of various, simultaneous failures and their combined effect on the probability of events. There are a number of test cases which shall demonstrate the effects of different scenarios on the potential of a gas release and the possibility of fire and/or explosions. Similarly, to add to the validation of the model through these test cases, the effect of initially observing a consequence, such as: a leak or an ignition, is demonstrated through the change in the probability of the prior nodes. This is a potential route to identifying the main unknown cause of a consequence.

It is important to note that before any evidence is inserted into the model, the probability of a there being a "Continuous Release" and the sate "Y-Leak" in the "Consequence" node are quite high. This is because they are directly affected by the "Gas Detection" node. Before evidence is inserted, the "Gas Detection" node shows a low probability of detection, and hence the model assumes a higher probability of a release. It can be seen in the test cases that once the probability of detection inadvertently increases because of the presence of fuel gas, the probability of a leak as a consequence reduces. The effects of the detection system failing is demonstrated in the test cases to ascertain the severity of the probability changes to the potential consequences.

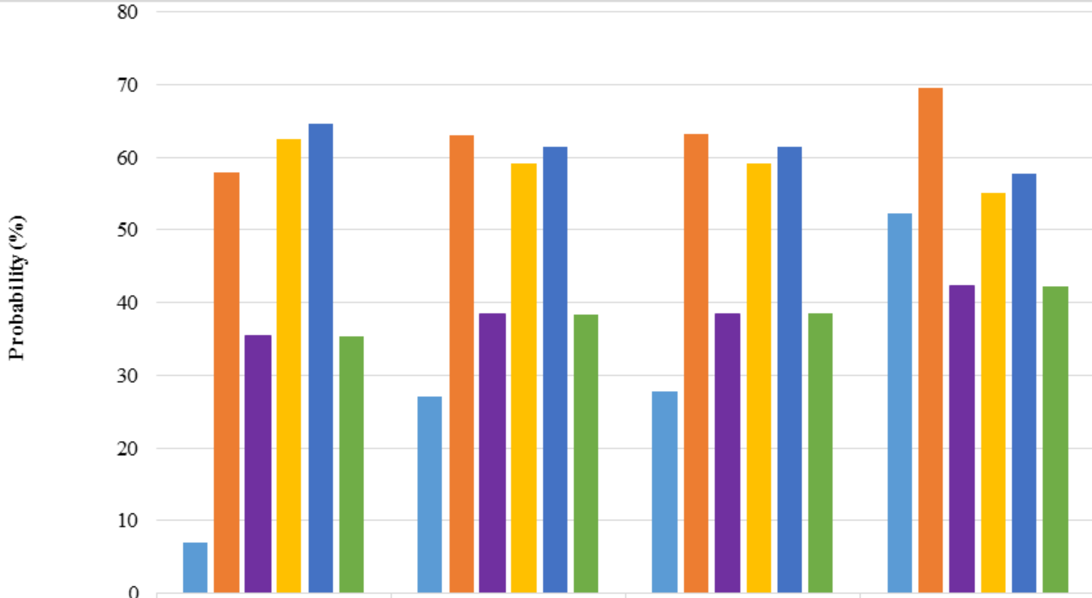
The primary purpose of Test Case 1 is to demonstrate partial validation of the model by demonstrating the behaviour of the probabilities is akin to a real-world scenario. Test Case 2 shall demonstrate the effects, on the BN, of a barrier failure along with the presence of an ignition source. Furthermore, Test Case 3 shall demonstrate the effects on prior probabilities given evidence inserted in the consequence node. Finally, a sensitivity analysis shall provide further validation utilising the *Parameter Sensitivity Wizard* in the *Hugin* software.

5.5.1 Test Case 1: Control System and Physical/Structural Failures

This case study demonstrates the effects of individual and combined control system failures within the fuel gas release model. This case study is split into four test cases: 1A) is a demonstration of the effects of control system failures on the network, 1B) is a demonstration of the control system failures with the presence of an ignition source, 1C) is a demonstration of the effects of Physical/Structural failures on the network, and 1D) is a demonstration of the effects of Physical/Structural failures on the network with the presence of an ignition source.

5.5.1.1 Test 1A: Control System Failures without Ignition

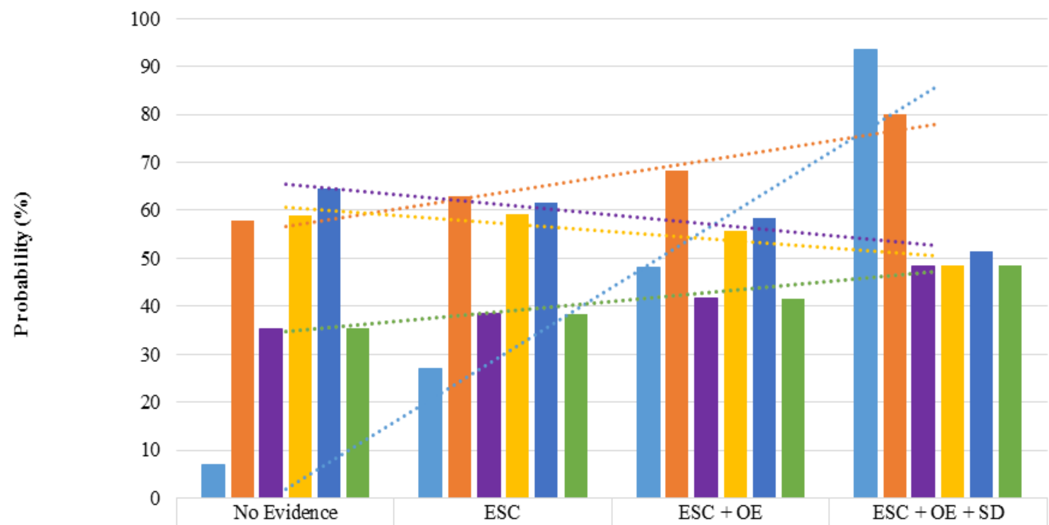
In the context of the presented model, the probability of a fuel gas release from a gas turbine due to the turbines control system, is mostly dependent on three key events; “Exceeding System Capability” (ESC), “Operational Error” (OE) and “System Defects” (SD). These events can occur either individually or in conjunction with each other. The effect on the likelihood of a gas release is demonstrated along with the effects on the fuel shut off system. The consequences from these likelihoods is also demonstrated. In this case the likelihood of a continuous fuel release is analysed as well as the probability of the “Consequence” node being in states “Y-Leak” and “None”. It is not key to analyse the “Y-Ignition” state as this test does not include the possibility of an ignition source.



	No Evidence	ESC	OE	SD
CSF	6.92	27.1	27.8	52.3
Gas Release	57.85	63	63.18	69.5
Fuel Off	35.39	38.43	38.53	42.25
Continuous Release	62.48	59.21	59.09	55.08
Y-Leak	64.56	61.53	61.43	57.71
None	35.41	38.45	38.55	42.27

Figure 5-5: Effects of the turbine control system failures on the posterior probabilities of "Gas Release", "Fuel Shut Off", "Continuous Gas Release" and "Consequence; States: Y-Leak & None"

The results are presented by means of a bar chart shown in Figure 5-5, which demonstrates the probability of gas release, fuel shut off, continuous release, the consequences and the effect on the overall control system failure, on the y-axis. The x-axis shows which individual event is presumed to be occurring. From the results, it is evident that a major system defect would have the greatest effect on the probability of the gas release, as shown by the increase in probability from 57.85% without evidence, to 69.5% when a potential system defect causes a failure. It can be seen that the effects of a system defect in the control system produces the more significant changes in in the likelihood of there not being a consequence due to the increase in the probability in gas release. The key information to be taken is the significance in the change of posterior probability's given the evidence inserted. This method provides a basic sensitivity analysis along with probability interpretation. Furthermore, the likelihood of consequences and continuous release decreases with the inserted evidence in control system failures as it is assumed in the model that the gas detection system has no reason to not function correctly at this stage. Therefore, the increase in the probability and level of gas release will increase the probability of gas detection and hence the probability that the fuel will be shut off. This is a scenario that would be expected in a real-world situation.



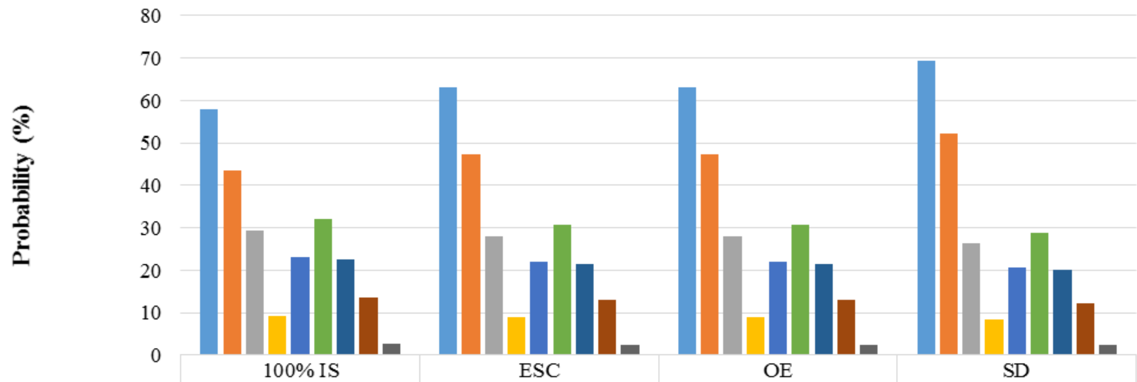
	No Evidence	ESC	ESC + OE	ESC + OE + SD
CSF	6.92	27.1	47.99	93.6
Gas Release	57.85	63	68.33	79.98
Fuel Off	35.39	38.43	41.56	48.42
Continuous Release	58.81	59.21	55.82	48.42
Y-Leak	64.56	61.53	58.39	51.55
None	35.41	38.45	41.58	48.43

Figure 5-6: Cumulative effects of the turbine control system failures on the posterior probabilities of "Gas Release", "Fuel Shut Off", "Continuous Gas Release" and "Consequence; States: Y-Leak & None"

Figure 5-6 shows the cumulative effect of the control system failures. As with the individual failures, the cumulative failures demonstrates that when the gas detection system is assumed to function as normal, the likelihood of the fuel being shut off and there being no consequences increases. Adversely, the probability of there being a continuous release and a leak consequence decreases.

5.5.1.2 Test 1B: Control System Failures with Ignition

As stated in Test 1A, the probability of a fuel gas release from a gas turbine due to the turbines control system, is dependent on three key initial events; “Exceeding System Capability”, “Operational Error” and “System Defects”. Test 1A then demonstrated the effects of each failure on the BN model as both individual effects and the cumulative effects. This test expands upon the findings in Test 1A by again demonstrating the individual and cumulative effects of the control system failure, except in this test there is assumed to be an Ignition Source (IS) present. This will illustrate the effect the initial failures has on the accident and consequence nodes. The results are again presented in a bar chart (Figure 5-7) which shows the probability of gas detection, immediate or delayed ignition, explosion, fire, the potential damage incurred and the overall consequences on the y-axis. The x-axis shows the nodes where evidence has been input. The first column in the table in Figure 5-7 shows posterior probabilities of several nodes given that there are no control system failures but there is evidence of an IS.

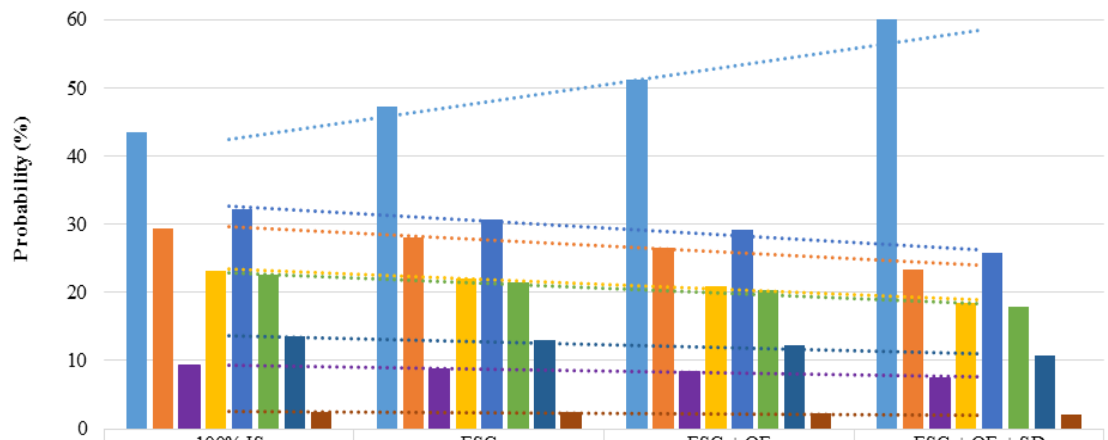


	100% IS	ESC	OE	SD
Gas Release	57.85	63	63.18	69.5
Gas Detection	43.4	47.25	47.38	52.1
Y-Ignition	29.34	27.97	27.92	26.23
Y-Leak	9.29	8.85	8.84	8.3
Immediate	23.13	22.04	22.01	20.68
Delayed	32.2	30.69	30.64	28.78
Explosion	22.51	21.45	21.42	20.12
Fire	13.56	12.93	12.9	12.12
F&Ex Damage	2.55	2.44	2.43	2.29

Figure 5-7: Effects of Turbine Control System failures, with an ignition source present, on the posterior probabilities of "Gas Detection", "Consequences", "Immediate/Delayed Ignition", "Explosion", "Fire" and "Damage due to Fire & Explosion"

From the graph, it can be seen that the probability of there being a gas release, given any of the initial failures, is the same as Test 1A despite there being an ignition source present. This provides some partial validation to the model as it indicates the nodes that should be independent from each other, such as: “Ignition Source” and “Gas Release”. Furthermore, as with test 1A, the initial event “System Defects” demonstrates the largest effects on the model. It can also be seen that the probability of gas detection increases proportionally to the probability of gas release. This affects the relationship between the probability of detection and the probability of accidents and consequence. For example, in the event that there is only an ignition source present the probability of there being either fire or an explosion increases from 0.0113% to 13.56% and 0.0187% to 22.51% respectively (for marginal probabilities refer to Figure 5-4). This shows how the significant the presence of an ignition source is to the probability of fire and explosion before any other evidence is inserted. Continually, when evidence is then inserted into the “System Defects” node, the posterior probabilities for fire and explosion decrease from 13.56% to 12.12% and

22.51% to 20.12%. This is because the probability of the gas detection increases with the probability of the gas release, as it is assumed that the gas detectors function as expected. Furthermore, this in turn has an effect on the fuel gas shut off by increasing the probability that fuel gas will be shut off. Hence the probability that a fire or explosion will occur decreases.



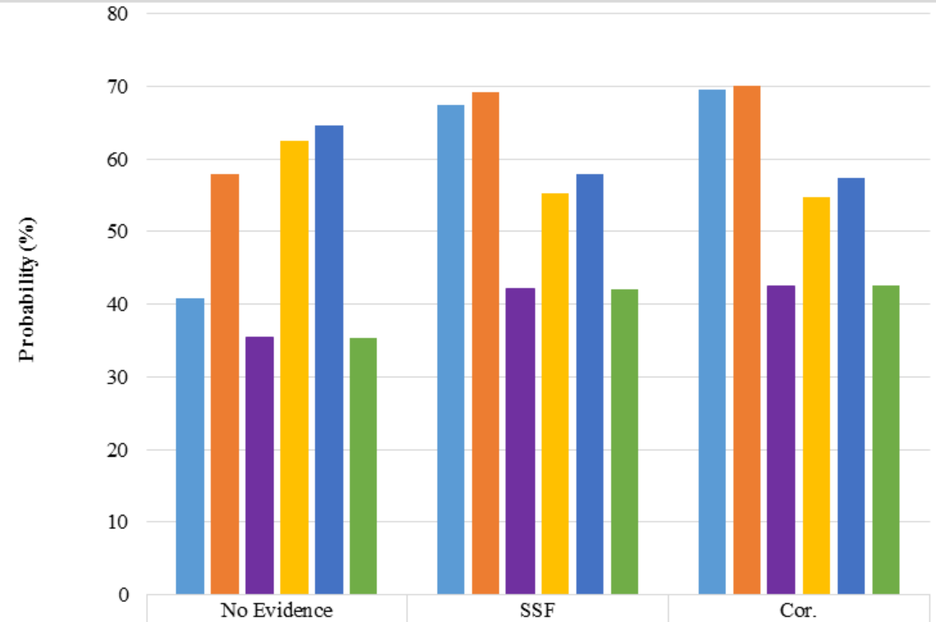
	100% IS	ESC	ESC + OE	ESC + OE + SD
Gas Detection	43.4	47.25	51.23	59.93
Y-Ignition	29.34	27.97	26.54	23.43
Y-Leak	9.29	8.85	8.4	7.41
Immediate	23.13	22.04	20.92	18.47
Delayed	32.2	30.69	29.12	25.71
Explosion	22.51	21.45	20.36	17.97
Fire	13.56	12.93	12.27	10.83
F&Ex Damage	2.55	2.44	2.31	2.04

Figure 5-8: Cumulative effects of Turbine Control System failures, with an ignition source present, on the posterior probabilities of "Gas Detection", "Consequences", "Immediate/Delayed Ignition", "Explosion", "Fire" and "Damage due to Fire & Explosion"

Figure 5-8 shows the cumulative effect of the control system failures while there is an assumed IS present. As with the individual failures, the cumulative failures demonstrate that when the gas detection system is assumed to function as normal, the likelihood of the fuel being shut off again decreases. It is also poignant to notice that given the presence of an ignition source, the probability that there will be fire or explosion significantly increases before any evidence is present for the initial failures. Adversely, the probability of there being a fire or explosion given evidence for the initial failures decreases. This is due to the probability of a gas release increasing, hence increasing the probability of the gas being detected, and further increasing the probability that the fuel gas will be shut off.

5.5.1.3 Test 1C: Physical/Structural Failures without Ignition

Test Cases 1C and 1D are similar to the previous cases, 1A and 1B, in that they demonstrate the effects of initial failures on the BN model both with and without an ignition source present. However, tests 1C and 1D are concerned with the effects that Physical and Structural failures potentially have on the BN model. It is important to specify that the analysis in the Hugin BN software is applied to only discrete chance nodes and therefore the inference node "Fuel Gas Feed Impact" is not included in the analysis. Figure 5-9 shows the effects of the individual initial events, "Structural Support Failure" (SSF) and "Corrosion" (Cor.), on the posterior probabilities of gas release, fuel shut off, continuous release, the consequences (states "*Y-leak*" and "*None*") and the effect on the



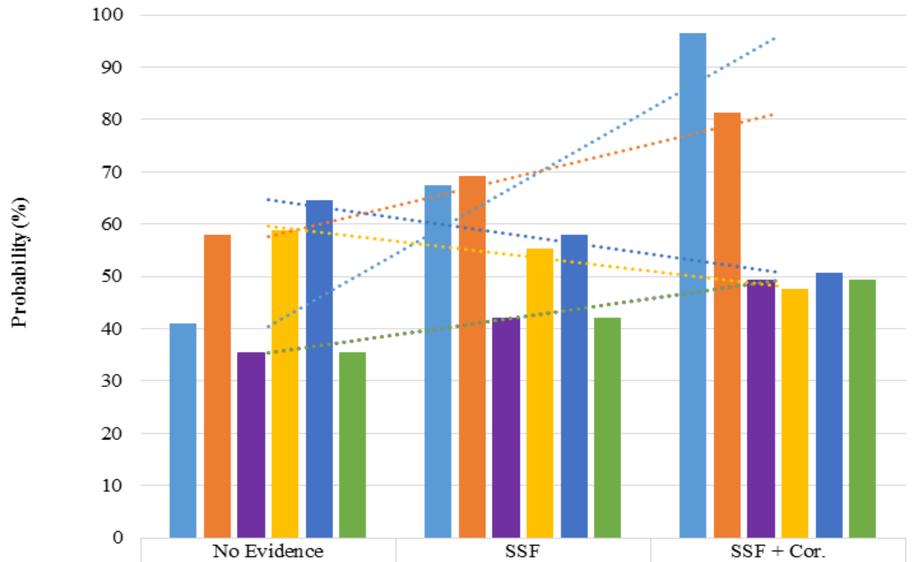
	No Evidence	SSF	Cor.
PSF	40.88	67.4	69.59
Gas Release	57.85	69.21	70.01
Fuel Off	35.39	42.08	42.55
Continuous Release	62.48	55.27	54.76
Y-Leak	64.56	57.88	57.41
None	35.41	42.1	42.57

Figure 5-9: Effects of the physical and structural failures on the posterior probabilities of "Gas Release", "Fuel Shut Off", "Continuous Gas Release" and "Consequence; States: Y-Leak & None"

overall physical failure, on the y-axis. The x-axis shows the individual event which is assumed to be occurring.

From the graph in Figure 5-9 it can be seen that of the two events, represented as chance nodes, corrosion demonstrates the largest effect on a potential fuel gas release. It is evident that a failure caused by corrosion would have the greatest effect on the probability of the gas release, as shown by the increase in probability from 57.85% without evidence, to 70.01% when corrosion potentially causes a failure. Similarly, a failure caused by corrosion also produces the largest percentage change in the likelihood that a consequence will not occur. The effects that a failure due to corrosion has on the posterior probabilities in the model also represents the largest percentage change out of the five initial events.

As with the previous test cases, the probability of there being a leak consequence and continuous gas release decreases with the insertion of evidence at the root nodes, due to



	No Evidence	SSF	SSF + Cor.
PSF	40.88	67.4	96.4
Gas Release	57.85	69.21	81.37
Fuel Off	35.39	42.08	49.23
Continuous Release	58.81	55.27	47.55
Y-Leak	64.56	57.88	50.73
None	35.41	42.1	49.25

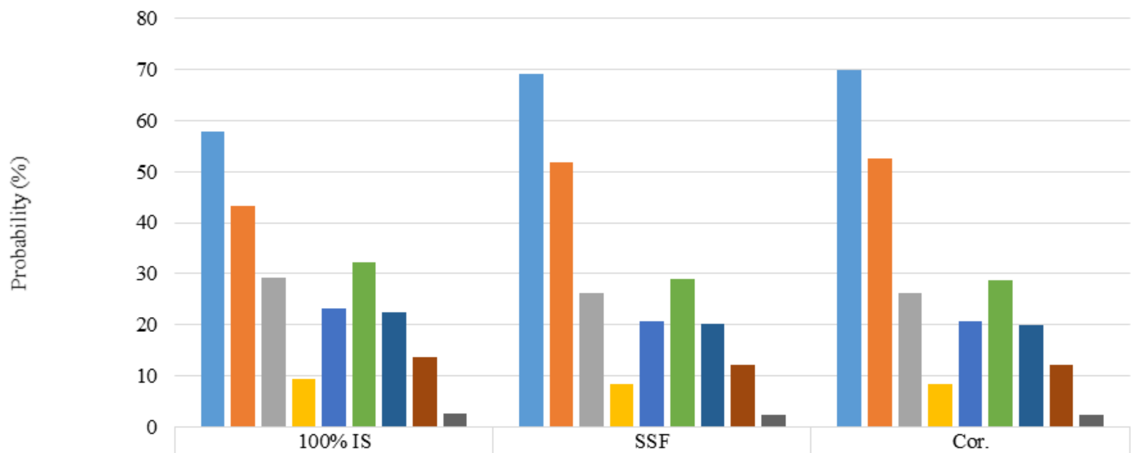
Figure 5-10: Cumulative effects of the physical and structural failures on the posterior probabilities of "Gas Release", "Fuel Shut Off", "Continuous Gas Release" and "Consequence; States: Y-Leak & None"

the probability of a release being detected given an increase in the probability that a release will occur. Furthermore, as with Test Case 1A the key information be taken is the significance in the change of posterior probability's given the evidence inserted. This method provides a basic sensitivity analysis along with probability interpretation, as well as partial validation to the BN model.

Figure 5-10 shows the cumulative effect of the physical and structural failures. As with the individual failures, the cumulative failures demonstrate that when the gas detection system is assumed to function as normal, the likelihood of the fuel being shut off and the probability of there being no consequences increases. Alternatively, the probability of there being a continuous release and a leak consequence decreases.

5.5.1.4 Test 1D: Physical/Structural Failures with Ignition

As stated in Test 1C, the probability of a fuel gas release from a gas turbine due to the physical and structural failures, is dependent on key initial events; "Structural Support Failures", and "Corrosion". Test 1C then demonstrated the effects of each failure on the BN model as both individual effects and the cumulative effects. This test expands upon the findings in Test 1C by again demonstrating the individual and cumulative effects of the physical and structural failures, except in this test there is assumed to be an IS present. This will illustrate the effect the initial failures has on the accident and consequence nodes. The results are again presented in a bar chart as shown in Figure 5-11 which shows the probability of gas detection, immediate or delayed ignition, explosion, fire, the potential damage incurred and the overall consequences on the y-axis. The x-axis shows the nodes where evidence has been input. The first column in the table in Figure 5-11 shows the probability of there being no evidence inserted in the control system nodes but does indicate that there is an ignition source.

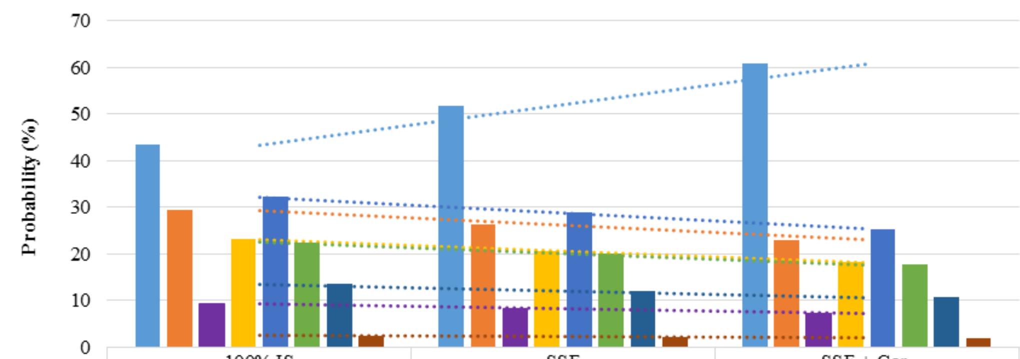


	100% IS	SSF	Cor.
Gas Release	57.85	69.21	70.01
Gas Detection	43.4	51.88	52.48
Y-Ignition	29.34	26.31	26.1
Y-Leak	9.29	8.33	8.26
Immediate	23.13	20.74	20.57
Delayed	32.2	28.87	28.63
Explosion	22.51	20.18	20.01
Fire	13.56	12.16	12.06
F&Ex Damage	2.55	2.29	2.27

Figure 5-11: Effects of Physical and Structural failures, with an ignition source present, on the posterior probabilities of "Gas Detection", "Consequences", "Immediate/Delayed Ignition", "Explosion", "Fire" and "Damage due to Fire & Explosion"

From the graph it can be seen that the probability of there being a gas release, given any of the initial failures, is the same as Test Case 1C despite there being an ignition source present. This again provides some partial validation to the model as it indicates the nodes that should be independent from each other, such as: “Ignition Source” and “Gas Release”. This has previously been demonstrated in Test Case 1B. Furthermore, as with Test Case 1C, the initial event “Corrosion” demonstrates the largest effects on the model. It can also be seen, as with Test 1B, that the probability of gas detection increases proportionally to the probability of gas release. This affects the relationship between the probability of detection and the probability of accidents and consequence. For example, in the event that there is only an ignition source present the probability of there being either fire or an explosion increases from 0.0113% to 13.56% and 0.0187% to 22.51% respectively (for marginal probabilities refer to Figure 5-4). It is important to note that this percentage increase is identical to the increase demonstrated in Test Cases 1C when only an ignition source is present. Continually, when evidence is then inserted into the “Corrosion” node, the posterior probabilities for fire and explosion decrease from 13.56% to 12.06% and 22.51% to 20.01%. This is because the probability of the gas detection increases with the probability of the gas release, as it is assumed that the gas detectors function as expected. Furthermore, this in turn has an effect on the fuel gas shut off by increasing the probability that fuel gas will be shut off. Hence the probability that a fire or explosion will occur decreases. The percentages changes demonstrated in Figure 5-10 and Figure 5-11 show that the event “Corrosion” has the greatest effect on posterior probabilities in the BN model of all of the initial events.

Figure 5-12 shows the cumulative effect of the physical and structural failures while there is an assumed ignition source present. As with the previous Test Cases, the cumulative failures demonstrate that when the gas detection system is assumed to function as normal,



	100% IS	SSF	SSF + Cor.
Gas Detection	43.4	51.88	60.96
Y-Ignition	29.34	26.31	23.06
Y-Leak	9.29	8.33	7.3
Immediate	23.13	20.74	18.18
Delayed	32.2	28.87	25.3
Explosion	22.51	20.18	17.69
Fire	13.56	12.16	10.66
F&Ex Damage	2.55	2.29	2.01

Figure 5-12**:** Cumulative effects of Turbine Control System failures, with an ignition source present, on the posterior probabilities of "Gas Detection", "Consequences", "Immediate/Delayed Ignition", "Explosion", "Fire" and "Damage due to “Fire & Explosion"

the likelihood of the fuel being shut off again decreases. Adversely, the probability of there being a fire or explosion given evidence for the initial failures decreases.

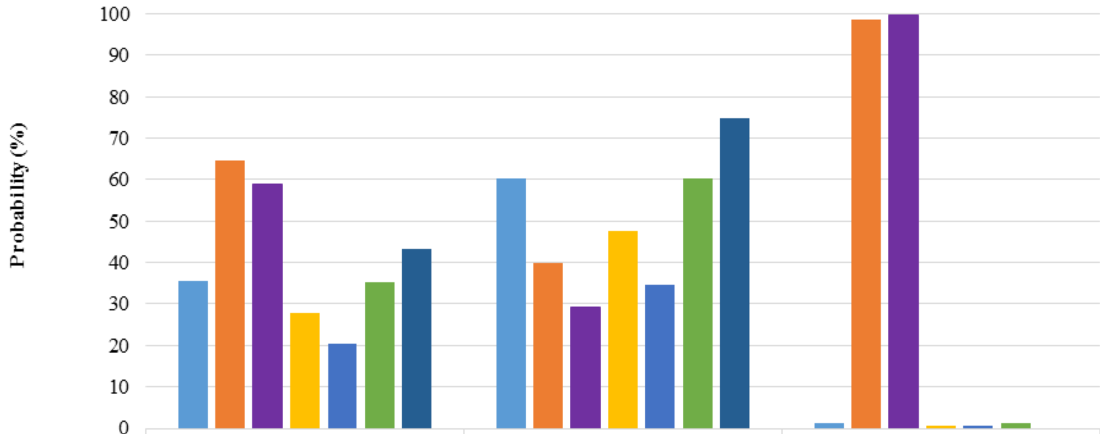
Test Cases 1A, 1B, 1C and 1D demonstrate the cause and effect relationship that the five initial events have on the posterior probabilities in the BN model. The sixth root node, “ignition Source”, is also applied to the analysis to demonstrate the combined effects of the initial events with an ignition source present. This established some partial validation to the model as the posterior probabilities are increased and decreased as one would expect given evidence inserted at the root nodes. One key element demonstrated in the four test cases is that of the relationship between gas release and gas detection. As the probability of there being gas released increases, the probability of gas detection proportionally increases. This is because in a real scenario, it is assumed that when gas is present in the offshore module, the gas detectors would sense it and hence the gas would be shut off, either by the Turbine Control System (TCS) or the Fire & Gas system (F&G). This, as demonstrated by the Test Cases, decreases the probability of and accident or sever consequences. However, it is important to demonstrate the effects a dysfunctional barrier, such as the gas detection system, has on the posterior probabilities of the BN model. Test Case 2 outlines this type of scenario.

5.5.2 Test Case 2: Gas Release and No Detection with and without an Ignition Source

This case study demonstrates the effects of the probability of a gas release being 100% “*Yes*” on the BN model. Along with the gas release, the effect of the gas detection not functioning, i.e. Gas Detection being 100% “*No*” will also be analysed. Therefore, this case study is split into two test cases: 2A) is a demonstration of the effects of a gas release and no gas detection without an ignition source, 2B) is a demonstration of the effects of no gas detection combined with an ignition source being present.

5.5.2.1 Test 2A: Gas Release, no Gas Detection, no Ignition Source

In the context of the presented model, the probability of a fuel gas release from a gas turbine due to the turbines control system, is dependent on five key events; “Exceeding System Capability”, “Operational Error”, “System Defects”, “Structural Support Failure” and “Corrosion”. As demonstrated in Test Case 1 these events can occur either individually or in conjunction with each other. In test 2A is assumed that one or more of these events have occurred and a Gas Release (GR) is observed. In this case the likelihood of a continuous fuel release is analysed as well as the probability of the “Consequence” node being in states “Y-Leak” and “None”. It is not key to analyse the “Y-Ignition” state as this test does not include the possibility of an ignition source. The analysis is presented in Figure 5-13.



	No Evidence	GR (Yes)	GD (No)
None	35.41	60.2	1.22
Y-Leak	64.56	39.78	98.74
Continuous Release	58.81	29.26	99.565
TCS	27.76	47.47	0.58
F&G	20.37	34.7	0.61
Fuel off	35.39	60.19	1.182
Gas Detection	43.4	74.866	0

Figure 5-13: Effects of “Gas Release” being “Yes=100%” and “Gas Detection” being “No=100%” on “Consequences”, “Continuous Gas Release”, “Fuel Shut Off” (TCS, F&G and Fuel Off) and “Gas Detection”

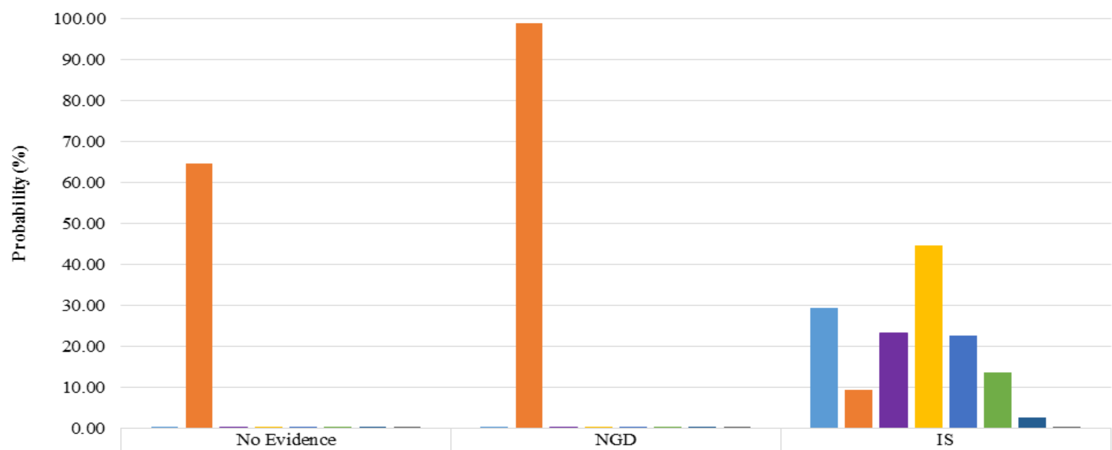
From the graph in Figure 5-13 it can be seen that when there is 100% chance of a fuel gas release, the probability of gas detection increases from 43.4% to 74.87%. This is due to the assumption that the gas detection system functions as expected, i.e. in the event of a gas release it is assumed, with some confidence, that the gas detection system will detect the gas in the atmosphere and the fuel will be shut off. This is also demonstrated by the posterior probability of the three fuel shut off nodes: “TCS”, “F&G” and “Fuel Shut Off”. Given a 100% probability of a gas release and hence a 74.87% probability of gas detection, the posterior probabilities of the fuel being shut off is as follows: i) TCS shuts off fuel increases from 27.76% to 47.47%, ii) F&G system shuts off fuel increases from 20.37% to 34.7%, and iii) the probability that the fuel will be shut off by either or both systems increases from 35.37% to 60.19%. Similarly, the posterior probabilities of a continuous release and the consequence of a severe leak decrease from 58.81% to 29.26% and 64.56% to 39.78% respectively. This shows that the BN model can represent the behaviour of safety barriers in the event of a fuel gas leak. Furthermore, while the posterior probabilities of a consequence and continuous release still seem substantial, it is the significance of the change in probability that is of importance. These significant changes demonstrate that the barriers have a large effect on the mitigating of accidents and consequences regarding offshore systems. However, the importance of these barriers can also be demonstrated by assuming that they do not function or are simply not present.

From the graph in Figure 5-13 it can be seen that the right most column shows the posterior probabilities given that the Gas Detection (GD) has a 100% of failing or not functioning. The graph and data table show that in the event that there is a gas release and the gas detectors do not function then there is a very high probability of there being a gas leak as a consequence as well as a continuous leak from the system. The continuous leak would occur because the fuel shut off systems would not react to the gas detection. This effect can be seen in the posterior probabilities of the fuel shut off systems. In the event that gas detection is in state "*No=100%*" then the probability that the fuel will be shut off by either the TCS or the F&G system are as follows; i) the probability that the TCS shuts off the fuel decreases from 27.76% to 0.58%, ii) the probability that the F&G system shuts off the fuel decreases from 20.37% to 0.61%, and iii) the probability that the fuel will be shut off by either or both systems decreases from 35.37% to 1.18%. This illustrates the dependency that the fuel shut off systems have on the operational of the gas detection system. Furthermore, given a gas release and no gas detection, it can be seen that the probability of a continuous gas release increases from 58.81% to 99.57%, and the probability of a gas leak as a consequence increases from 64.56% to 98.74%. These significance of these percentage increases in the posterior probabilities indicates that the gas detection system is a vital barrier in the mitigation of accidents resulting from fuel gas releases.

However, this analysis considerers only the repercussions of a fuel gas release without the possibility of an ignition source being present. In the event that there is a gas release and the gas detection system fails to operate as required, the fuel has a high probability to continue to be released and accumulate in the offshore module. This poses a huge issue should the gas release not be discovered by means other than the gas detection system. In the event that an ignition source is present, there is potential to cause a fire or an explosion. It is understood that should the gas be allowed to continuously release and accumulate, there is an ever increasing probability that an explosion will occur. Hence, it is vital that this scenario be analysed to show the potential, significant alterations to the probabilities that accidents and severe consequences will occur. Test Case 2B shall analyse the effects of an ignition source given that a fuel gas release is not detected.

5.5.2.2 Test 2B: Gas Release, no Gas Detection, with an Ignition Source

As demonstrated in Test Case 2A, it is assumed that one or more events has led to a gas release being observed. In this case the likelihood of a continuous fuel release was analysed as well as the probability of the “Consequence” node being in states “Y-Leak” and “None”. However in this Test Case, the emphasis shall be on a gas release not being detected and the effects that an ignition source has on the posterior probabilities of several nodes. The nodes in question are; “Consequences” (States “*Y-Ignition”* and “*Y-Leak*”), “Immediate/Delayed Ignition” (States “*Immediate”* and “*Delayed*”), “Explosion”, “Fire”, “Damage due to Fire & Explosion” and “Explosion Damage to Adjacent Areas”. The effects of the analysis are to be analysed both as individual occurrences and a cumulative



	No Evidence	NGD	IS
Y-Ignition	0.02	0.04	29.34
Y-Leak	64.56	98.74	9.29
Immediate	0.02	0.03	23.13
Delayed	0.03	0.04	44.67
Explosion	0.02	0.03	22.50
Fire	0.01	0.02	13.50
F&Ex Damage	0.00	0.00	2.55
Adjacent Mod.	4.10E-05	6.31E-05	0.049

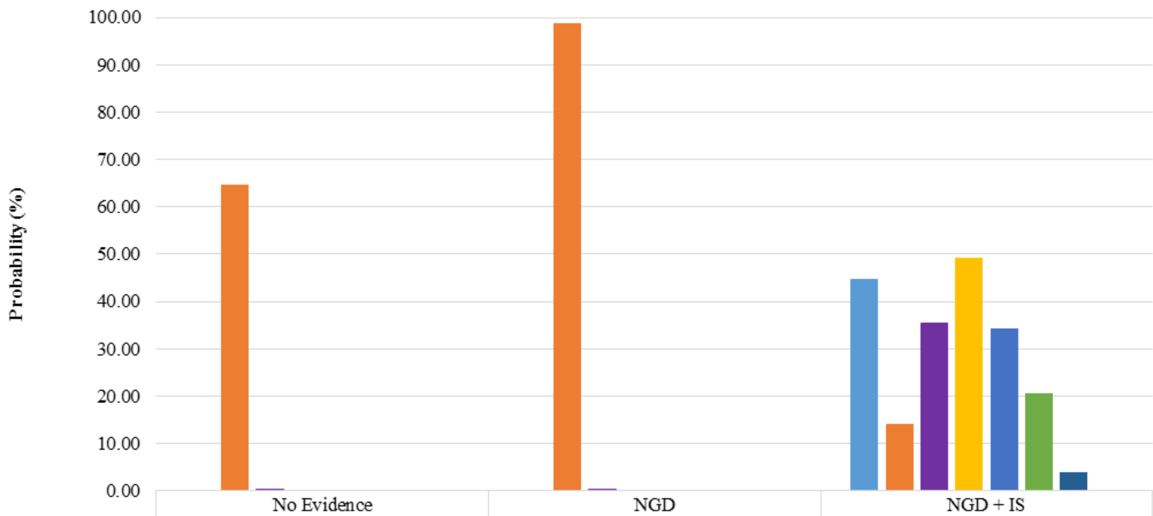
Figure 5-14: Effects of “Gas Detection” being “No=100%” and “Ignition Source” being “Yes=100%” on “Consequences” (States “Y-Ignition” and “Y-Leak”), “Immediate/Delayed Ignition” (States “Immediate” and “Delayed”), “Explosion”, “Fire”, “Damage due to Fire & Explosion” and “Explosion Damage to Adjacent Areas”

occurrence. Figure 5-14 shows the individual effects of an undetected gas leak (NGD) and the presence of an IS.

The emphasis in this analysis is on the more severe accidents and consequences in terms of fire, explosion and the damage that they can cause. From the graph in Figure 5-14 it can be seen that in the event of a 100% failure of the gas detection system, the probability of there being any accidents or consequences related to ignition remain virtually negligible. It can been seen that the probability of there being a gas leak as a consequence, however, increases from 64.56% to 98.74%. This first stage of the test demonstrates that the ignition related accidents and consequences have a very unlikely occurrence probability, according to the BN model, unless there are both a fuel source and an ignition source present.

The second column in Figure 5-14 demonstrates the effects on the fire & explosion consequences given only an ignition source present, assuming that the probability of a gas release is at the marginal probability of 57.85%. The purpose of this is to show how sensitive the fire & explosion consequences are given an ignition source and a likely chance of a gas release. It can be seen that the posterior probabilities increase drastically when an ignition source is present. The probability that there will be a delayed ignition demonstrates the largest percentage change to the posterior probability as it increases from 0.03% to 44.67%, with the probability of an immediate ignition increasing from 0.02% to 23.13%. Furthermore, the second largest percentage change to the posterior probabilities is the likelihood of there being ignition as a consequence, as it increases from 0.02% to 44.88%. Figure 5-14 also shows that the probability of there being only a gas leak as a consequence decreases from 64.56% to 9.29% due to the increase probability of there being an immediate or delayed ignition.

The second stage of Test Case 2B is to demonstrate the cumulative effects of the fuel gas not being detected and the presence of an ignition source, as shown by Figure 5-15. It can be seen that the second column in Figure 5-15 that the probabilities are only the posterior probabilities given no gas detection. This is the same as Figure 5-14 to demonstrate the percentage changes when an ignition source is also present. The third column shows the cumulative effects of a failed gas detector and an ignition source. The posterior probabilities display a very similar pattern to the posterior probabilities when there is only an ignition source present as shown in Figure 5-14. However, in this case (the cumulative effects) the posterior probabilities are much greater, i.e. the probability of there being an ignition as a consequence ("*Y-Leak*") given an ignition source only is 29.34% when



	No Evidence	NGD	NGD + IS
Y-Ignition	0.02	0.04	44.88
Y-Leak	64.56	98.74	14.20
Immediate	0.02	0.03	35.38
Delayed	0.03	0.04	49.25
Explosion	0.02	0.03	34.43
Fire	0.01	0.02	20.74
F&Ex Damage	0.00	0.00	3.91
Adjacent Mod.	4.10E-05	6.31E-05	0.0761

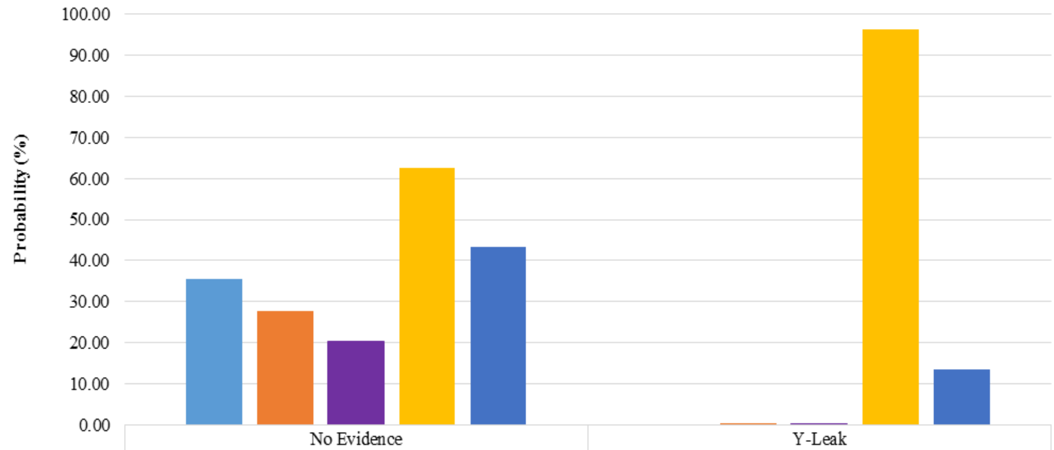
Figure 5-15: Cumulative effects of "Gas Detection" being "No=100%" and "Ignition Source" being "Yes=100%" on "Consequences" (States "Y-Ignition" and "Y-Leak"), "Immediate/Delayed Ignition" (States "Immediate" and "Delayed"), "Explosion", "Fire", "Damage due to Fire & Explosion"

compared to the cumulative effects of NGD + IS which increases the probability to 44.88%. This shows large percentage increases in the probabilities of potential ignition accidents and consequences. Furthermore, it is important to state that even though there is a gas detection failure and an ignition source present, the probability of there being an ignition accident or consequence is not 100%. This is because the relationships between the nodes in the BN takes into account the fact that for an ignition to occur there must be an ideal air to fuel mixture. This ideal mixture is approximately 5 – 15% of fuel in the air (HSE, 2008b). The data for the CPTs in the BN was analysed to accommodate for the ideal mixture variable.

5.5.3 Test Case 3: Effects of Observed Consequences on Prior Probabilities

In order to provide further verification of the BN model it is important to demonstrate the effects of inserting evidence as a consequence and observing the effects on prior nodes. The focus node in this test case is the "Consequence" node, with attention being focused on inserting 100% evidence to states "*Y-Leak*" and "*Y-Ignition*". The effects of 100% "*Y-Leak*" focuses on the changes in the probabilities of the gas release barriers and continuous release. Whereas, 100% "*Y-Ignition*" focuses on the probability changes of the ignition, fire and explosion accident and consequence nodes. The "*Y-Ignition*" analysis does not focus on the barriers as the prior probabilities would be the same as the effects demonstrated by 100% "*Y-Leak*".

Figure 5-16 demonstrates the effects of 100% "*Y-Leak*" on the prior probabilities of "Fuel Supply off", "TCS Fuel Shut off", "F&G Fuel Shut off", "Continuous Gas Release" and "Gas Detection". The graph shows that given 100% probability of "*Y-Leak*", the prior probabilities concerned with the fuel shut off system nodes, all being State "*Yes*", greatly decrease to almost zero. Similarly, the probability of the gas being detected also decreases. However, not to the extent of the fuel shut off systems. The probability of gas detection decreases from 43.4% to 13.44%. This shows that in the event of a gas leak the most likely barrier to fail would be the fuel shut off system. However, the barrier that displays the most significant change in probability is the gas detection system. Where the TCS and F&G show decreases of 27.66% and 20.35% respectively, the gas detection system demonstrates a total decrease of 29.96%. This indicates that while the fuel shut off system is the most likely barrier to fail in the event of a gas leak, the gas detection system demonstrates the most significant effect on a gas release. Finally, the probability of a continuous gas release increases 62.48% to 96.19%. This significant increase is to be

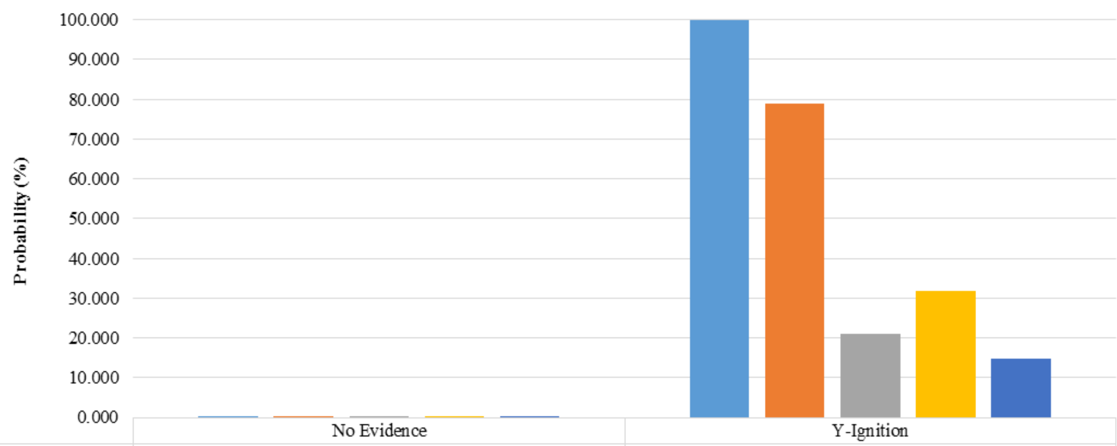


	No Evidence	Y-Leak
Fuel Supply Off	35.39	0.00
TCS Shut off Fuel	27.76	0.10
F&G Shut off Fuel	20.38	0.03
Continuous Release	62.48	96.19
Gas Detection	43.40	13.44

Figure 5-16: Effects of 100% "Y-Leak" on the prior probabilities of "Fuel Supply off", "TCS Fuel Shut off", "F&G Fuel Shut off", "Continuous Gas Release" and "Gas Detection"

expected as there is a 100% probability of a leak. The probability of a continuous release is not 100% as there is 13.44% that the gas may be detected.

Figure 5-17 shows the effects on the prior probabilities of “Ignition Source”, “Immediate/Delayed Ignition”, “Fire” and “Explosion” given 100% probability of the consequence state “*Y-Ignition*”. The graph in Figure 5-17 indicates that prior to a 100% consequence of ignition, the likelihood of any ignition, fire and explosion accidents or consequences are almost negligible. However, when evidence is inserted into the state “*Y-Ignition*” in the consequence node, the prior probabilities greatly increase. The most obvious increase is the probability of an ignition source being present, which increases to 100%. This is due to an ignition source being required along with the fuel gas in order to have an ignition take place. Continually, the probability of there being and immediate or a delayed ignition increase from 0.019% and 0.027% to 78.82% and 21.18% respectively. The immediate ignition is determined to be the more likely source of the ignition consequence as the delayed ignition is more dependent on the ideal gas mixture variable.



	No Evidence	Y-Ignition
Ignition Source	0.083	100.00
Imm.	0.019	78.82
Del.	0.027	21.18
Fire	0.011	31.69
Explosion	0.019	14.80

Figure 5-17: Effects of 100% "Y-Ignition" on the prior probabilities of “Ignition Source”, “Immediate/Delayed Ignition”, “Fire” and “Explosion”

This is also reflected on the probability of fire or explosion. As the probability of a delayed ignition is lower that of an immediate ignition, the probability of a fuel gas fire is greater than the probability of an explosion. The probability of there being a fire increases from 0.011% to 31.69% when compared to the increase from 0.019% to 14.8%. This shows that the accident type that contributes the most to the ignition consequence, given that there is a fuel gas ignition consequence, is a fuel gas fire.

5.6 Sensitivity Analysis

Sensitivity Analysis (SA) is essentially a measure of how responsive or sensitive the output of the model is when subject to variations from its inputs. Having the understanding of how a model responds to changes in its parameters is important when trying to maximise its potential and ensuring correct use of the model. SA provides a degree of confidence that the BN model has been built correctly and is working as intended. In the context of this research, SA will be used as a demonstration to determine how responsive an event node is to variations in other nodes. Knowing the most influential nodes can assist in the experimentation and further expansion of the model. Similarly, nodes which have very little influence can be altered or discarded (Matellini, 2012) (Loughney, *et al*., 2016).

The SA conducted for the fuel gas release model focuses on the node “Consequences”, more specifically, its state “*Y-Leak*” and the nodes representing the barriers for fuel gas release. However, the analysis will be conducted using smaller increases and decreases in the probabilities of the parent nodes as opposed to inserting 100% occurrence probability into the input node CPTs, as demonstrates in Test Cases 1, 2 and 3.

