An Integrated Model for Asset Reliability, Risk and Production Efficiency Management in Subsea Oil and Gas Operations

By

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Abstract

The global demand for energy has been predicted to rise by 56% between 2010 and 2040 due to industrialization and population growth. This continuous rise in energy demand has consequently prompted oil and gas firms to shift activities from onshore oil fields to tougher terrains such as shallow, deep, ultra-deep and arctic fields. Operations in these domains often require deployment of unconventional subsea assets and technology.

Subsea assets when installed offshore are super-bombarded by marine elements and human factors which increase the risk of failure. Whilst many risk standards, asset integrity and reliability analysis models have been suggested by many previous researchers, there is a gap on the capability of predictive reliability models to simultaneously address the impact of corrosion inducing elements such as temperature, pressure, pH corrosion on material wear-out and failure. There is also a gap in the methodology for evaluation of capital expenditure, human factor risk elements and use of historical data to evaluate risk. This thesis aims to contribute original knowledge to help improve production assurance by developing an integrated model which addresses pump-pipe capital expenditure, asset risk and reliability in subsea systems.

The key contributions of this research is the development of a practical model which links four sub-models on reliability analysis, asset capital cost, event risk severity analysis and subsea risk management implementation. Firstly, an accelerated reliability analysis model was developed by incorporating a corrosion covariate stress on Weibull model of OREDA data. This was applied on a subsea compression system to predict failure times. A second methodology was developed by enhancing Hubbert oil production forecast model, and using nodal analysis for asset capital cost analysis of a pump-pipe system and optimal selection of best option based on physical parameters such as pipeline diameter, power needs, pressure drop and velocity of fluid. Thirdly, a risk evaluation method based on the mathematical determinant of historical event magnitude, frequency and influencing factors was developed for estimating the severity of risk in a system. Finally, a survey is conducted on subsea engineers and the results along with the previous models were developed into an integrated assurance model for ensuring asset reliability and risk management in subsea operations.

A guide is provided for subsea asset management with due consideration to both technical and operational perspectives. The operational requirements of a subsea system can be measured, analysed and improved using the mix of mathematical, computational, stochastic and logical frameworks recommended in this work.

Acknowledgements

I dedicate this thesis to God Almighty for giving me inspiration, strength and knowledge throughout my academic sojourn, and particularly throughout the course of this research.

Special thanks to my beloved parents Emeka and Uche Okaro, my brothers Nwachukwu, Ifeanyi and Izunna for their unfailing love, financial, moral, and emotional support which brought me this far. I will always love you!

My heartfelt gratitude goes out to the entire staff of Newcastle University and particularly Professor Longbin Tao - my supervisor whose constant guidance, encouragement, and constructive criticism kept me on the right track till the end of this research.

Lastly, I sincerely appreciate the encouragement, concern and assistance offered by my dear friends, research fellows, well-wishers, and even survey participants who I am unable to explicitly acknowledge here due to space constraints.

Thank you all for your efforts and may God bless you!!

Author’s Declaration

I have read and understood the rules on cheating, plagiarism and appropriate referencing as outlined in the ethics handbook and I declare that the work contained in this thesis is my own, unless otherwise acknowledged. I wish to further declare that some parts of this thesis may contain relevant texts and/or data from my published and unpublished works which were either quoted verbatim or further analysed to new revealing depths.

Signed: OKARO, IKENNA ANTHONY

This dissertation is relevant to the Subsea Engineering and Management degree because it addresses the problems of asset reliability and risk management in subsea production firms. The research was inspired by the perceived increase in the amount of failure risks, costs, accidents and safety concerns surrounding the operations of subsea oil and production facilities.

List of Publications.

Okaro I.A, Tao L., (2016), Reliability Analysis and Optimisation of Subsea Compression System Facing Operational Covariate Stress, *Reliability Engineering and System Safety*. 156 (2016) 159 – 174.

Okaro I.A., Tao L., (2015), OMAE 2015-41871. Subsea Oil and Gas Production Using Artificial Lifts and Nodal Analysis. *Proceedings of 34th American Society of Mechanical Engineers (ASME), International Conference on Offshore Mechanics and Arctic Engineering Conference (OMAE)*, May 31-June 5, NL, Canada.

List of Unpublished Articles.

Okaro I., (2012), Strategic Operational Risk Management in UK Manufacturing Companies, *Masters' Thesis*, University of Warwick, United Kingdom, August 2012.

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Abbreviations

AZ/NZS	Australian/New Zealand
BS	British Standard
COSO	Committee of Sponsoring Organisations
CRO	Chief Risk Officer
EFQM	European Foundation for Quality Management
FMEA	Failure, Mode and Effects Analysis
FMECA	Failure, Mode and Effects and Criticality Analysis
FTA	Fault Tree Analysis
HR	Human Resource
HRM	Human Resource Management
ISO	International Standard Organisation
IT	Information Technology
JIT	Just-In-Time
MPS	Materials Planning Schedule
MRP	Materials Resource Planning
OHS	Occupational Health and Safety