A possible way of undertaking this is to manually insert evidence into the input nodes, one by one, and subsequently analyse the effect on the output node via its posterior probability. When doing this the input nodes are increased or decreased by equal percentages, individually. This allows for clear comparison of their impact upon the output node. However, this manual method was not applied to this analysis. Instead a parameter sensitivity wizard within the Hugin BN software was used. In this program wizard the input node is individually paired with the output node in its desired state. In this case that was "Consequence" in the state "*Y-Leak*". A state for each of the input nodes was purposely selected. The input nodes for the SA are the barrier nodes; "Gas Detection", "TCS Fuel Shut off", "F&G System Fuel Shut off" and "Fuel Supply off". All nodes are set to state "*Yes*" in the parameter sensitivity wizard, with the exception of "Fuel Supply off" as this node is the child of "TCS Fuel Shut off" and "F&G Fuel Shut off". Therefore, this node has been set to states "*Yes – TCS: Yes, F&G: No"* and "*Yes – TCS: No, F&G: Yes*". This allows for the sensitivity of this node to be determined given the output of its parent nodes. This method is also necessary as in the event both the parent nodes are in states "*Yes*" or "*No*", the probability of "Fuel Supply off" is either 1 or 0 and therefore cannot be analysed in the sensitivity parameter wizard in the Hugin Software. Following this a sensitivity value from Hugin was obtained for each input node and using Microsoft Excel a graph was constructed to show the results.

From the graph in Figure 5-18 it can be seen that the most influential factor on "Consequence: *Y-Leak*" is "Gas Detection", whilst the least influential is "Fuel Supply off: *TCS=No, F&G=Yes*". This concurs with the graph as "F&G System Shut off Fuel" has a smaller effect on the consequence that "TCS Shut off Fuel". Continually, if the probability of "Gas Detection: State - *Yes*" increases by 10%, then the probability of

"Consequence: State – *Y-Leak*" decreases by 4.6%. Whereas, if the probability of "Fuel Supply off: State - *TCS=No, F&G=Yes*" increases by 10%, then the probability of "Consequence: State – *Y-Leak*" decreases by 0.8%. From the graph, it is also apparent that the sensitivity function is a straight line which further adds to the model validation. The sensitivity values computed within Hugin are shown in Table 5-7.

It is important to state that the sensitivity values are negative as they have a negative effect on the focus node "consequence". In other words, as the probability of gas detection, for example, increases, then the probability that there will be a gas leak decreases.

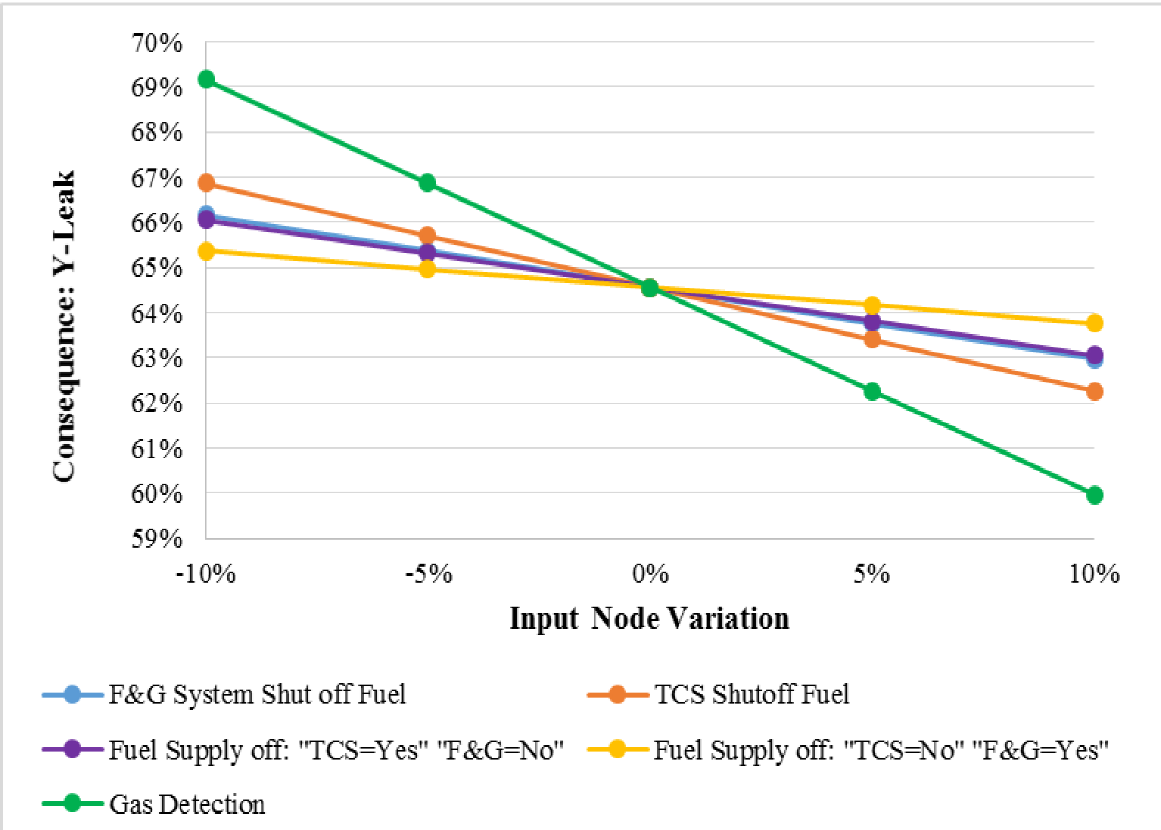


Figure 5-18: Sensitivity Functions for the Input Nodes for Event "Consequence"

Table 5-7: Sensitivity Values for the Input Nodes for Event "Consequence"

Input Node	Sensitivity Value
F&G System Shut off Fuel	-0.16
TCS Shut off Fuel	-0.23
Fuel Supply off: “TCS=Yes, F&G=No”	-0.15
Fuel Supply off: “TCS=No, F&G=Yes”	-0.08
Gas Detection	-0.46

5.7 Discussion and Conclusion

This chapter has outlined a Bayesian Network model which demonstrates the cause and effect relationships that several initial failures can have on an offshore electrical generation system. In particular, the potential for a fuel gas release from the gas turbine which drives the electrical generation system. The research presented here expanded upon the work presented in Chapter 4, which illustrates the cause effect relationship of one component failure within an electrical generator and the general consequences that can result. The BN model presented in this research expands on this by incorporating part of the model in Chapter 4 along with several initial failures to analyse a specific consequence in further detail. This consequence concerns itself with a possible fuel gas release and the potential fire and explosion hazards that can occur. However, while it is easier to demonstrate the effects of accidents involving fire and explosion, it is not easy to demonstrate the consequences of a leak without an ignition source. These consequences are equally important for offshore platform operators due to the improved HSE regulations within Safety Cases regarding hazards to the environment in any instance. Therefore, in the event that there is a fuel gas leak without ignition, it poses a large issue for operators and duty holders given that the release is undetected. While it is not as severe as a hydrocarbon release into the sea, it is still vital as it is the ejection of natural gas into the atmosphere which can have severe consequences depending on the weather conditions. The BN model also clearly demonstrates that it can provide an effective and applicable method of determining the likelihood of various events under uncertainty, and more importantly show increased uses as a dynamic risk assessment tool. Given the research presented it is now much clearer to see the advantages for Bayesian Networks and Bayesian Theory being applied to create dynamic risk assessment tools to work in conjunction with Safety Cases and in an Integrity Case.

Continuing with the Fuel Gas Release model, three Test Cases were used to demonstrate the models validity and to demonstrate its effectiveness to provide clear cause and effect relationships between initial failures, mitigating barriers, accidents and consequences. Similarly, given the specific scenario of fuel gas release, it is clearly demonstrated in the test cases how severe the consequences can be given that the initial failures occur or the mitigating barriers do not function as intended. The first Test Cases (1A, 1B, 1C and 1D) were designed to demonstrate that the model functioned as expected and provided some partial validation before the conducting Test Cases 2 and 3. Test Case 1 focused on the initial failures and their impact on the potential and severity of a fuel gas release as well as the impact on the model with the presence of an ignition source. This established some partial validation to the model as the posterior probabilities are increased and decreased as one would expect given evidence inserted at the root nodes. A key element demonstrated in Test Case 1 is the vital relationship between a gas release and the probability of the release being detected. Test Case 2 expanded upon Test Case 1 by demonstrating the level of consequences that can occur, through probabilities, given that a specific barrier failed to operate. In this case the failed barrier was the gas detection system. The consequences of this were demonstrated with and without an ignition source present. The effects on the BN showed that the gas detection system is vital in the mitigation of a fuel gas release and the fire and explosion consequences. This is due to the Fuel Shut off systems being linked to the detection system. If a gas release is not detected then the fuel system cannot shut the release off. Finally, Test Case 3 illustrated the effects of inserting evidence in the "Consequence" node and analysing the effects on the prior probabilities. It was concluded that in the event of a gas leak (100% state: "*Y-Leak*") the probability that either the TCS or the F&G system would shut off the fuel was negligible. However, the probability of the gas not being detected showed the most significant change in probability. Furthermore, given that the probability of "*Y-Ignition*" is 100%, it was determined that the most significant type of ignition was "immediate" and hence a fire was the most likely cause.

In relation to the validation of the model a sensitivity analysis was carried out to determine how responsive the output of the model is to various modifications in the inputs and subsequently validate that the model works as expected. This exercise is vital as it provides an indication to what the most important variables. In addition, inputs can be ranked or weighted in terms of their importance upon the output or final consequences. For example, in the Fuel Gas Release model, "Gas Detection" had a much larger effect on the possibility of "Consequence: *Y-Leak*". The more advantageous element of conducting SA in BNs is that they take into consideration the chain of events below the input node leading to the output node, which presents a closer approximation to reality (Loughney, *et al*., 2016).

CHAPTER 6:

DECISION MAKING ANALYSIS FOR OFFSHORE WIRELESS SENSOR NETWORK DESIGN

Summary

In this chapter, the development of a WSN for an offshore system is presented. The system in question is the electrical generation units. The intention is to design the structure of a number of WSNs within the electrical generation system with varying connection types and methods of relaying data. The research is concerned only with the design of the WSNs, i.e. the hardware and orientation of the sensor nodes and not the software, programming or data protection. This should provide a good base, once an ideal WSN design is determined, to expand the network further incorporating more attributes and develop the necessary software to complete the WSN. Sensitivity Analysis and validation are provided for the analysis.

6.1 Wireless Sensor Network Designs

6.1.1 WSN Design Outline

The problem considers a region of an offshore platform to be covered by wireless sensor nodes. The number of sensors is determined by the requirements of the application. Typically, each sensor node has a sensing radius and it is required that the sensor provides coverage of the specified region with a high probability. The sensing and transmitting radius of the node depends on the phenomenon that is being sensed as well as the sensing hardware of the node. Hence, in general, the number of sensor nodes is dictated by the application. In this research, the application is known and so the problem of where to deploy the sensor nodes is an easy one to solve. The application here is the integrity of the electrical generation equipment on board an offshore platform. More specifically the Thistle Alpha Platform located in the North Sea. The WSNs to be proposed will focus on the key areas where integrity of the electrical generation equipment must be maintained. These key areas are outlined by Meggitt: Gas Turbine Sensing and Monitoring.

In order to first develop the WSNs topology, one must know the domain in which the sensors will be deployed. In this problem, the sensors will be distributed within the electrical generators located within the electrical generation module of the Thistle Alpha platform. There are a number of steps involved in the generation of the domain.

1. Domain – The domain must first be established in order to definitively and accurately place the sensor nodes.
2. Dimensions – The dimensions of the domain must be specified in order to determine the size of the sensor field, as well as to determine the worst-case battery life and in the case of multi-hop connectivity, determine the average size of each nodes transmitting radius.
3. Sensor placement – Once the dimensions of the domain are known the sensor nodes can theoretically be placed to begin forming the network. The nodes are placed based upon the phenomenon that they are going to be detecting.
4. Data Transmission – Once the sensors nodes have been appropriately placed, a decision is made as to whether the network should be single-hop or multi-hop based upon a given set of criteria.

The WSN designs proposed in this research are only part of the initial stages of developing the Asset Integrity Case or NUI-Installations. The WSNs are not to be considered as complete models for real-time application at this moment in time.

6.1.2 Establishing the Domain and Dimensions

The domain has already been identified as the electrical generation module on the Thistle Alpha Platform. As stated in Chapter 4, the Thistle Alpha Platform, located in the North Sea, has three gas turbine driven electrical generators, (termed Unit A, Unit B & Unit C), each of which is capable of providing 100% of the platform power requirements. The platform is currently part of the Thistle Late Life Extension (LLX) strategy, which aims to recover over 35 million barrels of oil through to 2025 from the Thistle and Deveron oil fields. In order for the platform to be operable to 2025 and beyond, the LLX strategy incorporates a series of major initiatives to improve structural and topside integrity,

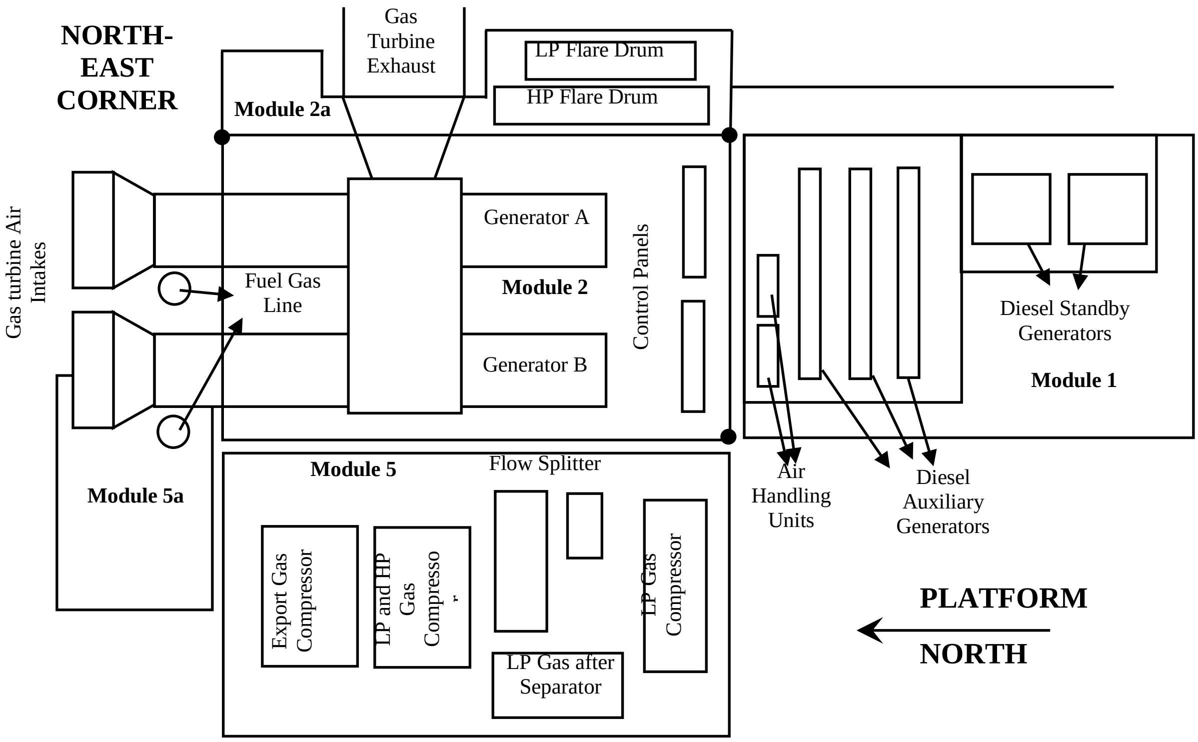


Figure 6-1**:** Plan view of the location of generator Unit A and B (adapted from Appendix E)

upgrade safety and control systems, improve the oil production and water treatment process and provide reliable power. This make this platform the perfect candidate to base the Asset Integrity Case development around, as previously stated in Chapters 4 and 5. Figure 6-1 shows the generic outline of the main electrical generation module, which houses generator unit's A and B (Cresswell, 2010).

While Figure 6-1 gives a good overview of the generic layout and location of equipment, it is not enough to accurately create a size model of the generator module (Module 2). However, it is possible to determine the dimensions of the module and the equipment from the plot plans of the Thistle Alpha platform (see Appendix E). From these more detailed plans, the dimensions of module 2, the electrical generators and the orientation of equipment in the space can be determined. Table 6-1 gives an outline of the key dimensions. All equipment dimensions, i.e. turbine and alternator are external measurements.

Table 6-1: Dimensions of module 2 and electrical generation equipment

Item	Measurement
Module Length	27m
Module Width	13.8m
Module height	10m
Height to Mezzanine	6m
Total Generator Length	17m
Alternator Length	7.8m
Alternator Width	4.3m
Alternator Height	4.3m

Gas Turbine Length	9.2m
Gas Turbine Width	2.9m
Gas Turbine Height	3.5m
Spacing between Alternators	0.9m
Distance of Unit A from the Module Wall	1.4m

From these dimensions, it is possible to produce a much more accurate and scale depiction of module 2 on the Thistle Alpha Platform. Figure 6-2 and Figure 6-3 show the module 2 deck level and side elevation respectively. These figures are adapted from the Thistle Alpha platform plot plans in Appendix E.

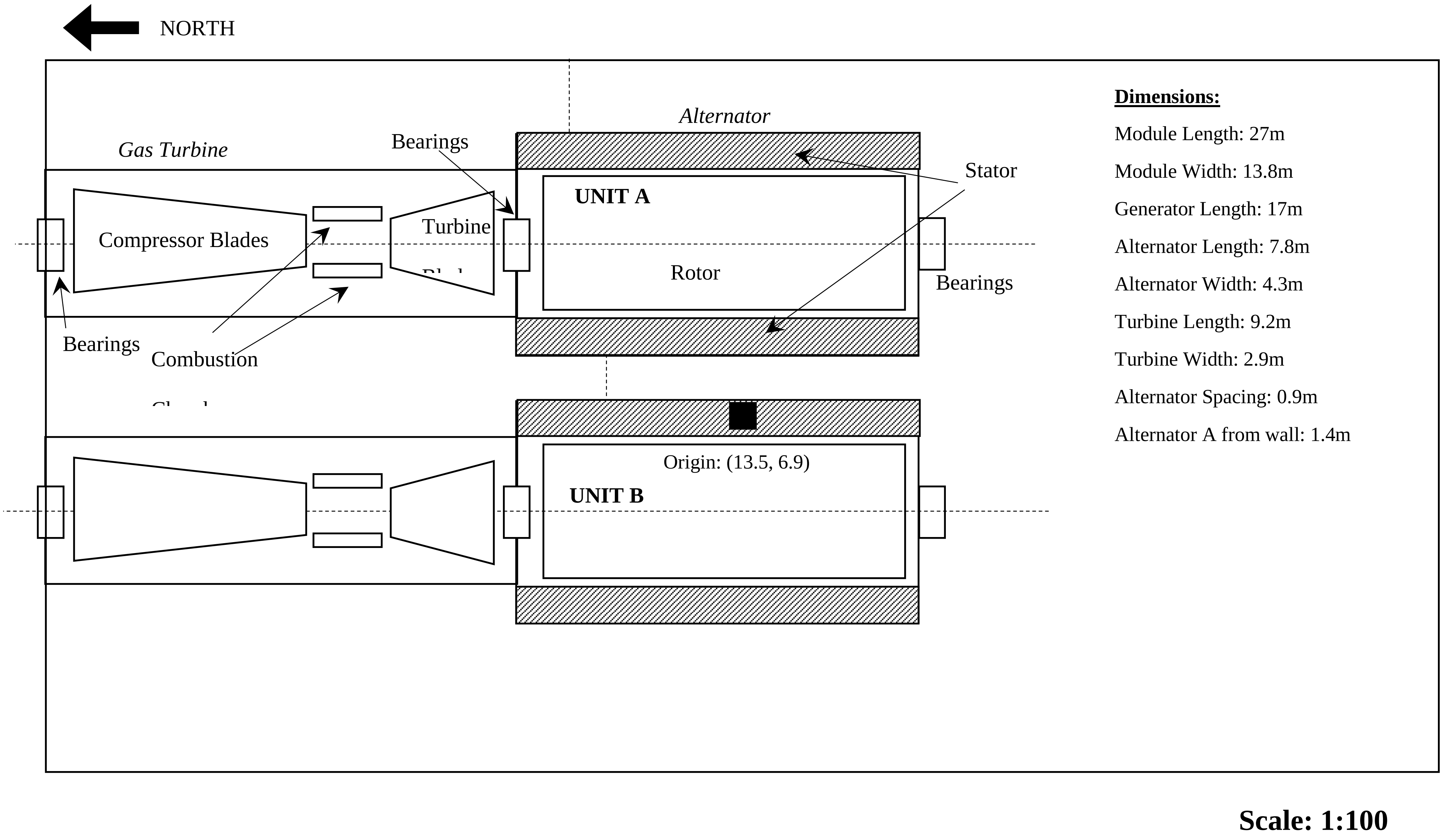


Figure 6-2: Module 2 schematic with dimensions (Deck View)

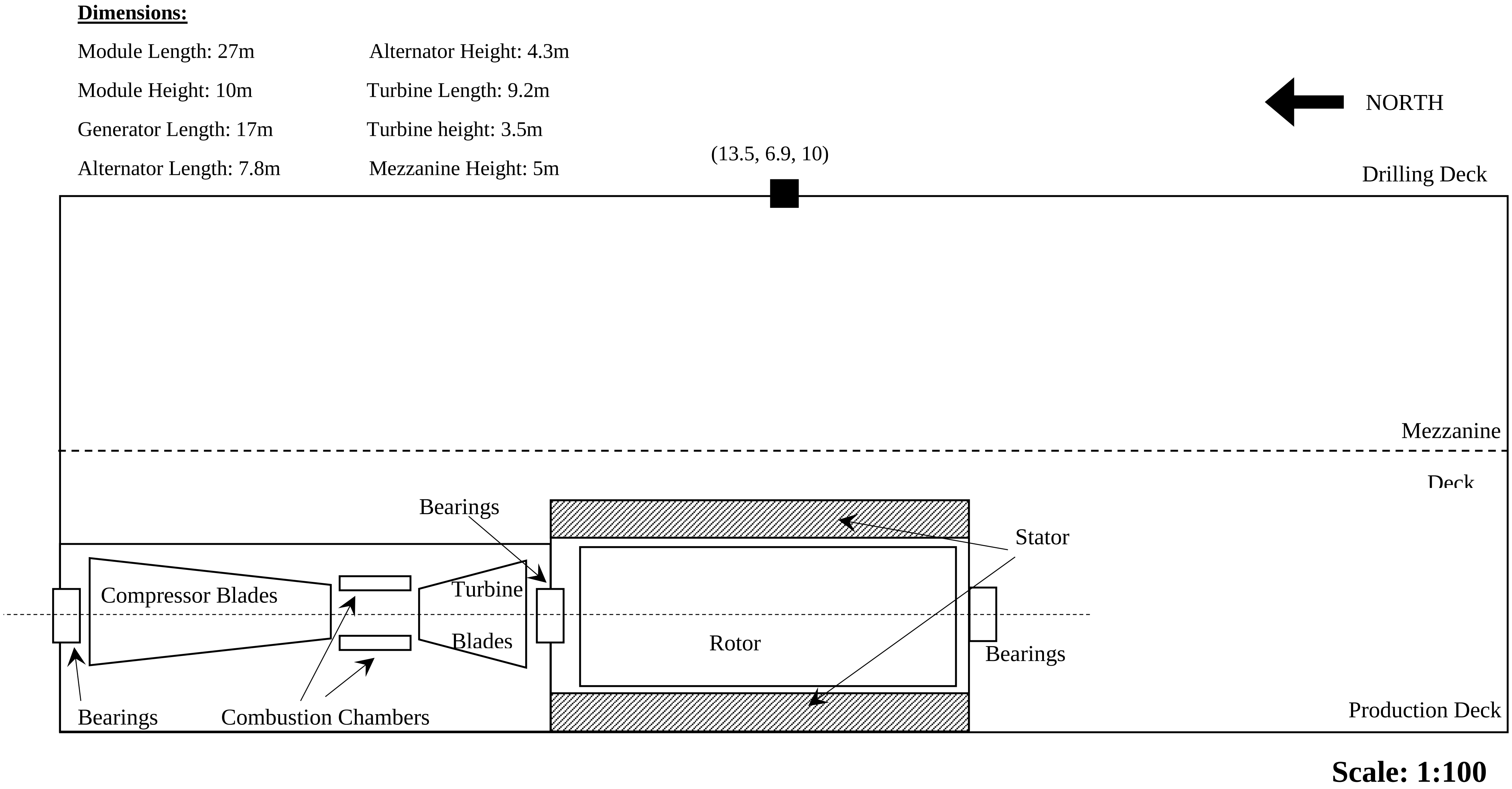


Figure 6-3: Module 2 schematic with dimensions (Side Elevation)

6.1.3 Sensor Placement

Now that the domain and dimensions of said domain have been identified, it is possible to place the sensor nodes and determine the size of the sensor field and determine battery power given the type of communication. The nodes are dependent entirely on what they are detecting and are placed accordingly. In this research the focus is on the integrity of the gas turbine generator as well as developing the Asset Integrity Case, and so a finite number of nodes will be proposed to keep the initial WSNs simple at these initial stages.

It is necessary to identify where the sensor nodes should best be deployed in order to accurately maintain integrity. A key place to begin is to currently identify where gas turbines and alternators already have wired sensors in place to monitor the integrity of equipment. Meggitt Sensing systems currently identifies a number of key areas where wired sensing and condition monitoring takes place within an electrical generation unit (Meggitt, 2016). These are outlined as follows:

1. Absolute vibration – The sensors here determine the seismic vibration of the system relative to the Earth (Zargar, 2014).
2. Shaft vibration – These sensors monitor the levels of vibration incurred by the main generator shaft that runs through the gas turbine and the alternator. The sensor here provides data on the vibration of the shaft against the bearings (Zargar, 2014).
3. Shaft Displacement – Sensors and probes here are used to measure the movement of the shaft in the vicinity of the probe. They cannot measure the bending of the shaft away from the probe. Displacement probes indicate problems such as unbalance, misalignment, and oil whirl (Zargar, 2014).

4. Static oil pressure – Sensors here measure the force per unit area exerted on the walls of a container by the stationary fluid. In this case the stationary fluid is the bearing oil (Kiameh, 2003).
5. Temperature – The sensors here simply measure the temperature of various areas of the generator such as: temperature of the combustion, the exhaust gases and the bearing lube oil (Kiameh, 2003).
6. Speed – This sensor measures the speed of the main shaft at the bearings in-between the gas turbine and the alternator. This node indicates as to whether the turbine is in danger of running overspeed or not at the required speed. Typically, the gas turbines on the Thistle Alpha platform run at 3,600 rpm (RMRI Plc., 2009).
7. Combustion pressure - The combustion section has the difficult task of controlling the burning of large amounts of fuel and air. It must release the heat in a manner that the air is expanded and accelerated to give a smooth stream of uniformly-heated gas at all starting and operating conditions. This must be accomplished with minimum pressure loss and maximum heat release. Therefore, monitoring the combustion pressure is vital for the operation of the turbine (Kiameh, 2003).
8. Blade health - Heavy duty industrial gas turbines are widely used in power generation plants worldwide. Axial flow compressor and expansion turbine are key subsystems of the gas turbine. Due to inlet air flow aero dynamic load and rotor rotation, various mode displacement and vibration on the turbine blades are excited. Excessive vibration may accumulate high cycle fatigue and thermal mechanical stress on a rotor blade, and cracks may initiate and propagate over time. Having sensors here to detect and monitor blade cracks and provide early

warning before material liberation is the main focus for any blade health monitoring system (Yu & Shrivastava, 2016).

9. Emissions – The purpose of sensors here is to detect the quality of the exhaust emissions from the gas turbine. There are strict regulations in place that regulate the levels of NOx and CO_2 in turbine emissions. Most air pollution NOx measurements are done on a volumetric concentration basis, in parts per million by volume (ppmv) or in some cases in a weight/volume fraction such as mg/m^3. Uncontrolled gas turbine NOx emissions are in the 150–300 ppmv range (about 300–600 mg/m^3) (Klein, 2012).

Alternator discharge – Sensors here measure the level of partial electrical discharge from the alternator. Partial discharge is an electrical discharge that occurs across a localised area of the insulation between two conducting electrodes, without completely bridging the gap. It can be caused by discontinuities or imperfections in the insulation system. Discharge monitoring thus gives an indication of deterioration of the insulation and is an indicator of incipient faults (HVPD, 2016)

As these key areas have been identified and outlined, the locations of the sensors can be assigned. Figure 6-4 shows the prime locations for the wireless sensor nodes within the gas turbine and the alternator.

As shown in Figure 6-4, there are 31 proposed sensor nodes within each generator unit. As the module consists of two generators, the sensor field is comprised of 62 sensor nodes at this initial stage. Starting from the left of Figure 6-4, it can be seen that there are 3 nodes on the first bearing set monitoring the absolute vibration, the static oil pressure and the temperature. This arrangement at the first bearing is consistent with the application of

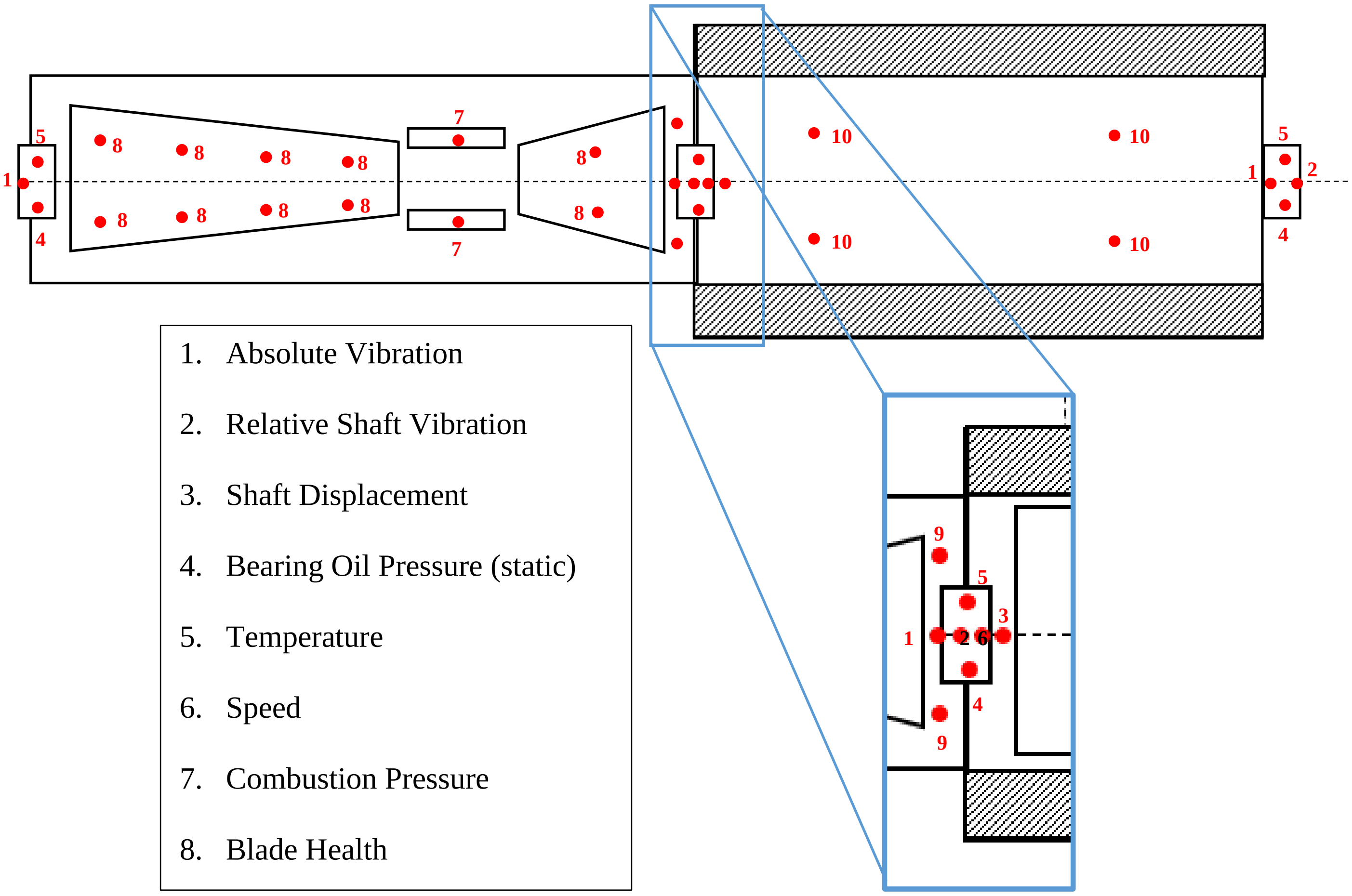


Figure 6-4: Proposed locations of the wireless sensor nodes within the electrical generator

probes and sensors at this position (Meggitt, 2016). Following this to the compressor turbine, there are eight nodes monitoring the blade health, as is the case with the power turbine. There are combustion pressure sensors monitoring the combustion chambers due to the small margins of pressure loss available. Continuing through the generator to the exhaust of the power turbine and the bearings between the turbine and the alternator. There are two nodes monitoring the emissions of the turbine as well as six nodes on the bearing. There are more nodes here due to it being a midpoint location on the main shaft. Therefore, along with the absolute vibration, oil pressure and temperature sensors, there are also nodes monitoring the speed of the shaft at the exit of the power turbine, the relative vibration of the shaft to the middle bearing and the displacement of the shaft. Monitoring the displacement and relative vibration of the shaft here are key as it is a potential vibration node point of the shaft, due to its locating from the two end bearings (Kiameh, 2003). Moving through the alternator, there are four nodes monitoring the partial discharge. Finally, there are four further nodes on the final bearing after the alternator. The nodes here again include absolute vibration, static pressure and temperature nodes, just as the first bearing. However, there is also a relative shaft vibration sensor due to there being an exciter after the alternator, which does not form part of the analysis but must still be treated as though it is there in relation to the operation of the generator (RMRI Plc., 2009) (Kiameh, 2003).

6.1.4 Data Transmission

Now that there are a proposed number of sensors with a stated purpose, it is possible to determine the method of data transmissions. There are two main data transmission types; single-hop and multi-hop, as outlined in Chapter 2. However, it is possible to split these further. It is possible to have single-hop routing directly to the gateway node and single-hop transmission via cluster heads. Similarly, it is possible to have multi-hop connectivity based upon the size of each sensors average radius of connectivity, i.e. multi-hop with a large radius, *R*, and multi-hop with a small radius, *R*.

In this research four types of data transmission are to be analysed and compared against a set criteria to determine the most applicable for use in integrity monitoring an offshore environment. It is important to note that the gateway node is assumed to be at the origin point as shown in Figure 6-2 and Figure 6-3 and any cluster head nodes are assumed to be on the mezzanine deck in Figure 6-3. These four forms of transmission are outlined as follows:

A. **Single-hop -** Nodes connect directly to the Gateway node. Due to congestion, Nodes transmit data in sequence. i.e. Node 1 transmits data, Node 2 cannot transmit until the gateway has received information from Node 1, and so on. Complexity is not applicable to the Single-hop design as all nodes send data to the same destination and do not relay data, as shown in Chapter 2.

B. **Single-hop with Cluster nodes -** Nodes transmit data to the nearest cluster node in sequence. Hence, several nodes can transmit simultaneously to different cluster nodes. This requires less battery power than Single-hop as there are two short connections from the node to the cluster and from the cluster to the gateway, as opposed to one connection over a longer distance. However, the battery power in this instance is also dependent on the number packets from other nodes being relayed to the gateway.

C. **Multi-hop with a smallest sensor node radius** - Nodes relay (transmit/ receive) information from each other to achieve the best route from the source node to the cluster node. The small radius denotes the smallest transmittable distance of the node. i.e. it would require more connections to reach the cluster node. This requires more battery than Single-hop as the nodes must transmit and receive data.

D. **Multi-hop with a largest sensor node radius** - The theory is the same for the Multi-hop (Small *R)*, however, nodes have a larger sensor radius and can transmit/receive data from nodes further away. Meaning fewer connections to the cluster node. Requires much increased battery power to transmit/receive over a large area. Due to the large area, the network can almost act as a single-hop cluster network.

Even with the four types of data transmission outlined, further information would be required to even attempt to determine the most suitable configuration. This information would be the specification of specific components, such as, the individual sensor nodes, the battery life, and transceiver electronics. This would involve further research into the most suitable components for use offshore and would begin to incorporate the software of the WSN. Hence the selection of the most suitable WSN is to be determined through the use of linguistic terms to outline the most important attributes and criteria for application of a WSN to an offshore electrical generation module for integrity monitoring.

Given the dimensions adapted from the Thistle plot plans (see Figure 6-2 and Figure 6-3) and the proposed location of the sensor nodes (see Figure 6-4) it would be possible to determine the node furthest from the gateway node at the top and centre of module 2. This would be the beginnings of the calculation to determine the maximum battery life of the network. However, too many assumptions are required and further information is needed to complete the calculations. Furthermore, this would only demonstrate which WSN would be the most suitable based upon on criteria of Battery Power. This would not be sufficient to produce logical decision for WSN application. there are other attributes that contribute to the design of the WSNs. Hence, a decision-making methodology shall be utilised, based upon a set of criteria and attributes to determine the most suitable WSN.

6.2 Numerical Study and Assessment

The decision-making methodology outlined in Chapter 3 shall be applied to the problem of determining the most suitable WSN design for use in offshore asset integrity monitoring. The fundamental part of developing a coherent decision-making method, with the ability to deliver coherent results, lies in its evaluation hierarchy and the allocation the belief degrees and weights. As the domain, definition and objective of the problem have been determined, the evaluation hierarchy can be developed. From there the data acquisition and analysis can be conducted to utilise the ER algorithm outlined in Chapter 3. Finally, the WSNs can be ranked in terms of their suitability and a sensitivity analysis and validation can be carried out.

The first three steps of the decision-making methodology have been followed and identified by Section 6.1. The remaining sections in Chapter 6 shall identify step 4 and onwards in the decision-making methodology.

6.2.1 Evaluation Hierarchy

In order to apply the ER algorithm to the decision of the most suitable WSN design for use in an offshore system, a set of variables and a hierarchical structure of general and basic attributes must first be defined. The variables and hierarchical structure are based upon the hardware requirements for a WSN and for application on an offshore platform. In this analysis, there are three general attributes outlined and eight basic attributes. The hierarchical structure is demonstrated by Figure 6-5.

Figure 6-5 shows the three general attributes to be Complexity, Resilience and Maintainability. The General and Basic attributes of the evaluation hierarchy have been developed from a number of sources that consistently outline these attributes as being the key factors in the generation of a WSN, in terms of the topology and hardware selection (Chong & Kumar, 2003) (Carlsen, *et al*., 2008) (Akhondi, *et al*., 2010) (Fischione, 2014) (IEC, 2014). These general attributes are outlined as follows:

- Complexity is defined as the intricacy of the WSN. Usually, this would be the number of nodes and their location, however, this is already bounded by the scenario on board an offshore platform. Hence, the complexity is defined by three basic attributes relating to the design and hardware:

  - Transmission over the shortest possible route: The ability of the network to transmit information over the shortest possible route from one sensor node to the Gateway node.
  - Transmission over the longest possible route: The ability of the network to relay information over the longest possible distance to the Gateway given that one or more nodes fail to transmit/receive data.
  - Large number of cluster head nodes: The necessity of the network to have many cluster nodes in order to reliably transmit data to the Gateway.

- Resilience is defined as the WSNs ability to deal with faults to the system. As this research does not include any software analysis, the issue of cyber-attacks cannot be fully analysed therefore, the resilience of the WSNs is determined by two basic attributes.
  - Battery power: This has already been outlined in some detail, and in this analysis, it is defined as: The ability of the network to have a substantial source of battery power for the longevity of the network life and reduced time between maintenance. Battery power must be sufficient to power the sensors, initially, for several months.
  - Relaying data: This is a key attribute as it deals with the ability of the network to relay information between nodes in the event of sensor node failures and/or network disruptions.

- Maintainability: This focuses on the capability of the WSN design to be easy to maintain, its self-sustainability and the costs incurred by installation and maintenance. It is outlined by three basic attributes:
    - Ease of Maintenance: This is dependent on the Complexity of the nodes, i.e. the number of components within the nodes (sensor, transmitter, receiver, battery size). Location is not a factor as all nodes in this study are located within the electrical power generator.
    - Auto-Configuration: The ability of the network to auto configure on start-up and after maintenance. Nodes that can relay information can ease this issue, however, it is easier to program networks to auto-configure with less complex and fewer connections.
    - Cost: The cost of the network is determined by the number of nodes required (including cluster nodes), the sophistication of the nodes (battery size, transmitters, receivers and sensors) and the cost of maintenance.

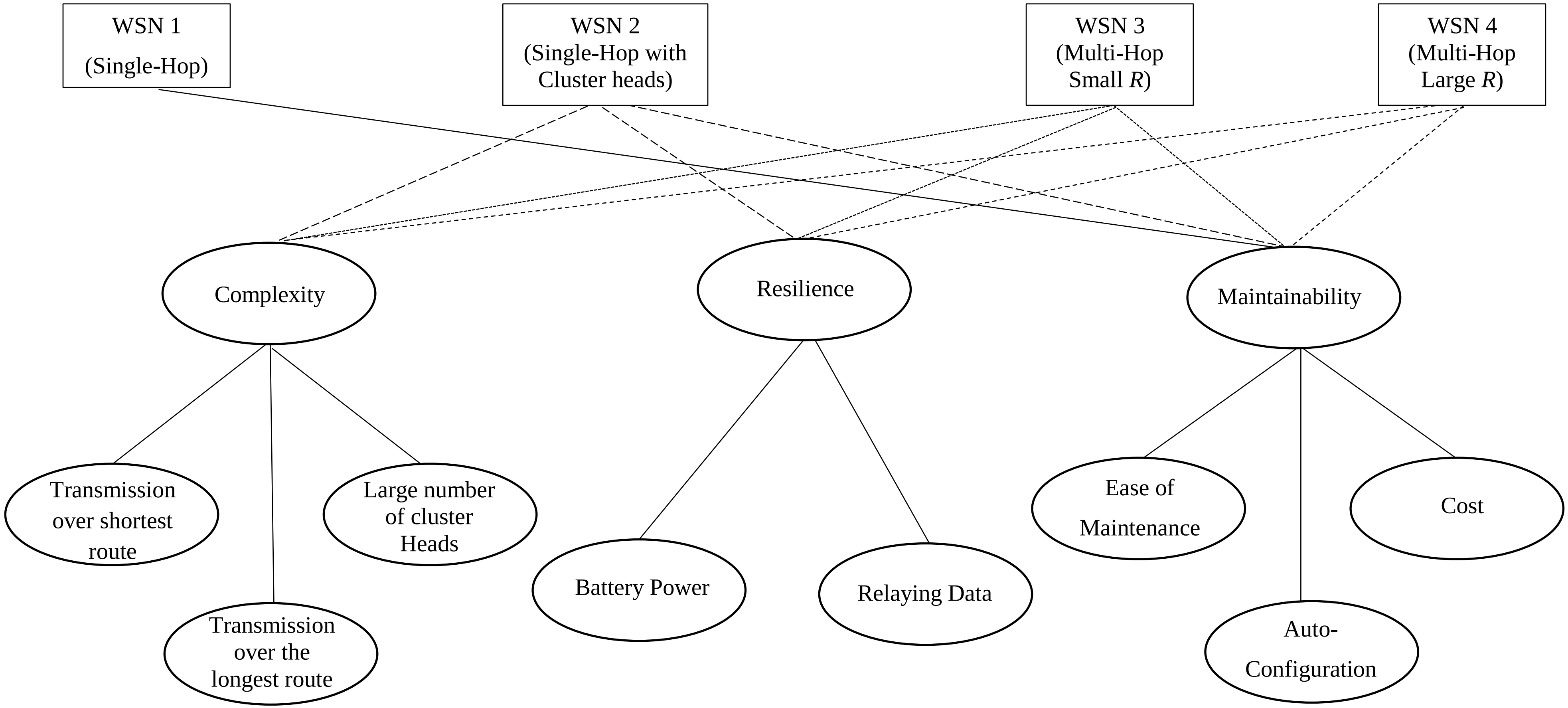


Figure 6-5: Evaluation Hierarchy for the four WSN designs

It can be seen from Figure 6-5 that WSN 1 (Single-Hop) is not associated with the first two general attributes Complexity and Resilience. This is due to a number of reasons; firstly, as the network is single-hop, the issue of transmitting over the shortest or longest route is not applicable. As previously outlined, the single-hop transmission has each node transmit their data one after another in sequence, directly to the gateway. Hence there is only one possible transmission route that each node can transmit data. Secondly, there aren't any cluster heads associated with this transmission type, therefore it is not possible to associate WSN 1 with any number of cluster heads, and subsequently cannot relate it to the general attribute, Complexity. Thirdly, as the data is theoretically transmitted over only one possible route for each node, there is no ability or need for WSN 1 to relay data. Similarly, as the general attribute, Resilience has only two basic attributes, it cannot possibly be included in the analysis for Resilience. However, it can be included in the analysis for Maintainability as all basic attributes are relatable to WSN 1.

6.2.2 WSN Assessment Problem

In this section, the ER algorithm is applied to analyse the suitability of four different WSN designs for use in asset integrity monitoring of an offshore electrical power generator. The four WSN designs are based around the type of data transmission, they are as follows: Single-hop transmission, Single-hop transmission with cluster head nodes, Multi-hop transmission with a small sensor node radius and multi-hop transmission with a large sensor node radius. The four WSNs shall be denoted as WSN 1, WSN 2, WSN 3 and WSN 4 respectively.

Before the analysis can be conducted the weights of each attribute, both general and basic (outlined in Figure 6-5), must be determined and the belief degrees of the basic attributes must be determined based upon a set of evaluation grades. Initially, the weights of the attributes are assumed to be normalised, with further analysis demonstrating the weights through pairwise comparison and Analytical Hierarchy Process (AHP). These weights through AHP and the belief degrees are determined by qualitative assessment from expert judgement through the use of questionnaires. This questionnaire is demonstrated in Appendix J.

As outlined previously, three general suitability attributes are considered, which are Complexity, Resilience and Maintainability. These attributes are generic and difficult to assess directly. Therefore, lower level attributes are required. The attribute hierarchy is shown in Table 6-2 along with the notation for each attribute and their weights (ω_i and ω_{ij}). Initially these weights are to be normalized, i.e. each attribute is to be the same weight with their sum equal to 1. As shown by Equation 6-1a, b, c & d:

$$\omega_1 = \omega_2 = \omega_3 = 1/3 \tag{6-1a}$$

$$\omega_{11} = \omega_{12} = \omega_{13} = 1/3 \tag{6-1b}$$

$$\omega_{21} = \omega_{22} = 1/2 \tag{6-1c}$$

$$\omega_{31} = \omega_{32} = \omega_{33} = 1/3 \tag{6-1d}$$

However, the belief degrees must be determined against the evaluation grades for each basic attribute. This is done through part b of the questionnaire demonstrated in Appendix J. Five experts and their judgements were used to complete the qualitative questionnaire across disciplines of offshore engineering and computer science. This allowed for a more comprehensive view point as the designs of the WSN are to be used on-board an offshore platform. The five experts are to remain anonymous, however, their expertise are outlined as follows:

Expert 1 is currently in the employment of a leading classification society and holds a university qualification at the MSc. Level. This person has 8 years of experience at sea and more than 5 years as an offshore safety manager.

Expert 2 is currently in the employ of a leading provider of risk management services and holds a university qualification at Ph.D. level. This person has 10 years of experience as an offshore technical director.

Expert 3 is currently a CEO of a leading energy service and holds a university qualification at Ph.D. level.

Expert 4 is currently in the employ of a UK university as a senior lecturer and researcher. This person has 10 years' experience in research areas involving the progression of the Internet of Things and interdisciplinary technologies. This person also holds a university qualification at Ph.D. level.

Expert 5 is currently in the employ of a UK university as a senior lecturer and researcher. This person has 10 years' experience in research areas involving the progression of the Internet of Things and Computer, communication and control technologies. This person also holds a university qualification at Ph.D. level.

Each of the five experts completed the questionnaire in Appendix J. This allowed for the completion of the belief degrees for the basic attributes. The belief degrees are generated by taking the average for each attribute given what evaluation grade each expert has highlighted. The hierarchy and normalised weights of all attributes is demonstrated in Table 6-2, as well as the completed belief degrees for each basic attribute.

Table 6-2: Generalised decision matrix for WSN suitability assessment with normalised weights and belief degrees

General Attributes	Basic Attributes	WSN 1 Single-Hop	WSN 2 Single Hop (Cluster)	WSN 3 Multi-Hop (Small Radius)	WSN 4 Multi-Hop (Large Radius)	Evaluation Grades	
Complexity (x) (ω_1 = 0.333)	Transmission over the shortest route (e_1) (ω_{11} = 0.333)		0.6	0.2	0.2	H_1	Poor
			0	0.2	0	H_2	Indifferent
			0.4	0.6	0.2	H_3	Average
			0	0	0	H_4	Good
			0	0	0.6	H_5	Excellent
	Transmission over the longest route (e_2) (ω_{12} = 0.333)		0	0.4	0.8	H_1	
			0	0.2	0	H_2	
			0.6	0.4	0.2	H_3	
			0	0	0	H_4	
			0.4	0	0	H_5	
	Large number of Cluster nodes (e_3) (ω_{13} = 0.333)		0.6	0.2	0.6	H_1	
			0	0	0	H_2	
			0	0.2	0.3	H_3	
			0.2	0.2	0.1	H_4	
			0.2	0.4	0	H_5	
Resilience (y) (ω_2 = 0.333)	Battery Power (e_4) (ω_{21} = 0.5)		0	0	0.2	H_1	
			0.2	0.2	0	H_2	
			0.2	0	0	H_3	
			0.4	0.2	0.2	H_4	
			0.2	0.6	0.6	H_5	
	Relaying Data (e_5) (ω_{22} = 0.5)		0.2	0	0	H_1	
			0	0	0	H_2	
			0	0.2	0.4	H_3	
			0.2	0	0	H_4	
			0.6	0.8	0.6	H_5	
Maintainability (z) (ω_3 = 0.333)	Ease of Maintenance (e_6) (ω_{31} = 0.333)	0	0	0.2	0.4	H_1	
		0	0.4	0	0	H_2	
		0	0.2	0.4	0	H_3	
		0.5	0.4	0.4	0.4	H_4	
		0.5	0	0	0.2	H_5	
	Auto-Configuration (e_7) (ω_{32} = 0.333)	0	0	0.2	0.4	H_1	
		0.2	0.2	0	0	H_2	
		0.2	0.4	0.4	0.4	H_3	
		0.2	0.4	0.2	0	H_4	
		0.4	0	0.2	0.2	H_5	
	Cost (e_8) (ω_{33} = 0.333)	0.2	0	0.4	0.4	H_1	
		0	0.4	0	0	H_2	
		0.2	0.4	0	0	H_3	
		0.6	0	0.6	0.2	H_4	
		0	0.2	0	0.4	H_5	

6.2.3 Normalized Weight Aggregation Assessment Utilising the ER Algorithm

The problem is how the judgements in Table 6-2 can be aggregated to arrive at an assessment as to the best suited WSN for asset integrity monitoring on and offshore platform. The weight assessment for the attributes has already been outlined as being hypothetical by assuming normalised weights for each attribute.

To demonstrate the procedure of the ER algorithm the detailed steps of the calculation shall be shown for generating the assessment for the WSN 3's Complexity (y), by aggregating the three basic attributes Transmission over shortest route (e_1), Transmission over the longest route (e_2) and large number of cluster nodes (e_3). The evaluation grades have been defined in Equation 3-21. From Table 6-2 and Equation 3-25 the following can be stated:

$$\beta_{1,1} = 0.2, \quad \beta_{2,1} = 0.2, \quad \beta_{3,1} = 0.6, \quad \beta_{4,1} = 0, \quad \beta_{5,1} = 0$$

$$\beta_{1,2} = 0.4, \quad \beta_{2,2} = 0.2, \quad \beta_{3,2} = 0.4, \quad \beta_{4,2} = 0, \quad \beta_{5,2} = 0$$

$$\beta_{1,3} = 0.2, \quad \beta_{2,3} = 0, \quad \beta_{3,3} = 0.2, \quad \beta_{4,3} = 0.2, \quad \beta_{5,3} = 0.4$$

As stated previously, it is assumed initially that all three weights are of equal importance. So, from Equation 6-1b the weights are, $\omega_{11} = \omega_{12} = \omega_{13} = 1/3$. From Equations 3-26 and 3-27 the basic probability masses can be calculated:

$$m_{1,1} = 0.2/3, \quad m_{2,1} = 0.2/3, \quad m_{3,1} = 0.6/3, \quad m_{4,1} = 0, \quad m_{5,1} = 0,$$

$$\sum_{n=1}^{N} m_{n,1} = 0.333, \quad \therefore m_{H,1} = 0.667$$

$$m_{1,2} = 0.4/3, \quad m_{2,2} = 0.2/3, \quad m_{3,2} = 0.4/3, \quad m_{4,2} = 0, \quad m_{5,2} = 0,$$

$$\sum_{n=1}^{N} m_{n,2} = 0.333, \quad \therefore m_{H,2} = 0.667$$

$$m_{1,3} = 0.2/3, \qquad m_{2,3} = 0, \qquad m_{3,3} = 0.2/3, \qquad m_{4,3} = 0.2/3, \qquad m_{5,3} = 0.4/3,$$

$$\sum\nolimits_{n=1}^{N} m_{n,3} = 0.333, \qquad \therefore m_{H,3} = 0.667$$

It is now possible to use Equations 3-29, 3-30 and 3-31 to calculate the combined probability masses. Firstly, attributes e_1 and e_2 are to be aggregated. As stated by Equation 3-31:

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

$$i = 1, \dots, L-1$$

Equation 3-31 is solved in stages to determine $K_{I(2)}$, as follows:

$$\sum\nolimits_{\substack{t=1 \\ j \neq t}}^{5} m_{t,I(1)} m_{j,2} = (m_{1,1} m_{2,2}) + (m_{1,1} m_{3,2}) + (m_{1,1} m_{4,2}) + (m_{1,1} m_{5,2})$$

$$= \left(\frac{0.2}{3} . \frac{0.2}{3}\right) + \left(\frac{0.2}{3} . \frac{0.4}{3}\right) + (0) + (0) = 0.0133$$

$$\sum\nolimits_{\substack{t=2 \\ j \neq t}}^{5} m_{t,I(1)} m_{j,2} = (m_{2,1} m_{1,2}) + (m_{2,1} m_{3,2}) + (m_{2,1} m_{4,2}) + (m_{2,1} m_{5,2})$$

$$= \left(\frac{0.2}{3} . \frac{0.4}{3}\right) + \left(\frac{0.2}{3} . \frac{0.4}{3}\right) + (0) + (0) = 0.0178$$

$$\sum\nolimits_{\substack{t=3 \\ j \neq t}}^{5} m_{t,I(1)} m_{j,2} = (m_{3,1} m_{1,2}) + (m_{3,1} m_{2,2}) + (m_{3,1} m_{4,2}) + (m_{3,1} m_{5,2})$$

$$= \left(\frac{0.6}{3} . \frac{0.4}{3}\right) + \left(\frac{0.6}{3} . \frac{0.2}{3}\right) + (0) + (0) = 0.04$$

$$\sum\nolimits_{\substack{t=4 \\ j \neq t}}^{5} m_{t,I(1)} m_{j,2} = (m_{4,1} m_{1,2}) + (m_{4,1} m_{2,2}) + (m_{4,1} m_{3,2}) + (m_{4,1} m_{5,2})$$

$$= (0) + (0) + (0) + (0) = 0$$

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

$$= (0) + (0) + (0) + (0) = 0$$

$$K_{I(2)} = [1 - (0.0133 + 0.0178 + 0.04)]^{-1} = 1.077$$

Given that the value of $K_{I(2)}$ has been determined, Equations 3-29 and 3-30 can now be utilised, along with the basic probability masses, as follows:

$$m_{n,I(i+1)} = K_{I(i+1)} \begin{pmatrix} m_{n,I(i)}m_{n,i+1} + m_{n,I(i)}m_{H,i+1} \\ +m_{H,I(i)}m_{n,i+1} \end{pmatrix} \quad n = 1, \dots, N$$

$$m_{H,I(i+1)} = K_{I(i+1)}m_{H,I(i)}m_{H,i+1}$$

$$m_{1,I(2)} = K_{I(2)}(m_{1,1}m_{1,2} + m_{1,1}m_{H,2} + m_{H,1}m_{1,2}) = 0.1531$$

$$m_{2,I(2)} = K_{I(2)}(m_{2,1}m_{2,2} + m_{2,1}m_{H,2} + m_{H,1}m_{2,2}) = 0.1004$$

$$m_{3,I(2)} = K_{I(2)}(m_{3,1}m_{3,2} + m_{3,1}m_{H,2} + m_{H,1}m_{3,2}) = 0.2679$$

$$m_{4,I(2)} = K_{I(2)}(m_{4,1}m_{4,2} + m_{4,1}m_{H,2} + m_{H,1}m_{4,2}) = 0$$

$$m_{5,I(2)} = K_{I(2)}(m_{5,1}m_{5,2} + m_{5,1}m_{H,2} + m_{H,1}m_{5,2}) = 0$$

$$m_{H,I(2)} = K_{I(2)}m_{H,1}m_{H,2} = 0.4785$$

As the first two basic attributes, e_1 and e_2, have been aggregated, it is possible to combine the above results with the third attribute e_3 as follows:

Equation 3-31 is again solved in stages to find $K_{I(3)}$, as follows:

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

$$= 0.0408$$

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

$$= 0.0335$$

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

$$= 0.0715$$

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

$$= 0$$

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

$$= 0$$

$$K_{I(3)} = [1 - (0.0408 + 0.0335 + 0.0715)]^{-1} = 1.1707$$

Given that the value of $K_{I(3)}$ has been determined, Equations 3-29 and 3-30 can now be utilised, along with the basic probability masses, as follows:

$$m_{1,I(3)} = K_{I(3)}\left(m_{1,I(2)}m_{1,3} + m_{1,I(2)}m_{H,3} + m_{H,I(2)}m_{1,3}\right) = 0.1688$$

$$m_{2,I(3)} = K_{I(3)}\left(m_{2,I(2)}m_{2,3} + m_{2,I(2)}m_{H,3} + m_{H,I(2)}m_{2,3}\right) = 0.0784$$

$$m_{3,I(3)} = K_{I(3)}\left(m_{3,I(2)}m_{3,3} + m_{3,I(2)}m_{H,3} + m_{H,I(2)}m_{3,3}\right) = 0.2674$$

$$m_{4,I(3)} = K_{I(3)}\left(m_{4,I(2)}m_{4,3} + m_{4,I(2)}m_{H,3} + m_{H,I(2)}m_{4,3}\right) = 0.0373$$

$$m_{5,I(3)} = K_{I(3)}\left(m_{5,I(2)}m_{5,3} + m_{5,I(2)}m_{H,3} + m_{H,I(2)}m_{5,3}\right) = 0.0747$$

$$m_{H,I(3)} = K_{I(3)}m_{H,I(2)}m_{H,3} = 0.3734$$

As the basic attributes e_1, e_2 and e_3 have been aggregated, the combined belief degrees are calculated using Equation 3-32:

$$\beta_n = \frac{m_{n,I(L)}}{1 - m_{H,I(L)}}, \qquad n = 1, \dots, N, \qquad i = 1, \dots, L$$

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

$$\beta_1 = \frac{m_{1,I(3)}}{1 - m_{H,I(3)}} = \frac{0.1688}{1 - 0.3734} = 0.2694$$

$$\beta_2 = \frac{m_{2,I(3)}}{1 - m_{H,I(3)}} = \frac{0.07848}{1 - 0.3734} = 0.1251$$

$$\beta_3 = \frac{m_{3,I(3)}}{1 - m_{H,I(3)}} = \frac{0.2674}{1 - 0.3734} = 0.4267$$

$$\beta_4 = \frac{m_{4,I(3)}}{1 - m_{H,I(3)}} = \frac{0.0373}{1 - 0.3734} = 0.0596$$

$$\beta_5 = \frac{m_{5,I(3)}}{1 - m_{H,I(3)}} = \frac{0.0747}{1 - 0.3734} = 0.1192$$

$$\sum_{n=1}^{N} \beta_n = 1, \qquad \therefore \quad \beta_H = 0$$

Therefore, the assessment for the Complexity of WSN 3 by aggregating Transmission over the shortest route (e_1), Transmission over the longest route (e_2) and large number of cluster heads (e_3), is given by:

$$S(Complexity) = S(e_1 \oplus e_2 \oplus e_3)$$

$$= \{(Poor, 0.2694), (Indifferent, 0.1251), (Average, 0.4267),$$

$$(Good, 0.0596), (Excellent, 0.1192)\}$$

It is important to note that changing the aggregation order does not change the final results in any way.

6.2.3.1 Results and Analysis of Normalized Weight Aggregation

The calculations demonstrated in Section 6.2 for the assessment of WSN 3 in terms of its Complexity were repeated for the other basic attributes for each of the WSNs proposed. The results were then aggregated further to give the overall beliefs for the general attributes for each of the WSNs. All of the calculations were completed using Microsoft Excel as it provided a simple way of inputting the ER algorithm and displaying the results clearly. Given the information demonstrated in Table 6-2 the assessment for the general attributes for each WSN were calculated. Table 6-3 shows the aggregated assessment for the general attributes for each WSN design.

Table 6-3**:** Aggregated assessment for the general attributes for each WSN design

General Attributes	WSN 1	WSN 2	WSN 3	WSN 4	Evaluation Grades	
	Single-Hop	Single Hop (Cluster)	Multi-Hop (Small Radius)	Multi-Hop (Large Radius)		
Complexity (ω_1 - = 1/3)		0.413	0.269	0.575	H_1	Poor
		0.000	0.125	0.000	H_2	Indifferent
		0.335	0.427	0.225	H_3	Average
		0.060	0.060	0.029	H_4	Good
		0.192	0.119	0.172	H_5	Excellent
Resilience (ω_2 = 1/3)		0.091	0.000	0.085	H_1	
		0.091	0.081	0.000	H_2	
		0.091	0.081	0.169	H_3	
		0.309	0.081	0.085	H_4	
		0.418	0.758	0.661	H_5	
Maintainability (ω_3 = 1/3)	0.059	0.000	0.265	0.428	H_1	
	0.059	0.342	0.000	0.000	H_2	
	0.124	0.342	0.258	0.118	H_3	
	0.464	0.258	0.419	0.188	H_4	
	0.295	0.059	0.059	0.266	H_5	

Similarly Figure 6-6, Figure 6-7 and Figure 6-8 show the graphical representation of each of the aggregated assessment of the general attributes for each WSN.

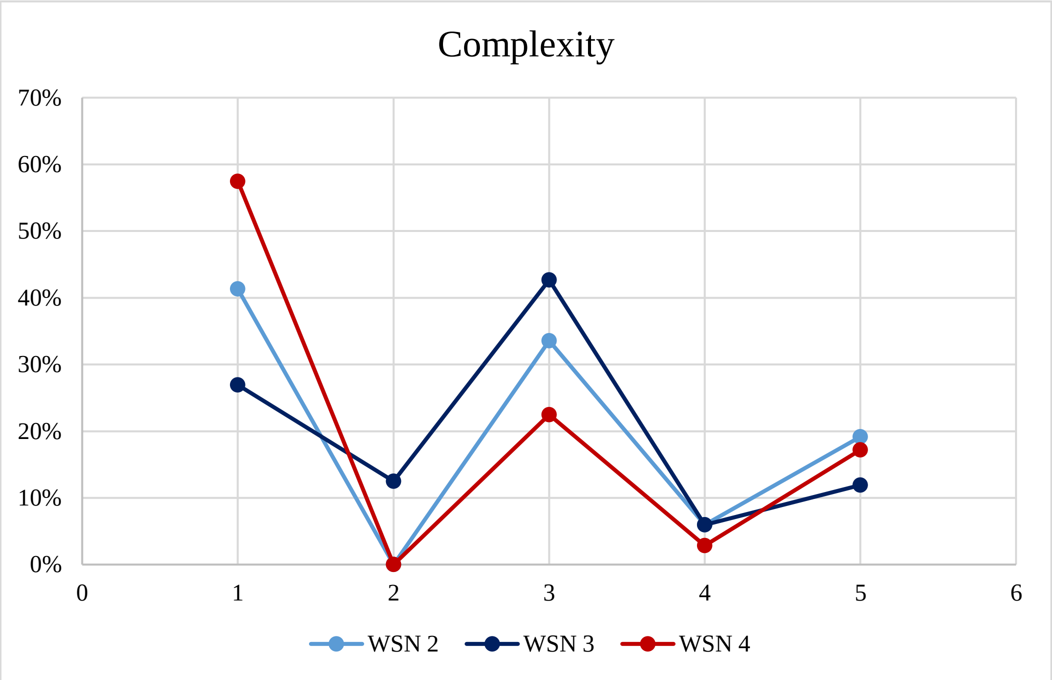


Figure 6-6: Graph showing the aggregated assessment for the Complexity of WSNs 2, 3, and 4

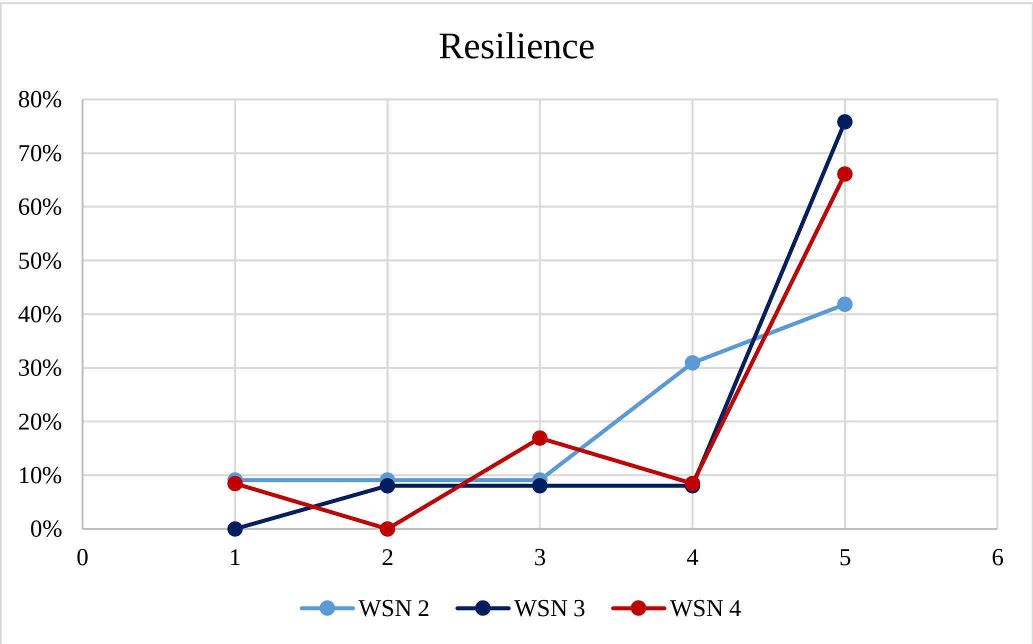


Figure 6-7: Graph showing the aggregated assessment for the Resilience of WSNs 2, 3, and 4

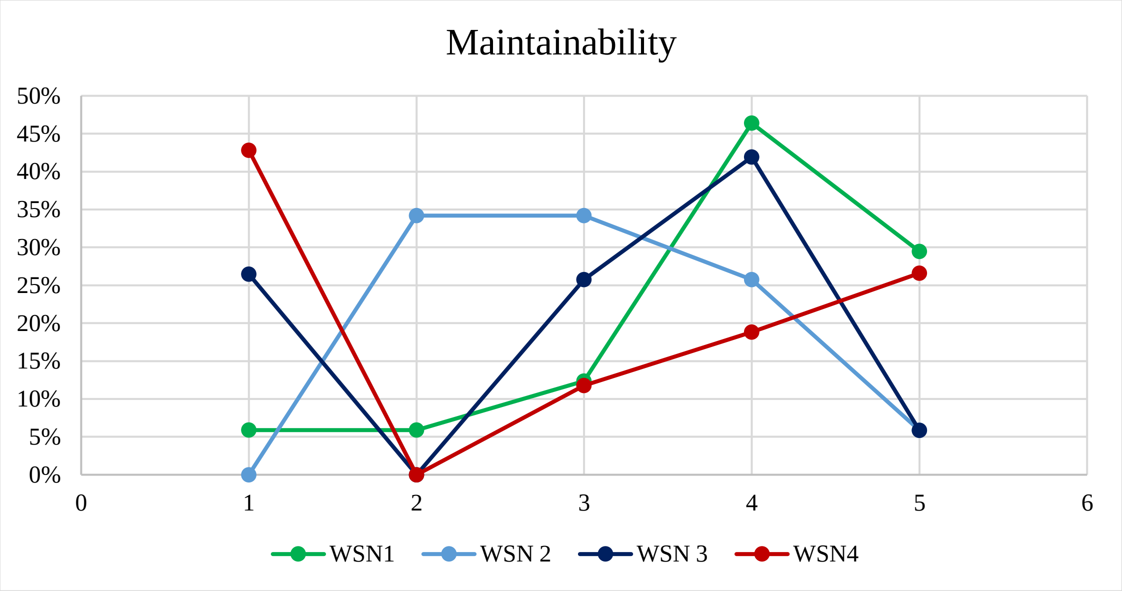


Figure 6-8: Graph showing the aggregated assessment for the Maintainability of each of the WSNs

From the graphs in Figure 6-6, Figure 6-7 and Figure 6-8 it is possible to distinguish some of the differences between the WSNs and rank them, however, this can be very difficult. For example, it would seem that WSN 3 fairs better in terms of resilience than WSN 2 or 4. Similarly, in the only case where WSN 1 is assessed, maintainability, it also seems to be the best performing WSN design. However, WSN 1 cannot be assessed in complexity or resilience as it is a very simple design in terms of its data transmission. It therefore makes sense that WSN 1 performs better than the other WSNs in terms of maintainability.

Continuing on the procedure of ranking the WSNs, it is necessary to determine their overall performance and suitability for offshore use. This is done by aggregating the general attributes still further using the ER algorithm. This demonstrates the overall suitability of WSNs 2, 3 and 4. Table 6-4 and Figure 6-9 demonstrate overall suitability beliefs for the WSNs. In Table 6-4 the beliefs relating to the overall suitability of the WSNs are shown as a percentage.

Table 6-4: Overall suitability of the WSNs to be applied to asset integrity monitoring in offshore installations

		OVERALL SUITABILITY		
Evaluation Grades		WSN 2	WSN 3	WSN4
1	Poor	16.13%	17.63%	36.99%
2	Indifferent	13.83%	6.52%	0.00 %
3	Average	26.49%	26.30%	16.32%
4	Good	21.11%	18.32%	9.22%
5	Excellent	22.43%	31.20%	37.46%
		1	1	1

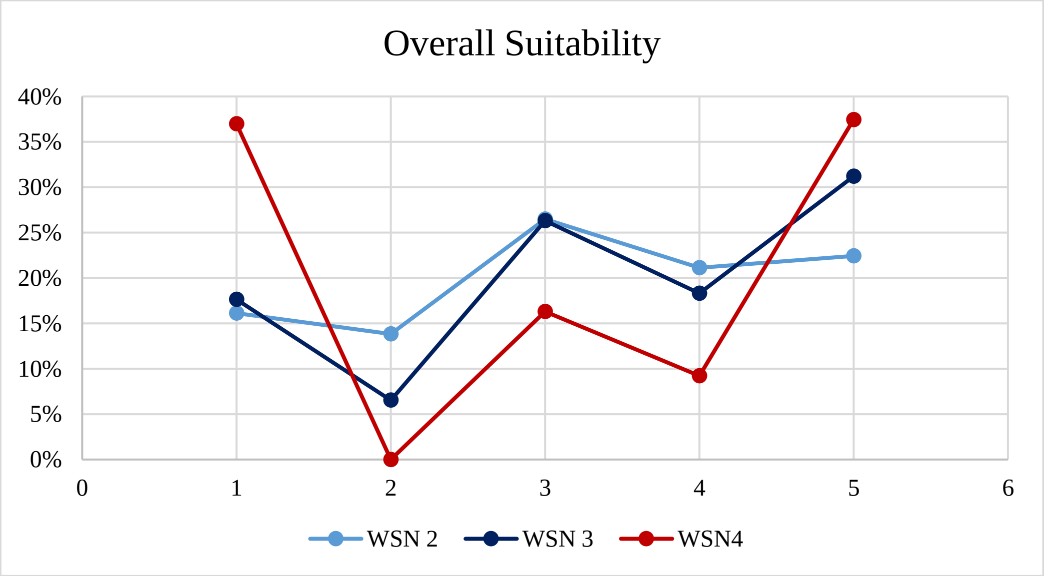


Figure 6-9: graph showing the overall aggregated assessment for the WSNs

Again, it is difficult to accurately rank the WSNs performance based on the graph and data in Figure 6-9 and Table 6-4. It can be seen that WSN 3 may be the most suitable design as it scores consistently high from *Average* to *Good* to *Excellent*. However, this is by no means a clear indicator of which WSN performs the best. Therefore, as stated in Section 3.7.1.2, each WSN must be ranked by estimating their utility grades.

The WSN designs can be ranked based upon their aggregated belief degrees from the ER algorithm. This can be done through utility assessment. Suppose the utility of an evaluation grade, H_n, is denoted by $u(H_n)$. The utility of the evaluation grade must be determined beforehand, with $u(H_1) = 0$ and $u(H_5)=1$ assuming there are five evaluation grades (Yang, 2001). If there is not preference information available then the values of $u(H_n)$ can be assumed to be equidistant, as shown by Equation 3-33:

$$u(H_n) = \{u(H_1) = 0, u(H_2) = 0.25, u(H_3) = 0.5, u(H_4) = 0.75, u(H_5) = 1\}$$

$$u(H_n) = \{u(Poor) = 0, \quad u(Indifferent) = 0.25, \quad u(Average) = 0.5,$$
$$u(Good) = 0.75, \quad u(Excellent) = 1\}$$

The estimated utility for the general and basic attributes, $S(z(e_i))$, given the set of evaluation grades is given by Equation 3-34:

$$u\Big(S\big(z(e_i)\big)\Big) = \sum_{n=1}^{N} u(H_n)\beta_n\,(e_i)$$

Equation 3-34 can be used as the belief degrees sum to 1, therefore there can be no upper or lower bound limit on the utility estimation, just one utility value for each WSN. Each WSN can be ranked both in terms of each general attribute and the overall suitability of the WSNs. By applying Equation 3-34 and the data in Table 6-3 to the general attribute Complexity for WSN 3, its utility score can be determined.

$$\begin{aligned} u\big(S(Complexity)\big) \\ &= (u(H_1)\beta_1) + (u(H_2)\beta_2) + (u(H_3)\beta_3) + (u(H_4)\beta_4) + (u(H_5)\beta_6) \\ &= (0 \times 0.269) + (0.25 \times 0.125) + (0.5 \times 0.427) + (0.75 \times 0.06) \\ &+ (1 \times 0.119) = 0.409 \end{aligned}$$

The utility estimation is calculated the same was for each general attribute for each WSN and for the overall suitability for each WSN. These results are tabulated and the WSNs can be ranked accordingly.

Table 6-5 shows the utility values for the general attribute complexity for WSNs 2, 3 and 4. It can be seen that WSN 3 has the greatest ability to deal complex data transmissions, with WSN 2 performing better than WSN 4. In other words, in terms of their complexity:

$$WSN\ 3 > WSN\ 2 > WSN\ 4$$

Table 6-5: Utility values and ranking of WSNs, 2, 3 and 4 for the general attribute Complexity

Complexity (x) belief					
Grades		u(Grades)	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.413	0.269	0.575
H2	Indifferent	0.25	0.000	0.125	0.000
H3	Average	0.5	0.335	0.427	0.225
H4	Good	0.75	0.060	0.060	0.029
H5	Excellent	1	0.192	0.119	0.172
		u(Total)	0.404	0.409	0.306
		Ranking	2	1	3

Similarly, Table 6-6 shows the utility values for the general attribute resilience. Here WSN 3 again scores higher than the other WSNs. This is concurrent with the statement made regarding the best performing WSN based upon the graph in Figure 6-7. The order of ranking for Resilience is as follows:

$$WSN\ 3 > WSN\ 4 > WSN\ 2$$

Table 6-6: Utility values and ranking of WSNs, 2, 3 and 4 for the general attribute Resilience

Resilience (y) belief					
Grades		u(Grades)	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.091	0.000	0.085
H2	Indifferent	0.25	0.091	0.081	0.000
H3	Average	0.5	0.091	0.081	0.169
H4	Good	0.75	0.309	0.081	0.085
H5	Excellent	1	0.418	0.758	0.661
		u(Total)	0.718	0.879	0.809
		Ranking	3	1	2

Continually, Table 6-7 demonstrates the utility values for the general attribute Maintainability for all WSNs. Here it can be seen that WSN 1 fairs the best, as was stated when analysing the graph in Figure 6-8. The WSNs rank in order from 1 to 4 in terms of their maintainability. This would make sense as the transmission types of each WSN also become more complex from WSN 1 to WSN 4. The order of ranking for maintainability is as follows:

$$WSN\ 1 > WSN\ 2 > WSN\ 3 > WSN\ 4$$

Table 6-7: Utility values and ranking of WSNs, 1, 2, 3 and 4 for the general attribute Maintainability

Maintainability (z) belief						
Grades		u(Grades)	WSN 1	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.059	0.000	0.265	0.428
H2	Indifferent	0.25	0.059	0.342	0.000	0.000
H3	Average	0.5	0.124	0.342	0.258	0.118
H4	Good	0.75	0.464	0.258	0.419	0.188
H5	Excellent	1	0.295	0.059	0.059	0.266
		u(Total)	0.719	0.508	0.502	0.466
		Ranking	1	2	3	4

Finally, the WSNs are ranked based upon their overall performance and suitability for application in asset integrity monitoring of an offshore electrical power generator, utilising data from Table 6-4. Table 6-8 outlines the overall suitability belief for WSNs 2, 3 and 4. WSN 1 cannot be included as it was not assessed against general attributes Complexity and Resilience. It can be seen that WSN 3 would appear to be the most suitable design and data transmission choice for offshore applications. This is concurrent with the claim made previously following the analysis of Figure 6-9. The ranking for overall suitability is as follows:

$$WSN\ 3 > WSN\ 2 > WSN\ 4$$

Table 6-8**:** Overall utility values and ranking of WSNs, 2, 3 and 4

Overall Suitability Belief					
Grades		u(Grades)	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.161	0.176	0.370
H2	Indifferent	0.25	0.138	0.065	0.000
H3	Average	0.5	0.265	0.263	0.163
H4	Good	0.75	0.211	0.183	0.092
H5	Excellent	1	0.224	0.312	0.375
		u(Total)	0.550	0.597	0.525
		Ranking	2	1	3

The rankings demonstrated are conclusive given the expert judgements presented in Table 6-2. However, these rankings are generated based upon the assumption that all of the attributes are of equal weighting. In general, one would utilise a variety of weights to more accurately determine the most suitable WSN for offshore asset integrity monitoring and whether the rankings generated are reliable. Furthermore, it is possible or even necessary to improve the quality of original information to achieve reliable rankings. This improvement in information can potentially come from utilising more experts to gain more coherent and accurate basic attribute beliefs. Similarly, it is also possible to utilise an increased number of evaluation grades. However, this drastically increases the complexity of the ER algorithm and could potential produce some unforced errors.

Following the analysis presented in Section 6.2, Section 6.3 shall demonstrate the outcomes of the ER algorithm with the same basic attribute beliefs. However, a pairwise and AHP analysis shall be employed to more accurately determine the weights of each attribute. This should strengthen the accuracy of the post analysis rankings and comparisons can be made as to the differences between the rankings when utilising normalised weights and calculated weights.

6.3 Numerical Study and Analysis with Calculated Weights Utilising the ER Algorithm

The numerical analysis in Section 6.2 has dealt with the selection problem of the most suitable WSN design for use on board an offshore installation. The purpose of which is to monitor the asset integrity of the electrical power generator, as outlined in Section 6.1. It demonstrated that the ER algorithm can be utilised in this decision-making process. However, the analysis presented in Section 6.2 relied on normalised weighting for the basic and general attributes, with the beliefs for the basic attributes determined by expert judgement through part B of the questionnaire outlined in Appendix J. This section focuses on conducting the decision-making analysis again but by determining the relative weights of the attributes through Pairwise Comparison and AHP methods. This was done through part A of the questionnaire sent to experts.

6.3.1 Determining Relative Weights of the Attributes

The Pairwise Comparison and AHP methods have been outlined in Chapter 3 and a numerical demonstration was given in Chapter 4. The same methodology is applied and a numerical assessment is included for completeness.

Referring to the general attributes in part A of the questionnaire in Appendix J, and the evaluation hierarchy in Figure 6-5, a numerical assessment of the AHP method is demonstrated, utilising a 3×3 pairwise comparison matrix. Table 6-10 is a pairwise comparison matrix expressing the qualified judgement regarding the relative priority of *x*, *y* and *z*. An explanation of the abbreviations is given in Table 6-9.

Table 6-9: Criteria required for the general attributes in the evaluation hierarchy

General Attributes	
Complexity	x
Resilience	y
Maintainability	z

Table 6-10: Pairwise Comparison matrix for the general attributes

	x	y	z
x	1.00	0.48	0.66
y	2.09	1.00	1.95
z	1.52	0.51	1.00
SUM	4.61	1.99	3.61

A standardised matrix is calculated to show the performance ratio of the general attributes. This is done by dividing the importance rating in each cell by the sum of its column. From here the relative weights of the criteria can be calculated by averaging the rows in the standardised matrix. A measure to know if the data is performing correctly is that all of the columns in the standardised matrix must sum to 1.0. The standardised matrix with calculated relative weights for the general attributes is shown in Table 6-11. These step by step calculations, as a whole, represent Equation 3-12.

Table 6-11: Standardised Matrix of system criteria along with their relative weights.

	x	y	z	**Weight**
x	0.22	0.24	0.18	**21.34%**
y	0.45	0.50	0.54	**49.86%**
z	0.33	0.26	0.28	**28.80%**
SUM	1	1	1	**100.00%**

The next phase of AHP is the consistency ratio calculation. Each value in the columns of Table 6-10 is multiplied by the weight value of each criterion in Table 6-11. For example, each value in the column 'x' of Table 6-10 is multiplied by the weight of the 'x' row in Table 6-11. Once these figures have been calculated, they are to be summarised by row, as shown in Table 6-12. A Sum Weight is then calculated by dividing the summarised row of Table 6-12 by the corresponding weight in Table 6-11. For example, 'Sum Row' 'x' is divided by the weight in row 'x' in Table 6-11. The full results are shown in Table 6-12.

Table 6-12: The product of the Pairwise Comparison matrix values and the calculated weights (columns 2- 4). Along with the sum of each row and the sum weight of each criteria.

	x	y	z	Sum Row	Sum Weight
x	0.21	0.24	0.19	0.64	3.01
y	0.45	0.50	0.56	1.51	3.02
z	0.32	0.26	0.29	0.87	3.01

The λ_{max} value is then calculated by dividing the sum of the 'Sum Weights' by the number of criteria, 'n' in the pairwise comparison, which in this case is 3. Hence, λ_{max} is calculated as:

$$\lambda_{\max} = \frac{3.008 + 3.02 + 3.012}{3} = 3.013$$

Next the CI is computed using Equation 3-14:

$$CI = \frac{3.013 - 3}{3 - 1} = 0.007$$

Subsequently the CR is calculated using Equation 3-13. There are 3 criteria in this pairwise comparison under evaluation, so the corresponding RI is 0.58, as shown in Table 3-2. The CR of the system level criteria can now be calculated as follows:

$$CR = \frac{0.007}{0.58} = 0.011$$

The CR value of the system level criteria is 0.011. This means that the degree of consistency within the pairwise comparison is acceptable as the CR value is less than 0.10.

Similar calculations were conducted for the other criteria in the pairwise comparison with the other CRs being 0.01, 0.01 and 0.06. These again are acceptable as it is less than 0.10. The full pairwise comparison and AHP results are shown in Appendix K. CR calculations are not possible for matrices of less than 2×2 as the Saaty RI values for 2×2 matrices are zero.

Utilising the Pairwise Comparison and AHP methods, the weights for all of the basic and general attributes are calculated. These weights are shown in Table 6-13. It can already be seen that the weights are far from equal. For example, In the first analysis, the weights for x were outlined as $\omega_1 = \omega_2 = \omega_3 = 1/3$, however, they have now been calculated as, $\omega_1 = 0.5309,\ \omega_2 = 0.1618,\ \omega_3 = 0.3075$.

Table 6-13: Calculated weights for the general and basic attribute for use in the ER algorithm

x			y		z			SUM
21.34%			49.86%		28.80%			100.00%
e1	e2	e3	e4	e5	e6	e7	e8	
53.09%	16.16%	30.75%	65.08%	34.92%	53.62%	20.46%	25.92%	
SUM			SUM		SUM			
100.00%			100.00%		100.00%			

6.3.2 Calculated Weight Aggregation Assessment and Analysis Utilising the ER Algorithm

The problem now is aggregating the judgements in Table 6-2 to arrive at an assessment as to the best suited WSN for asset integrity monitoring on and offshore platform. The weight assessment for the attributes has been outlined through Pairwise Comparison and AHP analysis, with the relative weights demonstrated in Table 6-13. The method of applying the ER algorithm is the same as in Section 6.2, with the exception of substituting the normalised weights for calculated weights. In theory, this is deemed to be step towards more accurate rankings of the WSNs (Yang & Xu, 2002). Therefore, the calculation shall not be demonstrated again. The focus here is the comparison of the rankings between the normalised weights and calculated weights.

By applying the beliefs in Table 6-2, the weights in Table 6-13 and the ER algorithm calculation demonstrated in Section 6.2, it is possible to determine the belief structure for the General attributes and rank the WSNs in accordance with the performance with each attribute. Table 6-14 shows the new calculated belief structure for the general attributes.

Similarly, Figure 6-10, Figure 6-11 and Figure 6-12 show the graphical representation of each of the aggregated assessment of the general attributes for each WSN.

Table 6-14**:** Belief structure for the general attribute using calculated weights through AHP

General Attributes	WSN 1 Single-Hop	WSN 2 Single Hop (Cluster)	WSN 3 Multi-Hop (Small Radius)	WSN 4 Multi-Hop (Large Radius)	Evaluation Grades	
Complexity (ω_1 - 21.34%)		0.561	0.225	0.405	H_1	Poor
		0.000	0.141	0.000	H_2	Indifferent
		0.309	0.498	0.226	H_3	Average
		0.044	0.046	0.123	H_4	Good
		0.086	0.091	0.342	H_5	Excellent
Resilience (ω_2 - 49.86%)		0.041	0.000	0.135	H_1	
		0.143	0.129	0.000	H_2	
		0.143	0.037	0.078	H_3	
		0.359	0.129	0.135	H_4	
		0.313	0.704	0.652	H_5	
Maintainability (ω_3 - 28.80%)	0.035	0.000	0.238	0.423	H_1	
	0.026	0.380	0.000	0.000	H_2	
	0.063	0.276	0.306	0.052	H_3	
	0.505	0.309	0.430	0.285	H_4	
	0.371	0.035	0.026	0.240	H_5	

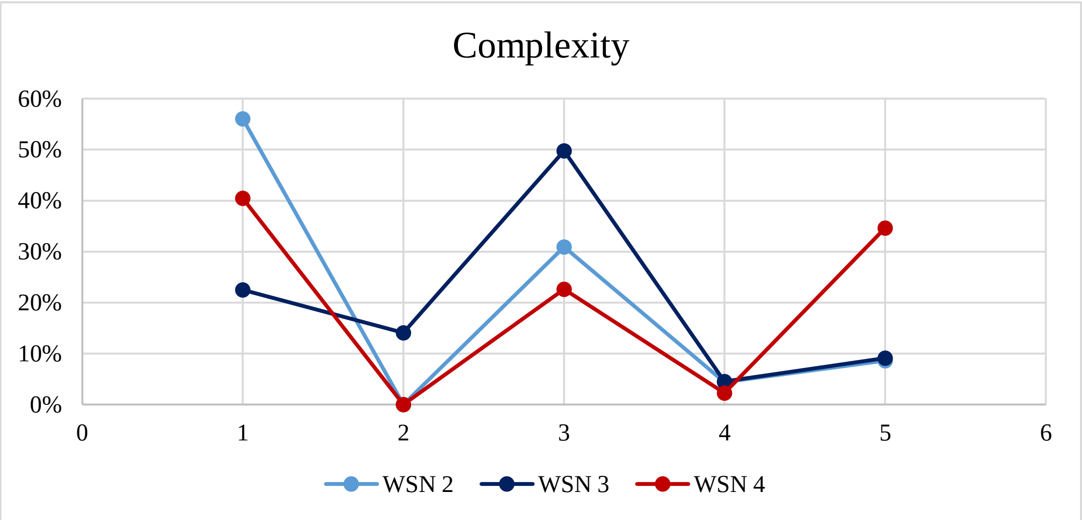


Figure 6-10: Graph showing the aggregated assessment for the Complexity of WSNs 2, 3, and 4 from calculated weights

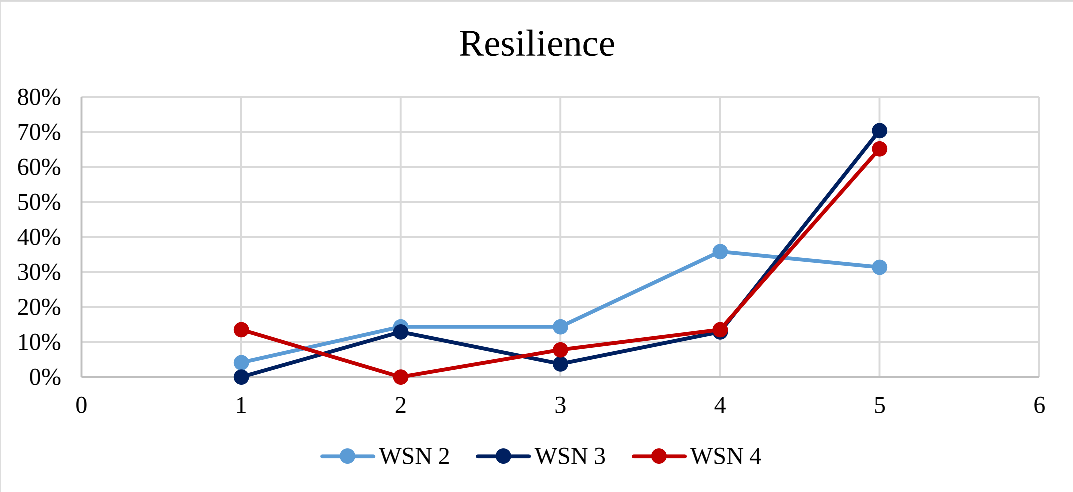


Figure 6-11: Graph showing the aggregated assessment for the Resilience of WSNs 2, 3, and 4 from calculated weights

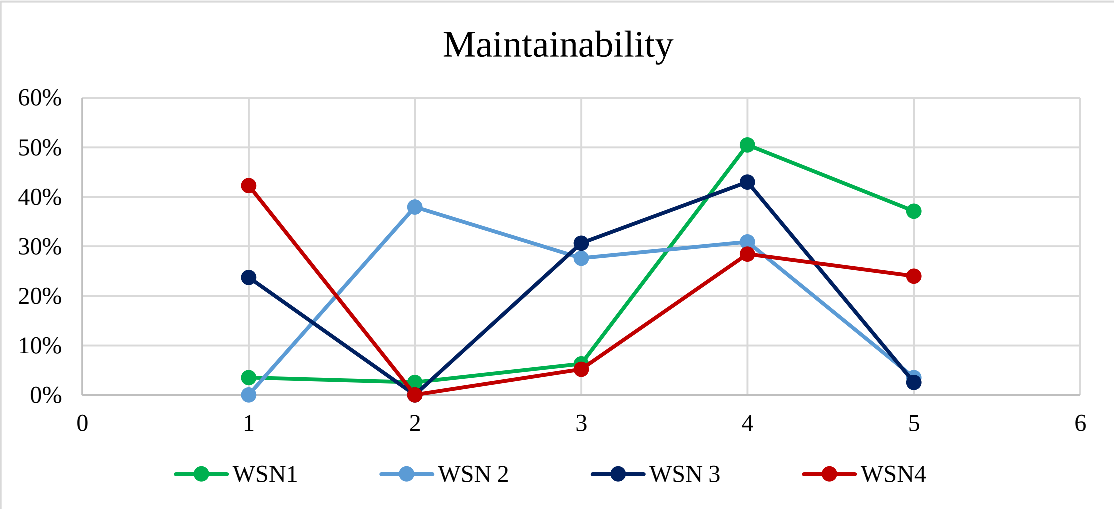


Figure 6-12: Graph showing the aggregated assessment for the Maintainability of WSNs 1, 2, 3, and 4 from calculated weights

From the graphs in Figure 6-10, Figure 6-11 and Figure 6-12 it is again possible to distinguish some of the differences between the WSNs and rank them. However, this can be very difficult, for example, it is difficult to determine the most suitable WSN in terms of the complexity of the WSNs. Similarly, in the only case where WSN 1 is assessed, maintainability, it also seems to be the best performing WSN design as its highest-ranking beliefs are across the evaluation grades of *good* and *excellent*. However, WSN 1 cannot be assessed in complexity or resilience as it is a very simple design in terms of its data transmission. It therefore makes sense that WSN 1 performs better than the other WSNs in terms of maintainability. This is also in accordance with the assessment made when the weights were normalised in the initial analysis. Furthermore, it can be seen in Figure 6-11 that both WSNs 3 and 4 outperform WSN 2. However, it is difficult to determine which of the two WSN designs fair better in terms of their resilience.

Continuing the procedure of ranking the WSNs, it is necessary to determine their overall performance and suitability for offshore use with the new calculated weights. This is done by aggregating the general attributes still further using the ER algorithm. This demonstrates the overall suitability of WSNs 2, 3 and 4. Table 6-15 and Figure 6-13 demonstrate overall suitability beliefs for the WSNs. In Table 6-15 the beliefs are shown as a percentage.

Table 6-15: Overall suitability of the WSNs to be applied to asset integrity monitoring in offshore installations

Evaluation Grades		OVERALL SUITABILITY		
		WSN 2	WSN 3	WSN4
1	Poor	11.085%	9.270%	25.047%
2	Indifferent	17.660%	9.760%	0.000%
3	Average	20.927%	18.360%	8.850%
4	Good	30.254%	19.410%	14.407%
5	Excellent	20.073%	43.200%	51.697%
		1	1	1

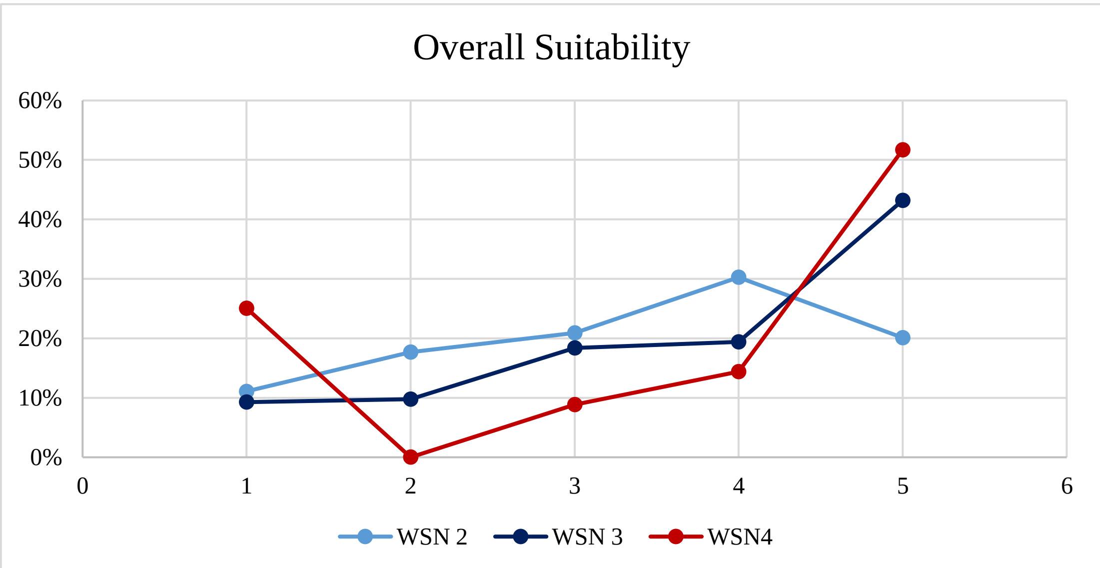


Figure 6-13**:** Graph showing the overall aggregated assessment for the WSNs from the calculated weights

It can be seen by Figure 6-13 that it is difficult to ascertain the most suitable WSN configuration for use offshore for asset integrity monitoring. However, what can be said is that WSNs 3 and 4 just out perform WSN 2 as they both have their highest beliefs at the top evaluation grade, e*xcellent*. Furthermore, when comparing the overall suitability graph from the normalised weights in Figure 6-9 with the graph in Figure 6-13, it can be seen that the aggregated assessment is much more coherent when the weights are calculated instead of normalised. This partially reinforces the claims by Yang & Xu, (2002) and Fu & Yang (2012) that applying calculated weights over normalised weights should present a more accurate analysis and results. In order to more accurately rank the WSNs in terms of their performance and suitability the utility estimation analysis demonstrated in Section 6.2.3.1 shall be applied further to determine the ranking of each WSN and to compare the results with the ranking with normalised weights.

6.3.3 Utility Ranking Based on ER Analysis with Calculated Weights

The WSN designs can be ranked based upon their aggregated belief degrees from the ER algorithm. This can be done through utility assessment. Suppose the utility of an evaluation grade, H_n, is denoted by $u(H_n)$. The utility of the evaluation grade must be determined beforehand, with $u(H_1) = 0$ and $u(H_5)=1$ assuming there are five evaluation grades (Yang, 2001). If there is not preference information available then the values of $u(H_n)$ can be assumed to be equidistant, as shown by Equation 3-33:

$$u(H_n) = \{u(H_1) = 0, u(H_2) = 0.25, u(H_3) = 0.5, u(H_4) = 0.75, u(H_5) = 1\}$$

$$u(H_n) = \{u(Poor) = 0, \quad u(Indifferent) = 0.25, \quad u(Average) = 0.5, \quad u(Good) = 0.75, \quad u(Excellent) = 1\}$$

The estimated utility for the general and basic attributes, $S(z(e_i))$, given the set of evaluation grades is given by Equation 3-34:

$$u\left(S\big(z(e_i)\big)\right) = \sum_{n=1}^{N} u(H_n)\beta_n\,(e_i)$$

Equation 3-34 can be used as it is because the belief degrees sum to equal 1, therefore there can be no upper or lower bound limit on the utility estimation, just one utility value for each WSN. Each WSN can be ranked both in terms of each general attribute and the overall suitability of the WSNs. By applying Equation 3-34 and the data in Table 6-14 to the general attribute Complexity for WSN 3, its utility score can be determined.

$$\begin{aligned} &u\big(S(Complexity)\big) \\ &\qquad = (u(H_1)\beta_1) + (u(H_2)\beta_2) + (u(H_3)\beta_3) + (u(H_4)\beta_4) + (u(H_5)\beta_6) \\ &\qquad = (0 \times 0.2225) + (0.25 \times 0.141) + (0.5 \times 0.498) + (0.75 \times 0.046) \\ &\qquad + (1 \times 0.91) = 0.409 \end{aligned}$$

The utility estimation is calculated the same was for each general attribute for each WSN and for the overall suitability for each WSN. These results are tabulated and the WSNs can be ranked accordingly.

Table 6-16 shows that WSN 4 performs better it terms of the networks ability to deal with complex transmissions and connection, with WSN 3 fairing much better than WSN 2. In terms of their ability to deal with complex transmission s and connections the WSNs are ranked as follows:

$$WSN\ 4 > WSN\ 3 > WSN\ 2$$

Table 6-16: Utility values and ranking of WSNs, 2, 3 and 4 for the general attribute Complexity from calculated weights

Complexity (x) belief					
Grades		u(Grades)	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.561	0.225	0.405
H2	Indifferent	0.25	0.000	0.141	0.000
H3	Average	0.5	0.309	0.498	0.226
H4	Good	0.75	0.044	0.046	0.023
H5	Excellent	1	0.086	0.091	0.347
		u(Total)	0.274	0.409	0.477
		Ranking	3	2	1

As stated previously when analysing Figure 6-11, it was clear that WSNs 3 and 4 clearly outperformed WSN 2, however, it was not possible to distinguish the performances of WSN 3 and WSN 4. Based on the rankings calculated in Table 6-17 it is clear that WSN 3 out performs WSN 4 in terms of its resilience. Hence the ranking order of the WSNs for the attribute resilience is as follows:

$$WSN\ 3 > WSN\ 4 > WSN\ 2$$

Table 6-17: Utility values and ranking of WSNs, 2, 3 and 4 for the general attribute Resilience from calculated weights

Resilience (y) belief					
Grades		u(Grades)	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.041	0.000	0.135
H2	Indifferent	0.25	0.143	0.129	0.000
H3	Average	0.5	0.143	0.037	0.078
H4	Good	0.75	0.359	0.129	0.135
H5	Excellent	1	0.313	0.704	0.652
		u(Total)	0.690	0.852	0.792
		Ranking	3	1	2

Continuing in with the ranking of the WSNs based on their performance against each general attribute, Table 6-18 shows the ranking of each WSN for Maintainability. It can be seen that WSN 1 drastically out performs WSNs 2, 3 and 4 in terms of their capabilities as an easily maintainable network. Hence the ranking of the WSN is as follows:

$$WSN\ 1 > WSN\ 3 > WSN\ 2 > WSN\ 4$$

Table 6-18: Utility values and ranking of WSNs, 1, 2, 3 and 4 for the general attribute Maintainability from calculated weights

Maintainability (z) belief						
Grades		u(Grades)	WSN 1	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.035	0.000	0.238	0.423
H2	Indifferent	0.25	0.026	0.380	0.000	0.000
H3	Average	0.5	0.063	0.276	0.306	0.052
H4	Good	0.75	0.505	0.309	0.430	0.285
H5	Excellent	1	0.371	0.035	0.026	0.240
		u(Total)	0.788	0.500	0.501	0.480
		Ranking	1	3	2	4

Finally, the WSNs are ranked based upon their overall performance from the ER algorithm with calculated weights utilising information provided in Table 6-15. Table 6-19 outlines the overall suitability belief for WSNs 2, 3 and 4. WSN 1 cannot be included as it was not assessed against general attributes Complexity and Resilience. It can be seen that WSN 3 would appear to be the most suitable design and data transmission choice for offshore applications. This provides some clarity to the analysis of Figure 6-13 where it could be seen that either WSN 3 or WSN 4 would be the most suitable configuration based upon the analysis with calculated weights. The ranking for overall suitability is as follows:

$$WSN\ 3 > WSN\ 4 > WSN\ 2$$

Table 6-19: Overall utility values and ranking of WSNs, 2, 3 and 4 based on calculated weights

Overall Suitability Belief					
Grades		u(Grades)	WSN 2	WSN 3	WSN 4
H1	Poor	0	0.111	0.093	0.250
H2	Indifferent	0.25	0.177	0.098	0.000
H3	Average	0.5	0.209	0.184	0.089
H4	Good	0.75	0.303	0.194	0.144
H5	Excellent	1	0.201	0.432	0.517
		u(Total)	0.576	0.694	0.669
		Ranking	3	1	2

The rankings demonstrated are conclusive given the expert judgements presented in Table 6-2 and the relative weights established in Table 6-13. It is clear from the data presented in the graphs and tables that utilising calculated weights as opposed to normalised weights organises the aggregated belief structures much more coherently. This allows for a more accurate estimation of the rankings by simply analysing the data without calculating the utility estimations for absolute rankings. However, the rankings of the WSNs for the general attributes and the overall assessment must be compared in terms of the results for normalised weights and calculated weights.

6.4 Comparison of Results given Normalised Weights and Calculated Weights

In theory, the application of calculated weights through expert judgement and AHP analysis should prove to be more accurate than the method of normalising the relative weights of attributes. To determine the validity of this statement, Table 6-20 shows the utility values and rankings of each WSN against the general attributes and the final overall assessment.

Table 6-20**:** Utility estimations and ranks of each WSN for the general attributes and overall assessment for normalised weights and calculated weights

	WSN 1	**WSN 2**	**WSN 3**	**WSN 4**
Complexity (x)				
Normalised				
u(Total)		0.404	0.409	0.306
Ranking		2	1	3
Calculated				
u(Total)		0.274	0.409	0.477
Ranking		3	2	1
Resilience (x)				
Normalised				
u(Total)		0.718	0.879	0.809
Ranking		3	1	2
Calculated				
u(Total)		0.690	0.852	0.792
Ranking		3	1	2
Maintainability (x)				
Normalised				
u(Total)	0.719	0.508	0.502	0.466
Ranking	1	2	3	4
Calculated				
u(Total)	0.788	0.500	0.501	0.480
Ranking	1	3	2	4
Overall				
Normalised				
u(Total)		0.550	0.597	0.525
Ranking		2	1	3
Calculated				
u(Total)		0.576	0.694	0.669
Ranking		3	1	2

It is immediately apparent from Table 6-20 that the utility values and ranks of the WSNs are not completely the same for normalised weights as they are for calculated weights. In terms of complexity the ranks are slightly different in that for the normalised weighting system WSN 3 performs the best with WSN 4 performing the worst. However, when the calculated weights method is used, WSN 4 is apparently the most preferred method of data transmission. Furthermore, the utility values for the normalised weight method show very little difference in terms of the actual values, 0.404, 0.409 and 0.306 for WSNs 2, 3 and 4 respectively. However, when the calculated weights are used, the utility values differ much more drastically with 0.274, 0.409 and 0.477 for WSNs 2, 3 and 4 respectively. This shows that the equal assignment of weights has a large effect on the outcomes of the ranking estimations. Typically, one would expect WSNs 3 and 4 to be able to cope with more complex data transmission than WSN 2 (Mhatre & Rosenberg, 2004) (Fischione, 2014). This would lead one to suggest that the ranking generated from utilising calculated weights is more accurate than normalising the weights.

When the rankings for the resilience attribute are analysed it can be seen that the ranks of each WSN are identical for both normalised and calculated weights. However, what can be seen is greater differences between the utility values. Where, WSNs 2, 3 and 4 for normalised weights show utility values of 0.718, 0.879 and 0.809 respectively. These values are rather similar when compared to the values generated when using calculated weights, where, WSN 2, 3 and 4 show utility values of 0.69, 0.852 and 0.792 respectively. The ranking order of both methods follow the literature in terms of the type of WSN that would be more resilient in terms of battery power and the ability to relay data. It stands to reason that WSN 2 would not have performed well in terms of relaying data, whereas WSN 3 and 4 would have predictably performed much better in their ability to relay data as well have a substantial battery life (Fischione, 2014) (IEC, 2014).

Furthermore, in the analysis of Maintainability, where all four WSNs were able to be analysed, it is WSN 1, in both cases, that demonstrates that it is the best performing WSN in terms of maintainability. This would be logical as it is in theory the least complex of all the WSN designs. Similarly, the utility values for the normalised weight method and the calculated weight method do not differ very much. In both instances WSN 1 ranks first and WSN 4 ranks second, with WSNs 2 and 3 in the middle with very similar utility estimations. The utility estimations for normalised weights read as, 0.719, 0.508, 0.502 and 0.466 for WSNs 1, 2, 3 and 4 respectively. These do not change much when compared to the calculated weights utility intervals of, 0.788, 0.5, 0.501 and 0.48 for WSNs 1, 2 ,3 and 4 respectively. These out comes seem very much driven by the belief structure for the basic attributes as the calculated weights for the basic attributes do differ from the normalised weights. The calculated weights for attributes e_6, e_7 and e_8 are calculated as 53.62%, 20.46% and 25.92% respectively which are much different from the 33.33% for each attribute. Whereas in the belief structure of the basic attributes it is clear that for maintainability WSN 1 has high degrees of belief in the high evaluation grades of *good*, and *excellent.* Whereas, the belief degrees of the basic attributes for WSNs 2, 3 and 4 are generally aimed towards the grade *average*. Nevertheless, the assessment that WSN 1 is the more maintainable of the four WSN is backed up by the literature as it is by far the least complex WSN configuration. It would also make a fine selection for use as an asset integrity monitoring tool, on-board offshore platforms, where it not for the network lacking the ability to relay data and alter the transmission route of its transmitted information and data (Mhatre & Rosenberg, 2004) (Fischione, 2014).

Finally, the overall assessment grades for WSNs 2, 3 and 4 for normalised weights and calculated weights both show that WSN 3 is the most suited overall to be utilised as an asset integrity monitoring tool. As WSN 3 is a multi-hop configuration with the smallest possible sensor node radius and WSN 4 is identical except it incorporates the largest sensor node radius, it would stand to reason that is WSN 3 is preferred then WSN 4 would rank second. This can be seen in the calculated weight assessment where the WSNs are ranked WSN 3 > WSN 4 > WSN 2. However, in the normalised weight assessment, WSNs 2 and 4 are reversed in their ranking. This would suggest that the calculation of the weights for the general attributes and hence the overall assessment is more accurate that normalising the weights. Furthermore, it is clear that in some cases in the basic attribute analysis that a number of the results are driven by the basic attribute belief degrees much more than others.

Based upon the analysis presented in this research and the results generated, it is evident that should a WSN be applied to monitor the asset integrity of an offshore electrical power generation system, then a multi-hop configuration with a small sensor node radius would be the preferred option.

6.5 Sensitivity Analysis

Sensitivity Analysis (SA) is essentially a measure of how responsive or sensitive the output of the model is when subject to variations from its inputs. Having the understanding of how a model responds to changes in its parameters is important when trying to maximise its potential and ensuring correct use of the ER algorithm. In the context of this research, SA will be used as a demonstration to determine how deterministic the relative weights of the general attributes are in the calculation of the overall belief degrees. Knowing the most influential attributes can assist in the experimentation and further expansion of the evaluation hierarchy. Similarly, attributes which have very little influence can be altered or discarded (Matellini, 2012) (Loughney, *et al.*, 2016).

The SA conducted for the ER algorithm calculation focuses on WSN 3 (multi-hop with a small radius, *R*), specifically, the general attributes, Complexity, Resilience and Maintainability. The analysis will be conducted using small increases and decreases in the calculated weights of the attributes as opposed to just demonstrating the difference between normalised weights and calculated weights.

The method used to undertake the SA is to manually insert evidence into the weights of the attributes, one by one, and subsequently analyse the effect on the overall belief degree of WSN 3. This method involves individually increasing one attributes weight by 5% and 10% and decreeing the weight by -5% and -10%. However, this results in the final sum of the weights not being equal to 1.0 or 100%. Therefore, the remaining attribute weights are altered by the same amount as the focus attribute. In other words, if the node Complexity (x) is increased by 10%, the attributes Resilience and Maintainability are decreased by that 10% difference. i.e. when attribute *x* is increased by 10%, attributes *Y* and *z* are each decreased by 5% of *x*. This allows for the sum of the weights to remain equal to 1. Table 6-21, Table 6-22 and

Table *6-23* show the increase and decrease of the weights when a specific attribute is the focus of the SA

Table 6-21: Calculated Sensitivity Analysis weights when the general attribute Complexity is the focus

Complexity (x)			Resilience (y)		Maintainability (z)		SUM
10%	2.13%	23.47%	-5% of X	48.79%	-5% of X	27.73%	100.00%
5%	1.07%	22.41%	-2.5% of X	49.33%	-2.5% of X	28.27%	100.00%
0%		21.34%	0%	49.86%	0%	28.80%	100.00%
-5%	1.07%	20.27%	2.5% of X	50.39%	2.5% of X	29.33%	100.00%
-10%	2.13%	19.21%	5% of X	50.93%	5% of X	29.87%	100.00%

Table 6-22: Calculated Sensitivity Analysis weights when the general attribute Resilience is the focus

Resilience (y)			Complexity (x)		Maintainability (z)		SUM
10%	4.99%	54.85%	-5% of Y	18.85%	-5% of Y	26.31%	100.00%
5%	2.49%	52.35%	-2.5% of Y	20.09%	-2.5% of Y	27.55%	100.00%
0%		49.86%	0%	21.34%	0%	28.80%	100.00%
-5%	2.49%	47.37%	2.5% of Y	22.59%	2.5% of Y	30.05%	100.00%
-10%	4.99%	44.87%	5% of Y	23.83%	5% of Y	31.29%	100.00%

Table 6-23: Calculated Sensitivity Analysis weights when the general attribute Maintainability is the focus

Maintainability (z)			Complexity (x)		Resilience (y)		SUM
10%	2.88%	31.68%	-5% of Z	19.90%	-5% of Z	48.42%	100.00%
5%	1.44%	30.24%	-2.5% of Z	20.62%	-2.5% of Z	49.14%	100.00%
0%		28.80%	0%	21.34%	0%	49.86%	100.00%

-5%	1.44%	27.36%	2.5% of Z	22.06%	2.5% of Z	50.58%	100.00%
-10%	2.88%	25.92%	5% of Z	22.78%	5% of Z	51.30%	100.00%

The sensitivity analysis weights calculated in Table 6-21, Table 6-22 and

Table *6-23* are applied to the ER algorithm to demonstrate the effects of small changes on the overall belief degrees. Each belief degree is analysed against the effect each general attribute. Figure 6-14, Figure 6-15, Figure 6-16, Figure 6-17 and Figure 6-18 demonstrate the sensitivity results for each individual evaluation grade belief (*poor, indifferent, average, good* and *excellent*).

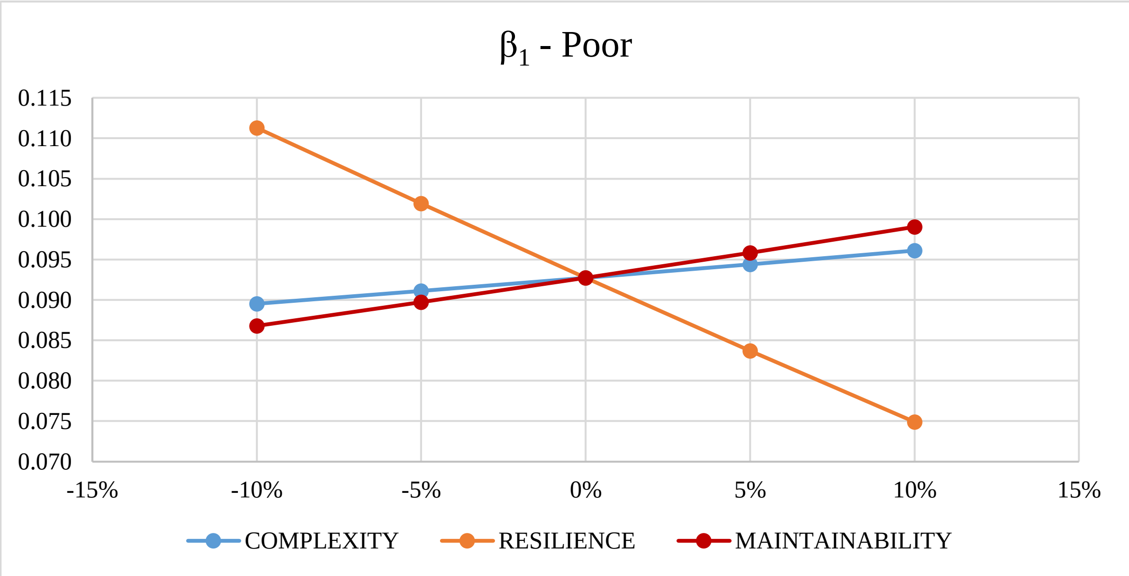


Figure 6-14: Sensitivity functions for the general attributes and their effect on the belief of the grade 'poor'

It can be seen from Figure 6-14 that the belief that the performance of WSN 3 is *poor* is affected much more by the weight of the attribute resilience than the other attributes. This is most likely due to the fact that the original weight of the resilience attribute is much larger than that of the other two attributes, hence would have a larger effect on the final belief degree. Furthermore, when the weight of the resilience attribute is decreased, the belief that WSN 3 is *poor* increases. This would concur with the beliefs aggregated from the basic attributes, where the overall resilience belief degree for WSN 3 was more

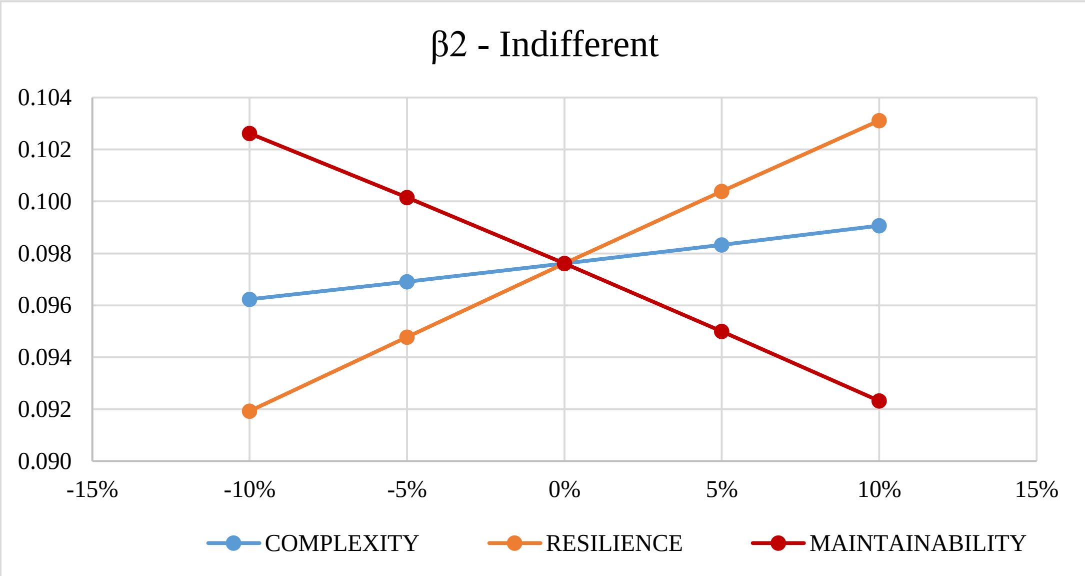


Figure 6-15: Sensitivity functions for the general attributes and their effect on the belief of the grade 'indifferent'

inclined to *good* and *excellent.* Hence if the influence of the resilience attribute decreases then the belief that WSN 3 is *poor* increases.

Figure 6-15 show the sensitivity of the belief degree of the grade *indifferent* given the SA weights of the general attributes for WSN 3. It can be seen that the grade *indifferent* is more sensitive to the weights of Resilience and Maintainability. The attribute Complexity has very negligible effect on the outcome of the grade *indifferent* as the belief aggregated from the basic attributes shows that the belief for Complexity tends more to average. Similarly, Resilience has a large effect again as it has the much larger weight than the other general attributes. Furthermore, as the weight of Maintainability decreases the belief degree increases. This is due to the aggregated belief degree generated from the basic attributes for WSN 3 for maintainability is 0. Hence, reducing the weight will increase the belief degree.

Figure 6-16 shows the sensitivity function for the for the belief degree of the grade *average*. It can be seen again that the weight of Resilience has the greatest effect on the belief degree. This can again be attributed to the fact that resilience has the largest weight and the largest effect. Similarly, the aggregated belief degree for resilience being average

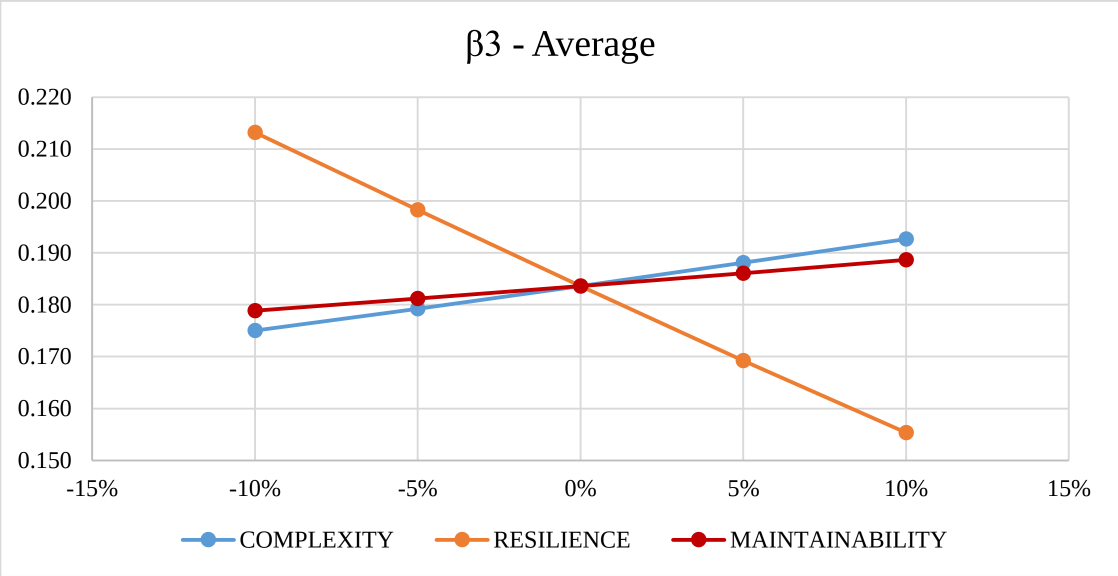


Figure 6-16**:** Sensitivity functions for the general attributes and their effect on the belief of the grade 'average'

is very small, hence as the weight decreases the belief degree increases. On the other hand, the belief degree does not vary much with the weights of complexity and maintainability. This stems from the fact that their weights are much lower than that of resilience and that they are similar. Furthermore, the aggregated belief degrees for the grade *average* are also substantial at 0.49 and 0.3 for complexity and maintainability respectively. Therefore, there is minor change in the belief degree. Complexity just has slightly more effect on the belief degree as its aggregated belief is larger than that of maintainability, but the original weight of complexity is slightly smaller than that of maintainability, 0.21 when compared to 0.28

Figure 6-17 shows the sensitivity functions for the overall belief degree of the grade *good*. It can be seen that the general attribute, maintainability, has the greatest effect on the outcome of the belief degree. This is due to the fact that the aggregated belief degree from the basic attributes is much greater, at 0.43, than that of 0.045, for complexity, and 0.12, for resilience.

Figure 6-17: Sensitivity functions for the general attributes and their effect on the belief of the grade 'good'

Finally, Figure 6-18 shows the sensitivity functions of the belief degree for the grade *excellent*. The graph demonstrates that the attribute resilience has great effect on the belief degree. This is for two key reasons; firstly, the weight of the attribute is the greatest and secondly the aggregated belief of the basic attributes shows that that resilience heavily tends to the grade *excellent*, with the belief at 0.7. This is a substantial value when

Figure 6-18: Sensitivity functions for the general attributes and their effect on the belief of the grade 'excellent'

compared to the aggregated beliefs of complexity and maintainability for the grade excellent which are 0.09 and 0.02 respectively.

6.6 Validation

In order for partial validation of the method of applying the ER algorithm to the decision-making process, it must first satisfy the four axioms stated in the decision-making methodology in Section 3.7. Examination of the analysis and results shows that when the weights are altered either drastically or by a small margin, then the belief degrees are also altered by similar margins. Similarly, the overall belief degrees and the general attribute beliefs are also very much reliant on the magnitude of the belief degrees of the basic attributes. Each axiom shall be identified and cross examined individually.

- *The independence axiom*: where a general attribute must not be assessed to an evaluation grade, H_n, if none of the basic attributes in E are assessed to H_n.. This axiom can be said to be satisfied because when the aggregation of the general attribute maintainability is analysed, for WSN 2, it can be seen that none of the basic attributes are assessed to the grade *poor*, i.e. $\beta_{n,i} = 0$ for $i = 1, \ldots, L$. because of this, the belief degree of the evaluation grade, *indifferent*, for the general attribute, maintainability, should also be equal to 0, i.e. $\beta_{n,} = 0$, and it is. Hence, in this instance the independence axiom is satisfied. Furthermore, when Table 6-2, showing the belief degrees for the basic attributes, is examined and compared with the aggregated belief degree of the general attributes (Table 6-3and Table 6-14) it can be seen that when all basic attributes have a belief degree of zero, for a given evaluation grade, then the general attribute belief is also zero.
- *The consensus axiom*: where the general attributes should be precisely assessed to a grade H_n, if all of the basic attributes in E are assessed to H_n. This axiom can

be said to be satisfied by the example of the aggregation of the basic attributes of maintainability for WSN 2. The initial belief degrees for the evaluation grades, *indifferent* and *average,* of the basic attributes e_1, e_2 and e_3 are *Indifferent(0.4, 0.2, 0.4)* and *average(0.2, 0.4, 0.4,)* respectively. For the three basic attributes, there are similar values of belief degree. When the general attribute weights are equal, the axiom is satisfied, in this case, by the aggregated belief degree of the basic attributes for the grades *indifferent* and *average*, which are 0.342 for both. This demonstrates that when $\beta k_{, i} = 1$ and $\beta_{n, i} = 0$ for $i = 1, ...,L$ and $n = 1, ..., N, n \neq k$, then $\beta_{k,} = 1$ and $\beta_{n,} = 0$ $(n = 1, ..., N, n \neq k)$. This trend can be seen across all of the data aggregation for all of the attributes. Hence, the ER analysis satisfies the consensus axiom.

- *The completeness axiom*: where all basic attributes in *E* are completely assessed to a subset of evaluation grades, hence the general attributes should be completely assessed to the same subset of grades. This is true throughout the entire analysis whereby all attributes are assessed to the same set of evaluation grades of: *poor*, *indifferent, average, good* and *excellent*. Therefore, this axiom can be said to be satisfied.
- *The incompleteness axiom*: where if an assessment for any basic attribute in E is incomplete, then the assessment for the general attribute should be incomplete to a certain degree. This is consistent throughout the analysis as there aren't any incomplete belief degrees, all belief degrees sum to equal one for each attribute. This can be seen throughout the entire analysis. The initial belief degrees for the basic attributes sum to one for each attribute. Subsequently, the aggregated belief degrees for the general attributes also sum to equal one, and finally, the overall

assessment beliefs for each WSN also sum to equal one. Therefore, there are no incomplete assessments and the axiom can be said to be satisfied.

Having satisfied the four outlined axioms for the ER algorithm, it can be said that the methodology and process are reasonably validated.

6.7 Discussion

While the analysis presented in this research proved to be conclusive, there is still room for improvement. The initial designs of the wireless sensor networks are only concerned with hardware and transmission configurations and not any software at all. Immediately this is an area for improvement. The software plays a key role in the operation and resilience of a WSN, in terms of the data that can be detected and transmitted and the issue of cyber-protection. Further study is need in the area of software design and selection, in relation to the designs and assessment outlined in this research.

Similarly, in terms of the decision-making algorithm, there are a number of areas that would benefit from further work and improvement. Initially the assessment contains eight basic attributes and three general attributes, which can be extended given the application of software analysis. This would inevitably make the analysis and results much more coherent, by covering the comparison of a number of WSN designs based upon the application of software. It is also possible to apply a larger selection of evaluation grades. In this work five evaluation grades were used to reduce complexity in the decision-making algorithm, but more grades can be utilised. For example, Ren, J. *et al.* (2014) apply the use of three different evaluation grading systems for three risk assessment areas. Each evaluation grading system contains seven evaluation grades. This provides a much more accurate generation of the basic attribute belief degrees. However, utilising an increased number of evaluation grades requires further aggregation through the use of fuzzy reasoning.

Similarly, it is possible to improve the analysis at the point of utility estimation through the use of the probability method. This involves calculating the utilities of the evaluation grades as opposed to estimating them, as was done in this research (Yang & Xu, 2002). The probability method is initially the same as estimating the utilities for the extreme evaluation grades, i.e. *Poor = 0* and *Excellent = 1*. However, the remaining grades are no estimated they are determined by experts who are given a choice of two upper and lower bound situations. As outlined by Yang J. (2001), the expert is given two "tickets" or situations, in Yang's work the two tickets are probability of a chance to win a car with top performance, *p*, and probability of a chance to win a car with the worst performance, *1-p*. The decision-maker is asked to identify a probability value, *p*, at which the two tickets are equivalent. The decision-maker determines what value the probability holds at for a given evaluation grade, at which point an upper and lower bound utility is produced for the evaluation grade. This is repeated similarly for the other evaluation grades. This method provides a more accurate way of determining ranks as it provides an upper and lower bound utility value.

Finally, a further path to expand upon the decision-making within this research is to apply extended ER algorithms to the outline situation. One unique ER rule in particular has been developed by Yang & Xu (2013). Their research establishes a unique ER rule to combine multiple pieces of independent evidence conjunctively with weights and reliabilities. They propose the novel concept of Weighted Belief Distribution (WBD) extended to WBD with Reliability (WBDR) to characterise evidence in complement of Belief Distribution (BD) introduced in the D–S theory of evidence. Hence, the new ER rule constitutes a generic conjunctive probabilistic reasoning process, which is applicable to combine multiple pieces of independent evidence with different weights and reliabilities in a wide range of areas such as multiple criteria decision analysis. Application of this ER rule could improve the analysis as it can determine if there is conflict between subjective information sources, and hence one may be reliable. in the event that two pieces of evidence conflict, the weighted average rule is applied to the belief degrees and in theory increases the reliability of the belief degrees (Yang & Xu, 2013).

6.8 Conclusion

Real world decision problems and assessments are often complex and involve multiple attributes with high uncertainty. Hence, it is essential to conduct a coherent, rational, reliable, and transparent decision analysis. This research investigated the possible configurations and designs of Wireless Sensor Networks that could feasibly operate within an offshore electrical power generator for the purpose of asset integrity monitoring. While initially, attempts were made to distinguish the most suitable WSN based upon their required battery energy, it was found that this, while informative, was not a feasible method of determining the best suited WSN. Therefore, a set of qualitative criteria and attributes was outlined to assist with the decision. Similarly, the Evidential Reasoning approach was investigated and utilised for the purpose of determining the most suitable WSN design by aggregating the multiple attributes.

The ER approach establishes a nonlinear relationship between an aggregated assessment for general attributes and an original assessment of basic attributes. The numerical analysis of the research dealt with the design selection problem outlined previously with key information and data taken from literature and expert judgements. It demonstrated that the ER approach could accurately be used as a viable decision -making tool in the design selection of WSN. Furthermore, the application of estimated weights and calculated weights demonstrates how sensitive the Evidential Reasoning algorithm is to changes initial data entries. From the analysis, it is clear that the ER approach can be applied to a number of Multi Attribute Decision Analysis problems with or without uncertainty.

This research set out to outline a number of WSN configurations for use in the offshore industry and determine the most suitable based upon a set of design criteria. Four WSN configurations were drawn up: i) WSN 1 – Single-hop, ii) WSN 2 – Single-hop with cluster nodes, iii) WSN 3 – Multi-hop with a small sensor radius and iv) WSN 4 – Multi-hop with a large sensor radius. Following this a qualitative evaluation hierarchy was established to further solve the decision-making problem, i.e. which WSN would me most suitable for application within an electrical power generation module. The ER approach and algorithm was applied to each of the WSNs based upon the outlined attribute hierarchy. The subsequent analysis determined that a multi-hop configuration with a small sensor radius would be the ideal solution to asset integrity monitoring of an offshore electrical generator.

CHAPTER 7:

DISCUSSION & FURTHER RESEARCH

Summary

This chapter discusses the research and analysis provided in this thesis, with particular emphasis on the applicability of the work and its application to offshore oil and gas platforms. The ability of the dynamic risk assessment methodology and BN techniques to adapt to various areas of an offshore platform has been demonstrated through the case studies presented in Chapters 4 and 5. Similarly, the initial development of the topology of a WSN and flexibility of the decision-making methodology has been analysed in detail in Chapter 6. Additional research limitations are addressed as well as proposals for further research.

7.1 Development and Applicability of the Research

This thesis develops two risk assessment models in the form of BNs (Chapters 4 and 5) and a suitable WSN for asset integrity monitoring (Chapter 6), all applied to the electrical power generator of a fixed offshore platform in the North Sea. These BN models and WSN facilitate the key requirements for the development of an NUI-Asset Integrity Case. The rationale for this research originates from the growing need for a dynamic risk assessment framework to operate in conjunction with safety cases to assist with the correct enforcement of offshore safety case regulations. While certain offshore incident data suggests that the numbers of incidents has gradually decreased since the introduction of safety case regulations in 1992, and subsequent amendments, there still remains an issue of potential under-reporting and fluctuation of incidents within the offshore industry (see Chapter 2 and Appendix D).

The BNs lie at the core of the research as they form the basis for the dynamic risk assessment required for the Asset Integrity Case to be a success. These BNs have been constructed in order to assess two key factors:

1. Initially, a BN has been developed, in Chapter 4, and used to model the cause and effect relationship of a specific component failure within a module of an offshore platform. It has been stated that offshore systems can be very complex and when coupled with the volume of data required to model failures within these systems, it makes BNs a challenge to model effectively. As well as in some cases a lack of reliable data means that some risk assessment models cannot always be applied. With this in mind, the Initial BN model, which deals with a single component failure within module 2 of the Thistle Alpha Platform, demonstrates that BNs can provide an effective and applicable method of determining the likelihood of various events under uncertainty. The model can be used to investigate various scenarios around the systems and components outlined and to show the beginnings of establishing where attention should be focused within the objective of preventing offshore incidents, as well as having a clear representation of specifically where these accidents can originate from.
2. A BN model was developed, in Chapter 5, which demonstrated the cause and effect relationships that several initial failures can have on an offshore electrical generation system. In particular, the potential for a fuel gas release from the gas turbine which drives the electrical generation system. The research presented in Chapter 5 here expanded upon the work presented in Chapter 4, which illustrates the cause effect relationship of one component failure within an electrical generator and the general consequences that can result. The BN model presented Chapter 5 expands on this by incorporating part of the model in Chapter 4 along with several initial failures to

analyse a specific consequence in further detail. This consequence concerns itself with a possible fuel gas release and the potential fire and explosion hazards that can occur. However, while it is easier to demonstrate the effects of accidents involving fire and explosion, it is not easy to demonstrate the consequences of a leak without an ignition source. These consequences are equally important for offshore platform operators due to the improved HSE regulations within Safety Cases regarding hazards to the environment in any instance. Therefore, in the event that there is a fuel gas leak without ignition, it poses a large issue for operators and duty holders given that the release is undetected. While it is not as severe as a hydrocarbon release into the sea, it is still vital as it is the ejection of natural gas into the atmosphere which can have severe consequences depending on the weather conditions.

The purpose of both BN models, more so the model in Chapter 4, was to demonstrate that the BN modelling theory and techniques could be applied to dynamic risk assessment for asset integrity monitoring of offshore equipment. However, there can often be gaps between research and practice. Many useful research theories and ideas can go unused and wasted. In this thesis a number of case studies and test cases are used to demonstrate the real world applicability of the dynamic BN risk assessment models, particularly in Chapter 5. This is key as it is an attempt to bridge the gap between the research and practical issues in the offshore industry. This is achieved and demonstrated in Chapter 4 by showing how severe the consequences can be when a single component, in a rotor retaining ring, suffers a failure. Furthermore, the model in Chapter 5 expands on this by demonstrating several component failures and the severity of the consequences. The consequences in Chapter 5 are outlined in two ways. Firstly, the potential environmental implications of an undetected fuel gas leak, and secondly, the level of consequences if an undetected gas leak is ignited. These consequences take the form fire and explosion, as well as damage to the equipment in the immediate vicinity and potential damage to equipment in adjacent offshore modules. The models presented in Chapters 4 and 5 focus on the risk assessment aspect of the asset integrity case utilising data from previously known incidents, however, this is not the case in the real world. Incidents and accidents are extremely difficult to predict, hence the development and analysis of a number of remote sensing methods was conducted in Chapter 6.

Chapter 6 set out to address the issue that real world decision problems and assessments are often complex and involve multiple attributes with high uncertainty. Hence, it is essential to conduct a coherent, rational, reliable, and transparent decision analysis. This research investigated the possible configurations and designs of Wireless Sensor Networks that could feasibly operate within an offshore electrical power generator for the purpose of asset integrity monitoring. A set of qualitative criteria and attributes was outlined to assist with the decision. Similarly, the Evidential Reasoning approach was investigated and utilised for the purpose of determining the most suitable WSN design by aggregating the multiple attributes. Chapter 6 outlined a number of WSN configurations for use in the offshore industry and determined the most suitable based upon a set of design criteria. Four WSN configurations were drawn up: i) WSN 1 – Single-hop, ii) WSN 2 – Single-hop with cluster nodes, iii) WSN 3 – Multi-hop with a small sensor radius and iv) WSN 4 – Multi-hop with a large sensor radius. The subsequent analysis determined that a multi-hop configuration with a small sensor radius would be the ideal solution to asset integrity monitoring of an offshore electrical generator.

The issue of remote sensing is key within the development of the Asset Integrity Case as it relies on the continuous supply and updating of data to the dynamic risk assessment models. Having a strategic and fully operational WSN continually monitoring asset integrity of offshore equipment, particularly equipment in remote and hazardous locations, can significantly aid with the reduction of severe offshore incidents and accidents. The application of this has the potential to reverse the industry perspective of combating incidents from reactive to predictive.

7.2 Research Limitations

The overall limitations of the research have been outlined in Chapter 1, with more specific limitations stated in each analytical chapter (chapters 4, 5 and 6). However, having completed the research, some further key points can be added. The points are as follows:

- When considering the BNs, the majority of the nodes have incorporated a binary method, i.e. the states of most nodes are either “Yes” or “No”. This limits the BN models in terms of time-based factors. Similarly, this limits the verification and validation of the models to be partially complete. For a full, comprehensive validation, the models would have to be tested on board an offshore platform in real time.
- Furthermore, when considering the limited number of states of some nodes in the BNs, it reduces the complexity of the CPTs within the nodes. This is to combat the limitations regarding the scarcity of available data. Applying the models in the real world situations would allow for more complex and intricate CPTs to be used to increase the accuracy of the BN models and analysis.
- When considering the WSNs in Chapter 6, only the hardware and topology was considered for analysis. This was to reduce complexity in the development of the WSNs and approaching the software based areas of WSNs would drastically increase the complexity and time frame of the research.
- Similarly, the WSNs incorporated a finite number of sensor nodes within the electrical generator. This is again to reduce the complexity of the analysis.

However, it was also to only outline the components and parameters for asset integrity monitoring. It would be much more ideal to consider a much larger number of more specific components to apply the WSN to.

When considering the scope and application of the research for the development of the Asset Integrity Case, a key weakness is the age of the data that is used when compared to the aged of the data required. What this means is the Asset Integrity Case would function in real time with continuously updated data sets. However, in this research only historical data can be utilised. This again reiterates the point of practically applying the Asset Integrity Case framework, BN models and WSNs to an actual offshore safety critical element and/or system. Similarly, some aspects of the analysis require the opinions of some experts. This data would undoubtedly need re-assessing as new experts would replace the old ones. This in turn affects the level of experience and well as a difference of intellect and opinion.

7.3 Further Research

As mentions in the previous section there are areas of limitations within the research, these areas are a good focus for developing the research further. Some further research sections have been demonstrated in Chapters 4, 5 and 6. Considering the BN in Chapter 4, a suggestion of developing the research to fuel gas fire was applied in Chapter 5. However, further development was discussed in terms of other potential generator failures. It was suggested that possible modification to the model could be addition of instances that induce mechanical failures. In a similar way that a retaining ring within an alternator can cause damage and failures of an electrical generator, the turbine running overspeed can has a similar effect. A turbine running overspeed has many of its own causes, such as loss of load and control system failure, and are not shown here as these are hypotheses that can be expanded on. Overspeed Excursion would potentially have an effect on the mechanical equipment related to the rotor on the generator. Nodes indicating “Turbine Running Overspeed” as a failure and “Overspeed Detection” could be incorporated into the model. These nodes would potentially have an effect on the retaining ring, the generator bearings, the turbine blades and the exciter, by increasing the stresses on these components that have small mechanical tolerances. From the “Overspeed Excursion” it is possible that “Overspeed Detection” could occur and potentially shut down the turbine and eliminate the possibility of event escalation.

Similarly, the research concerning the development of WSNs can be improved by applying the development of the WSN software for data aggregation. The initial designs of the wireless sensor networks are only concerned with hardware and transmission configurations and not any software at all. This has been previously stated in Chapters 1 and 6. Immediately this is an area for improvement. The software plays a key role in the operation and resilience of a WSN, in terms of the data that can be detected and transmitted and the issue of cyber-protection. Further study is needed in the area of software design and selection, in relation to the designs and assessment outlined in this research. This would solidify WSNs as a vital tool in the Asset Integrity Case. Similarly, the development of the software for a given WSN would allow the framework outlined in Chapter 3 to be fully applied to a real time asset integrity analysis of an offshore system.

There are a number of areas in which the research can be further expanded and improved. Some of these points are outlined as follows:

- Work can be done to develop the Asset Integrity Case framework and methodology across multiple areas and safety critical elements of an offshore installations.

- Expansion of the BN in Chapter 4 has already be discussed in terms of the turbine running overspeed or the fuel gas release within chapter 5. However, it is also possible to expand the model in terms of other aspects, such as: an electrical overload from the switchboard or the possibility of unburnt fuel gas in the Exhaust system.
- The states within the BNs in Chapters 4 and 5 can be expanded from the simple binary, "Yes" and "No", system. This is briefly demonstrated by some nodes in the BNs, such as: the size of a HC leak in Chapter 4 or the level of consequences in Chapter 5. Further expansion can be considered in terms of continuous nodes for time related failures and releases. Similarly, the type of failure can be taken into account in individual nodes, such as: in the "Rotor Retaining Ring Failure" node in Chapter 4, the states could be specific in terms of the level of failure. i.e. "Fatigue/Stress Cracking" and "Fragmentation". This would provide a basis for expansion into more specific consequences and allow the BN model to be more accurate.
- Further work can also be conducted in terms of the quality of data used. Continually, sourcing the most recent data sets would improve the accuracy of the model. Similarly, utilising a greater number of experts when gathering primary data through questionnaires and surveys. Similarly, the application of AHP and the symmetric method to construct CPTs in the absence of data are not the only methods that can be applied. A possible technique to consider would be the use of Noisy-OR which is applied by Matellini, (2012) to construct CPTs where data is unavailable. A disadvantage of Noisy-OR is that it assumes that the causes in the BN are independent. Although this assumption simplifies model development and CPTs treatment, it is not consistent with many applications and restricts the

possibility to model interactions among causes. However, Ashrafi *et al.*, (2017) applies the use of Recursive Noisy-OR (RN-OR) which allows combination of dependent Common Performance Conditions (CPCs). RN-OR theory presents a rule relating various CPT values to each other to estimate the probability of an effect, given various causal dependencies (Ashrafi, *et al.*, 2017). This could be a potential avenue to pursue as an alternative for constructing CPTs without available data.

- Additional case studies can be undertaken with the results analysed first hand by experts in the industry. This would determine whether the developed integrity case would be ready for real world experimentation.
- Similarly, it is possible to improve the analysis at the point of utility estimation through the use of the probability method. This involves calculating the utilities of the evaluation grades as opposed to estimating them, as was done in this research. This area for further expansion is presented in more detail in Chapter 6.

The presented suggestions are not the only areas in which the research can be further developed. Much more research is required before any dynamic risk assessment and integrity monitoring techniques, such as the Asset Integrity Case, are applied to the offshore industry. However, if the research presented in this thesis can be used to support the claims and ideas for development of dynamic risk assessment for offshore installations, then it can be deemed to be a value to the offshore industry.

7.4 Conclusion

An overview of the BN models in Chapters 4 and 5 are presented as well as the development of a WSN in Chapter 6. The analysis and results of the research contained in Chapters 4, 5 and 6 and its applicability to the offshore industry have been discussed.

More importantly, the applicability of BNs as a viable method for developing dynamic risk assessment models was clearly highlighted. As well as, the flexibility of both BN models as in terms of risk analysis and risk evaluation. Similarly, the development of the WSNs in Chapter 6 was highlighted, emphasising the unity between the data gathering method of remote sensing and detecting of asset integrity and the analysis of said data within a dynamic risk assessment model. Furthermore, the application of the Asset integrity Case framework and methodology was also discussed. Finally, the limitations of the research were featured and some further research ideas aimed at improving the research were also indicated. These further research ideas aim to address the limitations of the research.

CHAPTER 8:

CONCLUSION

Summary

This chapter highlights the main aims and objectives regarding the development of a NUI-Asset Integrity Case. The application of the proposed Asset Integrity Case framework, outlined in Chapter 3, is also analysed and discussed. A key part of the research and Asset Integrity case development is the formulation of a coherent dynamic risk assessment methodology and model. The importance of the model in addressing dynamic asset integrity monitoring are highlighted. Furthermore, the applicability and application of WSNs for integrity monitoring on offshore platforms is also highlighted.

8.1 Conclusions

This research project set out develop and test methodologies development of an NUI-Asset Integrity Case, to work alongside safety case regulations, enabling the offshore industry to move towards a situation where asset integrity can be continually and remotely monitored. The research targeted the fulfilment of stated aims and Objectives Outlined in Chapter 1. The assessment and conclusions of these objectives are outlined below.

i. *Identify a key offshore system that can be utilised as a base study for the Asset Integrity Case.*

   This objective assessed in Chapters 1 and 2. When analysing the occurrence of various offshore incidents, it was apparent that incidents regarding gas turbine driven offshore generators are a consistent issue, as stated by HSE, Health and Safety Executive, (2008). This showed that there were approximately 307 hazardous events over a 13 year period, from 1991 to 2004. However, as the Asset Integrity Case would operate alongside safety case regulations, ensuring the continued enforcement, more information would be provided. It was demonstrated that there was a significant trend in terms of the release of key safety case regulations and offshore incidents. Particular attention was focused on the trends between ship to platform collision incidents in the North Sea and the release of relevant regulations. Trends between gas turbine incidents and regulations were difficult to identify due to the vast levels of under-reporting, as stated in Chapter 2. For example, from 1992 to 2014, 40% of fuel gas and power turbine gas releases were not detected by an automatic sensor, but were detected by human detection. The human detection includes smell, visual and a portable detector. In the instances of human detection, the recording of information is scarce, with 56% of fuel gas release incidents having little to no information regarding the location and cause of the release and in some cases, the extent of the dispersion. Furthermore, the majority of the 56% of releases with incomplete information and data were regarded as "Significant", in terms of their severity level (HSE, 2014). This was a key driver in determining a key offshore area to focus the development of the NUI-Asset Integrity Case. As the Asset Integrity Case was to focus purely on the asset integrity and not on personnel, developing the integrity case around a system that demonstrated under-reporting due to human error was vital. Similarly, by developing the integrity case around gas turbine incidents and failures, it could further be expanded and first developed for an offshore area that would clearly benefit from a system of continuous asset integrity management.

ii. *Develop a substantial research methodology and Asset Integrity Case framework for producing a dynamic risk assessment model utilising risk assessment and decision-making modelling methods.*

This objective was dealt with in Chapter 3. A proposed framework for the development of the NUI-Asset Integrity Case was outlined in order to facilitate accurate development and research outcomes. The core of the framework was developed and analysed in Chapters 4 and 5 through demonstration of BNs as a viable method for generating dynamic risk assessment models. The framework also incorporated the development and decision making analysis of a WSN for remote asset integrity monitoring, as outlined in Chapter 6.

The importance of such a framework is key as it demonstrates a methodology for developing dynamic risk assessment in conjunction with remote monitoring methods, which has not been presented before. The components of the framework link together in such a way that the BN models are continually expanded to improve clarity and accuracy. The linking of the components makes the framework an enhanced risk management framework, with key expansions, additions and modifications for application in the development of the Asset Integrity Case.

The framework incorporates to distinct methodologies in a dynamic risk assessment methodology and a decision-making methodology. The dynamic risk assessment methodology focuses on the development and application of dynamic risk assessment models in the offshore industry. While in this research BNs are utilised as the modelling tool for the dynamic risk assessment, the frameworks flexibility allows for the inclusion of another modelling method. This is possible as the data gathering step within the framework are not completely geared to the development of BNs. Similarly, the decision-making methodology for the development of WSNs can also utilise other decision-making techniques other than Evidential Reasoning which was applied in this research.

The flexibility of the framework and methodologies is a key factor in developing an asset Integrity Case for other systems and safety critical elements of an offshore platform. However, the applicability of the framework depends heavily on the practical value of the dynamic risk assessment and decision-making methodologies. The best and most efficient way of demonstrating the frameworks applicability would be to conduct real-time field tests on an offshore platform for an extended period of time. Nevertheless, having such a framework can develop not only the management and application of the process but also be utilised as a basis for new and improved ideas.

i. *Develop flexible risk assessment and decision-making models for modelling offshore risk under uncertainty. As well as developing a number of viable methods that allows for the detecting and monitoring of asset integrity without a human presence on board an offshore installation.*

This objective was dealt with in Chapters 4, 5 and 6. Following from the literature review and the development of the Asset integrity case framework, it was concluded that the application BNs to the development of the dynamic risk assessment model would be ideal. Following the literature review it was determined that there were several advantages of using BNs over alternate approaches, for example, in BNs diverse data, expert judgement and empirical data can all be combined. This is very useful in situations where there is incomplete data or a complete absence of data, and thus other forms of data and information can be incorporated into the network (Bolstad, 2007). The advantageous nature of BNs over other methods is outlined by Khakzad, *et al.*, (2011), with the exclusive nature of comparing BNs and Fault Tree Analysis (FTA) in safety analysis within the process industry. It was concluded by them that a BN is a superior technique in safety analysis due to its flexible structure, which allows for it to fit a wide variety of accident scenarios. In conjunction to this, BNs provide a clear visual representation of what they are representing and can be a very powerful tool for formulating ideas and expanding the model in itself (Fenton & Neil, 2013). This trait is shared by other risk modelling techniques; however, BNs are particularly adaptable method. BNs also facilitate inference and the ability to update predictions through the insertion of new evidence or observations into its parameters. This makes them a very useful tool when dealing with uncertainty.

Thus, two BN models were developed utilising the methodology outlined in Chapter 3. Both models focused on the cause and effect relationship of gas turbine failures, within an offshore electric power generator. The idea was that later expansion could be applied due to the flexible nature of BNs to accommodate new situations and data. This trait was demonstrated in Chapter 5 where the BN model in Chapter 4 was expanded to focus on a more niche area of the gas turbine and ultimately focus more on the possible fire and explosion consequences. What the culmination of Chapters 4 and 5 demonstrated is that BNs are viable tool for a dynamic risk assessment model within the Asset Integrity Case. Furthermore, these models were validated to ensure a certain degree of accuracy and confidence within the results, thus, developing a flexible method of demonstrating dynamic risk assessment for an offshore system.

Continually, Chapter 6 dealt with the application of the decision making methodology to determine the most suitable method for remote asset integrity monitoring. After the literature review, in Chapter 2, a number of WSNs were outlined based upon the four main types of data transmission for WSNs. Similarly, based on industry standards, the location of 62 wireless sensor nodes were proposed within the electrical generation system. These were strategically located, with a given function, to develop a comprehensive WSN. The chapter set out to outline a number of WSN configurations for use in the offshore industry and determine the most suitable based upon a set of design criteria. Four WSN configurations were drawn up: i) WSN 1 – Single-hop, ii) WSN 2 – Single-hop with cluster nodes, iii) WSN 3 – Multi-hop with a small sensor radius and iv) WSN 4 – Multi-hop with a large sensor radius. Following this a qualitative evaluation hierarchy was established to further solve the decision-making problem, i.e. which WSN would be most suitable for application within an electrical power generation module. The ER approach and algorithm was applied to each of the WSNs based upon the outlined attribute hierarchy. The subsequent analysis determined that a multi-hop configuration with a small sensor radius would be the ideal solution to asset integrity monitoring of an offshore electrical generator.

vi. Provide validation of the risk assessment and decision-making models, through the use of case studies, to demonstrate a reasonable level of confidence in the results.

This objective was dealt with throughout Chapters 4, 5 and 6. In terms of validating the research, a number of axioms were demonstrated. These axioms must be satisfied for both methodologies to show a good level of validity.

In Chapter 4 the partial validation was conducted through the inserting of evidence in the form of the initiating component failing or not failing, the posterior probabilities for the final events decrease or increase depending on the node in question. This analysis also demonstrates that nodes closer to the focus node, in this case node 1, will display a larger influence than those which are further away. This exercise of increasing each of the influencing nodes as well as the changes displayed when increasing or decreasing the probability of the initial event occurring satisfied the three axioms stated, thus giving some validation to the BN Model in Chapter 4.

Similarly, in Chapter 5 three test cases were used to demonstrate the models validity and to demonstrate its effectiveness to provide clear cause and effect relationships between initial failures, mitigating barriers, accidents and consequences. Given the specific scenario of fuel gas release, it is clearly demonstrated in the test cases how severe the consequences can be given that the initial failures occur or the mitigating barriers do not function as intended. Test case 1 was designed to demonstrate that the model functioned in accordance with the stated axioms. Therefore, some partial validation could be stated before conducting Test Cases 2 and 3. Test Case 2 expanded upon Test Case 1 by demonstrating the level of consequences that can occur, through probabilities, given that a specific barrier failed to operate. The effects on the BN showed that the gas detection system is vital in the mitigation of a fuel gas release and the fire and explosion consequences. Finally, Test Case 3 illustrated the effects of inserting evidence in the "Consequence" node and analysing the effects on the prior probabilities. The results achieved from all three test cases provided some validation to the BN model.

In terms of the decision-making analysis in Chapter 6, a separate set of axioms was outlined in the decision-making methodology in Chapter 3.

In order for the decision-making analysis to have any degree of confidence these four axioms must have first been fulfilled. Examination of the analysis and results shows that when the weights are altered either drastically or by a small margin, then the belief degrees are also altered by similar margins. Each Axiom was identified and cross examined individually.

Furthermore, all three Chapters were further validated through a Sensitivity Analysis (SA). SA is a measure of how responsive or sensitive the output of the model is when subject to variations from its inputs. Having the understanding of how models respond to changes in parameters is important when trying to maximise potential and ensuring correct use of the modelling techniques throughout the research project. In the context of this research, SA was used in Chapters 4 and 5 as degree of confidence that the BN model has been built correctly and is working as intended. In Chapter 6, SA is demonstration to determine how deterministic the relative weights of the general attributes are in the calculation of the overall belief degrees

8.2 Concluding Remarks

A summary of the main conclusions from the research developed in this thesis are presented below:

- A proposed framework and methodology for the development of an NUI-Asset Integrity Case which links the development of a dynamic risk assessment model, along decision-making analysis to determine the most suitable remote detection method for asset integrity management.
- Two methodologies are presented in Chapter 3: the first demonstrating the formulation of a coherent BN model, and the second demonstrating a valid method of conducting a decision-making analysis through the ER technique.
- Two BN models are presented in Chapters 4 and 5 demonstrating the cause and effect relationship of failures within an offshore electrical generation system. The first model in Chapter 4 demonstrating the applicability of BNs as a good basis for a dynamic risk assessment modelling tool. The second BN in Chapter 5 expands on the BN in Chapter 4 by applying several component failures to demonstrate undetected fuel gas release consequences of a gas turbine.
- A decision-making algorithm is applied to four WSN designs in order to determine the most suitable for use as a remote detection method for asset integrity monitoring.

The research presented in this thesis has produced a number of contributions to knowledge. Some of these contributions can be said to be more significant than others, but all have the potential to be applied to real world offshore situations, systems and safety critical elements. The idea of the NUI-Asset Integrity Case proposed requires further research and work in order to be at the point of readiness for implementation along with safety cases for offshore platforms. There are increasing, continued changes to offshore safety case regulations and enforcement throughout platforms located across the UKCS, in conjunction with the fluctuation of incidents with the enforcement of regulations. This will result in further opportunities in research, such as the work presented in this thesis, to be considered for application in the offshore industry. In addition, the call for accurate coherent dynamic risk assessment tools, for integrity management, for use in the offshore and maritime industry is ever increasing. The research presented in this thesis may well assist with the facilitation of such risk assessment tools and safety case regulation enforcement by furthering the available techniques within the offshore oil and gas industry.

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APPENDICIES

APPENDIX A: Asset Integrity Case Development for Normally Unattended Offshore Installations: Bayesian Network Modelling

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Asset integrity case development for normally unattended offshore installations: Bayesian network modelling

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ABSTRACT: This research proposes the initial stages of the application of Bayesian Networks in conducting quantitative risk assessment of the integrity of an offshore system. The main focus is the construction of a Bayesian network model that demonstrates the interactions of multiple offshore safety critical elements to analyse asset integrity. A NUI (Normally Unattended Installation) - Integrity Case will enable the user to determine the impact of deficiencies in asset integrity and demonstrate that integrity is being managed to ensure safe operations in situations whereby physical human to machine interaction is not occurring. The Integrity Case can be said to be dynamic as it shall be continually updated for an installation as the Quantitative Risk Analysis (QRA) data is recorded. This allows for the integrity of the various systems and components of an offshore installation to be continually monitored. The Bayesian network allows cause-effect relationships to be modelled through clear graphical representation. The model accommodates for continual updating of failure data.

INTRODUCTION

This research focuses on the development of an Initial Bayesian Network (BN) model for modelling system and component failures on a large offshore installation. The intention of the presented research is to model a sequence of events following a specific component failure, under certain conditions and assumptions. This sequence of events is then applied to a BN model using a proposed methodology. This should provide a base with which to expand the BN model to facilitate the requirement of having a dynamic risk assessment model within an NUI (Normally Unattended Installation) - Integrity Case.

An Asset Integrity Case will enable the user to determine the impact of deficiencies in asset integrity on the potential loss of life and demonstrate that integrity is being managed to ensure safe operations. The Integrity Case is an extended Safety Case. Where safety cases demonstrate that safety procedures are in place, the Integrity Case shall ensure that the safety procedures are properly implemented. The Integrity Case can be applicable to operations for any large scale asset, and in the case of this research the large asset for which the Integrity Case shall be developed is an offshore installation (RMRI Plc., 2011). By expanding on this Integrity Case proposal, it is intended that an Integrity Case be developed for a Normally Unattended Installation (NUI) in conjunction with a dynamic risk assessment model to maintain a live representation of an offshore installations integrity. Furthermore, it is proposed that the NUI-Integrity Case be initially developed utilising a manned installation, but modelling failure and risks without human presence on board. This is due to a much larger range of failure data being available regarding manned installations as opposed to unmanned installations. Similarly, should a risk assessment model be feasible for various hazardous zones of an installation, and the dynamic model proves to be effective in the detection of failures and mapping of consequences, it may be possible to reduce the number of personnel on board manned offshore installations, to reduce the risk of injury and fatality.

The paper is structured as follows. Section 2 presents a brief background into the origins of the research. A proposed methodology of constructing a BN model is shown in section 3. Section 4 outlines and analyses a case study to demonstrate the proposed methodology. Section 5 summarizes the work.

BACKGROUND

Offshore Safety Assessment

Following the public inquiry into the Piper Alpha disaster, the responsibilities for offshore safety regulations were transferred from the Department of Energy to the Health and Safety Commission (HSC) through the Health and Safety Executive (HSE) as the singular regulatory body for safety in the offshore industry (Wang, 2002) (Department of Energy, 1990). In response to this the HSE launched a review of all safety legislation and subsequently implemented changes. The propositions sought to replace the legislations that were seen as prescriptive to a more "goal setting" approach. Several regulations were produced, with the mainstay being the Health and Safety at Work Act (HSE, Health and Safety Executive, 1992). Under this a draft of the offshore installations safety case regulations was produced. The regulations required operational safety cases to be prepared for all offshore installations, both fixed and mobile. Within this all new fixed installations require a design safety case and for mobile installations, the duty holder is the owner (Wang, 2002).

After many years of employing the safety case approach in the UK offshore industry, the regulations were expanded in 1996 to include verification of Safety Critical Elements (SCEs). Also the offshore installations and wells regulations were introduced to deal with various stages of the life cycle of the installation. SCEs are parts of an installation and its plant, including computer programs or any part whose failure could cause or contribute substantially to or whose purpose of which is to prevent or limit the effect of a major accident (Wang, 2002) (HSE, Health and Safety Executive, 1996).

Recently, however, it is felt that an expansion on Safety Cases is necessary, especially in the offshore and marine industry, as they are static documents that are produced at the inception of offshore installations and contains a structured argument demonstrating that the evidence contained therein is sufficient to show that the system is safe (Auld, 2013). However, this is the full extent of the Safety Case, it involves very little updating unless an operational or facility change is made. It can be difficult to navigate through a safety case; they can be difficult for project teams and regulators to understand, as well as often being monolithic (Risktec, 2013). This is where the e-Safety Case comes into play. e-Safety Cases are html web-based electronic Safety Cases. They are much easier to navigate and have clear concise information about the safety of the facility they are provided for. However, the QRA data (Quantified Risk Assessment) is only updated with the release of updated regulations (Cockram & Lockwood, 2003). Over the past 10 years it has been stated that a dynamic risk assessment model is required within the offshore and process industries. Khakzad, *et al*., (2013) proposed to apply BN to Bow-Tie (BT) analysis. They postulated that the addition of BN to BT would help to overcome the static limitations of BT and show that the combination could be a substantial dynamic risk assessment tool. Similarly, in the oil, gas & process industry Yang & Mannan, (2010) proposed a methodology of Dynamic operational Risk Assessment (DORA). This starts from a conceptual framework design to mathematical modelling and to decision making based on cost-benefit analysis. Furthermore, Eleye-Datubo, *et al*. (2006) proposed an offshore decision-support solution, through BN techniques, to demonstrate that it is necessary to model the assessment domain such that the probabilistic measure of each event becomes more reliable in light of new evidence being received. This method is prefered, as opposed to obtaining data incrementally, causing uncertainty from imperfect understanding and incomplete knowledge of the domain being analysed. Finally, RMRI Plc. (2011) proposed the idea of a dynamic decision making tool in an Asset Integrity Case.

The Integrity Case, an idea proposed by RMRI Plc. (Risk Management Research Institute), can be said to be dynamic as it shall be continually updated with the QRA data for an installation as the QRA data is recorded. This allows for the integrity of the various systems and components of a large asset, such as an offshore installation, to be continually monitored. This continual updating of the assets QRA data allows for the users to have a clearer understanding of the current status of an asset. It also allows the user to identify the impact of any deviation from specified performance standards, as well as facilitate more efficient identification of appropriate risk reduction measures, identify key trends within assets (*i.e.* failures, failure modes). Reporting to regulators would improve greatly and it would provide a historical audit trail for the asset. Furthermore, the integrity of an asset is maintained so that potential loss of life is kept ALARP. This means that an asset may continue safe operations under circumstances that may have instigated precautionary shutdown, resulting in considerable cost savings for the owner and operator (RMRI Plc., 2011).

METHODOLOGY

Modelling and Analysis Steps

There are many step-by-step procedures in use that allow for construction of the various parts of the BN model. The procedures are useful as it allows for maintaining consistency throughout the process and offers an element of confidence to the model. The procedures have varying parts depending on the context of the model and how much information is already available (Neil, *et al*., 2000). However, there are key elements which all the procedures follow, these are:

Establish the domain and project definition

This involves putting boundaries in place for the model. In this analysis the domain is to be defined as a module on a large offshore installation. The model begins with an initial component failure and tracks the cause and effect relationship of this failure on various other components and systems. The model ends with outlined consequences. The objective of the model involves stating what results are expected to be achieved from the model. For the model in this research the focus is on the interaction of the components and their probability of occurrence.

Identify the set of variables relative to the problem

This involves filtering possible parameters that are relevant to the description and objective. For the model the initial variables were devised utilising a sequence of events diagram. This sequence of events diagram represents the steps of various events with their order and causality. The events in the diagram are connected with arcs and arrows. This allows for a straightforward transition to a BN.

Form Nodes and Arcs for the BN

The events and consequences in the sequence of events are translated to corresponding parent and child nodes in the Bayesian Network. The sequence of events, however, is basic and the arcs do not directly translate to the BN and are determined in Step 4. The nodes can be expressed as positive or negative. The causality between the events is translated to corresponding Conditional Probability Tables (CPTs). The CPTs are constructed in Step 5. Once the relevant nodes are identified, they are input into a BN software package, HuginResearcher7.7, and connected. This entails referring to the sequence of events from the initial failure to determine the most effective way of connecting the nodes together. The network is reviewed to ensure there are no missing factors.

Data acquisition and analysis

Primarily, data is sought from various sources including: industrial & academic publications, offshore risk assessment projects, as well as databases such as: the Offshore Reliability Database (OREDA), HSE & the International Association of Oil and Gas Producers database (OGP). However, should data not be widley available or the CPT for a node be much to large to constuct utilising data from the outlined sources, then expert judgement is to be utilised. The expert judgement is to be obtained using the Pairwise Comparision (PC) technique and analysed with the Analytical Hierarchy Process (AHP). The data from the AHP analysis is translated to the CPTs using a Symmetric Method. The data from relevent sources is then used to create the marginal or conditional probability tables.

Analysis of BN model and Sensitivity Analysis

This step concerns itself with the analysis of the BN model using Bayesian Inference. The probability of failure on demand of the operation is obtained by forward analysis. The posterior probabilities of the influencing factors can be calculated through backward analysis, given some evidence entered into the model. the propogation of the BN is conducted using Hugin Researcher 7.7. The results of the analysis provide useful information in handling the the effect of one failure on multiple components and systems. These results are demonstrated through a Sensitivity Analysis. The data for this analysis is again produced by the Hugin Researcher 7.7 software.

Validation of the BN Model

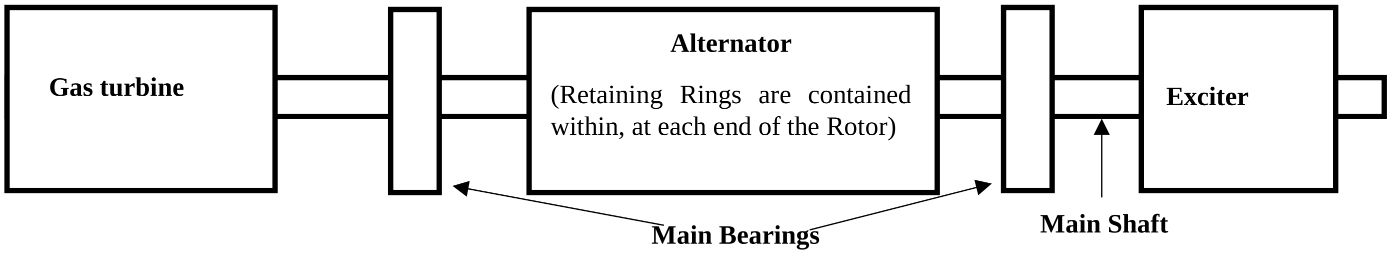

Figure 1. Generic diagram of an electrical generator unit

Validation is a key aspect of the methodology as it provides a reasonable amount of confidence to the results of the model. In carrying out a full validation of the model, the parameters should be closely monitored for a given period of time. For modelling a specific failure within an electrical generator, this exercise is not practical. In current work and literature, there is a three axiom based validation procedure, which is used for partial validation of the proposed BN model. The three axioms to be satisfied are as follows (Jones, *et al*., 2010):

Axiom i:
A small increase or decrease in the prior subjective probabilities of each parent node should certainly result in the effect of a relative increase or decrease of the posterior probabilities of the child node.

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

Axiom iii:
The total influence magnitudes of the combination of the probability variations from “x” attributes (evidence) on the values should always be greater than that from the set of “x-y” (y ϵ x) attributes.

CASE STUDY

Establish domain and model definition

In order to demonstrate the proposed methodology a case study is used to evaluate of the effects a rotor retaining ring failure has on an offshore electrical generation unit. As well as other key systems, within and adjacent to a module of a large offsore installation.

The electrical generation unit is considered to be of a generic layout for electrical generation on a large platform. The generator consists of a primary alternator, driven by a gas turbine. Located after the alternator is the exciter. The alternator rotor and shaft are forged in one piece with the exciter coupled on to one end. The opposite end of the shaft is coupled to the turbine drive shaft, which has an approximate operating speed of 3,600 rpm. The main shaft is supported by two main bearings, housed in pedastals, on stools on the baseplate. One bearing is situated between the turbine and the alternator and the other between the alternator and the exciter. A generic flowdiagram of an electrical generation unit is illustrated by Figure 1.

Identifying the set of variables relative to the problem

The variables are identified based upon the failure of one specific component, in this case a Rotor Retaining Ring. Should one of the retaining rings fail, the main shaft would become unbalanced causing potential fragmentation of the rings inside the alternator. Given the extreme tolerances’ within the generator construction, the unbalanced shaft could also cause damage to other areas of the equipment, such as: the turbine blades and the exciter. Should the retaining ring fail within the alternator casing and fragment, debris would be created within the casing. Furthermore with the machine operating at approximately 3,600rpm, an out of balance shaft would cause substantial vibrations, which could cause the main bearings to fail. Should the bearings fail, causing the shaft to become misaligned, it would result in increased damage to the turbine, alternator and exciter (RMRI Plc., 2009).

From this the most likely point of failure within the turbine is the turbine blades shearing. Multiple blade failure could lead to the turbine casing not fully containing the turbine blade debris. This would result in turbine blades being expelled through the turbine casing as high velocity projectiles. Continually, the violent shaft vibrations and misalignment could have a severe impact on the exciter and may result in the exciter, weighing approximately one tonne, becoming detached from the main shaft. Some catastrophic failures have resulted in the exciter breaking up and some have had the exciter remain mostly intact (RMRI Plc., 2009). Should the bearings not fail, the alternator stator coils & casing, can provide enough resistance and are substantial enough to prevent the debris from the retaining ring penetrating the alternator casing. However, it is possible for the fragments to be expelled axially towards either the turbine or the exciter or both. (U.S. Nuclear Regulatory Commission, 2008).

In the event of one or two rotor retaining ring failures, significant damage could occur within the alternator casing and fragments of the retaining ring could be expelled axially. Should the ring debris be expelled, it is assumed that it will travel in two possible direction; i) towards the turbine or ii) towards the exciter and out of the casing. Should the debris travel to the turbine there is potential for the fragments to impact the fuel gas line within the turbine. This then provides the escalation to a fire (given the location of the potential release, ignition is assumed). Should the debris travel out of the casing towards the exciter, it is considered by RMRI. Plc (2009) that while the axial velocity may be considerable, it is likely to be lower than the radial velocity that the debris would be expelled at were the casing and stator not there. Therefore, while it is possible for the ring debris to penetrate the casing, they would not have the required velocity to penetrate the module walls or deck. From this it is deemed that if retaining ring failure does not cause a bearing failure, then the consequence of the event is likely to be limited to the damages caused by the retaining ring (U.S. Nuclear Regulatory Commission, 2008).

However, should the main bearing fail, the potential consequences become much more severe. The significant damage caused by the bearing failure can potentially produce high velocity projectiles from the turbine blades being expelled and/or the exciter becoming detached (RMRI Plc., 2009). In these events, there is potential for the projectiles to impact the hydrocarbon containment around the module.

Form Nodes and Arcs for the BN

The initial model is demonstrated in Figure 2 and is designed around the variables identified

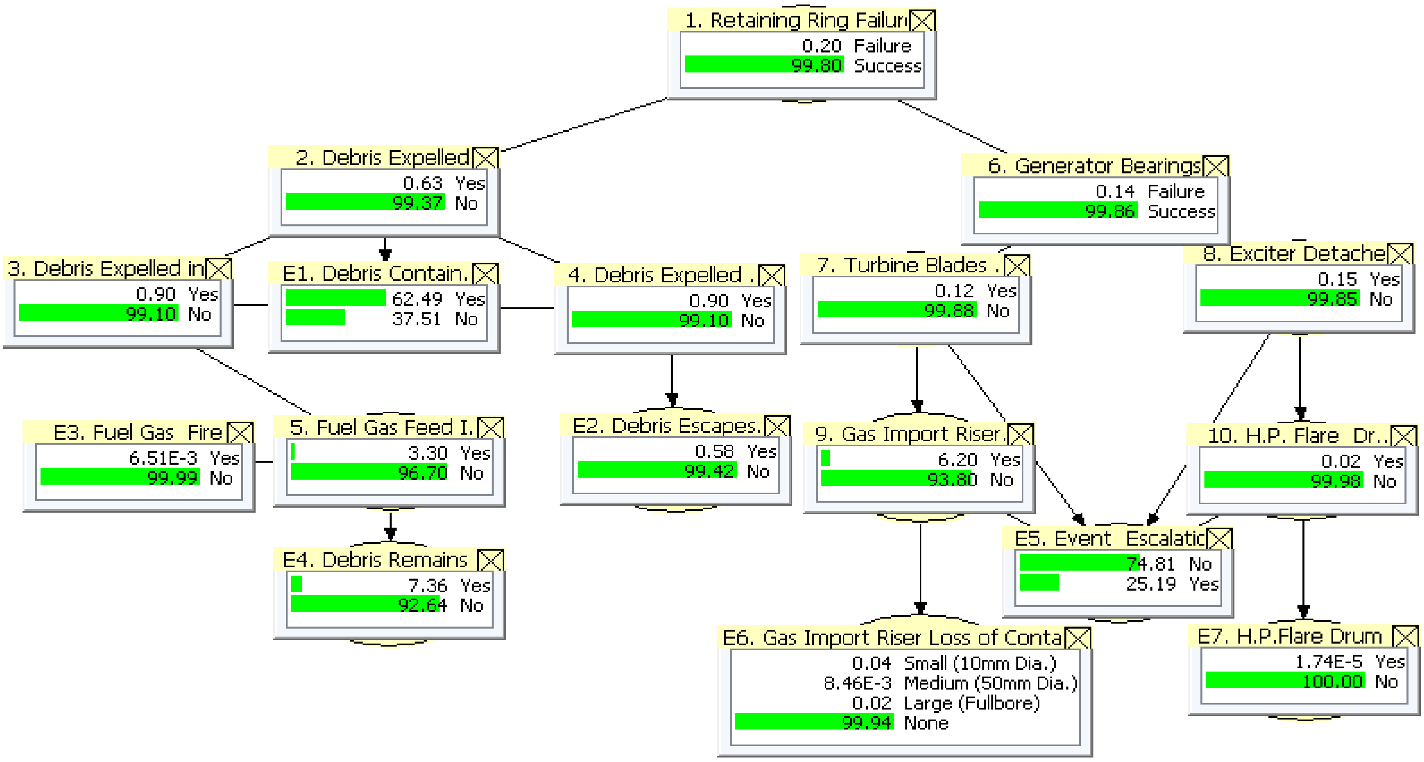

Figure 2. BN Model shown with the Marginal Probabilities for each node.

section 4.2, and is to represent the cause and effect of one initial component failure has on systems within the stated domain. The Initial BN model is not a direct representation of the sequence of events in terms of the section of the model where possible debris is expelled. Within the sequence of events if the debris is not expelled initially, it is assumed to remain in the alternator, yet if debris expelled, it is assumed to travel towards the exciter. Similarly, should the debris not be expelled to the exciter, it is assumed to be expelled towards the turbine. While this is all possible, it is more realistic to assume that if the debris is created from the retaining ring failure, it has the potential travel to the turbine and the exciter in the same instance. However, it is possible for debris to be expelled to the exciter and not to the gas turbine, whereby some debris would remain in the alternator. The way in which the BN model is created ensures it contains all relevant possible outcomes.

In this case the analysis is conducted within an electrical generation module of a large offshore installation. The initial model is made up of seventeen chance nodes labelled 1 to 10 and E1 to E7. The latter nodes represent the possible events that can result from the initial mechanical failure. All nodes have two states ("Yes" and "No") except for event node E6 which has four ("Small", "Medium", "Full-bore" and "None"). The BN constructed from the variables outlined is shown in Figure 2.

Data acquisition and analysis

It is important to note that the numerical results of the model are not significant in terms of being absolute, but rather to serve to demonstrate the practicability of the model. Once a full set of verified data is fed into the model, the confidence level associated with planning and decision making under uncertainty will improve.

To complete the CPTs within a BN, certain data and knowledge is required regarding each specific node. For some nodes data is limited or not available. For cases where there is an absence of hard data, CPTs must be completed through subjective reasoning or the application of expert judgement. This process can be demonstrated by looking at the node "Event Escalation". This node represents the chance of escalation following key component failures. The parents of this node are: "Turbine Blades Expelled", "Exciter Detaches", "Gas Import Riser Piping Impact" and "HP Flare Drum Shell Impact". In order to put together an appropriate estimate, experts must judge the situation and provide their opinions. This data acquisition can be either qualitative or quantitative in nature. However, the child node "Event Escalation" has a CPT which is too large for an expert to simply fill with their own judgements and opinions. Therefore, an effective way to gather information, to fill these large CPTs, from experts is to apply the use of a Pairwise Comparison (PC) technique in questionnaires and make use of the Analytical Hierarchy Process (AHP) to analyse the results, combined with the symmetric method algorithm to fill the large CPTs (Zhang, *et al*., 2014).

The AHP will produce a weighting for each parent criterion in the pairwise comparison matrix. These weighting are applied to a symmetric method which is utilised to fill large CPTs. The symmetric method provides an input algorithm which consists of a set of relative weights that quantify the relative strengths of the influences of the parent-nodes on the child-node, and a set of probability distributions the number of which grows only linearly, as opposed to exponentially, with the number of associated parent-nodes (Lin & Kou, 2015) (Saaty,

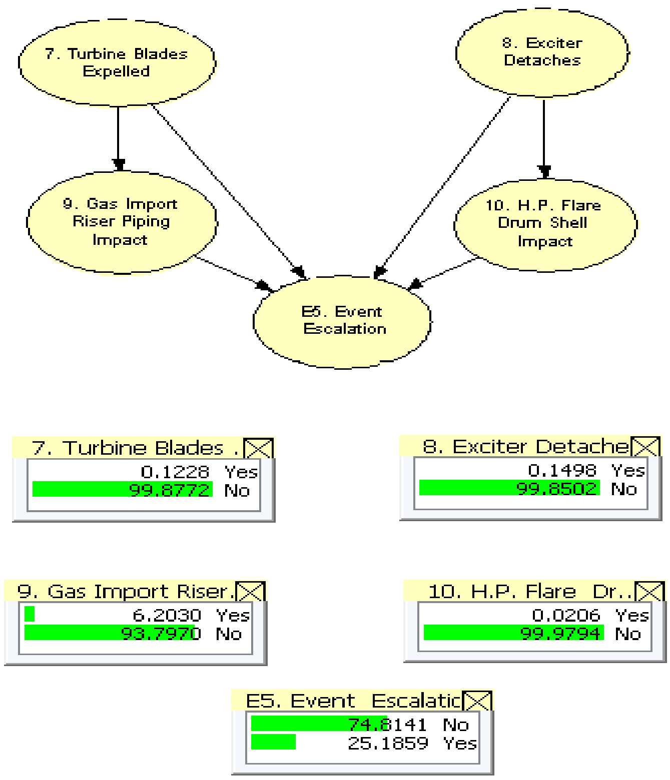

Figure 3. A) Specific section of BN to be analysed. B) Prior Probabilities for Event E5 and its parent nodes.

1980).

The PC, AHP and symmetric methods are not to be oulined here. However, the PC and AHP methods can be found in detail in Saaty, (1980) and Koczkodaj & Szybowski., (2015). The symmetric method can be found in Das, (2008). Figure 2 shows the complete BN and the marginal probability distributions for each node.

Results and Disscussions

Analysis of BN model and Sensitivity Analysis

Quantitaive analysis is carried out on a specific section of the Initial BN model, shown in Figure 3, concerning the event "E5. Event Escalation" and its parents.

Quantitative Analysis

This analysis involved systematically inserting evidence into each of the parent nodes and finally the child node. In addition, nodes 7 and 8 have a parent node "Generator Bearings" which has no evidence inserted, and there is no evidence inserted anywhere else within the model. However, in this section of the BN model nodes 7 and 8 are parents of nodes 9 and 10 respectively, and therefore will alter the posterior probabilities of these nodes when evidence is inserted. This relationship has been left in the analysis to give an accurate representation of the posterior probabilities of the event E5, which is the focus node in this analysis. Several scenarios are considered for the BN analysis and validation.

The first scenario is gas turbine blades being expelled as projectiles from the generator housing. This is completed by inserting 100% to state "Yes" in node 7. This increases the probability of the events escalating from 25.19% to 35.09%. This increase would involve some concern as a potential escalation from this is the impact of the turbine blades on the Gas Import Riser. Subsequently the probability of gas import riser impact increases from 6.2% to 25%.

Furthermore, the second scenario involves the expulsion of the turbine blades along with a gas riser impact (100% "Yes" to nodes 7 and 9). This results in the probability of there being escalation increasing from 35.09% to 61.42%. This is a very large increase as the impact of a gas riser is the largest threat to escalation, due to the loss of containment of the gas, this hypothesis was also confirmed by expert opinion. It can also be noted that evidence is inserted into nodes 7 and 9, there is no effect on nodes 8 and 10, which is to be expected as they should be independent from each other. Should this scenario have the potential to occur, immediate action should be taken to prevent a major accident in the form of LOC of hydrocarbons and potential explosion & fire.

The third scenario demonstrates the potential for escalation by showing that the generator's exciter detaches, along with turbine blades expelled and gas riser impact (100% "Yes" to nodes 7, 8 and 9). It shows that again the potential for escalation increases from 61.42% to 63.86%. This scenario also increases the probability of the HP flare drum being impacted from 1.47% to 10%, dues to the influence of the Exciter Detaching (represented by node 8).

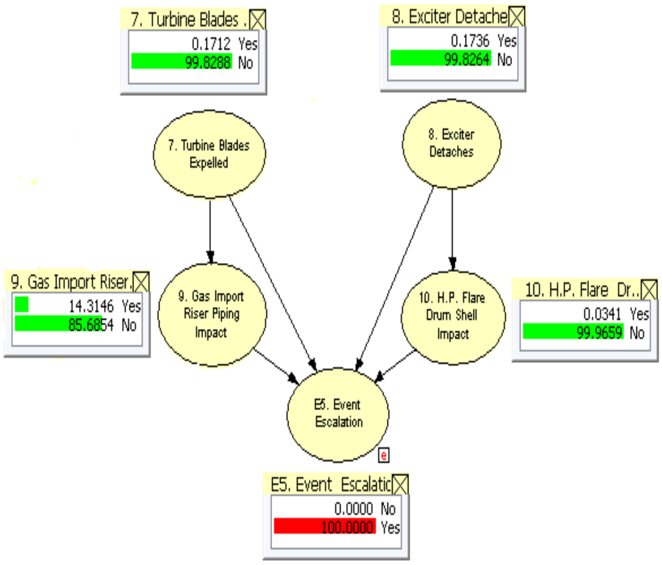

Figure 4. BN Model Illustrating when "Event Escalation" takes place.

Scenario five demonstrates the final influencing factor on the possibility of event escalation, whereby the HP flare drum is impacted (100% "Yes" to nodes 7, 8, 9 and 10). This increases the potential for escalation from 63.86% to 77%.

The final scenario, shown in Figure 4, demonstrates the effect of there being an escalated event, for example, observing an explosion or a fire within the area of the platform containing the electrical generator, and the effect this has on the influencing parameters. This serves to obtain areas that would require closer inspection. This scenario has given insight to the possible causes of the event escalation, based upon the data presented. Here the influencing factors are: "Turbine Blades Expelled" – Yes, increases from 0.12% to 0.17%; "Exciter Detaches" –Yes, increases from 0.15% to 0.17%; "Gas Import Riser Piping Impact" – Yes, Increases from 6.2% to 14.31%; and "HP Flare Drum Shell Impact" – Yes, increasing from 0.02% to 0.03%.

Input node: “state”	Sensitivity value
7. Turbine blades expelled: “No”	-0.095
8. Exciter detaches: “No	-0.029
9. Gas import riser impact: “No”	-0.263
10. HP flare drum shell impact: “No”	-0.073

Sensitivity Analysis

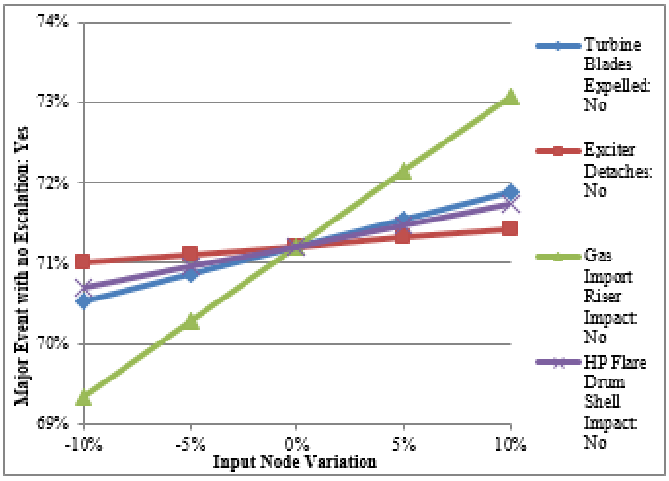

Figure 5. Sensitivity Functions for the four input nodes acting upon Event "E5. Event Escalation"

The Sensitivity Analysis conducted for the Initial BN model focuses on the event E5 and its parent nodes, shown in Figure 3, to further validate the claims in Secton 4.5.1.1. However, the analysis will be conducted using smaller increases and decreases in the probabilities of the parent nodes as opposed to inserting 100% occurrence probability into the input node CPTs.

From the graph in Figure 5 it can be seen that the most influential factor on “Event Escalation” is “Gas import Riser Impact”, whilst the least influential is “Exciter Detaches”. If the probability of State - ‘No’, “Gas Riser Impact” increases by 10%, then the probability of “Event Escalation” decreases by 2.63%. Whereas, if the probability of State - ‘No’ Detaches” increases by, “Exciter 10%, then the probability of “Event Escalation” only decreases by 0.29%. From the graph it is also apparent that the sensitivity function is a straight line which further add to the model validation. The sensitivity values computed within Hugin are shown in Table 1.

It should be noted that the sensitivity values within Table 1 are negative as in their current states of ‘No’, they have a negative effect on the outcome of “Event Escalation” – ‘Yes’. For example; with the probability of “Turbine Blades Expelled” increasingly being ‘No’, it is less likely that “Event Escalation” – ‘Yes’ occurs.

Table 1. Sensitivity Values for the four input nodes acting upon Event "E5. Event Escalation"

Validation of the BN Model

For partial validation of the model, it should satisfy the three axioms stated in Section 3.2.5. Examination of a specific part of the model (shown in Figure 3), reveals when node 7 is set to 100% ‘Yes’, this produces a revised increase in probability for “Event Escalation” occurring from 25.19% to 35.09%. A further change including both nodes 7 and 9, set at 100% ‘Yes’, results in a further increase in the potential for “Event Escalation” occurring. Continually, nodes 7, 8, and 9 being set to 100% ‘Yes’, again results in an increase for the potential for “Event Escalation” being of the state ‘Yes’.

When nodes 7, 8, 9 and 10 are set to 100% ‘Yes’, it produces yet another increase in the probability of “Event Escalation occurring from 63.86% to 77.00%. Finally,

This exercise of increasing each of the influencing nodes satisfies the three axioms states in Section 3.2.5, thus giving partial validation to the BN Model.

CONCLUSIONS

This research has outlined the Bayesian Network technique that has been used to model the cause and effect relationship of a specific component failure of an electrical generation system, within a module of an offshore platform. It has been stated that offshore systems can be very complex and when coupled with the volume of data required to model failures within these systems, it makes BNs a challenge to model effectively. As well as in some cases a lack of reliable data means that some risk assessment models cannot always be applied. With this in mind, the BN model demonstrates that BNs can provide an effective and applicable method of determining the likelihood of various events under uncertainty. The model can be used to investigate various scenarios around the systems and components outlined and to show the beginnings of establishing where attention should be focused within the objective of preventing offshore incidents, as well as having a clear representation of specifically where these accidents can originate from. The presented method of modelling offshore risk assessment is to be improved upon in future research. It has the potential to model larger areas with several systems and their components to gain a much wider understanding of how offshore systems interrelate.

There are several interesting and relevant possibilities that can be considered and explored with relative ease now that the core structure of the BN model has been constructed. However, before expanding the model it is vital to maintain that it must remain practical and close to reality from the perspective of gathering data and generating results. Continually too many variables which display vague information or increasingly irrelevant effects can diminish the quality of results and findings.

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APPENDIX B: Bayesian Network Modelling of an Offshore Electrical Generation for Applications within an Asset Integrity Case for Normally Unattended Offshore Installations (Abstract)

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Bayesian network modelling of an offshore electrical generation system for applications within an asset integrity case for normally unattended offshore installations

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ABSTRACT: This paper proposes the initial stages of the application of Bayesian Networks in conducting quantitative risk assessment of the integrity of an offshore system. The main focus is the construction of a Bayesian Network (BN) model that demonstrates the interactions of multiple offshore safety critical elements to analyse asset integrity. The majority of the data required to complete the BN was gathered from various databases and past risk assessment experiments and projects. However, where data was incomplete or non-existent, expert judgement was applied through Pairwise Comparison, Analytical Hierarchy Process (AHP) and a Symmetric Method to fill these data gaps and to complete larger Conditional Probability Tables (CPTs). A NUI (Normally Unattended Installation) - Integrity Case will enable the user to determine the impact of deficiencies in asset integrity and demonstrate that integrity is being managed to ensure safe operations in situations whereby physical human to machine interaction is not occurring. The Integrity Case can be said to be dynamic as it shall be continually updated for an installation as the Quantitative Risk Analysis (QRA) data is recorded. This allows for the integrity of the various systems and components of an offshore installation to be continually monitored. The Bayesian network allows cause-effect relationships to be modelled through clear graphical representation. The model accommodates for continual updating of failure data.

Keywords: Offshore safety, Integrity case, Bayesian networks, Offshore installations, Electrical generation systems

APPENDIX C: Bayesian Network Modelling for Offshore Installations: Gas Turbine Fuel Gas Release with Potential Fire and Explosion Consequences

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Bayesian network modelling for offshore installations: Gas turbine fuel gas release with potential fire and explosion consequences

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ABSTRACT: This paper illustrates the benefits of applying a Bayesian Network in quantitative risk assessment. The focus of the illustration is based on the potential release of fuel gas from a gas turbine used for electrical power generation on an offshore platform. The potential consequences that follow said release, such as: fire, explosion and damage to equipment within an electrical generation module are also analysed. The construction of a Bayesian Network model, based upon initial research work, shall illustrate the interactions of potential initial failures, hazards, barriers (gas detectors and fuel shut off systems) and the subsequent consequences of a fuel gas release. This model allows for quantitative analysis to show partial validity of the BN. Partial validity of the model is demonstrated in a series of test case.

INTRODUCTION

This work focuses on the development of a Bayesian Network (BN) model for modelling control system and physical failures of a gas turbine utilized in offshore electrical generation. The intention is to model a sequence of events following several component failures, under certain conditions and assumptions. These initial failures are defined in two categories; control system failures and physical or structural failures. This should provide a base with which to expand the BN to facilitate the requirement of having a dynamic risk assessment model that allows for accurate representation of the hazards and consequences associated with gas turbine fuel gas releases.

The research presented within this report is an expansion of previous research conducted for an electrical generation system of an offshore installation. The initial research, conducted by Loughney & Wang (2016), focused on creating a dynamic risk assessment model for an electrical generation system, based upon one initial component failure in the form of a Rotor Retaining ring failure. The dynamic risk assessment model is for application in an Integrity Case. The Integrity Case is, in principle, an extended Safety Case. From the initial research a sequence of events and a BN was produced to demonstrate the cause and effect relationships between the safety critical elements of the electrical generator. The BN demonstrated a number of potential consequences, such as: Gas Import Riser failure, High Pressure Gas Flare Drum failure and Fuel Gas Release & fire. These final consequences were not expanded or demonstrated in great detail to keep the initial model as less complex as possible while achieving valid results. This is where the research presented in this paper expands upon this. The BN to be presented here is an expansion of the previous model, focused on the consequence Fuel Gas release and Fire & Explosion. In the initial BN, a gas fire was represented as one event in the network, this research expands by constructing an entire new network to demonstrate the consequence of Fuel Gas release in much more detail (RMRI Plc., 2009).

BACKGROUND

Gas turbines are used for a variety of purposes on offshore installations, such as: power generation, compression pumping and water injection, most often in remote locations. Gas turbines are most commonly duel fueled. They have the ability to run on fuel taken from the production process under normal operations, known as fuel gas. They can also run on diesel fuel in emergency circumstances. Typically, offshore gas turbines run from 1 to 50 MW and may well be modified from aero-engines or industrial engines. The most often used gas turbines are Aeroderivative, particularly for the gas generator. It is known that relatively little information is contained within safety cases regarding the operation and safety of gas turbines. What is contained is the model, manufacture, ISO power rating (in Mega Watts (MW)), the fuel types and the location of the turbine shown on the respective installations drawings. Additional information can be found on occasion, such as: text regarding the power generation package or back-up generators. However, information in reference to integrity management and maintenance can be very limited (HSE, 2006). This information, or lack of, provides sound reasoning to produce dynamic risk assessment models regarding the integrity and safety of gas turbines.

Industrial power plants are critical systems on board offshore platforms as they supply electrical power to safety critical systems, which not only provide safe working for crew and other personnel, they also protect the integrity of the offshore platforms systems and structures. All of this protection stems from power supplied by the electrical generation systems, which is why offshore platforms and marine vessels ensure they have back-up generators in the event that one or two generators fail to operate (Perera, *et al.*, 2015). Usually, on offshore platforms, there are three electrical generation systems, with two in the same module and the third in a separate module on a higher level which usually acts as the emergency generator. Despite the safety precautions behind the number of generators and their locations, there is still the possibility of all generators failing to operate (Ramakrishnan, 2007).

Furthermore, in recent years there has been a marked increase in fires associated with fuel gas leaks with offshore gas turbines. A detailed review of offshore gas turbines incidents conducted in 2005 showed that there were 307 hazardous events over 13-year period, from 1991 to 2004. The review concerned itself with over 550 gas turbine machines. The analysis concluded that the majority of incidents (approximately 40%) occurred during normal operations, with approximately 20% during start-up, another 20% during or after maintenance and the remaining 10% of fuel gas leaks occur during fuel changeover. With the majority of incidents occurring during normal operations, the fuel gas detection is heavily reliant on either turbine fuel detectors and/or fire and gas system detectors. This is due to the modules containing the electrical power generators being almost totally unmanned during normal operation. It was also found that based upon the review conducted on machines in the stated 13-year period, shows that approximately 22% of gas leaks remained undetected. Subsequently, 60% of those undetected leaks were found to have ignited (HSE, 2008).

It is situations such as those described that increase the requirement for a dynamic risk assessment model to accurately monitor the consequences of failures within gas driven generators as they are critical in the survival of crew members as well as the integrity of the respective offshore installation.

FUEL GAS RELEASE MODEL

The model representing the potential for fuel gas release from an offshore gas turbine, along with the further consequences of fire and explosion, begins at the point of several initiating events. These events are the beginning of the sequence of events and continues through the point of a potential gas release, the barriers involved in preventing and stopping the release and the potential consequences should these barriers fail. A full step by step procedure of constructing the BN can be found in the initial research of Loughney & Wang (2016).

Model Limitations

Space and Domain Limitations

The purpose of the model is to show what the effects of several component failures have on a gas turbine which can lead to a fuel gas release. Hence, the consequences of said fuel release are analyzed, and in order to do this, the boundaries of the model need to be defined. These boundaries are concerned with the affected area, the detail of the consequences and the ignition types & sources. The outlined assumptions and limitations concerned with the model domain are as follows:

- The model has been built for the situation where there the offshore platform contains no crew and hence does not consider fatalities. There are two key reasons for this: The first is that the BN model is to be for an NUI (Normally Unattended Installation) Integrity Case, where humans are not present on the platform for large periods of time, and are monitored from other platforms or onshore. Secondly, the BN is part of continual development of an Integrity Case which shall focus on maintaining the integrity of the equipment as a priority, as well as the effects of incidents on the environment. Hence fatalities are not part of the BN model consequences.

- The model is designed to demonstrate the hazards and consequences associated with the fuel gas release from an offshore gas turbine. Hence, the consequences regarding fire and explosion are not concerned with the probability of other hydrocarbon releases contributing to fires and explosions.
- The scope of the model is primarily within the power generation module of a large fixed offshore platform. Therefore, the section of the model assigned to the probability of equipment damage due to fire and explosion is confined to the equipment and machinery located only within the stated module.
- The model is representative of fuel gas being released into the module and not within the gas turbine itself. This is due to the fact that should there be a gas release the turbine, it is assumed that the combustion chamber is of sufficient temperature to ignite the fuel. However, the presence of an ignition source within the confines of the module is not a total certainty. The node “Ignition Source” represents this uncertainty and possibility of a source being present.
- While the level of consequence is confined to the module, and the presence of an ignition source is not certain, it is still possible for the gas levels to reach dangerous levels. These dangerous levels do not represent a direct threat to human personnel as it has been stated that humans are not present in the module. The dangerous levels relate to the potential environmental impact of harmful substances being released into the atmosphere. This is in conjunction with the revised requirement of safety cases for offshore installations to contain precautions for potential environmental impact of offshore incidents and accidents (HSE, 2015).

Data Limitations

It is important that some remarks are made regarding the uniformity of the data within the model. Statistics exist in a number of formats and originate from many sources. When formulating a model as specific and confined as the one being created, it is almost impossible to gather data sets from the same consistent sources.

It is important to understand that many statistics are not fully representative of reality. For instance, there are cases where the full extent of an incident is not reported, such as a fuel gas release. For example, from 1992 to 2014, 40% of fuel gas and power turbine gas releases were not detected by an automatic sensor, but were detected by human detection. The human detection includes smell, visual and a portable detector. In the instances of human detection, the recording of information is scarce, with 56% of fuel gas release incidents having little to no information regarding the location and cause of the release and in some cases, the extent of the dispersion. Furthermore, the majority of the 56% of releases with incomplete information and data were regarded as “Significant”, in terms of their severity level (HSE, 2014). It is inconsistencies within the data, such as this, that provide sound reasoning to limit data to automatic detection and fuel shut down barriers.

There are some differences in terms of data relating the type of installation operating the same type of gas turbine generator. However, the location of the installations is restricted to the UKCS (United Kingdom Continental Shelf) and the North Sea. Much of the data represented in the model is adapted from gas turbines operating on fixed platforms, yet it is not feasible to obtain data from all sources relating to fixed installations. This limitation with the data goes back to either the absence of data or the lack of appropriate data recording. Hence, data is obtained from fixed installations and FPSOs (Floating, Production, Storage and Offloading) which make use of very similar gas turbine machines.

There are also differences with the age of the data and the data sources used in the Fuel Gas Release model. All data utilized is taken from sources post 2002. Most of the data close to 2002 has been obtained from OREDA-2002 (Offshore Reliability Data) as full access to the database at this time was available. On the other hand most of the conditional data used to complete the CPTs (Conditional Probability Tables) for the nodes, in the BN, has come from risk assessment projects conducted on offshore installation for gas turbines, with the main focus of the projects being hydrocarbon and fuel gas release. These risk projects were conducted post-2009 by RMRI Plc., Petrofac and Maersk.

Finally, most of the nodes are based upon hard evidence statistics, while two of the nodes incorporate subjective judgement by utilizing a symmetric algorithm from hard evidence. By combining information in this way it allows for situations that have little to no information to be overcome. This process does not compromise the validation and analysis of the model however it is important to take note of this when interpreting the information presented in the results.

Structure of the Model

The fuel gas release model is shown in Figure 1, which also depicts the marginal probabilities for each node. The BN is primarily designed to represent key initial events of gas turbine failure, in two main areas: the turbine control system and the physical structure. Following the initial events and failures the BN model is designed to show the possible progression of these failures into fuel gas release and the potential fire & explosion consequences that can occur. There are a number of more intimate functions that the model provides. Firstly, the initial stages of the model demonstrate which initial event or hazard demonstrates the greater probability for potential gas release, as well as whether the greatest threat originates from the turbine control system or the physical structure. Secondly, the cause and effect relationships between the barriers is demonstrated in terms of the probability of whether a certain barrier operates as expected, based upon the operation of the previous barriers. Thirdly, the type of consequence that can occur following a fuel gas release. These consequences can be; none, a gas leak only, fire, explosion and resulting equipment damage from a fire and/or an explosion.

The graphical structure of the model is designed to keep the nodes that fall under the same group together and organized in a "top down" manner. The five root nodes and the inference node are close together at the top. Then the categorized nodes are next in the top down sequence. Continuing from the failures there is a potential incident, which then leads to the barrier nodes. Pending the probability of success or failure of the barriers there is potentially another incident ("Continuous Gas Release"). Following from the barriers there are further incidents, accidents and consequence nodes which are systematically introduced. One node does remain slightly anomalous from this organization. The "ignition Source" node is grouped along with the incidents, accidents and consequences as it directly affects one of the incidents.

There is one transfer node within the fuel gas release BN which links the initial research conducted by Loughney & Wang (2016). This node is "Fuel Gas Feed Impact". Through this node any updates from the initial BN model shall result in updates to the posterior probabilities of the fuel gas release BN. The model contains nineteen chance nodes with either two or three states. Figure 2 Demonstrates the Structure of the fuel gas release model.

Establishing Conditional Probabilities

When constructing a BN, the prior probabilities are required to be assigned locally to the probability link, $P(Parent(A_i)) \rightarrow P(Child(B_i))$, as a conditional probability, $P(B_i|A_i)$. Where i is the number of possible states of the parent node and the child node. However, it is not always a straightforward process to obtain the relevant data. In principle, the majority of the data can be acquired through failure databases or experimentation. However, designing and conducting experiments can prove difficult and historical data does not always satisfy the scope of certain nodes and CPTs within a BN. Therefore, in practice, it is necessary to rely on subjective probabilities provided by expert judgement as an expression of an individual's degree of belief. However, since subjective probabilities are based on informed guesses, it is possible for deviation to occur when the data is expressed as precise numbers. It is possible to apply a fully subjective approach to construct conditional Probability Tables (CPTs) in a BN (S. Loughney, 2016).

This process involved experts providing their judgement through a Pairwise Comparison (PC) method. The data from the PC is further analyzed using Analytical Hierarchy Process (AHP) and relative importance weights were determined from this for each parent node in question. These weights are then applied to an algorithm that allows a large child CPT to be constructed cell by cell. This method of compiling data for large CPTs proved simple to implement and produced accurate results for the BN. However, it was found that a time-consuming part was the gathering of data from experts through PC in questionnaires.

As the process of creating PC questionnaires, distributing them and waiting for feedback can be time consuming, this process is to be amended by utilizing hard data from risk assessment experimentation and historical data. This entails utilizing hard data from the parent nodes and sections of the child node CPT to create relative weights for the parent nodes and apply those to the symmetric method algorithm.

Symmetric Algorithm Utilizing Hard Data

The symmetric method provides an input algorithm which consists of a set of relative weights that quantify the relative strengths of the influences of the parent-nodes on the child-node, and a set of probability distributions the number of which grows only linearly, as opposed to exponentially, with the number of associated parent-nodes. Yet the most common method of gathering the required data for the algorithm is to use expert judgements. However, it is also possible to utilize the symmetric method with historic data and experimentation. While it is very difficult or not possible to complete a large CPT in a BN using only hard data, it is possible to obtain key conditional probabilities for a node and apply them to the symmetric method to complete the CPT.

The derivation symmetric method algorithm is not to be outlined here, but the method of determining the relative weights of parent nodes will be outlined. The derivation of the symmetric method can be found in Das, (2008).

Determining Relative Weights Utilizing Hard Data

To demonstrate the method of determining relative weights through hard data, take the example network in Figure 1.

While it is not possible to accurately obtain *P(D|A, B, C)* or even *P(D|A, B)* through historical or experimental data. It is possible to obtain the conditional probability of event *Z* give the individual parents. i.e.; *P(D|A)*, *P(D|B)* and *P(D|C)*. These conditional probabilities can be used to develop normalized weights for the parent nodes.

As mentioned previously, in the symmetric model the individual local conditional probabilities of the parent to child can be distributed by relative importance for the associated child node, i.e. the normalized weight. Hence, in normal space and using the notation outlined in Figure 1, the probability of *D* being of state *"Yes"* given that the probability of *A* being in state *"Yes"* is equal to $\hat{X}_a$, where $\hat{X}_a$ is the relative importance of the parent node *A*. This is applied across all the parent nodes and is demonstrated by Equation 1 (Riahi, 2010).

$$P(\hat{X}_a) = P(D = \text{"}Yes\text{"} | A = \text{"}Yes\text{"})$$

$$= \frac{P(X_a)}{\sum_{m=a,b,\dots}^{n} P(X_m)}$$

$$\dots \qquad (1)$$

$$P(\hat{X}_n) = P(D = \text{"}Yes\text{"} | n = \text{"}Yes\text{"})$$

$$= \frac{P(X_n)}{\sum_{m=a,b,\dots}^{n} P(X_m)}$$

Therefore,

$$P(\hat{X}_A) + P(\hat{X}_B) + \dots + P(\hat{X}_n) = 1$$

In normalized space, based on the influence of each parent node, the conditional probability of a binary child node "*D*" given each binary parent node, X_r, where $r = a, b, \dots, n.$, can be estimated using Equation 2.

$$\begin{aligned} P(D = \text{"}Yes\text{"} | A = \text{"}Yes\text{"}) &= w_1 \\ P(D = \text{"}Yes\text{"} | B = \text{"}Yes\text{"}) &= w_2 \\ &\dots \qquad (2) \\ P(D = \text{"}Yes\text{"} | n = \text{"}Yes\text{"}) &= w_n \end{aligned}$$

$$\sum_{n=1}^{n} w_n = 1$$

Following from Equations 1 and 2, it is possible to calculate the weights of the parents given the individual parent to child conditional probabilities (Riahi, 2010). In order to demonstrate the calculation of relative weights for parent nodes, the network shown in Figure 1 shall be used as an example. Table 1 shows the local conditional probabilities for the child node "Control System Failure" (*"D"*) given each individual child node.

Table 1: Individual conditional probabilities for Control System Failure

D	A	B	C	Sum
	Yes	Yes	Yes	
Yes	0.0584	0.0610	0.1330	0.2524

The information presented in Table 1 can be represented by Equation 3:

$$P(D = \text{“}Yes\text{”}|A = \text{“}Yes\text{”}) = 0.0584 = P(X_a)$$
$$P(D = \text{“}Yes\text{”}|B = \text{“}Yes\text{”}) = 0.0610 = P(X_b)$$
$$P(D = \text{“}Yes\text{”}|C = \text{“}Yes\text{”}) = 0.1330 = P(X_c) \quad (3)$$
$$\sum_{m=1}^{n} P(X_m) = 0.2524$$

Hence, with the individual conditional probabilities, the relative weights of the parent nodes can be calculated utilizing equation 1.

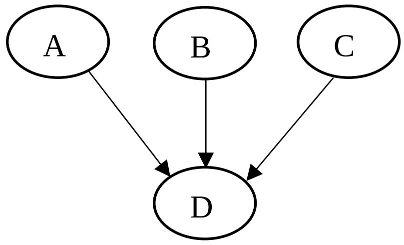

Figure 1: Simple BN representing 3 parents and 1 child

$$P(\hat{X}_a) = \frac{P(X_a)}{\sum_{m=a,b,..}^{n} P(X_m)} = \frac{0.0584}{0.2524} = 0.2314 = w_1$$

$$P(\hat{X}_b) = \frac{P(X_b)}{\sum_{m=a,b,...}^{n} P(X_m)} = \frac{0.0610}{0.2524} = 0.2417 = w_2$$

$$P(\hat{X}_c) = \frac{P(X_c)}{\sum_{m=a,b,...}^{n} P(X_m)} = \frac{0.1330}{0.2524} = 0.5269 = w_3$$

Following from this, Equation 2 can be used to show that the summation of the relative weights should be equal to 1.

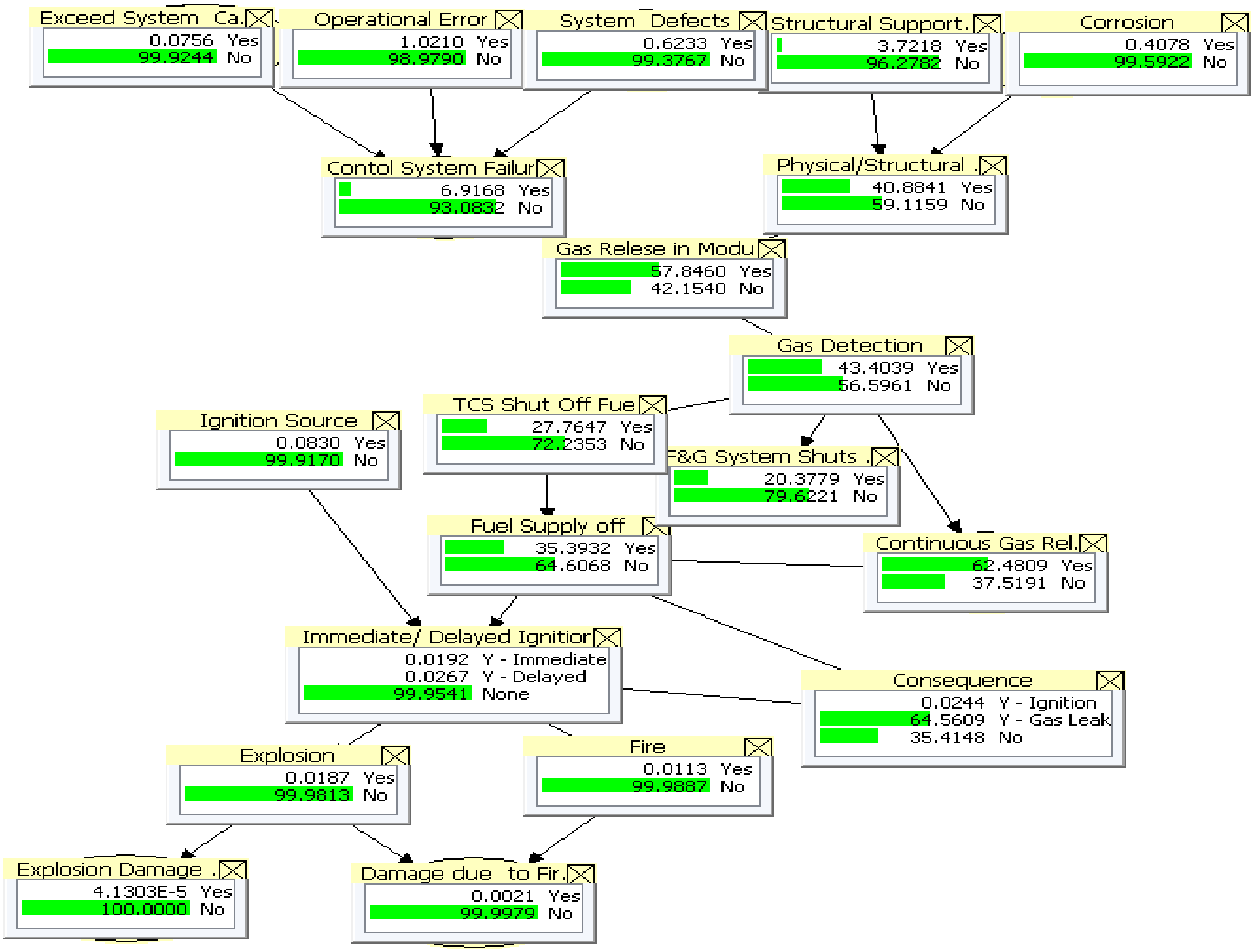

Figure 2: Marginal probabilities for each node within the Fuel Gas Release BN

$$\sum_{n=1}^{n} w_n = w_1 + w_2 + w_3 = 0.2314 + 0.2417 + 0.5269 = 1$$

As the relative weights for parent nodes *A, B* and *C* have been calculated and assigned accordingly, they can be applied to the weighted sum algorithm. Along with the linear compatible parental configuration to produce complete the CPT.

Two CPTs were compiled using this method due to the nature of their scope being specific to this model. These nodes are “Control System Failures” and “Physical/Structural Failures”. Figure 2 shows the complete BN and the marginal probability distributions for each node.

BN TEST CASES

The BN is now used to analyze a series of possible real world scenarios. All variables from external BNs, i.e. the transfer node “Fuel Gas Feed Impact”, are to remain unchanged and only those directly linked to the study for Fuel Gas Release shall be altered using the Hugin BN software. The Hugin software allows for evidence to be inserted to all nodes within the network in its “*Run Mode”* function. This evidence is to the degree of 100% in a given state of a node. It is the posterior probabilities that are of interest and are computed given particular evidence of specific nodes.

Test Case 1: Control System Failures

This case study demonstrates the effects of individual and combined control system failures within the fuel gas release model. The effect on the likelihood of a gas release is demonstrated along with the effects on the fuel shut off system. The consequences from these likelihoods is also demonstrated. In this case the likelihood of a continuous fuel release is analyzed as well as the probability of the “Consequence” node being in states “Y-Leak” and “None”. This case study is split into two test cases: 1A) is a demonstration of the effects of control system failures on the network, 1B) is a demonstration of the control system failures with the presence of an ignition source.

The probability of a fuel gas release from a gas turbine due to the turbines control system, is mostly dependent on three key events; “Exceeding System Capability” (ESC), “Operational Error” (OE) and “System Defects” (SD). The results of test case 1A are presented in Table 2, which shows the probability of gas release, fuel shut off, continuous release and the consequence (“Y_Leak” & “None”)

Table 2: Effects of the turbine control system failures on the posterior probabilities of "Gas Release", "Fuel Shut Off", "Continuous Gas Release" and "Consequence; States: Y-Leak & None"

Focus Nodes	No evidence (%)	ESC (%)	OE (%)	SD (%)
Gas Release	57.85	63.00	63.18	69.50
Fuel Off	35.39	38.43	38.53	42.25
Cont. Release	62.48	59.21	59.09	55.08
Y-Leak	64.56	61.53	61.43	57.71
None	35.41	38.45	38.55	42.27

It is evident that a major system defect would have the greatest effect on the probability of the gas release, as shown by the increase in probability from 57.85% without evidence, to 69.5% when a potential system defect causes a failure. The likelihood of consequences and continuous release decreases with the inserted evidence in control system failures as it is assumed in the model that the gas detection system has no reason to not function correctly at this stage. Therefore, the increase in the probability and level of gas release will increase the probability of gas detection.

Test 1B demonstrates the effects of the control system failures, in the presence of an Ignition Source (IS), on ignition, fire and explosion nodes. Table 3 demonstrates the results of test case 1B.

Table 3: Effects of Turbine Control System failures, with an ignition source present, on the posterior probabilities of “Gas Detection”, "Consequences", "Immediate/Delayed Ignition", "Explosion", "Fire" and "Damage due to Fire & Explosion"

Focus Nodes	100 % IS (%)	ESC (%)	OE (%)	SD (%)
Gas Detection	43.4	47.25	47.38	52.1
Y-Ignition	29.34	27.97	27.92	26.23
Y-Leak	9.29	8.85	8.84	8.30
Immediate Ig.	23.31	22.04	22.01	20.68
Delayed Ig.	32.20	30.69	30.64	28.78
Explosion	22.51	21.45	21.42	20.12
Fire	13.56	12.93	12.9	12.12
F&Ex Damage	2.55	2.44	2.43	2.29

The probability of gas detection increases proportionally to the probability of gas release. This affects the relationship between the probability of detection and the probability of accidents and consequence. When evidence is inserted into the “System Defects” node, the posterior probabilities for fire and explosion decrease from 13.56% to 12.12% and 22.51% to 20.12%. This is because the probability of the gas detection increases with the probability of the gas release, as it is assumed that the gas detectors function as expected. This also has an effect on the fuel gas shut off by increasing the probability that fuel gas will be shut off. Hence the probability that a fire or explosion will occur decreases.

Test Case 2: Gas Release without Gas Detection

Test case 2A demonstrates the effects a malfunctioning gas detection (No GD) system in the event of a gas release. In test 2A it is assumed that one or more of the initial events has occurred and a Gas Release (GR) is observed. In this case the likelihood of a continuous fuel release is analysed as well as the probability of the "Consequence" node being in states "Y-Leak" and "None". Table 4 demonstrates the results.

Table 4: Effects of a Gas Release without Gas Detection on "Consequences", "Continuous Gas Release", "Fuel Shut Off" (TCS, F&G and Fuel Off) and "Gas Detection"

Focus Nodes	No Evidence (%)	GR (%)	No GD (%)
Gas Detection	43.4	74.87	-
None	35.41	60.2	1.22
Y-Leak	64.56	39.78	98.74
Cont. Release	58.81	29.26	99.57
Fuel off: TCS	27.76	47.47	0.58
Fuel off: F&G	20.37	34.7	0.61
Fuel off (All)	35.39	60.19	1.18

If there is a gas release and the gas detectors do not function, then there is a very high probability of there being a gas leak as a consequence as well as a continuous leak from the system. The continuous leak would occur because the fuel shut off systems would not react to the gas detection. This effect can be seen in the posterior probabilities of the fuel shut off systems. Furthermore, given a gas release and no gas detection, the probability of a continuous gas release increases from 58.81% to 99.57%, and the probability of a gas leak, increases from 64.56% to 98.74%. The significance of these percentage increases in the posterior probabilities indicates that the gas detection system is a vital barrier in the mitigation of accidents resulting from fuel gas releases.

The emphasis of Test Case 2B shall be on a gas release not being detected and the effects that an Ignition Source (IS) has on the posterior probabilities of several nodes. The nodes in question are; "Consequences" (States "*Y-Ignition*" and "*Y-Leak*"), "Immediate/Delayed Ignition" (States "*Immediate*" and "*Delayed*"), "Explosion", "Fire", "Damage due to Fire & Explosion" and "Explosion Damage to Adjacent Areas". Table 5 demonstrates the results of Test Case 2B.

Table 5: Effects of no Gas Detection and presence of an Ignition Source on "Consequences" ("Y-Ignition" & "Y-Leak"), "Immediate/Delayed Ignition" ("Immediate" & "Delayed"), "Explosion", "Fire", "Damage due to Fire & Explosion" and "Explosion Damage to Adjacent Modules"

Focus Nodes	No Evidence (%)	No GD (%)	No GD & IS (%)
Y-Ignition	0.02	0.04	44.88
Y-Leak	64.56	98.74	14.20
Immediate Ig.	0.02	0.03	35.38
Delayed Ig.	0.03	0.04	49.25
Explosion	0.02	0.03	34.43
Fire	0.01	0.01	20.74
F&Ex Damage	0.00	0.00	3.91
Dam. Adj. Mod.	4.10E-05	6.31E-05	0.076

The emphasis in this analysis is on the more severe accidents and consequences in terms of fire, explosion and the damage that they can cause. From Table 5 it can be seen that in the event of a 100% failure of the gas detection system, the probability of there being any accidents or consequences related to ignition remain virtually negligible. However, the final column in Table 5 demonstrates the effects on the fire & explosion consequences given no gas detection and an ignition source present. The purpose of this is to show how sensitive the fire & explosion consequences are given an ignition source and a likely chance of a gas release. It can be seen that the posterior probabilities increase drastically when an ignition source is present without gas detection.

Test Case 3: Effects of observed Consequences (Y-Leak and Y-Ignition) on prior probabilities

To provide further verification of the BN model it is important to demonstrate the effects of inserting evidence as a consequence and observing the effects on prior nodes. The key node in this test case is the "Consequence" node, with attention being focused on inserting 100% evidence to states "*Y-Leak*" and "*Y-Ignition*". Table 6 demonstrates the effects of 100% "*Y-Leak*" on the mitigating barriers of a gas release.

Table 6: Effects of 100% "Y-Leak" on the prior probabilities of the mitigating barriers and "Continuous Release" as well as 100% *"Y-Ignition"* on the consequence and accident nodes.

Focus Nodes	No Evidence (%)	Y-Leak (%)	Y-Ignition (%)
Fuel off (All)	35.39	0.00	-
Fuel off: TCS	27.76	0.10	-
Fuel off: F&G	20.38	0.03	-
Cont. Release	62.48	96.19	-
Gas Detection	43.40	13.44	-
Ignition Source	0.083	-	100.00
Immediate Ig.	0.019	-	78.82
Delayed Ig.	0.027	-	21.18
Fire	0.011	-	31.69
Explosion	0.019	-	14.80

Table 6 shows that given 100% probability of "*Y-Leak*", the prior probabilities concerned with the fuel shut off system nodes, all being State "*Yes*", greatly decrease to almost zero. Similarly, the probability of the gas being detected also decreases. However, not to the extent of the fuel shut off systems. Table 6 also indicates that prior to a 100% consequence of ignition, the likelihood of any ignition, fire and explosion accidents or consequences are almost negligible. However, when evidence is inserted into the state "*Y-Ignition*" in the consequence node, the prior probabilities greatly increase.

CONCLUSIONS

The BN model presented in this research demonstrates the effect that several initial failures have on a potential fuel gas release as well as the potential fire and explosion hazards that can occur. These consequences are equally important for offshore platform operators due to the improved HSE regulations within Safety Cases regarding hazards to the environment in any instance. Therefore, if there is a fuel gas leak without ignition, it poses a large issue for operators and duty holders given that the release is undetected.

The analysis presented in the three test cases clearly demonstrates the vital role that the mitigating barriers play in preventing severe consequences due to a gas turbine fuel leak. The BN model also clearly demonstrates that it can provide an effective and applicable method of determining the likelihood of various events under uncertainty, and more importantly show increased uses as a dynamic risk assessment tool. This is especially applicable in monitoring offshore areas where human presence has been removed, i.e. NU-Installations.

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APPENDIX D: Ship to Platform Collision Data

No.	Year	Source	Accident Date	Name of Unit	Floating/Fixed	Type of Unit	Shelf	Damage
1	1971	WOAD	08/04/1971	NEPTUNE 7	Floating	Semi-submersible	UKCS	Minor damage
2	1972	WOAD	10/22/1972	ZAPATA NORDIC	Floating	Jack-Up	Norway	Minor damage
3	1973	WOAD	12/29/1973	BRITANIA	Floating	Jack-Up	UKCS	Minor damage
4	1974	WOAD	12/06/1974	BRITANIA	Floating	Jack-Up	UKCS	Minor damage
5	1974	WOAD	06/02/1974	ZAPATA UGLAND	Floating	Semi-submersible	UKCS	Minor damage
6	1975	WOAD	12/05/1975	STADRILL	Floating	Semi-submersible	UKCS	Insignif/no damage
7	1975	WOAD	10/28/1975	BORGNY DOLPHIN	Floating	Semi-submersible	UKCS	Significant damage
8	1975	WOAD	09/03/1975	FRIGG,10/1,CPD1	Fixed	Concrete structure	UKCS	Minor damage
9	1975	WOAD	8/29/1975	AUK,30/16,A	Fixed	Jacket	UKCS	Significant damage
10	1975	HSE	29/08/1975		Fixed	Fixed Steel	UKCS	Severe
11	1975	HSE			Fixed	Fixed Steel	UKCS	moderate
12	1975	HSE	20/09/1975		Floating	Jack-Up	UKCS	moderate
13	1975	HSE			Fixed	Fixed Steel	UKCS	Minor
14	1975	HSE	16/01/1975		Floating	Semi-submersible	UKCS	Minor
15	1975	HSE	17/01/1975		Floating	Semi-submersible	UKCS	Minor
16	1975	HSE	08/03/1975		Floating	Semi-submersible	UKCS	Minor
17	1975	HSE	19/06/1975		Floating	Semi-submersible	UKCS	Minor
18	1976	HSE			Fixed	Fixed Steel	UKCS	moderate
19	1976	HSE	14/08/1976		Floating	Semi-submersible	UKCS	moderate
20	1976	HSE			Floating	Semi-submersible	UKCS	Minor
21	1976	HSE			Floating	Jack-Up	UKCS	Minor
22	1976	HSE	25/02/1976		Floating	Semi-submersible	UKCS	Minor
23	1976	HSE	17/03/1976		Floating	Semi-submersible	UKCS	Minor
24	1976	HSE	08/04/1976		Floating	Semi-submersible	UKCS	Minor
25	1976	HSE	11/04/1976		Floating	Semi-submersible	UKCS	Minor
26	1976	HSE	12/04/1976		Floating	Semi-submersible	UKCS	Minor
27	1976	HSE	18/09/1976		Floating	Semi-submersible	UKCS	Minor
28	1976	HSE	17/10/1976		Fixed	Fixed Steel	UKCS	Minor

29	1976	HSE	25/10/1976		Floating	Semi-submersible	UKCS	Minor
30	1977	HSE	12/04/1977		Fixed	Fixed Steel	UKCS	Severe
31	1977	HSE	05/11/1977		Floating	Semi-submersible	UKCS	Severe
32	1977	HSE			Fixed	Fixed Steel	UKCS	moderate
33	1977	HSE	11/02/1977		Floating	Semi-submersible	UKCS	moderate
34	1977	HSE	18/02/1977		Floating	Semi-submersible	UKCS	moderate
35	1977	HSE	19/04/1977		Fixed	Fixed Steel	UKCS	moderate
36	1977	HSE	23/04/1977		Floating	Semi-submersible	UKCS	moderate
37	1977	HSE			Fixed	Fixed Steel	UKCS	Minor
38	1977	HSE			Fixed	Fixed Steel	UKCS	Minor
39	1977	HSE			Floating	Semi-submersible	UKCS	Minor
40	1977	HSE			Floating	Semi-submersible	UKCS	Minor
41	1977	HSE			Floating	Jack-Up	UKCS	Minor
42	1977	HSE			Fixed	Fixed Steel	UKCS	Minor
43	1977	HSE	14/01/1977		Floating	Semi-submersible	UKCS	Minor
44	1977	HSE	21/03/1977		Floating	Semi-submersible	UKCS	Minor
45	1977	HSE	06/05/1977		Fixed	Fixed Concrete	UKCS	Minor
46	1977	HSE	07/05/1977		Fixed	Fixed Steel	UKCS	Minor
47	1977	HSE	07/10/1977		Fixed	Fixed Concrete	UKCS	Minor
48	1977	HSE	22/11/1977		Fixed	Fixed Steel	UKCS	Minor
49	1977	HSE	17/12/1977		Floating	Semi-submersible	UKCS	Minor
50	1978	HSE			Floating	Semi-submersible	UKCS	Minor
51	1978	HSE			Floating	Semi-submersible	UKCS	Minor
52	1978	HSE			Floating	Semi-submersible	UKCS	Minor
53	1978	HSE			Floating	Semi-submersible	UKCS	Minor
54	1978	HSE			Floating	Jack-Up	UKCS	Minor
55	1978	HSE	04/01/1978		Floating	Semi-submersible	UKCS	Minor
56	1978	HSE	02/02/1978		Fixed	Fixed Steel	UKCS	Minor
57	1978	HSE	02/02/1978		Floating	Semi-submersible	UKCS	Minor
58	1978	HSE	13/02/1978		Floating	Semi-submersible	UKCS	Minor
59	1978	HSE	14/02/1978		Floating	Semi-submersible	UKCS	Minor
60	1978	HSE	31/03/1978		Floating	Semi-submersible	UKCS	Minor
61	1978	HSE	16/08/1978		Floating	Semi-submersible	UKCS	moderate

62	1978	HSE			Floating	Semi-submersible	UKCS	moderate
63	1978	HSE			Fixed	Fixed Steel	UKCS	moderate
64	1978	HSE			Fixed	Fixed Steel	UKCS	moderate
65	1978	HSE	10/01/1978		Floating	Semi-submersible	UKCS	moderate
66	1978	HSE	05/02/1978		Fixed	Fixed Steel	UKCS	moderate
67	1978	HSE	16/06/1978		Floating	Semi-submersible	UKCS	moderate
68	1978	HSE	05/08/1978		Floating	Semi-submersible	UKCS	moderate
69	1979	HSE			Floating	Semi-submersible	UKCS	moderate
70	1979	HSE			Fixed	Fixed Steel	UKCS	moderate
71	1979	HSE	28/06/1979		Fixed	Fixed Steel	UKCS	moderate
72	1979	HSE	06/11/1979		Floating	Semi-submersible	UKCS	moderate
73	1979	HSE	14/11/1979		Floating	Semi-submersible	UKCS	moderate
74	1979	HSE	19/11/1979		Floating	Semi-submersible	UKCS	moderate
75	1979	HSE	01/01/1979		Fixed	Fixed Steel	UKCS	Minor
76	1979	HSE			Fixed	Fixed Steel	UKCS	Minor
77	1979	HSE			Floating	Semi-submersible	UKCS	Minor
78	1979	HSE			Fixed	Fixed Steel	UKCS	Minor
79	1979	HSE			Floating	Semi-submersible	UKCS	Minor
80	1979	HSE			Floating	Semi-submersible	UKCS	Minor
81	1979	HSE	16/01/1979		Floating	Semi-submersible	UKCS	Minor
82	1979	HSE	03/02/1979		Fixed	Fixed Steel	UKCS	Minor
83	1979	HSE	11/03/1979		Floating	Semi-submersible	UKCS	Minor
84	1979	HSE	17/03/1979		Fixed	Fixed Steel	UKCS	Minor
85	1979	HSE	02/05/1979		Fixed	Fixed Steel	UKCS	Minor
86	1979	HSE	11/05/1979		Floating	Semi-submersible	UKCS	Minor
87	1979	HSE	07/09/1979		Fixed	Fixed Concrete	UKCS	Minor
88	1979	HSE	11/09/1979		Floating	Semi-submersible	UKCS	Minor
89	1979	HSE	16/10/1979		Fixed	Fixed Steel	UKCS	Minor
90	1979	HSE	23/10/1979		Fixed	Fixed Steel	UKCS	Minor
91	1979	HSE	27/11/1979		Floating	Semi-submersible	UKCS	Minor
92	1979	HSE	07/12/1979		Fixed	Fixed Steel	UKCS	Minor
93	1979	HSE	21/12/1979		Floating	Semi-submersible	UKCS	Minor
94	1979	WOAD	11/17/1979	NORSKALD	Floating	Semi-submersible	Norway	Minor damage

95	1980	WOAD	12/18/1980	OCEAN BOUNTY	Floating	Semi-submersible	UKCS	Significant damage
96	1980	WOAD	11/10/1980	BRENT,211/29,C	Fixed	Concrete structure	UKCS	Significant damage
97	1980	WOAD	10/20/1980	BRENT,211/29,C	Fixed	Concrete structure	UKCS	Significant damage
98	1980	WOAD	5/15/1980	TRANSWORLD RIG 58	Floating	Semi-submersible	UKCS	Significant damage
99	1980	WOAD	02/06/1980		Fixed	Fixed Steel		Significant damage
100	1980	HSE			Fixed	Fixed Steel	UKCS	Minor
101	1980	HSE			Fixed	Fixed Steel	UKCS	Minor
102	1980	HSE			Fixed	Fixed Steel	UKCS	Minor
103	1980	HSE			Fixed	Fixed Steel	UKCS	Minor
104	1980	HSE			Fixed	Fixed Steel	UKCS	Minor
105	1980	HSE	07/01/1980		Floating	Semi-submersible	UKCS	Minor
106	1980	HSE	18/04/1980		Fixed	Fixed Steel	UKCS	Minor
107	1980	HSE	21/05/1980		Fixed	Fixed Steel	UKCS	Minor
108	1980	HSE	23/05/1980		Floating	Semi-submersible	UKCS	Minor
109	1980	HSE	28/05/1980		Fixed	Fixed Steel	UKCS	Minor
110	1980	HSE	23/07/1980		Floating	Drill Ship	UKCS	Minor
111	1980	HSE	26/10/1980		Floating	Semi-submersible	UKCS	Minor
112	1980	HSE	25/11/1980		Fixed	Fixed Steel	UKCS	Minor
113	1981	WOAD	9/15/1981	DIXILYN-FIELD RIG 97	Floating	Semi-submersible	Norway	Significant damage
114	1981	WOAD	02/08/1981	DIRK	Floating	Jack-Up	Sweden	Minor damage
115	1981	WOAD	03/10/1981		Floating	Semi-submersible		Significant damage
116	1981	HSE			Fixed	Fixed Steel	UKCS	moderate
117	1981	HSE			Fixed	Fixed Steel	UKCS	moderate
118	1981	HSE	10/02/1981		Floating	Semi-submersible	UKCS	moderate
119	1981	HSE			Fixed	Fixed Steel	UKCS	Minor
120	1981	HSE			Fixed	Fixed Steel	UKCS	Minor
121	1981	HSE			Fixed	Fixed Steel	UKCS	Minor

122	1981	HSE			Fixed	Fixed Steel	UKCS	Minor
123	1981	HSE			Floating	Semi-submersible	UKCS	Minor
124	1981	HSE			Fixed	Fixed Steel	UKCS	Minor
125	1981	HSE			Fixed	Fixed Steel	UKCS	Minor
126	1981	HSE			Fixed	Fixed Steel	UKCS	Minor
127	1981	HSE	15/01/1981		Floating	Semi-submersible	UKCS	Minor
128	1981	HSE	16/01/1981		Fixed	Fixed Steel	UKCS	Minor
129	1981	HSE	12/02/1981		Floating	Semi-submersible	UKCS	Minor
130	1981	HSE	15/02/1981		Floating	Semi-submersible	UKCS	Minor
131	1981	HSE	16/02/1981		Fixed	Fixed Steel	UKCS	Minor
132	1981	HSE	01/03/1981		Fixed	Fixed Steel	UKCS	Minor
133	1981	HSE	19/03/1981		Fixed	Fixed Steel	UKCS	Minor
134	1981	HSE	10/04/1981		Fixed	Fixed Steel	UKCS	Minor
135	1981	HSE	25/05/1981		Fixed	Fixed Steel	UKCS	Minor
136	1981	HSE	13/07/1981		Fixed	Fixed Steel	UKCS	Minor
137	1981	HSE	04/08/1981		Fixed	Fixed Steel	UKCS	Minor
138	1981	HSE	20/09/1981		Fixed	Fixed Steel	UKCS	Minor
139	1981	HSE	27/09/1981		Fixed	Fixed Steel	UKCS	Minor
140	1981	HSE	02/10/1981		Fixed	Fixed Steel	UKCS	Minor
141	1981	HSE	06/10/1981		Floating	Semi-submersible	UKCS	Minor
142	1981	HSE	02/11/1981		Fixed	Fixed Steel	UKCS	Minor
143	1981	HSE	12/11/1981		Floating	Semi-submersible	UKCS	Minor
144	1981	HSE	24/12/1981		Fixed	Fixed Steel	UKCS	Minor
145	1982	WOAD	9/29/1982	SEDCO 707	Floating	Semi-submersible	Norway	Minor damage
146	1982	WOAD	7/20/1982	WESTERN PACESETTER 2	Floating	Semi-submersible	UKCS	Significant damage
147	1982	WOAD	4/13/1982	BORGLAND DOLPHIN	Floating	Semi-submersible	UKCS	Significant damage
148	1982	WOAD	07/01/1982	VALHALL,2/8A,QP	Fixed	Jacket	Norway	Insignif/no damage
149	1982	WOAD	4/13/1982	EKOFISK,2/4,H HOTEL	Fixed	Jacket	Norway	Minor damage
150	1982	HSE			Fixed	Fixed Steel	UKCS	Minor
151	1982	HSE	08/02/1982		Fixed	Fixed Steel	UKCS	Minor

152	1982	HSE	24/02/1982		Fixed	Fixed Steel	UKCS	Minor
153	1982	HSE	27/02/1982		Floating	Semi-submersible	UKCS	Minor
154	1982	HSE	06/04/1982		Fixed	Fixed Steel	UKCS	Minor
155	1982	HSE	06/05/1982		Fixed	Fixed Steel	UKCS	Minor
156	1982	HSE	13/05/1982		Floating	Semi-submersible	UKCS	Minor
157	1982	HSE	22/05/1982		Fixed	Fixed Steel	UKCS	Minor
158	1982	HSE	10/07/1982		Fixed	Fixed Steel	UKCS	Minor
159	1982	HSE	19/07/1982		Fixed	Fixed Steel	UKCS	Minor
160	1982	HSE	17/09/1982		Floating	Semi-submersible	UKCS	Minor
161	1982	HSE	24/09/1982		Fixed	Fixed Steel	UKCS	Minor
162	1982	HSE	13/12/1982		Fixed	Fixed Steel	UKCS	Minor
163	1982	HSE	28/12/1982		Floating	Semi-submersible	UKCS	Minor
164	1982	HSE			Fixed	Fixed Steel	UKCS	moderate
165	1982	HSE	25/03/1982		Fixed	Fixed Steel	UKCS	moderate
166	1982	HSE	09/07/1982		Fixed	Fixed Steel	UKCS	moderate
167	1982	HSE			Fixed	Fixed Steel	UKCS	moderate
168	1982	HSE	18/07/1982		Fixed	Fixed Steel	UKCS	moderate
169	1982	HSE			Floating	Semi-submersible	UKCS	moderate
170	1982	HSE	18/10/1982		Fixed	Fixed Steel	UKCS	moderate
171	1983	WOAD	01/12/1983	EKOFISK WEST,2/4A,D	Fixed	Jacket	Norway	Minor damage
172	1983	WOAD	6/29/1983	PENROD 85	Floating	Jack-Up	UKCS	Minor damage
173	1983	WOAD	11/10/1983	ODIN,30/10A	Fixed	Jacket	Norway	Minor damage
174	1983	HSE			Fixed	Fixed Steel	UKCS	moderate
175	1983	HSE	10/03/1983		Floating	Semi-submersible	UKCS	moderate
176	1983	HSE	09/11/1983		Floating	Semi-submersible	UKCS	moderate
177	1983	HSE	16/07/1983		Fixed	Fixed Steel	UKCS	Severe
178	1983	HSE			Fixed	Fixed Steel	UKCS	Minor
179	1983	HSE	21/01/1983		Floating	TLP	UKCS	Minor
180	1983	HSE	24/01/1983		Floating	Semi-submersible	UKCS	Minor
181	1983	HSE	02/02/1983		Floating	Jack-Up	UKCS	Minor
182	1983	HSE	05/02/1983		Fixed	Fixed Steel	UKCS	Minor
183	1983	HSE	24/03/1983		Floating	Jack-Up	UKCS	Minor
184	1983	HSE	28/05/1983		Floating	Semi-submersible	UKCS	Minor

185	1983	HSE	30/05/1983		Floating	Semi-submersible	UKCS	Minor
186	1983	HSE	15/07/1983		Fixed	Fixed Steel	UKCS	Minor
187	1983	HSE	17/07/1983		Fixed	Fixed Steel	UKCS	Minor
188	1983	HSE	10/08/1983		Fixed	Fixed Steel	UKCS	Minor
189	1983	HSE	16/08/1983		Floating	Semi-submersible	UKCS	Minor
190	1983	HSE	03/10/1983		Fixed	Fixed Steel	UKCS	Minor
191	1983	HSE	26/10/1983		Floating	Semi-submersible	UKCS	Minor
192	1983	HSE	18/11/1983		Floating	Semi-submersible	UKCS	Minor
193	1984	HSE	12/01/1984		Fixed	Fixed Steel	UKCS	Minor
194	1984	HSE	19/01/1984		Fixed	Fixed Steel	UKCS	Minor
195	1984	HSE	21/04/1984		Fixed	Fixed Steel	UKCS	Minor
196	1984	HSE	23/05/1984		Floating	Semi-submersible	UKCS	Minor
197	1984	HSE	30/05/1984		Fixed	Fixed Steel	UKCS	Minor
198	1984	HSE	14/07/1984		Floating	Semi-submersible	UKCS	Minor
199	1984	HSE	08/10/1984		Floating	Semi-submersible	UKCS	Minor
200	1984	HSE	21/11/1984		Floating	Semi-submersible	UKCS	Minor
201	1984	HSE	10/05/1984		Floating	Semi-submersible	UKCS	moderate
202	1984	HSE	28/08/1984		Floating	Semi-submersible	UKCS	moderate
203	1984	HSE	10/11/1984		Floating	Jack-Up	UKCS	moderate
204	1984	HSE	30/11/1984		Floating	Semi-submersible	UKCS	moderate
205	1985	WOAD	11/04/1985	GULLFAKS,34/10,B	Fixed	Concrete structure	Norway	Significant damage
206	1985	WOAD	6/26/1985	LEMAN,49/27,H	Fixed	Jacket	UKCS	Minor damage
207	1985	WOAD	08/01/1985	EKOFISK,2/4A,C	Fixed	Jacket	Norway	Minor damage
208	1985	WOAD	7/31/1985	GILBERT ROWE	Floating	Jack-Up	UKCS	Significant damage
209	1985	WOAD	7/31/1985	FORBES,43/8,AW	Fixed	Jacket	UKCS	Minor damage
210	1985	HSE	17/01/1985		Floating	Semi-submersible	UKCS	moderate
211	1985	HSE	05/01/1985		Floating	Semi-submersible	UKCS	Severe
212	1985	HSE	10/01/1985		Fixed	Fixed Steel	UKCS	Severe
213	1985	HSE	26/09/1985		Floating	Semi-submersible	UKCS	Severe
214	1985	HSE	13/01/1985		Fixed	Fixed Steel	UKCS	Minor
215	1985	HSE	29/03/1985		Floating	Jack-Up	UKCS	Minor

216	1985	HSE	04/05/1985		Fixed	Fixed Steel	UKCS	Minor
217	1985	HSE	11/05/1985		Fixed	Fixed Steel	UKCS	Minor
218	1985	HSE	04/06/1985		Fixed	Fixed Steel	UKCS	Minor
219	1985	HSE	11/07/1985		Fixed	Fixed Steel	UKCS	Minor
220	1985	HSE	04/08/1985		Floating	Jack-Up	UKCS	Minor
221	1985	HSE	10/08/1985		Fixed	Fixed Steel	UKCS	Minor
222	1985	HSE	15/09/1985		Fixed	Fixed Steel	UKCS	Minor
223	1985	HSE	18/09/1985		Fixed	Fixed Steel	UKCS	Minor
224	1985	HSE	22/10/1985		Fixed	Fixed Steel	UKCS	Minor
225	1986	WOAD	12/24/1986	ODIN,30/10A	Fixed	Jacket	Norway	Minor damage
226	1986	WOAD	5/25/1986	COD,7/11,A	Fixed	Jacket	Norway	Significant damage
227	1986	WOAD	7/29/1986	GULLFAKS,34/10,A	Fixed	Concrete structure	Norway	Insignif/no damage
228	1986	HSE			Fixed	Fixed Steel	UKCS	Minor
229	1986	HSE			Fixed	Fixed Steel	UKCS	Minor
230	1986	HSE			Fixed	Fixed Steel	UKCS	Minor
231	1986	HSE	05/01/1986		Floating	Jack-Up	UKCS	Minor
232	1986	HSE	08/06/1986		Fixed	Fixed Steel	UKCS	Minor
233	1986	HSE	08/10/1986		Fixed	Fixed Steel	UKCS	Minor
234	1986	HSE	11/10/1986		Fixed	Fixed Steel	UKCS	Minor
235	1986	HSE	12/12/1986		Fixed	Fixed Steel	UKCS	Minor
236	1986	HSE	13/12/1986		Fixed	Fixed Steel	UKCS	Minor
237	1986	HSE			Fixed	Fixed Steel	UKCS	moderate
238	1986	HSE			Fixed	Fixed Steel	UKCS	moderate
239	1986	HSE	22/01/1986		Floating	Semi-submersible	UKCS	moderate
240	1986	HSE	17/04/1986		Floating	Semi-submersible	UKCS	moderate
241	1987	WOAD	12/01/1987	EKOFISK,2/4A,A	Fixed	Jacket	Norway	Minor damage
242	1987	WOAD	10/05/1987	BRAE NORTH,16/7A,B	Fixed	Jacket	UKCS	Minor damage
243	1987	HSE	28/07/1987		Fixed	Fixed Steel	UKCS	Minor
244	1987	HSE	08/08/1987		Fixed	Fixed Steel	UKCS	Minor
245	1987	HSE	17/08/1987		Floating	Semi-submersible	UKCS	Minor
246	1987	HSE	06/09/1987		Fixed	Fixed Steel	UKCS	Minor

247	1987	HSE	02/10/1987		Fixed	Fixed Concrete	UKCS	Minor
248	1988	WOAD	15/05/1988	STATPIPE,16/11S,RISER	Fixed	Jacket	Norway	Insignif/no damage
249	1988	HSE	11/01/1988		Floating	Semi-submersible	UKCS	Minor
250	1988	HSE	20/05/1988		Floating	Semi-submersible	UKCS	Minor
251	1988	HSE	12/07/1988		Floating	Jack-Up	UKCS	Minor
252	1988	HSE	31/08/1988		Floating	Jack-Up	UKCS	Minor
253	1988	HSE	05/09/1988		Floating	Jack-Up	UKCS	Minor
254	1988	HSE	13/11/1988		Floating	Jack-Up	UKCS	Minor
255	1988	HSE	18/11/1988		Fixed	Fixed Steel	UKCS	Minor
256	1989	WOAD	12/14/1989	FRIGG,25/1,TCP2	Fixed	Concrete structure	Norway	Insignif/no damage
257	1989	WOAD	12/11/1989	GYDA,2/1	Fixed	Jacket	Norway	Minor damage
258	1989	WOAD	11/05/1989	DEEPSEA BERGEN	Floating	Semi-submersible	Norway	Significant damage
259	1989	HSE	28/08/1989		Floating	Semi-submersible	UKCS	Moderate
260	1989	HSE	01/01/1989		Floating	Jack-Up	UKCS	Minor
261	1989	HSE			Fixed	Fixed Steel	UKCS	Minor
262	1989	HSE			Fixed	Fixed Steel	UKCS	Minor
263	1989	HSE	03/02/1989		Floating	Jack-Up	UKCS	Minor
264	1989	HSE	08/04/1989		Floating	Jack-Up	UKCS	Minor
265	1989	HSE	08/04/1989		Fixed	Fixed Steel	UKCS	Minor
266	1989	HSE	23/04/1989		Floating	TLP	UKCS	Minor
267	1989	HSE	01/05/1989		Floating	Semi-submersible	UKCS	Minor
268	1989	HSE	20/05/1989		Floating	Jack-Up	UKCS	Minor
269	1989	HSE	15/06/1989		Floating	Semi-submersible	UKCS	Minor
270	1989	HSE	03/08/1989		Fixed	Fixed Steel	UKCS	Minor
271	1989	HSE	01/09/1989		Fixed	Fixed Steel	UKCS	Minor
272	1989	HSE	12/09/1989		Floating	Semi-submersible	UKCS	Minor
273	1989	HSE	18/09/1989		Fixed	Fixed Steel	UKCS	Minor
274	1989	HSE	21/09/1989		Floating	Semi-submersible	UKCS	Minor
275	1989	HSE	14/10/1989		Fixed	Fixed Steel	UKCS	Minor
276	1989	HSE	28/10/1989		Floating	Semi-submersible	UKCS	

277	1990	WOAD	09/11/1990	MONTROSE,22/17,A	Fixed	Jacket	UKCS	Significant damage
278	1990	WOAD	7/15/1990	POLYCONFIDENCE	Floating	Semi-submersible	UKCS	Significant damage
279	1990	WOAD	7/26/1990	POLYCONFIDENCE	Floating	Semi-submersible	Norway	Significant damage
280	1990	WOAD	5/18/1990	OSEBERG,30/9,A	Fixed	Concrete structure	Norway	Insignif/no damage
281	1990	WOAD	2/25/1990	LEMAN,49/27,G	Fixed	Jacket	UKCS	Minor damage
282	1990	WOAD	12/25/1990	ARCH ROWAN	Floating	Jack-Up	UKCS	Minor damage
283	1990	WOAD	7/22/1990	LEMAN,49/27,AP	Fixed	Jacket	UKCS	Significant damage
284	1990	WOAD	4/24/1990	STATFJORD,33/9A,A	Fixed	Concrete structure	Norway	Minor damage
285	1990	HSE	14/01/1990		Fixed	Fixed Steel	UKCS	Minor
286	1990	HSE	14/03/1990		Floating	Semi-submersible	UKCS	Minor
287	1990	HSE	21/03/1990		Floating	Jack-Up	UKCS	Minor
288	1990	HSE	22/04/1990		Fixed	Fixed Steel	UKCS	Minor
289	1990	HSE	29/04/1990		Fixed	Fixed Steel	UKCS	Minor
290	1990	HSE	25/05/1990		Fixed	Fixed Steel	UKCS	Minor
291	1990	HSE	28/06/1990		Fixed	Fixed Concrete	UKCS	Minor
292	1990	HSE	23/07/1990		Floating	Semi-submersible	UKCS	Minor
293	1990	HSE	11/10/1990		Floating	Semi-submersible	UKCS	Minor
294	1990	HSE	18/10/1990		Floating	Semi-submersible	UKCS	Minor
295	1990	HSE	22/10/1990		Fixed	Fixed Steel	UKCS	Minor
296	1990	HSE	16/11/1990		Floating	Jack-Up	UKCS	Minor
297	1990	HSE	03/12/1990		Fixed	Fixed Concrete	UKCS	Minor
298	1990	HSE	07/12/1990		Fixed	Fixed Steel	UKCS	Minor
299	1990	HSE	09/12/1990		Fixed	Fixed Steel	UKCS	Minor
300	1990	HSE	31/12/1990		Floating	Semi-submersible	UKCS	Minor
301	1990	HSE			Fixed	Fixed Steel	UKCS	moderate
302	1990	HSE	29/05/1990		Floating	Semi-submersible	UKCS	moderate
303	1990	HSE	12/10/1990		Floating	Semi-submersible	UKCS	Severe
304	1991	WOAD	10/21/1991	OCEAN KOKUEI	Floating	Semi-submersible	UKCS	Insignif/no damage

305	1991	WOAD	04/02/1991	POLAR PIONEER	Floating	Semi-submersible	Norway	Significant damage
306	1991	WOAD	4/15/1991	PENROD 81	Floating	Jack-Up	Netherlands	Minor damage
307	1991	WOAD	01/05/1991	WEST SOLE,48/6,WC	Fixed	Jacket	UKCS	Significant damage
308	1991	WOAD	11/03/1991	GYDA,2/1	Fixed	Jacket	Norway	Insignif/no damage
309	1991	WOAD	8/16/1991	WEST OMIKRON	Floating	Jack-Up	UKCS	Insignif/no damage
310	1991	HSE	10/02/1991		Floating	Semi-submersible	UKCS	moderate
311	1991	HSE	11/10/1991		Floating	Semi-submersible	UKCS	moderate
312	1991	HSE	01/01/1991		Floating	Jack-Up	UKCS	Minor
313	1991	HSE	03/01/1991		Floating	Semi-submersible	UKCS	Minor
314	1991	HSE	03/01/1991		Floating	Jack-Up	UKCS	Minor
315	1991	HSE	21/01/1991		Floating	Semi-submersible	UKCS	Minor
316	1991	HSE	04/03/1991		Floating	Jack-Up	UKCS	Minor
317	1991	HSE	09/03/1991		Floating	Semi-submersible	UKCS	Minor
318	1991	HSE	18/03/1991		Floating	Semi-submersible	UKCS	Minor
319	1991	HSE	28/04/1991		Fixed	Fixed Steel	UKCS	Minor
320	1991	HSE	22/08/1991		Fixed	Fixed Steel	UKCS	Minor
321	1991	HSE	31/08/1991		Fixed	Fixed Concrete	UKCS	Minor
322	1991	HSE	04/09/1991		Fixed	Fixed Steel	UKCS	Minor
323	1991	HSE	07/11/1991		Floating	Semi-submersible	UKCS	Minor
324	1991	HSE	18/11/1991		Floating	Jack-Up	UKCS	Minor
325	1991	HSE	27/11/1991		Floating	Semi-submersible	UKCS	Minor
326	1992	WOAD	12/23/1992	LEMAN,49/27,CP	Fixed	Jacket	UKCS	Minor damage
327	1992	WOAD	12/06/1992	GANNET,22/26,A	Fixed	Jacket	UKCS	Minor damage
328	1992	HSE	21/01/1992		Floating	Semi-submersible	UKCS	Minor
329	1992	HSE	31/01/1992		Floating	Semi-submersible	UKCS	Minor
330	1992	HSE	05/02/1992		Fixed	Fixed Steel	UKCS	Minor
331	1992	HSE	11/02/1992		Floating	Semi-submersible	UKCS	Minor
332	1992	HSE	27/02/1992		Fixed	Fixed Steel	UKCS	Minor
333	1992	HSE	07/04/1992		Floating	Semi-submersible	UKCS	Minor
334	1992	HSE	23/04/1992		Floating	Semi-submersible	UKCS	Minor

335	1992	HSE	04/05/1992		Fixed	Fixed Steel	UKCS	Minor
336	1992	HSE	07/05/1992		Floating	Semi-submersible	UKCS	Minor
337	1992	HSE	15/05/1992		Floating	Semi-submersible	UKCS	Minor
338	1992	HSE	21/05/1992		Fixed	Fixed Steel	UKCS	Minor
339	1992	HSE	27/05/1992		Floating	Semi-submersible	UKCS	Minor
340	1992	HSE	31/05/1992		Floating	Jack-Up	UKCS	Minor
341	1992	HSE	14/06/1992		Floating	Jack-Up	UKCS	Minor
342	1992	HSE	19/06/1992		Floating	Semi-submersible	UKCS	Minor
343	1992	HSE	20/09/1992		Floating	FPS	UKCS	Minor
344	1992	HSE	02/10/1992		Fixed	Fixed Steel	UKCS	Minor
345	1992	HSE	25/10/1992		Floating	Jack-Up	UKCS	Minor
346	1992	HSE	16/11/1992		Floating	Jack-Up	UKCS	Minor
347	1992	HSE	22/11/1992		Fixed	Fixed Steel	UKCS	Minor
348	1992	HSE	11/12/1992		Floating	Semi-submersible	UKCS	Minor
349	1992	HSE	16/12/1992		Floating	Semi-submersible	UKCS	Minor
350	1992	HSE	19/04/1992		Floating	Semi-submersible	UKCS	Severe
351	1993	WOAD	8/30/1993	ULA,7/12A,Q	Fixed	Jacket	Norway	Minor damage
352	1993	WOAD	5/20/1993	OSEBERG,30/9,A	Fixed	Concrete structure	Norway	Minor damage
353	1993	WOAD	04/12/1993	SLEIPNER,15/9,RISER	Fixed	Jacket	Norway	Insignif/no damage
354	1993	HSE	11/01/1993		Fixed	Fixed Steel	UKCS	Minor
355	1993	HSE	14/01/1993		Floating	Semi-submersible	UKCS	Minor
356	1993	HSE	16/01/1993		Fixed	Fixed Steel	UKCS	Minor
357	1993	HSE	02/02/1993		Floating	Semi-submersible	UKCS	Minor
358	1993	HSE	04/02/1993		Floating	Semi-submersible	UKCS	Minor
359	1993	HSE	06/02/1993		Floating	FPS	UKCS	Minor
360	1993	HSE	25/03/1993		Floating	Semi-submersible	UKCS	Minor
361	1993	HSE	27/03/1993		Floating	FPS	UKCS	Minor
362	1993	HSE	28/03/1993		Floating	Semi-submersible	UKCS	Minor
363	1993	HSE	01/07/1993		Floating	FPS	UKCS	Minor
364	1993	HSE	27/07/1993		Floating	Jack-Up	UKCS	Minor
365	1993	HSE	07/09/1993		Floating	Semi-submersible	UKCS	Minor
366	1993	HSE	29/10/1993		Fixed	Fixed Steel	UKCS	Minor

367	1993	HSE	10/12/1993		Fixed	Fixed Steel	UKCS	Minor
368	1994	WOAD	10/12/1994	VALHALL,2/8A,PCP	Fixed	Jacket	Norway	Minor damage
369	1994	WOAD	8/14/1994	WEST SIGMA	Floating	Jack-Up	UKCS	Insignif/no damage
370	1994	WOAD	04/03/1994	F G MCCLINTOCK	Floating	Jack-Up	UKCS	Significant damage
371	1994	WOAD	2/27/1994	SEDCO 706	Floating	Semi-submersible	Netherlands	Minor damage
372	1994	WOAD	8/21/1994	BRAGE,31/4	Fixed	Jacket	Norway	Insignif/no damage
373	1994	HSE	17/01/1994		Floating	Jack-Up	UKCS	Minor
374	1994	HSE	11/03/1994		Fixed	Fixed Concrete	UKCS	Minor
375	1994	HSE	14/03/1994		Fixed	Fixed Concrete	UKCS	Minor
376	1994	HSE	10/04/1994		Fixed	Fixed Steel	UKCS	Minor
377	1994	HSE	01/07/1994		Uknown		UKCS	Minor
378	1994	HSE	09/07/1994		Fixed	Fixed Steel	UKCS	Minor
379	1994	HSE	19/08/1994		Fixed	Fixed Steel	UKCS	Minor
380	1994	HSE	06/11/1994		Floating	Semi-submersible	UKCS	Minor
381	1994	HSE	01/12/1994		Fixed	Fixed Steel	UKCS	Minor
382	1994	HSE	11/12/1994		Fixed	Fixed Steel	UKCS	Minor
383	1995	HSE	11/09/1995		Floating	Jack-Up	UKCS	Minor
384	1995	HSE	17/11/1995		Floating	Jack-Up	UKCS	Minor
385	1995	HSE	23/12/1995		Floating	Semi-submersible	UKCS	Minor
386	1996	WOAD	9/15/1996	SCARABEO 5	Floating	Semi-submersible	Norway	Minor damage
387	1996	WOAD	05/08/1996	SCARABEO 5	Floating	Semi-submersible	Norway	Insignif/no damage
388	1996	WOAD	3/18/1996	ROSS RIG	Floating	Semi-submersible	Norway	Minor damage
389	1996	HSE			Fixed	Fixed Steel	UKCS	
390	1996	HSE			Fixed	Fixed Steel	UKCS	
391	1996	MAIB			Fixed	Fixed Steel	UKCS	None
392	1996	HSE			Fixed	Fixed Steel	UKCS	Minor
393	1996	HSE			Fixed	Fixed Steel	UKCS	Minor
394	1996	HSE			Fixed	Fixed Steel	UKCS	Minor
395	1996	HSE			Fixed	Fixed Steel	UKCS	Minor
396	1996	HSE			Fixed	Fixed Steel	UKCS	Minor

397	1997	WOAD	02/07/1997	NEDDRILL 9	Floating	Jack-Up	Netherlands	Insignif/no damage
398	1997	WOAD	02/11/1997	OSEBERG,30/9,B	Fixed	Jacket	Norway	Insignif/no damage
399	1997	WOAD	11/23/1997	VALHALL,2/8A,PCP	Fixed	Jacket	Norway	Insignif/no damage
400	1997	WOAD	08/12/1997	CAPTAIN, 13/22A, FPSO	Floating	FPSO/FSU	UKCS	Minor damage
401	1997	WOAD	3/26/1997	BYFORD DOLPHIN	Floating	Semi-submersible	Norway	Insignif/no damage
402	1997	WOAD	3/21/1997	DEEPSEA TRYM	Floating	Semi-submersible	Norway	Insignif/no damage
403	1997	HSE			Floating	Jack-Up	UKCS	Unspecified
404	1997	MAIB			Floating	FPS	UKCS	Unspecified
405	1997	HSE			Floating	Jack-Up	UKCS	Unspecified
406	1997	HSE			Fixed	Fixed Steel	UKCS	Unspecified
407	1997	HSE			Floating	FPS	UKCS	Unspecified
408	1997	HSE			Fixed	Fixed Steel	UKCS	Unspecified
409	1997	HSE			Fixed	Fixed Steel	UKCS	Unspecified
410	1997	HSE			Fixed	Fixed Steel	UKCS	None
411	1997	HSE			Fixed	Fixed Steel	UKCS	Minor
412	1997	HSE			Floating	FPS	UKCS	Minor
413	1997	HSE			Fixed	Fixed Steel	UKCS	Minor
414	1997	HSE			Floating	FPS	UKCS	Minor
415	1997	HSE			Floating	Semi-submersible	UKCS	Minor
416	1997	HSE			Fixed	Fixed Steel	UKCS	Minor
417	1997	HSE			Floating	Jack-Up	UKCS	Minor
418	1998	WOAD	04/09/1998	SCARABEO 5	Floating	Semi-submersible	Norway	Insignif/no damage
419	1998	WOAD	1/22/1998	MAERSK GUARDIAN	Floating	Jack-Up	Norway	Insignif/no damage
420	1998	WOAD	11/11/1998	VARG,15/12B,B-FPSO	Floating	FPSO/FSU	Norway	Insignif/no damage
421	1998	HSE			Floating	Semi-submersible	UKCS	Unspecified

422	1998	HSE			Floating	Jack-Up	UKCS	Unspecified
423	1998	HSE			Floating	FPS	UKCS	Unspecified
424	1998	HSE			Floating	Jack-Up	UKCS	Unspecified
425	1998	HSE			Floating	Jack-Up	UKCS	Unspecified
426	1998	HSE			Fixed	Fixed Concrete	UKCS	Unspecified
427	1998	HSE			Fixed	Fixed Steel	UKCS	Unspecified
428	1998	HSE			Floating	Semi-submersible	UKCS	Unspecified
429	1998	HSE			Floating	Jack-Up	UKCS	Unspecified
430	1998	HSE			Floating	FPS	UKCS	
431	1998	HSE			Floating	Semi-submersible	UKCS	Minor
432	1998	HSE			Fixed	Fixed Steel	UKCS	
433	1998	HSE			Floating	Semi-submersible	UKCS	
434	1998	HSE			Floating	Jack-Up	UKCS	
435	1998	HSE			Fixed	Fixed Concrete	UKCS	
436	1998	HSE			Uknown	Uknown	UKCS	
437	1999	WOAD	12/31/1999	GULLFAKS,34/10,A	Fixed	Concrete structure	Norway	Insignif/no damage
438	1999	WOAD	09/10/1999	EKOFISK,2/4,K WATERFLOOD	Fixed	Jacket	Norway	Minor damage
439	1999	WOAD	02/01/1999	DEEPSEA TRYM	Floating	Semi-submersible	Norway	Significant damage
440	1999	WOAD	2/23/1999	TRANSOCEAN ARCTIC	Floating	Semi-submersible	Norway	Insignif/no damage
441	1999	WOAD	11/29/1999	TRANSOCEAN WILDCAT	Floating	Semi-submersible	Norway	Minor damage
442	1999	WOAD	8/25/1999	BIDEFORD DOLPHIN	Floating	Semi-submersible	Norway	Insignif/no damage
443	1999	WOAD	6/20/1999	MAERSK GUARDIAN	Floating	Jack-Up	Norway	Insignif/no damage
444	1999	WOAD	5/31/1999	ELDFISK,2/7,A	Fixed	Jacket	Norway	Insignif/no damage
445	1999	HSE			Fixed	Fixed Steel	UKCS	Unspecified
446	1999	HSE			Floating	Semi-submersible	UKCS	Unspecified
447	1999	HSE			Uknown	Uknown	UKCS	None

448	1999	HSE			Fixed	Fixed Steel	UKCS	None
449	1999	HSE			Fixed	Fixed Steel	UKCS	None
450	1999	HSE			Floating	Jack-Up	UKCS	None
451	1999	HSE			Floating	Semi-submersible	UKCS	Minor
452	1999	HSE			Floating	Jack-Up	UKCS	Minor
453	1999	HSE			Floating	Semi-submersible	UKCS	Minor
454	1999	HSE			Fixed	Fixed Steel	UKCS	Minor
455	1999	HSE			Floating	Jack-Up	UKCS	Minor
456	1999	HSE			Floating	Semi-submersible	UKCS	Minor
457	1999	HSE			Fixed	Fixed Steel	UKCS	Minor
458	1999	HSE			Fixed	Fixed Steel	UKCS	Minor
459	2000	WOAD	4/13/2000	AASGARD B	Floating	Semi-submersible	Norway	Significant damage
460	2000	HSE			Fixed	Fixed Steel	UKCS	Unspecified
461	2000	HSE			Floating	Semi-submersible	UKCS	Unspecified
462	2000	HSE			Floating	Jack-Up	UKCS	Unspecified
463	2000	HSE			Uknown	Uknown	UKCS	None
464	2000	HSE			Fixed	Fixed Steel	UKCS	Minor
465	2000	HSE			Fixed	Fixed Steel	UKCS	Minor
466	2000	HSE			Fixed	Fixed Steel	UKCS	Minor
467	2000	HSE			Floating	Semi-submersible	UKCS	Minor
468	2000	HSE			Fixed	Fixed Steel	UKCS	Minor
469	2000	HSE			Floating	Semi-submersible	UKCS	Minor
470	2000	HSE			Fixed	Fixed Steel	UKCS	Minor
471	2000	HSE			Fixed	Fixed Steel	UKCS	Minor
472	2000	MAIB			Floating	Jack-Up	UKCS	Minor
473	2001	WOAD	4/23/2001	P/15(RIJN)-F	Fixed	Jacket	Netherlands	Insignif/no damage
474	2001	WOAD	1/19/2001	DEEPSEA BERGEN	Floating	Semi-submersible	Norway	Minor damage
475	2001	HSE			Floating	Semi-submersible	UKCS	Unspecified
476	2001	HSE			Floating	Semi-submersible	UKCS	Unspecified
477	2001	HSE			Fixed	Fixed Steel	UKCS	None
478	2001	HSE			Floating	Jack-Up	UKCS	Minor

479	2001	HSE			Fixed	Fixed Steel	UKCS	Minor
480	2001	HSE			Fixed	Fixed Steel	UKCS	Minor
481	2001	HSE	37013	, John Shaw	Floating	Semi-submersible	UKCS	Collision that causes damage
482	2001	HSE	37063	, Captain WPP	Fixed	Jacket	UKCS	Collision that causes damage
483	2001	HSE	37087	, Viking CD	Fixed	Fixed steel	UKCS	Collision that causes damage
484	2001	HSE	37192	, Murdoch 44/22A-MD	Fixed	Fixed Steel	UKCS	Collision that causes damage
485	2002	WOAD	12/29/2002	STENA DEE	Floating	Semi-submersible	UKCS	Insignif/no damage
486	2002	WOAD	05/08/2002	ROUGH,47/8,BD	Fixed	Jacket	UKCS	Significant damage
487	2002	HSE	05/01/2002	Ocean Guardian	Floating	Semi-submersible	UKCS	Collision that causes damage
488	2002	HSE	11/04/2002	Magellan	Floating	Jack-Up	UKCS	Collision that causes damage
489	2002	HSE	25/04/2002	Sedco 706	Floating	Semi-submersible	UKCS	Collision that causes damage
490	2002	HSE	19/10/2002	Alba FSU	Floating	FSU	UKCS	Collision that causes damage
491	2002	MAIB		BRAVO DELTA (Fixed Steel)	Uknown	Uknown	UKCS	Minor
492	2003	WOAD	11/21/2003	EIDER 211/16A	Fixed	Jacket	UKCS	Insignif/no damage
493	2003	HSE	37658		Floating	Jack-Up	UKCS	Collision that causes damage
494	2003	HSE	37764		Fixed	Fixed Steel	UKCS	Collision that causes damage
495	2003	HSE	37918		Fixed	Fixed Concrete	UKCS	Collision that causes damage

496	2003	HSE	37979		Floating	Jack-Up	UKCS	Collision that causes damage
497	2004	WOAD	03/07/2004	West Venture	Floating	Semi-submersible	Norway	Minor damage
498	2004	HSE	03/03/2004	C Prospect	Uknown	Uknown	UKCS	Collision that causes damage
499	2004	HSE	26/03/2004	Douglas Complex	Floating	Jack-Up	UKCS	Collision that causes damage
500	2004	HSE	26/08/2004	West Sole Alpha Platform	Fixed	Fixed Steel	UKCS	Collision that causes damage
501	2004	HSE	07/10/2004	Forties Charlie	Fixed	Fixed Steel	UKCS	Collision that causes damage
502	2005	WOAD	06/02/2005	Ekofisk T	Fixed	Concrete structure	Norway	Minor damage
503	2005	WOAD	4/14/2005	Ensco 70	Floating	Jack-Up	Denmark	Significant damage
504	2005	WOAD	4/27/2005	Grane	Fixed	Jacket	Norway	Significant damage
505	2005	WOAD	10/30/2005	BORGLAND DOLPHIN	Floating	Semi-submersible	Norway	Minor damage
506	2005	WOAD	06/02/2005	EKOFISK,2/4A,P	Fixed	Jacket	Norway	Minor damage
507	2005	WOAD	18/07/2005	Noble Al White	Floating	Jack-Up	Netherlands	Insignif/no damage
508	2005	HSE	27/03/2005	GSF Galaxy III	Floating	Jack-Up	UKCS	Collision that causes damage
509	2005	HSE	11/05/2005	Buchan Alpha	Floating	Semi-submersible	UKCS	Collision that causes damage
510	2005	HSE	21/05/2005	Forties Alpha	Fixed	Fixed Steel	UKCS	Collision that causes damage
511	2005	HSE	24/07/2005	Brent A	Fixed	Fixed Steel	UKCS	Collision that causes damage
512	2005	HSE	25/08/2005	Forties Delta	Fixed	Fixed Steel	UKCS	Collision that causes damage
513	2005	HSE	09/10/2005	Buchan A	Floating	Semi-submersible	UKCS	Collision that causes damage

514	2005	HSE	03/11/2005	BP Schiehallion FPSO	Floating	FPSO	UKCS	Collision that causes damage
515	2006	WOAD	11/13/2006	NJORD B	Floating	FPSO/FSU	Norway	Minor damage
516	2006	WOAD	02/10/2006	HEIMDAL,25/4,A	Fixed	Jacket	Norway	Insignif/no damage
517	2006	WOAD	06/03/2006	SNORRE, 34/7	Floating	TLP	Norway	Minor damage
518	2006	WOAD	06/07/2006	TYRA, 5504/6.2, TW-A	Fixed	Jacket	Denmark	Insignif/no damage
519	2006	WOAD	28/02/2006	BIDEFORD DOLPHIN	Floating	Semi-submersible	Norway	Insignif/no damage
520	2006	HSE	16/08/2006	Douglas DW	Fixed	Fixed Steel	UKCS	Collision that causes damage
521	2006	HSE	11/09/2006	Shearwater WHP	Fixed	Fixed Steel	UKCS	Collision that causes damage
522	2006	HSE	07/10/2006	Buzzard	Fixed	Fixed Steel	UKCS	Collision that causes damage
523	2006	HSE	25/10/2006	The FPSO Uisge Gorm	Floating	FPSO	UKCS	Collision that causes damage
524	2006	HSE	30/11/2006	Rig E92 - Vessel - Havila Fame	Floating	Jack-Up	UKCS	Collision that causes damage
525	2006	HSE	08/12/2006	ETAP CPF	Fixed	Fixed Steel	UKCS	Collision that causes damage
526	2007	WOAD	07/09/2007	Grane	Fixed	Jacket	Norway	Minor damage
527	2007	HSE	11/03/2007	FPSO Maersk Curlew	Floating	FPSO	UKCS	Collision that causes damage
528	2007	HSE	02/06/2007	Sea fox 4 and the power express	Floating	Jack-Up	UKCS	Collision that causes damage
529	2007	HSE	16/06/2007	Rowan Gorilla V11	Floating	Jack-Up	UKCS	Collision that causes damage
530	2007	HSE	08/07/2007	Sedco 704	Floating	Semi-submersible	UKCS	Collision that causes damage
531	2007	HSE	27/07/2007	Rowan Gorilla VI	Floating	Jack-Up	UKCS	Collision that causes damage

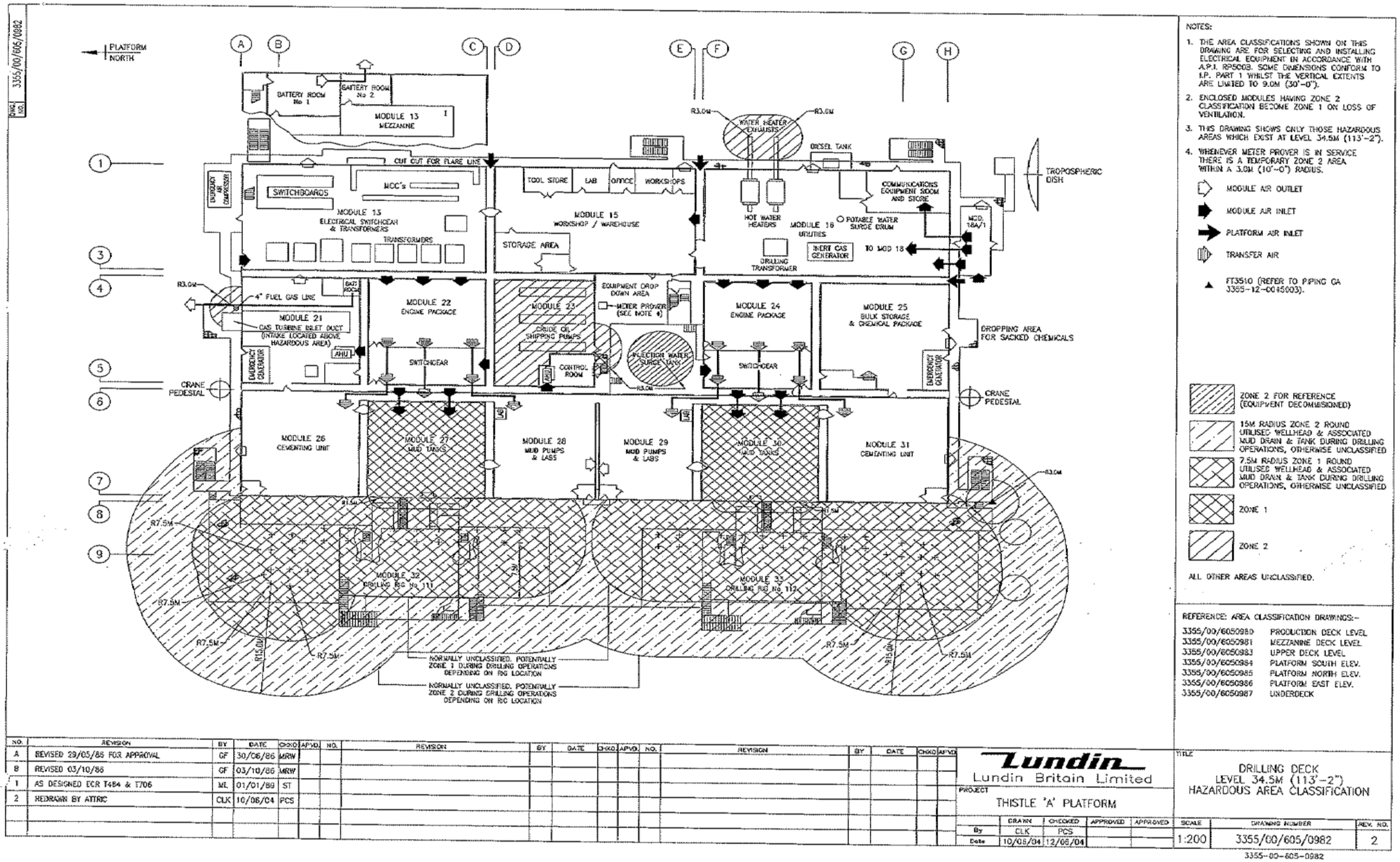
532	2007	HSE	28/07/2007	GSF Galaxy	Floating	Jack-Up	UKCS	Collision that causes damage
533	2007	HSE	31/07/2007	GSF Labrador	Floating	Jack-Up	UKCS	Collision that causes damage
534	2007	HSE	04/08/2007	Viking Echo Delta Platform NUI	Fixed	Fixed Steel	UKCS	Collision that causes damage
535	2007	HSE	01/10/2007	Leman Alpha	Fixed	Fixed Steel	UKCS	Collision that causes damage
536	2007	HSE	04/11/2007	Borgholm Dolphin	Floating	Semi-submersible	UKCS	Collision that causes damage
537	2007	HSE	24/12/2007	BP Harding Platform	Fixed	Fixed Steel	UKCS	Collision that causes damage
538	2008	WOAD	11/04/2008	TRANSOCEAN WINNER	Floating	Semi-submersible	Norway	Minor damage
539	2008	HSE	05/05/2008	Noble Julie Robertson	Floating	Jack-Up	UKCS	Collision that causes damage
540	2008	HSE	02/09/2008	Goldeneye Offshore Platform Installation	Fixed	Fixed Steel	UKCS	Collision that causes damage
541	2008	HSE	29/09/2008	Transocean Rather	Floating	Semi-submersible	UKCS	Collision that causes damage
542	2008	HSE	05/10/2008	ENSCO 100	Floating	Jack-Up	UKCS	Collision that causes damage
543	2008	HSE	06/10/2008	n.k	Uknown	Uknown	UKCS	Collision that causes damage
544	2008	HSE	03/11/2008	Stamford Well	Fixed	Fixed Steel	UKCS	Collision that causes damage
545	2008	HSE	17/11/2008	Sedco 704	Floating	Semi-submersible	UKCS	Collision that causes damage
546	2008	HSE	26/11/2008	Noble Julie Robertson	Floating	Jack-Up	UKCS	Collision that causes damage
547	2009	WOAD	02/04/2009	Ensco 92	Floating	Jack-Up	UKCS	Minor damage
548	2009	WOAD	05/03/2009	Thistle, 211/18A, A	Fixed	Jacket	UKCS	Insignif/no damage

549	2009	WOAD	10/09/2009	K5-P	Fixed	Jacket	Netherlands	Insignif/no damage
550	2009	WOAD	06/08/2009	EKOFISK,2/4,W	Fixed	Jacket	Norway	Total loss
551	2009	HSE	28/06/2009	Stena Spey	Floating	Semi-submersible	UKCS	Collision that causes damage
552	2009	HSE	08/10/2009	Schiehallion FPSO	Floating	FPSO	UKCS	Collision that causes damage
553	2010	WOAD	1/18/2010	Songa Dee	Floating	Semi-submersible	Norway	Significant damage
554	2010	HSE	40238	FPSO Petrojari Foinaven	Floating	FPSO	UKCS	Collision that causes damage
555	2010	HSE	40251	Ensco 100 MMSI 636009436 - Cygnus	Floating	Jack-Up	UKCS	Collision that causes damage
556	2010	HSE	40401	Byford Dolphin	Floating	Semi-submersible	UKCS	Collision that causes damage
557	2010	HSE	40460	Ocean Princess	Floating	Semi-submersible	UKCS	Collision that causes damage
558	2010	HSE	40503	Leman 49 / 27 / AC	Fixed	Fixed Steel	UKCS	Collision that causes damage
559	2011	WOAD	4/22/2011	Magnus,211/12, Production	Fixed	Jacket	UKCS	Insignif/no damage
560	2011	WOAD	09/03/2011	Unknown fixed platform WACP	Fixed	Uknown	Netherlands	Minor damage
561	2011	WOAD	1/23/2011	Ekofisk J	Fixed	Jacket	Norway	Minor damage
562	2011	HSE	40594	Britannia Platform	Fixed	Fixed Steel	UKCS	Collision that causes damage
563	2011	HSE	40695	Piper B Platform	Fixed	Fixed Steel	UKCS	Collision that causes damage
564	2011	HSE	40737	Noble Julie Robertson (Jack-up MODU)	Floating	Jack-Up	UKCS	Collision that causes damage
565	2011	HSE	40775	Gannet Alpha/ Edda Fides	Fixed	Fixed Steel	UKCS	Collision that causes damage

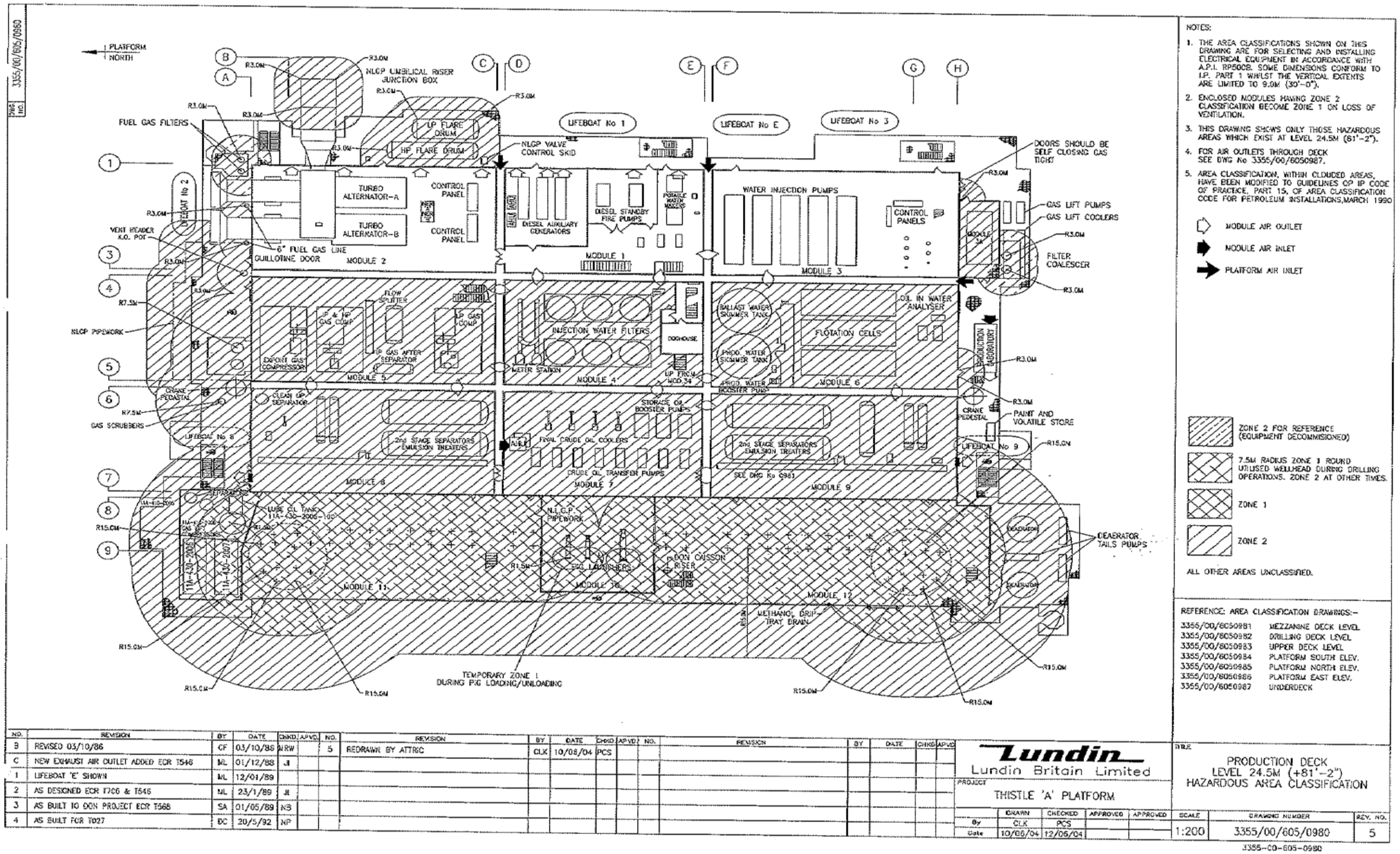
566	2011	HSE	40846.14236	Starboard Aft Column	Uknown	Uknown	UKCS	Collision that causes damage
567	2012	WOAD	03/11/2012	COSLPioneer	Floating	Semi-submersible	Norway	Insignif/no damage
568	2012	HSE	29/03/2012	North side of installation	Uknown	Uknown	UKCS	Collision that causes damage
569	2012	HSE	16/09/2012	Walk to work platform	Uknown	Uknown	UKCS	Collision that causes damage
570	2012	HSE	18/09/2012	Clipper PT leg C1	Fixed	Fixed Steel	UKCS	Collision that causes damage
571	2013	WOAD	01/04/2013	ELDFISK,2/7,B	Fixed	Jacket	Norway	Insignif/no damage
572	2013	WOAD	02/06/2013	VALHALL FLANKE NORD	Fixed	Jacket	Norway	Minor damage
573	2013	WOAD	12/10/2013	MAERSK INNOVATOR	Floating	Jack-Up	Norway	Insignif/no damage
574	2013	HSE	20/01/2013	unknown	Uknown	Uknown	UKCS	Collision that causes damage
575	2013	HSE	29/01/2013	Well Head Platform	Uknown	Uknown	UKCS	Collision that causes damage
576	2013	HSE	12/05/2013	Janice Alpha	Floating	Semi-submersible	UKCS	Collision that causes damage
577	2013	HSE	26/06/2013	Installation legs	Uknown	Uknown	UKCS	Collision that causes damage
578	2013	HSE	29/06/2013	Judy Riser Platform	Fixed	Fixed Steel	UKCS	Collision that causes damage
579	2013	HSE	22/09/2013	48/29A-48/29Q bridge	Fixed	Fixed Steel	UKCS	Collision that causes damage
580	2013	HSE	12/12/2013	Preload Tank 7P2	Uknown	Uknown	UKCS	Collision that causes damage
581	2014	HSE	04/01/2014	PW jacket	Fixed	Jacket	UKCS	Collision that causes damage

582	2014	HSE	01/03/2014	Nexen Golden Eagle Platform	Floating	Jack-Up	UKCS	Collision that causes damage
583	2014	HSE	30/05/2014	Leman Alpha AD1 Jacket leg B1.	Fixed	Fixed Steel	UKCS	Collision that causes damage

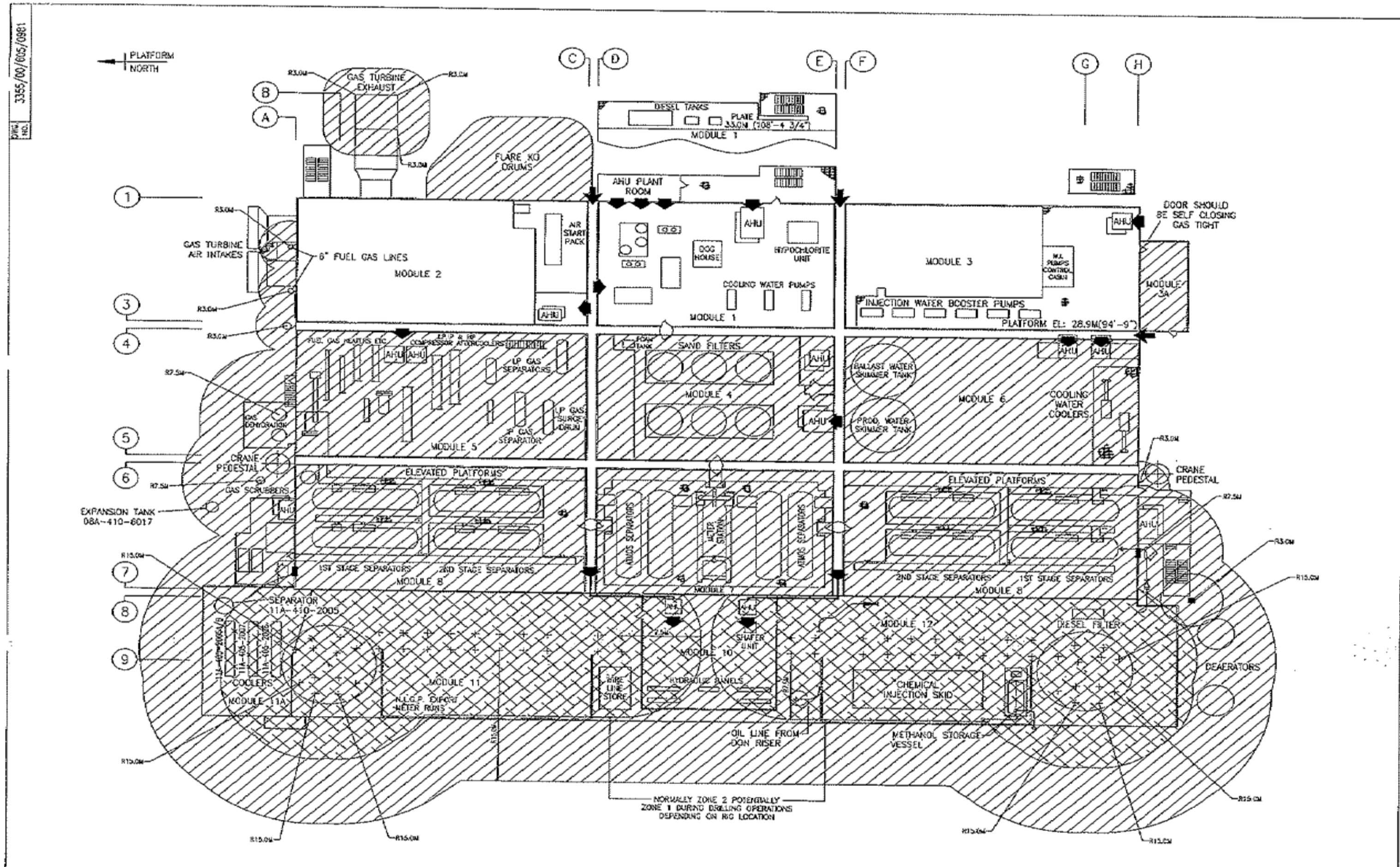
APPENDIX E: Thistle Plot Plans



DWG. NO. 3355/00/605/0982
PLATFORM NORTH
A B C D E F G H
1 3 4 5 6 7 8 9
BATTERY ROOM No 1
BATTERY ROOM No 2
MODULE 13 MEZZANINE
CUT OUT FOR FLARE LINE
EMERGENCY AIR COMPRESSOR
SWITCHBOARDS
MCC's
MODULE 13 ELECTRICAL SWITCHGEAR & TRANSFORMERS
TRANSFORMERS
TOOL STORE
LAB
OFFICE
WORKSHOPS
MODULE 15 WORKSHOP / WAREHOUSE
STORAGE AREA
R3.0M
WATER HEATER EXHAUSTS
DIESEL TANK
COMMUNICATIONS EQUIPMENT ROOM AND STORE
TROPOSPHERIC DISH
HOT WATER HEATERS
MODULE 16 UTILITIES
POTABLE WATER SURGE DRUM
INERT GAS GENERATOR
TO MOD 18
DRILLING TRANSFORMER
MOD. 16A/1
4" FUEL GAS LINE
MODULE 21
GAS TURBINE INLET DUCT (INTAKE LOCATED ABOVE HAZARDOUS AREA)
AHU
EMERGENCY GENERATOR
MODULE 22 ENGINE PACKAGE
SWITCHGEAR
MODULE 23 CRUDE OIL SHIPPING PUMPS
EQUIPMENT DROP DOWN AREA
METER PROVER (SEE NOTE 4)
CONTROL ROOM
INJECTION WATER SURGE TANK
MODULE 24 ENGINE PACKAGE
SWITCHGEAR
MODULE 25 BULK STORAGE & CHEMICAL PACKAGE
EMERGENCY GENERATOR
DROPPING AREA FOR SACKED CHEMICALS
CRANE PEDESTAL
CRANE PEDESTAL
MODULE 26 CEMENTING UNIT
MODULE 27 MUD TANKS
MODULE 28 MUD PUMPS & LABS
MODULE 29 MUD PUMPS & LABS
MODULE 30 MUD TANKS
MODULE 31 CEMENTING UNIT
MODULE 32 DRILLING RIG No 111
MODULE 33 DRILLING RIG No 112
R7.5M
R15.0M
R1.5M
NORMALLY UNCLASSIFIED. POTENTIALLY ZONE 1 DURING DRILLING OPERATIONS DEPENDING ON RIG LOCATION
NORMALLY UNCLASSIFIED. POTENTIALLY ZONE 2 DURING DRILLING OPERATIONS DEPENDING ON RIG LOCATION
NOTES:
1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M (30'-0").
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
3. THIS DRAWING SHOWS ONLY THOSE HAZARDOUS AREAS WHICH EXIST AT LEVEL 34.5M (113'-2").
4. WHENEVER METER PROVER IS IN SERVICE THERE IS A TEMPORARY ZONE 2 AREA WITHIN A 3.0M (10'-0") RADIUS.
MODULE AIR OUTLET
MODULE AIR INLET
PLATFORM AIR INLET
TRANSFER AIR
FT3510 (REFER TO PIPING GA 3355-12-0045003).
ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISSIONED)
15M RADIUS ZONE 2 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED
7.5M RADIUS ZONE 1 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED
ZONE 1
ZONE 2
ALL OTHER AREAS UNCLASSIFIED.
REFERENCE: AREA CLASSIFICATION DRAWINGS:-
3355/00/6050980 PRODUCTION DECK LEVEL
3355/00/6050981 MEZZANINE DECK LEVEL
3355/00/6050983 UPPER DECK LEVEL
3355/00/6050984 PLATFORM SOUTH ELEV.
3355/00/6050985 PLATFORM NORTH ELEV.
3355/00/6050986 PLATFORM EAST ELEV.
3355/00/6050987 UNDERDECK
NO. REVISION BY DATE CHKD APVD.
A REVISED 29/05/86 FOR APPROVAL GF 30/06/86 MRW
B REVISED 03/10/86 GF 03/10/86 MRW
1 AS DESIGNED ECR T484 & T706 ML 01/01/89 ST
2 REDRAWN BY ATTRIC CLK 10/06/04 PCS
Lundin
Lundin Britain Limited
PROJECT
THISTLE 'A' PLATFORM
TITLE
DRILLING DECK
LEVEL 34.5M (113'-2")
HAZARDOUS AREA CLASSIFICATION
DRAWN CHECKED APPROVED APPROVED
By CLK PCS
Date 10/06/04 12/06/04
SCALE 1:200
DRAWING NUMBER 3355/00/605/0982
REV. NO. 2
3355-00-605-0982



PLATFORM NORTH
NOTES:
1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M (30'-0").
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
3. THIS DRAWING SHOWS ONLY THOSE HAZARDOUS AREAS WHICH EXIST AT LEVEL 24.5M (81'-2").
4. FOR AIR OUTLETS THROUGH DECK SEE DWG No 3355/00/6050987.
5. AREA CLASSIFICATION, WITHIN CLOUDED AREAS, HAVE BEEN MODIFIED TO GUIDELINES OF IP CODE OF PRACTICE, PART 15, OF AREA CLASSIFICATION CODE FOR PETROLEUM INSTALLATIONS,MARCH 1990
MODULE AIR OUTLET
MODULE AIR INLET
PLATFORM AIR INLET
ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISSIONED)
7.5M RADIUS ZONE 1 ROUND UTILISED WELLHEAD DURING DRILLING OPERATIONS. ZONE 2 AT OTHER TIMES.
ZONE 1
ZONE 2
ALL OTHER AREAS UNCLASSIFIED.
REFERENCE: AREA CLASSIFICATION DRAWINGS:-
3355/00/6050981 MEZZANINE DECK LEVEL
3355/00/6050982 DRILLING DECK LEVEL
3355/00/6050983 UPPER DECK LEVEL
3355/00/6050984 PLATFORM SOUTH ELEV.
3355/00/6050985 PLATFORM NORTH ELEV.
3355/00/6050986 PLATFORM EAST ELEV.
3355/00/6050987 UNDERDECK
LIFEBOAT No 1
LIFEBOAT No E
LIFEBOAT No 3
LIFEBOAT No 2
LIFEBOAT No 8
LIFEBOAT No 9
FUEL GAS FILTERS
NLGP UMBILICAL RISER JUNCTION BOX
LP FLARE DRUM
HP FLARE DRUM
NLGP VALVE CONTROL SKID
DOORS SHOULD BE SELF CLOSING GAS TIGHT
TURBO ALTERNATOR-A
TURBO ALTERNATOR-B
CONTROL PANEL
6" FUEL GAS LINE GUILLOTINE DOOR
MODULE 2
DIESEL AUXILIARY GENERATORS
DIESEL STANDBY FIRE PUMPS
MODULE 1
WATER INJECTION PUMPS
CONTROL PANELS
MODULE 3
GAS LIFT PUMPS
GAS LIFT COOLERS
FILTER COALESCER
VENT HEADER K.O. POT
NLGP PIPEWORK
FLOW SPLITTER
LP & HP GAS COMP
IP GAS COMP
IP GAS AFTER SEPARATOR
EXPORT GAS COMPRESSOR
MODULE 5
INJECTION WATER FILTERS
METER STATION
DOGHOUSE
MODULE 4
BALLAST WATER SKIMMER TANK
PROD. WATER SKIMMER TANK
OIL IN WATER ANALYSER
FLOTATION CELLS
PRODUCTION LABORATORY
MODULE 6
CRANE PEDESTAL
GAS SCRUBBERS
CLEAN UP SEPARATOR
2nd STAGE SEPARATORS EMULSION TREATERS
MODULE 8
STORAGE OR BOOSTER PUMPS
FINAL CRUDE OIL COOLERS
CRUDE OIL TRANSFER PUMPS
MODULE 7
SEE DWG No 0981
MODULE 9
PAINT AND VOLATILE STORE
SEPARATORS
LUBE OIL TANK
N.L.G.P. PIPEWORK
PIG LAUNCHERS
DON CAISSON RISER
MODULE 11
MODULE 10
MODULE 12
METHANOL DRIP TRAY DRAIN
DEAERATOR TAILS PUMPS
TEMPORARY ZONE 1 DURING PIG LOADING/UNLOADING
R3.0M
R7.5M
R15.0M
NO. | REVISION | BY | DATE | CHKD. | APVD.
B | REVISED 03/10/86 | CF | 03/10/86 | NRW
C | NEW EXHAUST AIR OUTLET ADDED ECR T546 | ML | 01/12/88 | JI
1 | LIFEBOAT 'E' SHOWN | ML | 12/01/89
2 | AS DESIGNED ECR T706 & T546 | ML | 23/1/89 | JI
3 | AS BUILT TO DON PROJECT ECR T566 | SA | 01/06/89 | NB
4 | AS BUILT FOR T027 | DC | 20/5/92 | NP
5 | REDRAWN BY ATTRC | CLK | 10/06/04 | PCS
Lundin
Lundin Britain Limited
PROJECT THISTLE 'A' PLATFORM
TITLE PRODUCTION DECK LEVEL 24.5M (+81'-2") HAZARDOUS AREA CLASSIFICATION
DRAWN CLK 10/06/04
CHECKED PCS 12/06/04
SCALE 1:200
DRAWING NUMBER 3355/00/605/0980
REV. NO. 5
3355-00-605-0980



NOTES:

1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M (30'-0").
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
3. THIS DRAWING SHOWS ONLY THOSE HAZARDOUS AREAS WHICH EXIST AT LEVEL 29.5M (97'-2").
4. AREA CLASSIFICATION, WITHIN CLOUDED AREAS, HAVE BEEN MODIFIED TO GUIDELINES OF IP CODE OF PRACTICE, PART 15, OF AREA CLASSIFICATION CODE FOR PETROLEUM INSTALLATIONS,MARCH 1990

MODULE AIR OUTLET

MODULE AIR INLET

PLATFORM AIR INLET

GT55 (REFER TO PIPING GA 3355-12-0045003).

ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISSIONED)

7.5M RADIUS ZONE 1 ROUND UTILISED WELLHEAD DURING DRILLING OPERATIONS. ZONE 2 AT OTHER TIMES.

ZONE 1

ZONE 2

ALL OTHER AREAS UNCLASSIFIED.

REFERENCE: AREA CLASSIFICATION DRAWINGS:-

3355/00/6050980	PRODUCTION DECK LEVEL
3355/00/6050982	DRILLING DECK LEVEL
3355/00/6050983	UPPER DECK LEVEL
3355/00/6050984	PLATFORM SOUTH ELEV.
3355/00/6050985	PLATFORM NORTH ELEV.
3355/00/6050986	PLATFORM EAST ELEV.
3355/00/6050987	UNDERDECK

NO.	REVISION	BY	DATE	CHKD	APVD
A	REVISED 29/05/86	GF	30/05/86	MRW	
B	REVISED 03/10/86	GF	03/10/86	MRW	
1	AS DESIGNED ECR T706 & T546	ML	01/01/89	JI	
2	AS BUILT TO DON PROJECT ECR T568	SA	01/05/89	NB	
3	AS BUILT FOR T027	DC	20/05/92		
4	REDRAWN BY ATIKC	CLK	10/06/04	PCS	

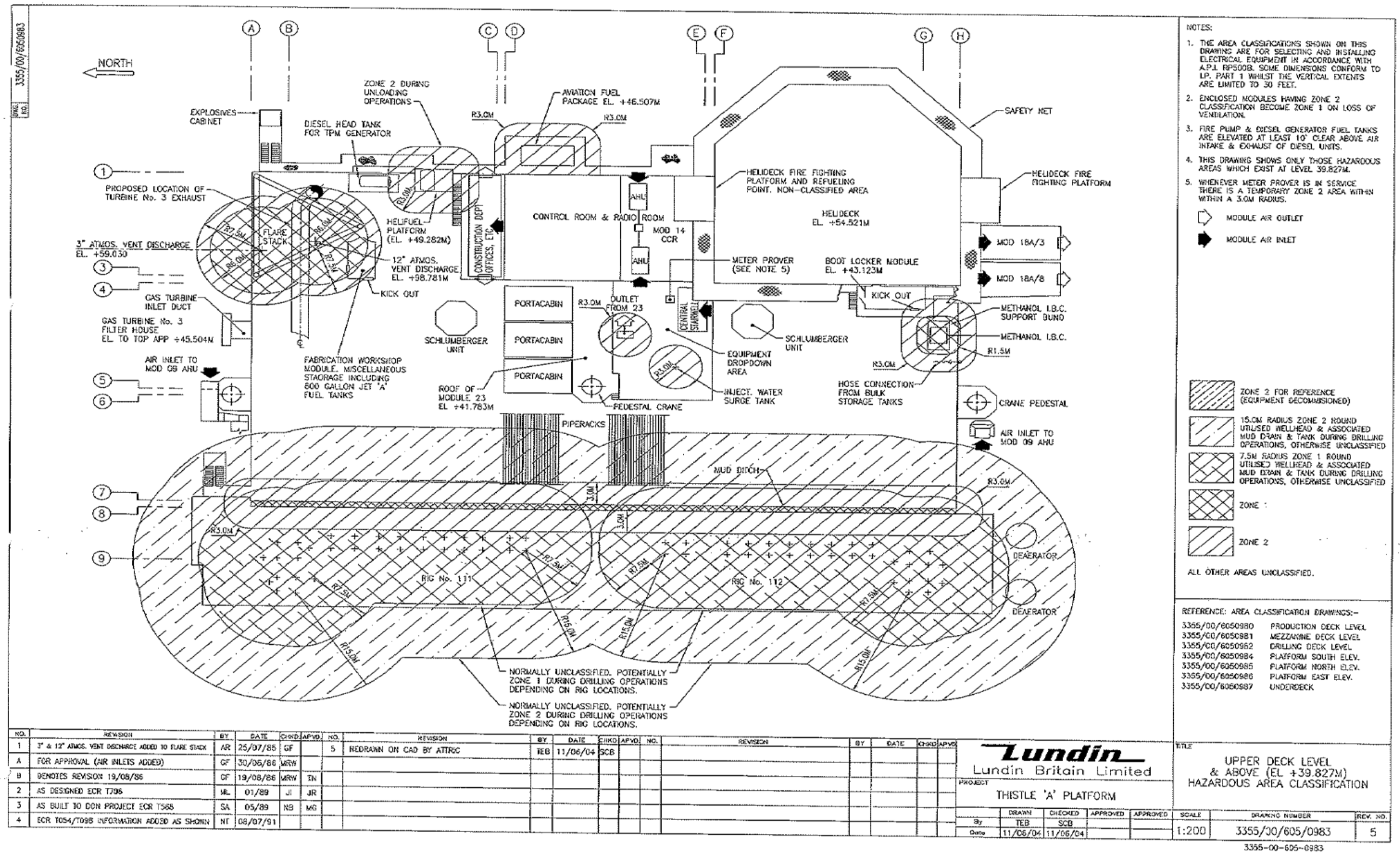
Lundin
Lundin Britain Limited

PROJECT
THISTLE 'A' PLATFORM

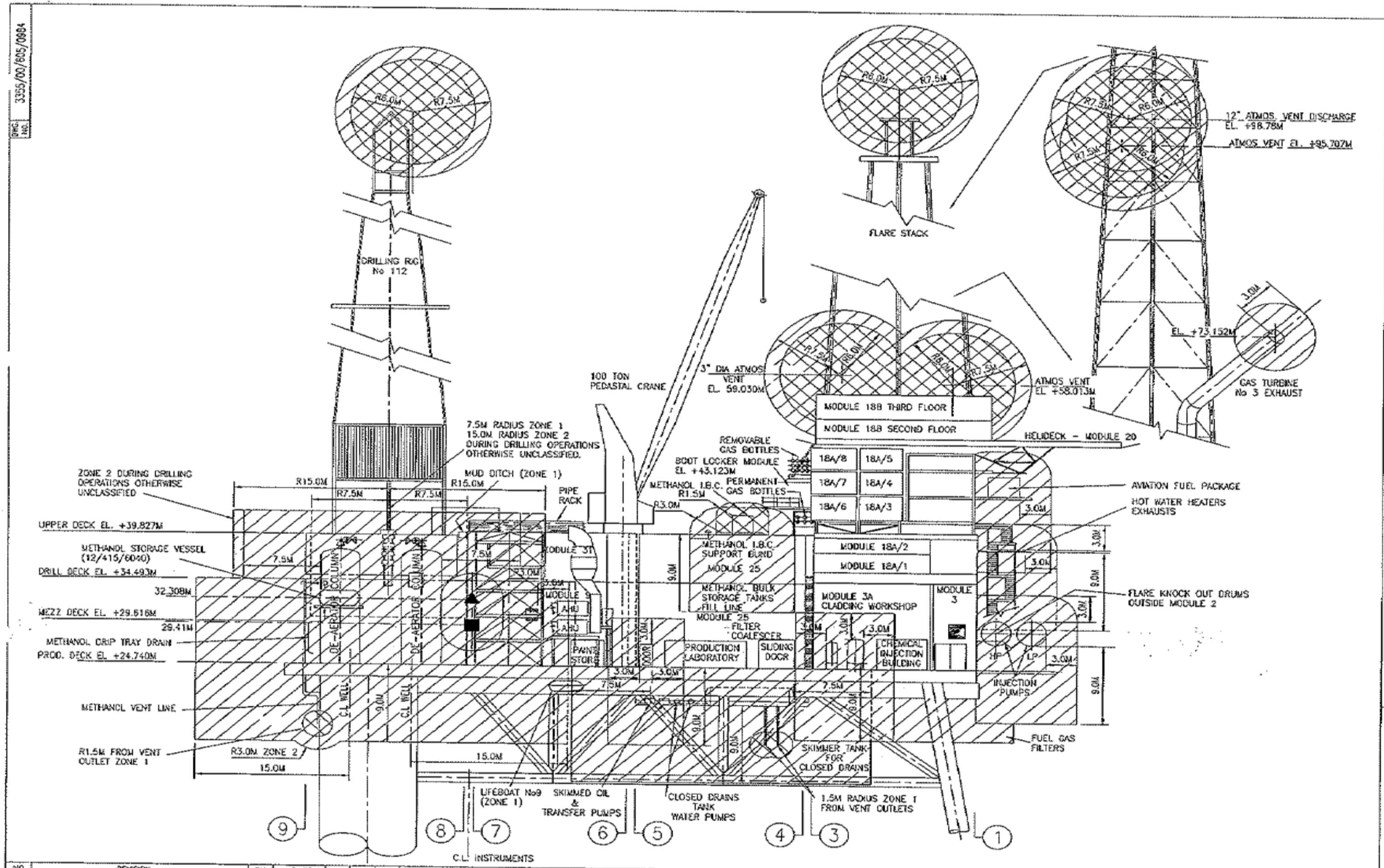
TITLE
MEZZANINE DECK
LEVEL 29.5M (97'-2")
HAZARDOUS AREA CLASSIFICATION

	DRAWN	CHECKED	APPROVED	APPROVED
By	CLK	PCS		
Date	10/06/04	12/06/04		

SCALE	DRAWING NUMBER	REV. NO.
1:200	3355/00/605/0981	4



DWG. NO. 3355/00/6050983
NORTH
EXPLOSIVES CABINET
ZONE 2 DURING UNLOADING OPERATIONS
DIESEL HEAD TANK FOR TPM GENERATOR
AVIATION FUEL PACKAGE EL. +46.507M
R3.0M
SAFETY NET
PROPOSED LOCATION OF TURBINE No. 3 EXHAUST
FLARE STACK
3" ATMOS. VENT DISCHARGE EL. +59.030
HELIFUEL PLATFORM (EL. +49.282M)
12" ATMOS. VENT DISCHARGE EL. +98.781M
KICK OUT
CONSTRUCTION DEPT OFFICES, ETC.
CONTROL ROOM & RADIO ROOM
MOD 14 CCR
AHU
HELIDECK FIRE FIGHTING PLATFORM AND REFUELING POINT. NON-CLASSIFIED AREA
HELIDECK EL. +54.521M
HELIDECK FIRE FIGHTING PLATFORM
METER PROVER (SEE NOTE 5)
BOOT LOCKER MODULE EL. +43.123M
MOD 18A/3
MOD 18A/8
GAS TURBINE INLET DUCT
GAS TURBINE No. 3 FILTER HOUSE EL. TO TOP APP +45.504M
PORTACABIN
OUTLET FROM 23
CENTRAL STAIRWELL
SCHLUMBERGER UNIT
METHANOL I.B.C. SUPPORT BUND
METHANOL I.B.C.
R1.5M
AIR INLET TO MOD 09 AHU
FABRICATION WORKSHOP MODULE, MISCELLANEOUS STAORAGE INCLUDING 800 GALLON JET 'A' FUEL TANKS
ROOF OF MODULE 23 EL +41.783M
PEDESTAL CRANE
EQUIPMENT DROPDOWN AREA
INJECT. WATER SURGE TANK
HOSE CONNECTION FROM BULK STORAGE TANKS
CRANE PEDESTAL
PIPERACKS
MUD DITCH
DEAERATOR
RIG No. 111
RIG No. 112
R7.5M
R15.0M
NORMALLY UNCLASSIFIED. POTENTIALLY ZONE 1 DURING DRILLING OPERATIONS DEPENDING ON RIG LOCATIONS.
NORMALLY UNCLASSIFIED. POTENTIALLY ZONE 2 DURING DRILLING OPERATIONS DEPENDING ON RIG LOCATIONS.
NOTES:
1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 30 FEET.
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
3. FIRE PUMP & DIESEL GENERATOR FUEL TANKS ARE ELEVATED AT LEAST 10' CLEAR ABOVE AIR INTAKE & EXHAUST OF DIESEL UNITS.
4. THIS DRAWING SHOWS ONLY THOSE HAZARDOUS AREAS WHICH EXIST AT LEVEL 39.827M.
5. WHENEVER METER PROVER IS IN SERVICE THERE IS A TEMPORARY ZONE 2 AREA WITHIN WITHIN A 3.0M RADIUS.
MODULE AIR OUTLET
MODULE AIR INLET
ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISIONED)
15.0M RADIUS ZONE 2 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED
7.5M RADIUS ZONE 1 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED
ZONE 1
ZONE 2
ALL OTHER AREAS UNCLASSIFIED.
REFERENCE: AREA CLASSIFICATION DRAWINGS:-
3355/00/6050980 PRODUCTION DECK LEVEL
3355/00/6050981 MEZZANINE DECK LEVEL
3355/00/6050982 DRILLING DECK LEVEL
3355/00/6050984 PLATFORM SOUTH ELEV.
3355/00/6050985 PLATFORM NORTH ELEV.
3355/00/6050986 PLATFORM EAST ELEV.
3355/00/6050987 UNDERDECK
NO. REVISION BY DATE CHKD. APVD.
1 3" & 12" ATMOS. VENT DISCHARGE ADDED TO FLARE STACK AR 25/07/85 GF
A FOR APPROVAL (AIR INLETS ADDED) GF 30/06/86 MRW
B DENOTES REVISION 19/08/86 GF 19/08/86 MRW TN
2 AS DESIGNED ECR T796 ML 01/89 JI JR
3 AS BUILT TO DON PROJECT ECR T568 SA 05/89 NB MG
4 ECR T054/T098 INFORMATION ADDED AS SHOWN NT 08/07/91
5 REDRAWN ON CAD BY ATTRIC TEB 11/06/04 SCB
Lundin
Lundin Britain Limited
PROJECT THISTLE 'A' PLATFORM
TITLE UPPER DECK LEVEL & ABOVE (EL +39.827M) HAZARDOUS AREA CLASSIFICATION
DRAWN TEB 11/06/04
CHECKED SCB 11/06/04
SCALE 1:200
DRAWING NUMBER 3355/30/605/0983
REV. NO. 5
3355-00-605-0983



NOTES:

1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M.
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.

FT 3510

GT 55

FRESH AIR INLET

ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISIONED)

15M RADIUS ZONE 2 ROUND UNUSED WELLHEAD DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED

ZONE 1

ZONE 2

ALL OTHER AREAS UNCLASSIFIED.

REFERENCE: AREA CLASSIFICATION DRAWINGS:-

3355/00/6050980	PRODUCTION DECK LEVEL
3355/00/6050981	MEZZANINE DECK LEVEL
3355/00/6050982	DRILLING DECK LEVEL
3355/00/6050983	UPPER DECK LEVEL
3355/00/6050985	PLATFORM NORTH ELEV.
3355/00/6050986	PLATFORM EAST ELEV.
3355/00/6050987	UNDERDECK

NO.	REVISION	BY	DATE	CHKD	APVD
B	DENOTES REVISION	GF	3/10/86	MRW	TWP
1	AS DESIGNED E.C.R 1546 & 1705	ML	1/89	JI	-
2	ASBUILT TO DON PROJECT E.C.R. 1568	S.A.	5/89	N.B.	-
3	3" ATMOS VENT EL. WAS 163'-8" 4" ATMOS VENT EL. WAS 160'-4"	FAM	10/5/90		
4	E.C.R. 1054 INFORMATION ADDED AS SHOWN	AJT	8/7/91	-	-
5	REDRAWN ON CAD BY ATTRIC	PCS	10/05/04	TEB	

Lundin
Lundin Britain Limited

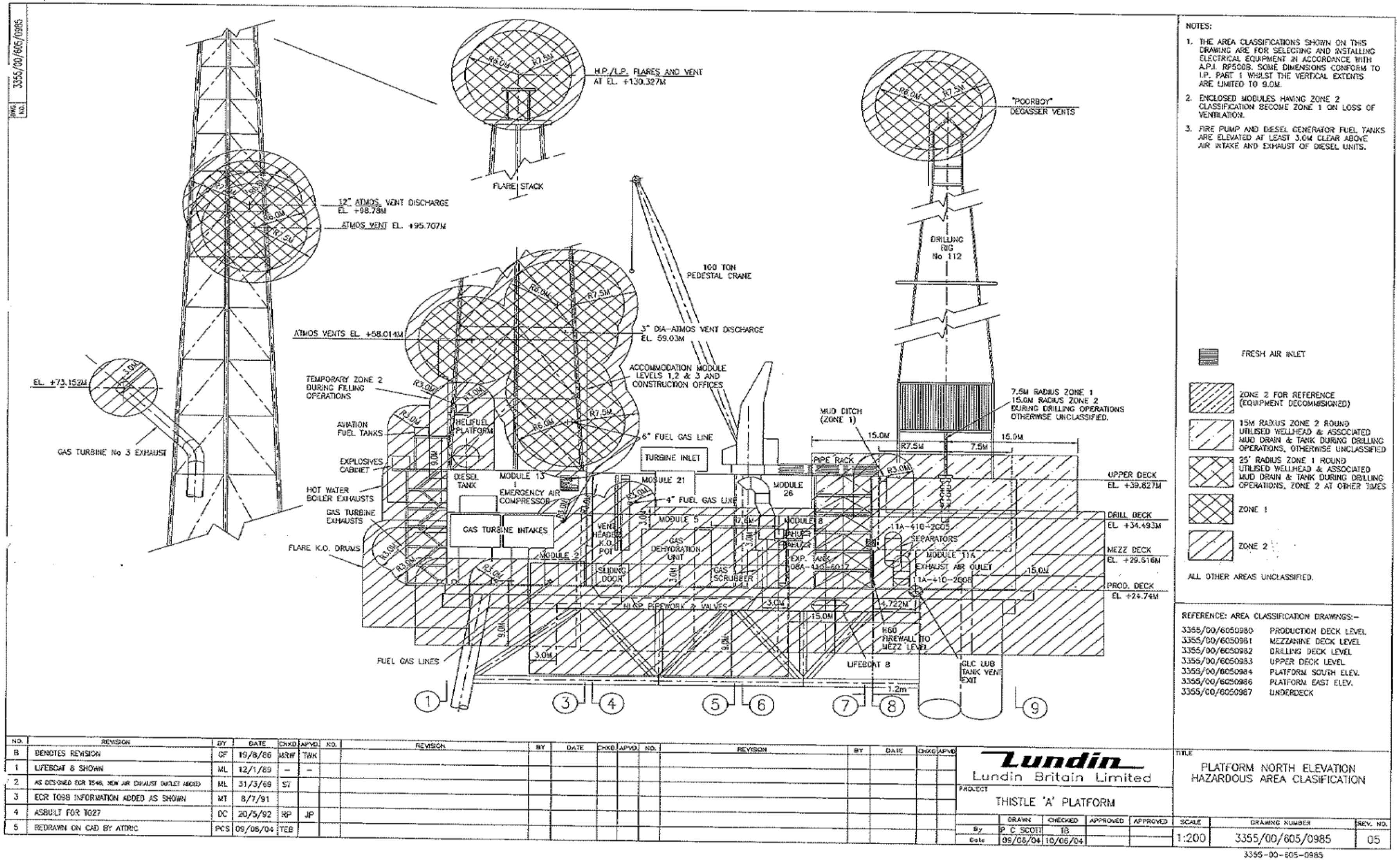
PROJECT: THISTLE 'A' PLATFORM

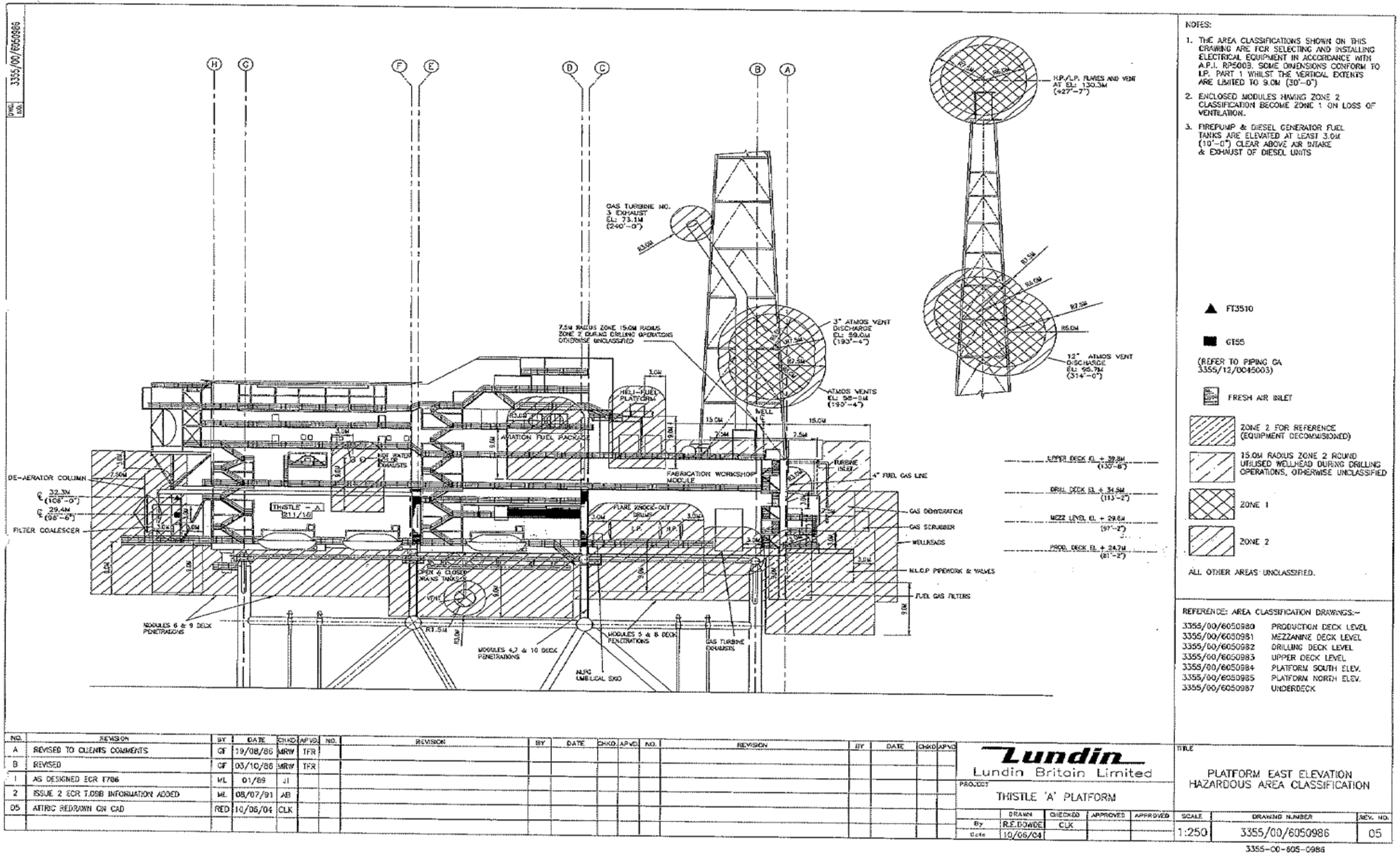
TITLE: PLATFORM SOUTH ELEVATION HAZARDOUS AREA CLASIFICATION

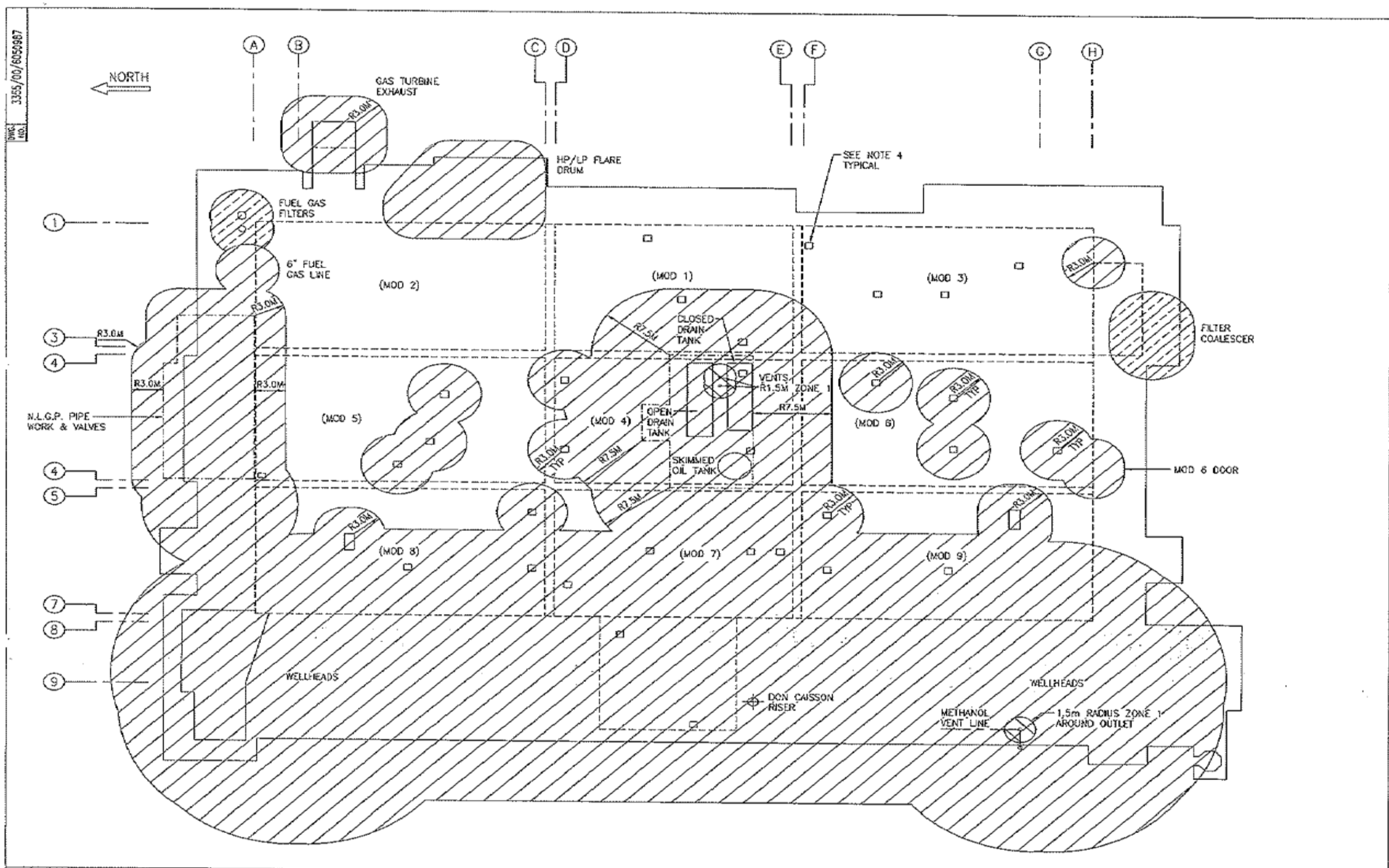
	DRAWN	CHECKED	APPROVED	APPROVED
By	P C SCOTT	TB		
Date	09/06/04	10/06/04		

SCALE	DRAWING NUMBER	REV. NO.
1:200	3355/00/605/0984	05

3355-00-605-0984


H.P./L.P. FLARES AND VENT AT EL. +130.327M
FLARE STACK
12" ATMOS. VENT DISCHARGE EL. +98.78M
ATMOS VENT EL. +95.707M
"POORBOY" DEGASSER VENTS
DRILLING RIG No 112
100 TON PEDESTAL CRANE
ATMOS VENTS EL. +58.014M
3" DIA-ATMOS VENT DISCHARGE EL. 59.03M
ACCOMMODATION MODULE LEVELS 1,2 & 3 AND CONSTRUCTION OFFICES
EL. +73.152M
GAS TURBINE No 3 EXHAUST
TEMPORARY ZONE 2 DURING FILLING OPERATIONS
AVIATION FUEL TANKS
HELIFUEL PLATFORM
EXPLOSIVES CABINET
HOT WATER BOILER EXHAUSTS
GAS TURBINE EXHAUSTS
FLARE K.O. DRUMS
DIESEL TANK
MODULE 13 EMERGENCY AIR COMPRESSOR
GAS TURBINE INTAKES
6" FUEL GAS LINE
TURBINE INLET
MODULE 21
4" FUEL GAS LINE
MODULE 26
MODULE 5
GAS DEHYDRATION UNIT
SLIDING DOOR
GAS SCRUBBER
MUD DITCH (ZONE 1)
PIPE RACK
7.5M RADIUS ZONE 1 15.0M RADIUS ZONE 2 DURING DRILLING OPERATIONS OTHERWISE UNCLASSIFIED.
11A-410-2005 SEPARATORS
MODULE 11A EXHAUST AIR OULET 11A-410-2006
H60 FIREWALL TO MEZZ LEVEL
LIFEBOAT 8
GLC LUB TANK VENT EXIT
FUEL GAS LINES
UPPER DECK EL. +39.827M
DRILL DECK EL. +34.493M
MEZZ DECK EL. +29.616M
PROD. DECK EL. +24.74M
NOTES:
1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M.
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
3. FIRE PUMP AND DIESEL GENERATOR FUEL TANKS ARE ELEVATED AT LEAST 3.0M CLEAR ABOVE AIR INTAKE AND EXHAUST OF DIESEL UNITS.
FRESH AIR INLET
ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISSIONED)
15M RADIUS ZONE 2 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED
25' RADIUS ZONE 1 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, ZONE 2 AT OTHER TIMES
ZONE 1
ZONE 2
ALL OTHER AREAS UNCLASSIFIED.
REFERENCE: AREA CLASSIFICATION DRAWINGS:-
3355/00/6050980 PRODUCTION DECK LEVEL
3355/00/6050981 MEZZANINE DECK LEVEL
3355/00/6050982 DRILLING DECK LEVEL
3355/00/6050983 UPPER DECK LEVEL
3355/00/6050984 PLATFORM SOUTH ELEV.
3355/00/6050986 PLATFORM EAST ELEV.
3355/00/6050987 UNDERDECK
B DENOTES REVISION GF 19/8/86
1 LIFEBOAT 8 SHOWN ML 12/1/89
3 ECR T098 INFORMATION ADDED AS SHOWN MT 8/7/91
4 ASBUILT FOR T027 DC 20/5/92 RP JP
5 REDRAWN ON CAD BY ATTRIC PCS 09/06/04 TEB
Lundin
Lundin Britain Limited
THISTLE 'A' PLATFORM
PLATFORM NORTH ELEVATION HAZARDOUS AREA CLASIFICATION
P C SCOTT 09/06/04 10/06/04
1:200
3355/00/605/0985
05
3355-00-605-0985


NOTES:
1. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M (30'-0")
2. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
3. FIREPUMP & DIESEL GENERATOR FUEL TANKS ARE ELEVATED AT LEAST 3.0M (10'-0") CLEAR ABOVE AIR INTAKE & EXHAUST OF DIESEL UNITS
FT3510
GT55
(REFER TO PIPING GA 3355/12/0045003)
FRESH AIR INLET
ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISSIONED)
15.0M RADIUS ZONE 2 ROUND UNUSED WELLHEAD DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED
ZONE 1
ZONE 2
ALL OTHER AREAS UNCLASSIFIED.
REFERENCE: AREA CLASSIFICATION DRAWINGS:-
3355/00/6050980 PRODUCTION DECK LEVEL
3355/00/6050981 MEZZANINE DECK LEVEL
3355/00/6050982 DRILLING DECK LEVEL
3355/00/6050983 UPPER DECK LEVEL
3355/00/6050984 PLATFORM SOUTH ELEV.
3355/00/6050985 PLATFORM NORTH ELEV.
3355/00/6050987 UNDERDECK
H.P./L.P. FLARES AND VENT AT EL: 130.3M (427'-7")
GAS TURBINE NO. 3 EXHAUST EL: 73.1M (240'-0")
3" ATMOS VENT DISCHARGE EL: 59.0M (193'-4")
12" ATMOS VENT DISCHARGE EL: 95.7M (314'-0")
ATMOS VENTS EL: 59.0M (193'-4")
7.5M RADIUS ZONE 15.0M RADIUS ZONE 2 DURING DRILLING OPERATIONS OTHERWISE UNCLASSIFIED
HELI-FUEL PLATFORM
AVIATION FUEL PACKAGE
FABRICATION WORKSHOP MODULE
FLARE KNOCK-OUT DRUMS
THISTLE - A 211/18
DE-AERATOR COLUMN
FILTER COALESCER
OPEN & CLOSED DRAINS TANKS
VENT
TURBINE INLET
4" FUEL GAS LINE
GAS DEHYDRATION
GAS SCRUBBER
WELLHEADS
M.L.C.P PIPEWORK & VALVES
FUEL GAS FILTERS
UPPER DECK EL + 39.8M (130'-8")
DRILL DECK EL + 34.5M (113'-2")
MEZZ LEVEL EL + 29.6M (97'-2")
PROD. DECK EL + 24.7M (81'-2")
MODULES 6 & 9 DECK PENETRATIONS
MODULES 4,7 & 10 DECK PENETRATIONS
MODULES 5 & 8 DECK PENETRATIONS
GAS TURBINE EXHAUSTS
NLPG UMBILICAL SKID
A REVISED TO CLIENTS COMMENTS GF 19/08/86 MRW TFR
B REVISED GF 03/10/86 MRW TFR
1 AS DESIGNED ECR 1786 ML 01/89 JI
2 ISSUE 2 ECR T.058 INFORMATION ADDED ML 08/07/91 AB
05 ATTRIC REDRAWN ON CAD RED 10/06/04 CLK
Lundin
Lundin Britain Limited
PROJECT THISTLE 'A' PLATFORM
TITLE PLATFORM EAST ELEVATION HAZARDOUS AREA CLASSIFICATION
DRAWN R.E.DOWDE 10/06/04 CHECKED CLK
SCALE 1:250
DRAWING NUMBER 3355/00/6050986
REV. NO. 05
3355-00-605-0986



NOTES:

1. FOR DETAILS OF HAZARDOUS AREAS ON PLATFORM PERIMETER SEE DRG No. 3355/00/6050980
2. THE AREA CLASSIFICATIONS SHOWN ON THIS DRAWING ARE FOR SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH A.P.I. RP500B. SOME DIMENSIONS CONFORM TO I.P. PART 1 WHILST THE VERTICAL EXTENTS ARE LIMITED TO 9.0M.
3. ENCLOSED MODULES HAVING ZONE 2 CLASSIFICATION BECOME ZONE 1 ON LOSS OF VENTILATION.
4. ☐ REPRESENTS MODULE AIR OUTLET THROUGH DECK

ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISIONED)

ZONE 1

ZONE 2

ALL OTHER AREAS UNCLASSIFIED.

REFERENCE: AREA CLASSIFICATION DRAWINGS:-

3355/00/6050980	PRODUCTION DECK LEVEL
3355/00/6050981	MEZZANINE DECK LEVEL
3355/00/6050982	DRILLING DECK LEVEL
3355/00/6050983	UPPER DECK LEVEL
3355/00/6050984	PLATFORM SOUTH ELEV.
3355/00/6050985	PLATFORM NORTH ELEV.
3355/00/6050986	PLATFORM EAST ELEV.

NO.	REVISION	BY	DATE	CHKD.	APVD.
	FOR DISCUSSION	GED	06/05/86		
	CLIENTS COMMENTS ADDED	GF	23/05/86		
0	FOR APPROVAL	GF	27/05/86		
A	NOTE 4 ADDED	GF	05/08/86		
B	REVISED TO CLIENTS COMMENTS	GF	19/08/86		
1	AS DESIGNED ECR T706	ML	01/89	JI	

NO.	REVISION	BY	DATE	CHKD.	APVD.
2	AS BUILT ECR T706	ML	02/89	JI	
3	AS BUILT TO DON PROJECT ECR T568	SA	05/89	NR	
04	REDRAWN ON CAD BY ATIRIC	TEB	08/06/04	SCB	

NO.	REVISION	BY	DATE	CHKD	APVD

Lundin

Lundin Britain Limited

PROJECT: THISTLE 'A' PLATFORM

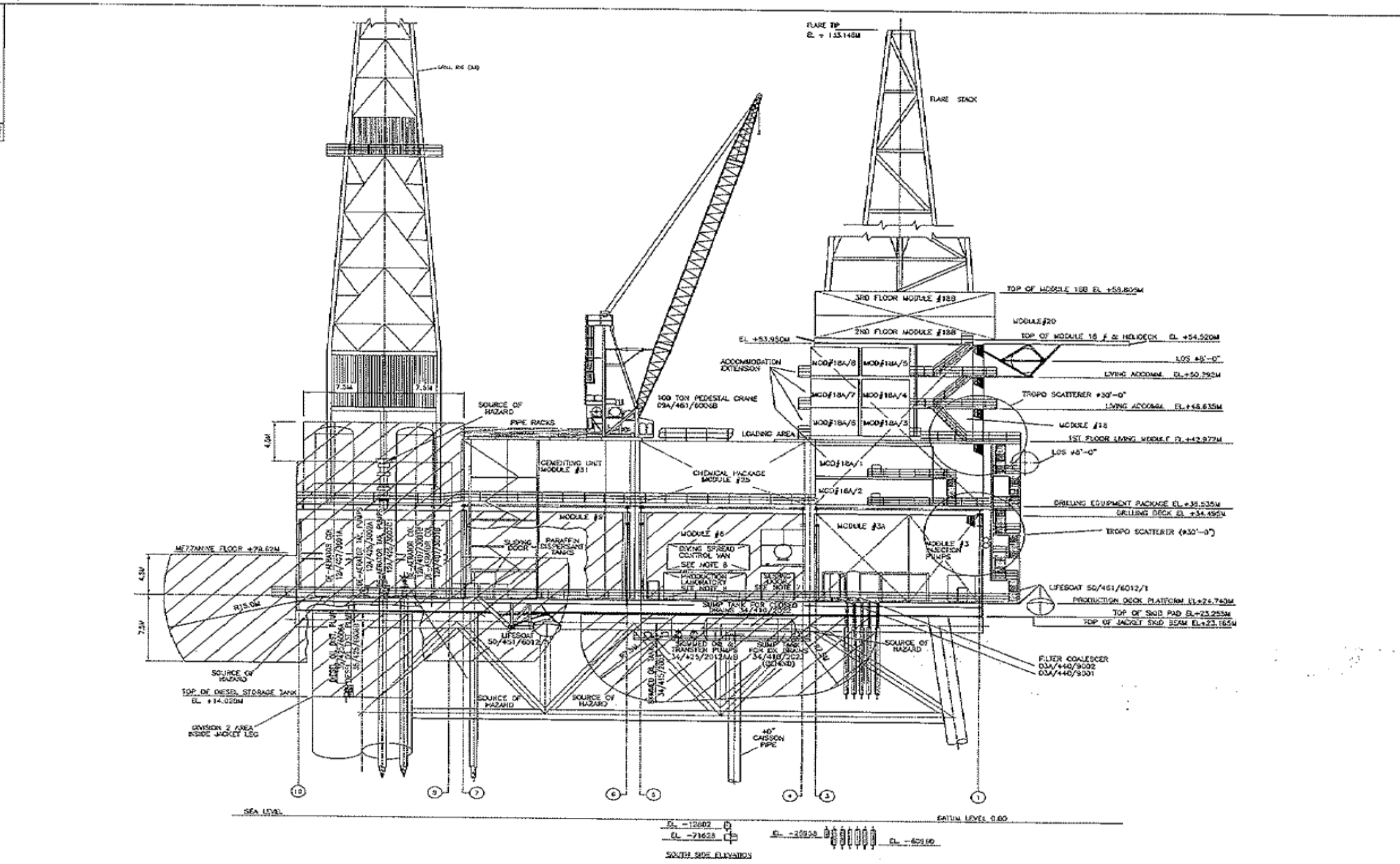
TITLE: UNDERDECK (BELOW LEVEL EL +24.740M) HAZARDOUS AREA CLASSIFICATION

	DRAWN	CHECKED	APPROVED	APPROVED
By	TEB	SCB		
Date	07/06/04	07/06/04		

SCALE	DRAWING NUMBER	REV. NO.
1:200	3355/00/6050987	4

3355-00-605-0987

DWG NO. 3355/00/6051004



NOTES:

1. THE AREA CLASSIFICATION SHOWN ON THIS DRAWING ARE FOR USE IN SELECTING AND INSTALLING ELECTRICAL EQUIPMENT IN ACCORDANCE WITH THE CODE OF THE INSTITUTE OF PETROLEUM. THE CODE OF PRACTICE CP 1003 PART 1&2 ARE THE REQUIREMENTS OF THE DEPARTMENT OF ENERGY.

2. THE CLASSIFICATION INDICATED IN THE CLASSIFIED MODULES IS BASED ON THE USE OF A MECHANICAL VENTING SYSTEM WITH THE CAPABILITY OF 'ADEQUATELY VENTILATING' THE MODULES.

3. ALL NON-CLASSIFIED MODULAR VENTILATING SYSTEMS SHALL HAVE ALARM SYSTEMS TO PROVIDE WARNING OF LOSS OF PRESSURE AND INITIATING A START FOR THE STANDBY VENTILATING FANS.

4. MAIN AND STANDBY FANS SHALL BE POWERED FROM TWO SEPARATE MOTOR CONTROL CENTRES.

5. EQUIPMENT ACCESS DOORS ARE TO BE CLOSED DURING NORMAL OPERATING CONDITIONS.

6. ALL ELECTRICAL EQUIPMENT ON THE DRILLING TOWER IS TO BE SUITABLE FOR DIVISION I

7. PERSONNEL DOOR IN SLIDING DOOR REMOVED.

8. PRODUCTION LABORATORY & DIVERS CONTROL VAN ARE UNCLASSIFIED DUE TO PRESSURISATION.

ZONE 2 FOR REFERENCE (EQUIPMENT DECOMMISIONED)

50' RADIUS ZONE 2 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED

25' RADIUS ZONE 1 ROUND UTILISED WELLHEAD & ASSOCIATED MUD DRAIN & TANK DURING DRILLING OPERATIONS, OTHERWISE UNCLASSIFIED

ZONE 1

ZONE 2

ALL OTHER AREAS UNCLASSIFIED.

REFERENCE: AREA CLASSIFICATION DRAWINGS:--

00/6051001	PRODUCTION DECK LEVEL
00/6051002	DRILL DECK LEVEL
00/6051003	MEZZANINE DECK LEVEL

NO.	REVISION	BY	DATE	CHKD.	APVD.	NO.	REVISION	BY	DATE	CHKD.	APVD.	NO.	REVISION	BY	DATE	CHKD	APVD
A	–	DA	–	–	–	4	FOR CONSTRUCTION ACCOMODATION EXTENSION ADDED	–	23/8/77	–	–						
B	FOR CLIENTS COMMENTS	–	–	–	–	5	FOR CONSTRUCTION PRODUCTION LAB 5 & PARAFFIN DISPERSANT TANKS ADDED	–	7/4/78	–	–						
0	ISSUED FOR CLIENTS APPROVAL	RP	4/11/74	DA	JA	6	FOR CONSTRUCTION MODULE 18/B ADDED	–	25/9/78	–	–						
1	APPROVED BY CLIENT	DA	17/12/74	DA	–	7	FOR CONSTRUCTION DIVING SYSTEM DETAILS ADDED.	–	3/1/79	–	–						
2	FOR CONSTRUCTION	MRV	6/7/76	–	–	8	REVISED AS SHOWN EORT412	GC	9/10/83	–	–						
3	FOR CONSTRUCTION EDCR315	–	25/11/78	–	–	9	REDRAWN ON CAD BY ATTRIC	LM	28/06/04	PCS							

Lundin

Lundin Britain Limited

PROJECT: THISTLE 'A'

TITLE: VIEW ON PLATFORM LOOKING NORTH AREA CLASSIFICATION

	DRAWN	CHECKED	APPROVED	APPROVED	SCALE	DRAWING NUMBER	REV. NO.
By	L MYERS	PCS			1:200	3355/00/6051004	9
Date	24/06/04	28/06/04					

3355/00/6051004

APPENDIX F: Offshore Data Questionnaire for Initial BN Model

Introduction

The goal of this study is to determine which factors have greater influence on two failure modes regarding offshore equipment, these are; i) The key factors affecting Severe Damage occurring to offshore equipment, on both attended and Normally Unattended (NU) installations; ii) The key factors affecting failure an offshore Electrical Generation system, on both attended and Normally Unattended (NU) installations. Hence, the Failure Mode and System & Component are outlined in Table 1, and these are the parameters to be evaluated utilising a *Pair-wise Comparison* technique. In all instances, the life of the crew is not part of the criteria, only damage to equipment.

*Table **1**: List of Failure Modes and System & Component Failures*

<table>
<tr><th>Failure Mode</th><th>System Level</th><th>Component Level</th></tr>
<tr><td rowspan="4">Severe Damage observed to an attended installation</td><td>Gas Import Riser Failure</td><td>N/A</td></tr>
<tr><td>High Pressure Gas Flare drum Failure</td><td>N/A</td></tr>
<tr><td rowspan="2">Electrical Generator Failure</td><td>Turbine Blades escaping housing and being expelled as projectiles</td></tr>
<tr><td>Generator Exciter detaching and becoming a projectile</td></tr>
<tr><td>Severe Damage observed to a NU installation</td><td colspan="2">N/A</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Failure of the Electrical Generation System on an attended installation</td><td rowspan="3">N/A</td><td>Turbine blade damage and failure</td></tr>
<tr><td>Armature damage and failure</td></tr>
<tr><td>Exciter damage and failure</td></tr>
<tr><td>Failure of the Electrical Generation System on a NU installation</td><td colspan="2">N/A</td></tr>
</table>

To proceed with the *Pair-wise Comparison* technique, one must first understand the weighting measurement used in the study. Table 2 contains two weighting scales for “IMPORTANT” and “UNIMPORTANT”, along with an explanation of what each weighting denotes.

*Table **2**: 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 2 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 offshore industry. The judgement provided should be focused on the objective presented for each section, and to do this please ‘mark’ (*) the importance weighting of each failure mode or component failure in the presented column. The following is a brief example of how to apply Table 2.

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 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.

Questionnaire

Severe Damage to Offshore Equipment

Objective: To select the most important factors affecting severe damage to offshore equipment.

1) **Observing and not observing failures.**

	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 it to have Severe Damage observed on an attended installation, compared to a NU installation?																	

2) **Observing System failures.**

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 Gas Import Riser failure, compared to HP Gas Flare drum failure?																	
To achieve the stated objective, how important is Gas Import Riser failure, compared to failure of an Electrical Generator?																	
To achieve the stated objective, how important is HP Gas Flare drum failure, compared to failure of an Electrical Generator?																	

3) Observing Component failures.

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 Turbine Blades expelled as projectiles, compared to the Exciter becoming a projectile?																	

Offshore Electrical Generator Unit failure.

Objective: To select the most important factors causing failure of an offshore Electrical Generation System.

1) Observing and not observing failures.

	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 failure of the Electrical Generation System on an attended installation, compared to a NU installation?																	

2) Observing Component Failures

	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 Turbine Blade failure, compared to Armature Failure?																	
To achieve the stated objective, how important is Turbine Blade failure, compared to Exciter Failure?																	
To achieve the stated objective, how important is Armature failure, compared to Exciter Failure?																	

APPENDIX G: AHP Results for Initial BN Model

PART A: Severe Damage

Failure Mode	
Severe Damage observed to an attended installation	SD
Severe Damage observed to a NU installation	SD - NUI

Pair-wise Comparisons

	SD	SD - NUI
SD	1	10/3
SD - NUI	29/100	1
SUM	129/100	217/50

	SD	SD - NUI	**Weight**
SD	0.77	0.77	**77.00%**
SD - NUI	0.23	0.23	**23.00%**
SUM	1	1	**100.00%**

	SD	SD - NUI	Sum	Sum Weight
SD	0.77	0.77	1.54	2.00
SD - NUI	0.23	0.23	0.46	2.00
			Count	2
			Lambda Max	2

System Failures	
Electrical Generator Failure	EG
Gas Import Riser Failure	GIR
High Pressure Gas Flare drum Failure	HPD

Pair-wise Comparisons

	GIR	HPD	EG
GIR	1	17/5	19/3
HPD	29/100	1	5

EG	4/25	1/5	1
SUM	29/20	461/100	12.26

Standardised Matrix

	GIR	HPD	EG	**Weight**
GIR	0.69	0.74	0.52	**64.88%**
HPD	0.20	0.22	0.40	**27.31%**
EG	0.11	0.04	0.08	**7.81%**
SUM	1	1	1	**100.00%**

				Sum Row	Sum Weight	
GIR	0.65	0.93	0.50	2.07	3.20	
HPD	0.19	0.27	0.38	0.85	3.10	
EG	0.10	0.06	0.08	0.24	3.02	
				Count	3	
				Lambda Max	3.11	
				CI	0.05	
				CR	**0.09**	**<0.1**

Component Failures	
Turbine Blades escaping housing and being expelled as projectiles	TBP
Generator Exciter detaching and becoming a projectile	GED

Pair-wise Comparisons

	TBP	GED
TBP	1	2
GED	12/25	1
SUM	37/25	61/20

	TBP	GED	**Weight**
TBP	0.67	0.67	**67.19%**
GED	0.33	0.33	**32.81%**
SUM	1	1	**100.00%**

	TBP	GED	Sum	Sum Weight

TBP	0.67	0.67	1.34	2.00
GED	0.33	0.33	0.66	2.00
			Count	2
			Lambda Max	2
			CI	0

PART B: Electrical Generator Failure

Failure Mode	
Failure of Electrical Generation system on attended installation	EG
Failure of Electrical Generation system on a NU- Installation	EG - NUI

Pair-wise Comparisons

	SD	SD - NUI
SD	1	5/3
SD - NUI	59/100	1
SUM	159/100	67/25

	SD	SD - NUI	**Weight**
SD	0.63	0.63	**62.73%**
SD - NUI	0.37	0.37	**37.27%**
SUM	1	1	**100.00%**

	SD	SD - NUI	Sum	Sum Weight
SD	0.63	0.63	1.25	2.00
SD - NUI	0.37	0.37	0.75	2.00

Count	2
Lambda Max	2

System Failures	
Turbine Blade Failure	TB
Armature Failure	AM
Exciter Failure	EX

Pair-wise Comparisons

	TB	AM	EX
TB	1	19/6	11/5
AM	1/3	1	1 2/9
EX	1/2	5/7	1
SUM	16/9	44/9	4 2/5

Standardised Matrix

	TB	AM	EX	**Weight**
TB	0.56	0.65	0.50	**56.98%**
AM	0.18	0.20	0.28	**21.95%**
EX	0.26	0.15	0.23	**21.07%**
SUM	1	1	1	**100.00%**

	GIR	HPD	EG	Sum	Sum Weight	
TB	0.57	0.70	0.46	1.73	3.03	
AM	0.18	0.22	0.26	0.66	2.99	
EX	0.26	0.16	0.21	0.63	2.99	
				Count	3	
				Lambda Max	3.00	
				CI	0.00	
				CR	**0.00**	**<0.1**

APPENDIX H: CPTs for the Initial BN Model

1. Retaining Ring Failure	
Failure	0.002
Success	0.998

2. Debris Expelled		
1	Failure	Success
Yes	0.25	0.006
No	0.75	0.994

3. Debris Expelled into Turbine		
2	Yes	No
Yes	0.5	0.006
No	0.5	0.994

4. Debris Expelled to Exciter		
2	Yes	No
Yes	0.5	0.006
No	0.5	0.994

5. Fuel Gas Feed Impact		
3	Yes	No
Yes	0.1	0.032
No	0.9	0.968

6. Generator Bearings		
1	Yes	No
Failure	0.066	0.001
Success	0.934	0.968

7. Turbine Blades Expelled		
6	Yes	No
Yes	0.25	0.0009
No	0.75	0.9991

8. Exciter Detaches		
6	Yes	No
Yes	0.5	0.0008
No	0.5	0.9992

9. Gas Import riser Impact		
7	Yes	No
Yes	0.25	0.062
No	0.75	0.938

10. HP Flare Drum shell Impact		
8	Yes	No
Yes	0.1	0.000057
No	0.9	0.999943

E1. Debris Contained in Alternator								
4	Yes				No			
3	Yes		No		Yes		No	
2	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0.37	0.43	0.51	0.57	0.43	0.49	0.57	0.63
No	0.63	0.57	0.49	0.43	0.57	0.51	0.43	0.37

E2. Debris Escapes Generator Housing		
4	Yes	No
Yes	0.0002	0.006
No	0.9998	0.994

E3. Fuel Gas Fire		
5	Yes	No
Yes	0.0002	0.0001
No	0.9998	0.9999

E4. Debris Remains in Turbine Housing		
5	Yes	No
Yes	0.0002	0.076
No	0.9998	0.924

E5. Event Escalation																
10	Yes								No							
8	Yes				No				Yes				No			
7	Yes		No		Yes		No		Yes		No		Yes		No	
9	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No	0.23	0.58	0.26	0.61	0.24	0.60	0.27	0.62	0.38	0.73	0.40	0.76	0.39	0.74	0.42	0.77
Yes	0.77	0.42	0.74	0.39	0.76	0.40	0.73	0.38	0.62	0.27	0.60	0.24	0.61	0.26	0.58	0.23

E6. Gas Import Riser LOC		
9	Yes	No
Small (10mm)	0.00066	0.00033
Med. (50mm)	0.00015	0.00008
Fullbore	0.00027	0.00017
None	0.99893	0.99942

E7. H.P. Flare Drum LOC		
10	Yes	No
Yes	0.000845	0.000007
No	0.999160	0.999993

APPENDIX I: CPTs for Fuel Gas Release BN Model

Exceed System Capability	
Yes	0.0008
No	0.9992

Structural Support Failure	
Yes	0.0372
No	0.9628

Operational Error	
Yes	0.0102
No	0.9898

Corrosion	
Yes	0.0041
No	0.9959

System Defects	
Yes	0.0062
No	0.9938

5. Fuel Gas Feed Impact (1)	
Yes	0.0330
No	0.9699

Control System Failures								
System	Yes				No			
Operational	Yes		No		Yes		No	
Exceed Sys.	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0.936	0.734	0.725	0.523	0.477	0.275	0.266	0.064
No	0.064	0.266	0.275	0.477	0.523	0.725	0.734	0.936

Physical/Structural Failures								
Fuel Impact (1)	Yes				No			
Corrosion	Yes		No		Yes		No	
Structural	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0.9640	0.6855	0.6758	0.3973	0.6027	0.3242	0.3145	0.0360
No	0.0360	0.3145	0.3242	0.6027	0.3973	0.6758	0.6855	0.9640

Gas Release in Module				
Control	Yes		No	
Physical	Yes	No	Yes	No
Yes	0.9502	0.7235	0.8199	0.3816
No	0.0498	0.2765	0.1801	0.6184

Gas Detection		
Release	Yes	No
Yes	0.74866	0.00230
No	0.25134	0.99770

TCS Shut Off Fuel		
Detection	Yes	No
Yes	0.63212	0.00580
No	0.36788	0.99420

F&G System Shut Off Fuel		
Detection	Yes	No
Yes	0.46154	0.00610
No	0.53846	0.99390

Fuel Supply Shut Off				
F&G	Yes		No	
TCS	Yes	No	Yes	No
Yes	1	0.99762	0.99563	0
No	0	0.00238	0.00437	1

Continuous Gas Release				
Fuel Off	Yes		No	
Detection	Yes	No	Yes	No
Yes	0	0.63212	0.28347	1
No	1	0.36788	0.71653	0

Ignition Source	
Yes	0.00083
No	0.99917

Ignition Type				
Ignition S	Yes		No	
Fuel Off	Yes	No	Yes	No
Y - Immediate	0	0.3580	0	0
Y - Delayed	0	0.4984	0	0
None	1	0.1436	1	1

Fire			
Ignition	Immediate	Delayed	None
Yes	0.35804	0.16400	0
No	0.64196	0.83600	1

Explosion			
Ignition	Immediate	Delayed	None
Yes	0	0.69904	0
No	1	0.30096	1

Equipment Damage due to Fire/Explosion				
Fire	Yes		No	
Explosion	Yes	No	Yes	No
Yes	0.1930	0.1662	0.0109	0
No	0.8070	0.8338	0.9891	1

Explosion Damage to Adjacent		
Explosio	Yes	No
Yes	0.002211	0
No	0.99789	1

Consequence						
Ignition	Immediate		Delayed		None	
Fuel Off	Yes	No	Yes	No	Yes	No
Yes - Ignition	0	1	0	0.1930	0	0
Yes - Leak Only	0	0	0	0.0003	0	1
No	1	0	1	0.8067	1	0

APPENDIX J: Wireless Sensor Network Data Questionnaire

Introduction

The goal of this study is to determine which factors have greater influence on the design characteristics of and offshore Wireless Sensor Network (WSN). The WSN in question focuses on key structural and operational integrity points of an offshore electrical generation system. The design criteria focus on three general attributes: i) the Complexity of the WSN, ii) The Resilience of the WSN, and iii) The Maintainability of the WSN. Each general attribute contains a set of sub-criteria or basic attributes as outlined in Table 1. Furthermore, the attributes are based around the design and orientation of the WSN. Four possible WSN orientations have been drawn up: i) Single-hop, ii) Single-hop with cluster nodes, iii) Multi-hop with the smallest possible sensor radius, and iv) Multi-hop with the largest possible sensor radius.

Part A consists of a Pairwise Comparison of the general and basic attributes, with Part B consisting of a grading assessment across the design attributes and the four WSN design orientations. All criteria is outlined in Table 1.

Table 1: List of Failure Modes and System & Component Failures

General Attributes	Basic Attributes
Complexity	Transmitting information over the shortest possible route Transmitting information over the longest possible route Large No. of cluster nodes in order to reliably transmit data
Resilience	Battery Life Relaying Data
Maintainability	Ease of Maintenance given the Complexity of the nodes Auto-Configuration Cost

To proceed with the *Pair-wise Comparison* technique, one must first understand the weighting measurement used in the study. Table 2contains two weighting scales for “IMPORTANT” and “UNIMPORTANT”, along with an explanation of what each weighting denotes.

Table 2: 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 2 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 offshore industry. The judgement provided should be focused on the objective presented for each section, and to do this please 'mark' (*) the importance weighting of each failure mode or component failure in the presented column. The following is a brief example of how to apply Table 2.

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 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.

Part A: Pairwise Comparison

General Attributes

Objective: To select the most important general attributes relating to the design of an offshore WSN.

	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 Complexity compared to Resilience?																	
To achieve the stated objective, how important is Complexity compared to Maintainability																	
To achieve the stated objective, how important is Resilience compared to Maintainability?																	

Basic Attributes (Complexity)

Objective: To select the most important basic complexity attributes relating to the design of an offshore WSN.

	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 to relay data over the shortest route compared to the longest route?																	
To achieve the stated objective, how important is to relay data over the shortest route compared to the Number of Cluster Nodes?																	
To achieve the stated objective, how important to relay data over the longest route compared to the number of Cluster Nodes?																	

Basic Attributes (Resilience)

Objective: To select the most important basic resilience attributes relating to the design of an offshore WSN.

	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 the Battery Power compared to the ability to Relay Data between sensor nodes (Transmit AND Receive)?																	

Basic Attributes (Maintainability)

Objective: To select the most important basic maintainability attributes relating to the design of an offshore WSN.

	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 Ease of Maintenance given the Complexity of the nodes compared to the ability for the WSN to Auto-Configure itself																	

after maintenance?																	
To achieve the stated objective, how important is Ease of Maintenance compared the cost of the WSN (both installation and maintenance)?																	
To achieve the stated objective, how important is the ability for the WSN to Auto-Configure itself after maintenance compared to the cost of the WSN (both installation and maintenance)?																	

Part B: Grading Assessment

This section concerns itself with the performance of the WNSs given the various criteria previously outlined. The grading system is split between the three main attributes and involves. The basic attributes within Complexity, Resilience and maintainability are graded on how well the design of the WSN performs. i.e. How well does a multi-hop network with a small radius perform given the need for the network to auto-configure after maintenance? Graded as: 1) Poor, 2) Indifferent, 3) Average, 4) good, 5) Excellent.

The design of the network and placement of the nodes requires there be 62 sensor nodes in the network, spread none uniformly, over a circular area of approximately $420m^2$.

Brief Descriptions of each network design:

Single-Hop:
Nodes connect directly to the Gateway node. Due to congestion, Nodes transmit data in sequence. i.e. Node 1 transmits data, Node 2 cannot transmit until the gateway has received information from Node 1, and so on. Complexity is not applicable to the S-H design as all nodes send data to the same destination and do not relay data.

Single-Hop (with Cluster nodes):
Nodes transmit data to the nearest cluster node in sequence. Hence, several nodes can transmit simultaneously to different cluster nodes. Theoretically requires less battery power than S-H as there are two short connections from the node to the cluster and from the cluster to the gateway. As opposed to on connection over a longer distance.

Multi-Hop (Small sensor radius):
Nodes relay (transmit/ receive) information from each other to achieve the best route from the source node to the cluster node. The small radius denotes the smallest transmittable distance of the node. i.e. it would require more connections to reach the cluster node. Theoretically requires more battery than S-H as the nodes must transmit and receive.

Multi-Hop (Large sensor radius):
The theory is the same for the M-HS, however, nodes have a larger sensor radius and can transmit/receive data from nodes further away. Meaning fewer connections to the cluster node. Requires much increased battery power to transmit/receive over a large area. Due to the large area, the network can almost act as a single-hop cluster network

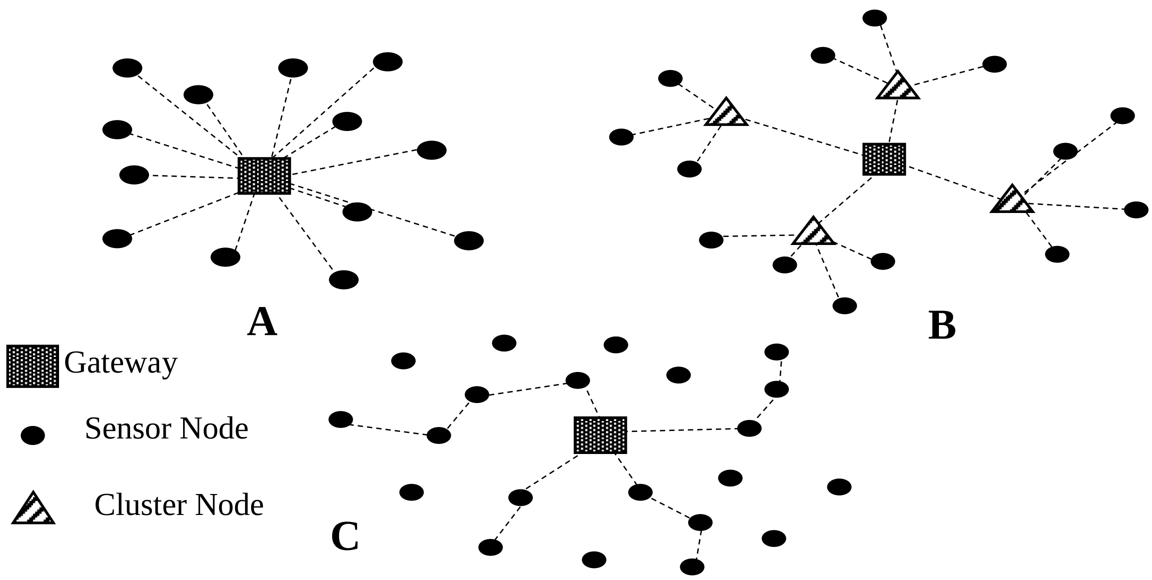


Figure 1: A) Single-Hop Network, B) Single-Hop Network with Cluster nodes, C) Multi-Hop Network

<table>
<tr><th colspan="5">Given each WSN type, please grade each attribute by its relevance to the design of the network using the Assessment Grades provided.</th><th>Assessment Grade</th></tr>
<tr><td>Main Attribute</td><td>Complexity</td><td>Single Hop (Cluster) (S-HC)</td><td>Multi-Hop (Small Radius) (M-HS)</td><td>Multi-Hop (Large Radius) (M-HL)</td><td rowspan="4">1 = Poor
2 = Indifferent
3 = Average
4 = Good
5 = Excellent</td></tr>
<tr><td rowspan="3">Basic Attributes</td><td>Transmitting information over the shortest possible route (e_1)</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td></tr>
<tr><td>Transmitting information over the longest possible route (e_2)</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td></tr>
<tr><td>Large No. of cluster nodes in order to reliably transmit data (e_3)</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td><td>1 □ 2 □ 3 □ 4 □ 5 □</td></tr>
<tr><td colspan="2" rowspan="4">e_1 = The ability of the network to transmit information over the shortest possible route to the Gateway node.

e_2 = The ability of the network to relay information over the longest possible distance to the Gateway given that one or more nodes fail to transmit/receive data.

e_3 = The necessity of the network to have many cluster nodes in order to reliably transmit data to the Gateway.</td><td colspan="4">S-H = Nodes connect directly to the Gateway node. Due to congestion, Nodes transmit data in sequence. i.e. Node 1 transmits data, Node 2 cannot transmit until the gateway has received information from Node 1, and so on. Complexity is not applicable to the S-H design as all nodes send data to the same destination and do not relay data.</td></tr>
<tr><td colspan="4">S-HC = Nodes transmit data to the nearest cluster node in sequence. Hence, several nodes can transmit simultaneously to different cluster nodes. Theoretically requires less battery power than S-H as there are two short connections from the node to the cluster and from the cluster to the gateway. As opposed to on connection over a longer distance.</td></tr>
<tr><td colspan="4">M-HS = Nodes relay (transmit/ receive) information from each other to achieve the best route from the source node to the cluster node. The small radius denotes the smallest transmittable distance of the node. i.e. it would require more connections to reach the cluster node. Theoretically requires more battery than S-H as the nodes must transmit and receive</td></tr>
<tr><td colspan="4">M-HL = The theory is the same for the M-HS, however, nodes have a larger sensor radius and can transmit/receive data from nodes further away. Meaning fewer connections to the cluster node. Requires much increased battery power to transmit/receive over a large area. Due to the large area, the network can almost act as a single-hop cluster network.</td></tr>
</table>

Given each WSN type, please grade each attribute by its relevance to the design of the network using the Assessment Grades provided.							Assessment Grade
Main Attribute	Resilience		Single-Hop	Single Hop (Cluster)	Multi-Hop (Small Radius)	Multi-Hop (Large Radius)	**1 = Poor** **2 = Indifferent** **3 = Average** **4 = Good** **5 = Excellent**
Basic Attributes	Battery Power (e_4)		1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	
	Relaying Data (e_5)		Not Applicable	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	

e_4 = The necessity of the network to have a substantial source of battery power for the longevity of the network life and reduced time between maintenance. Battery power must be sufficient to power the sensors for several months.

e_5 = The necessity of the network to relay information between nodes in the event of sensor node failures and/or network disruptions.

S-H = Nodes connect directly to the Gateway node. Due to congestion, Nodes transmit data in sequence. i.e. Node 1 transmits data, Node 2 cannot transmit until the gateway has received information from Node 1, and so on. Complexity is not applicable to the S-H design as all nodes send data to the same destination and do not relay data.

S-HC = Nodes transmit data to the nearest cluster node in sequence. Hence, several nodes can transmit simultaneously to different cluster nodes. Theoretically requires less battery power than S-H as there are two short connections from the node to the cluster and from the cluster to the gateway. As opposed to on connection over a longer distance.

M-HS = Nodes relay (transmit/ receive) information from each other to achieve the best route from the source node to the cluster node. The small radius denotes the smallest transmittable distance of the node. i.e. it would require more connections to reach the cluster node. Theoretically requires more battery than S-H as the nodes must transmit and receive

M-HL = The theory is the same for the M-HS, however, nodes have a larger sensor radius and can transmit/receive data from nodes further away. Meaning fewer connections to the cluster node. Requires much increased battery power to transmit/receive over a large area. Due to the large area, the network can almost act as a single-hop cluster network.

Given each WSN type, please grade each attribute by its relevance to the design of the network using the Assessment Grades provided.						Assessment Grade
Main Attribute	Maintainability	Single-Hop (S-H)	Single Hop (Cluster) (S-HC)	Multi-Hop (Small Radius) (M-HS)	Multi-Hop (Large Radius) (M-HL)	**1 = Poor** **2 = Indifferent** **3 = Average** **4 = Good** **5 = Excellent**
Basic Attributes	Ease of Maintenance given the Complexity of the nodes (e_6)	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	
	Auto-Configuration on start-up and after maintenance (e_7)	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	
	Cost by the number and sophistication of nodes and the cost of maintenance. (e_8)	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	1 □ 2 □ 3 □ 4 □ 5 □	

e_6 = Ease of maintenance is dependent on the Complexity of the nodes, i.e. the number of components within the nodes (sensor, transmitter, receiver, battery size). Location is not a factor as all nodes in this study are located within a gas turbine.

e_7 = The ability of the network to auto configure on start-up and after maintenance. Nodes that can relay information can ease this issue, however, it is easier to program networks to auto-configure with less complex and fewer connections.

e_8 = The cost of the network is determined by the number of nodes required (including cluster nodes), the sophistication of the nodes (battery size, transmitters and receivers) and the cost of maintenance

S-H = Nodes connect directly to the Gateway node. Due to congestion, Nodes transmit data in sequence. i.e. Node 1 transmits data, Node 2 cannot transmit until the gateway has received information from Node 1, and so on. Complexity is not applicable to the S-H design as all nodes send data to the same destination and do not relay data.

S-HC = Nodes transmit data to the nearest cluster node in sequence. Hence, several nodes can transmit simultaneously to different cluster nodes. Theoretically requires less battery power than S-H as there are two short connections from the node to the cluster and from the cluster to the gateway. As opposed to on connection over a longer distance.

M-HS = Nodes relay (transmit/ receive) information from each other to achieve the best route from the source node to the cluster node. The small radius denotes the smallest transmittable distance of the node. i.e. it would require more connections to reach the cluster node. Theoretically requires more battery than S-H as the nodes must transmit and receive

M-HL = The theory is the same for the M-HS, however, nodes have a larger sensor radius and can transmit/receive data from nodes further away. Meaning fewer connections to the cluster node. Requires much increased battery power to transmit/receive over a large area. Due to the large area, the network can almost act as a single-hop cluster network.

APPENDIX K: AHP Results for Wireless Sensor Network Analysis

General Attributes

General Attributes	
Complexity	x
Resilience	y
Maintainability	z

Pair-wise Comparisons

	x	y	z
x	1.00	0.48	0.66
y	2.09	1.00	1.95
z	1.52	0.51	1.00
SUM	4.61	1.99	3.61

Standardised Matrix

	x	y	z	**Weight**
x	0.22	0.24	0.18	**21.34%**
y	0.45	0.50	0.54	**49.86%**
z	0.33	0.26	0.28	**28.80%**
SUM	1	1	1	**100.00%**

	x	y	z	Sum Row	Sum Weight	
x	0.21	0.24	0.19	0.64	3.008	
y	0.45	0.50	0.56	1.51	3.020	
z	0.32	0.26	0.29	0.87	3.012	
				Count	3	
				Lambda Max	3.013	
				CI	0.007	
				CR	0.011	<0.1

Basic Attributes (Complexity)	
Transmitting information over the shortest possible route	e1
Transmitting information over the longest possible route	e2
Large No. of cluster nodes in order to reliably transmit data	e3

Pair-wise Comparisons			
	e1	e2	e3
e1	1	3	2
e2	0.334163	1	1/2
e3	0.525306	2.091279	1
SUM	1.859468	6.083835	3.381830189

Standardised Matrix				
	e1	e2	e3	**Weight**
e1	0.54	0.49	0.56	**53.09%**
e2	0.18	0.16	0.14	**16.18%**
e3	0.28	0.34	0.30	**30.73%**
SUM	1	1	1	**100.00%**

	e1	e2	e3	Sum	Sum Weight	
e1	0.53	0.48	0.59	1.60	3.01	
e2	0.18	0.16	0.15	0.49	3.00	
e3	0.28	0.34	0.31	0.92	3.01	
				Count	3	
				Lambda Max	3.01	
				CI	0.00	
				CR	0.01	<0.1

Basic attributes (Resilience)	
Battery Power	e4
Relaying Data	e5

Pair-wise Comparisons		
	e4	e5
e4	1	1 6/7
e5	0.536492	1
SUM	1.536492	2.86396

	e4	e5	**Weight**
e4	0.65	0.65	**65.08%**
e5	0.35	0.35	**34.92%**
SUM	1	1	**100.00%**

	e4	e5	Sum	Sum Weight	
e4	0.65	0.65	1.30	2.00	
e5	0.35	0.35	0.70	2.00	
			Count	2	
			Lambda Max	2	
			CI	0	
			CR	#DIV/0!	<0.1

Basic attributes (Maintainability)	
Ease of Maintenance given the Complexity of the nodes	e6
Auto-Configuration on start-up and after maintenance	e7
Cost	e8

Pair-wise Comparisons			
	e6	e7	e8
e6	1	3 1/2	1 5/8
e7	2/7	1	1
e8	5/8	1	1
SUM	2	5 1/2	3 2/3

Standardised Matrix				
	e6	e7	e8	**Weight**
e6	0.53	0.64	0.45	**53.62%**
e7	0.15	0.18	0.28	**20.46%**
e8	0.32	0.18	0.27	**25.92%**
SUM	1	1	1	**100.00%**

	e6	e7	e8	Sum	Sum Weight	
e6	0.54	0.71	0.42	1.67	3.12	
e7	0.15	0.20	0.26	0.62	3.04	
e8	0.33	0.20	0.26	0.79	3.05	
				Count	3	
				Lambda Max	3.07	
				CI	0.03	
				CR	0.06	<0.1

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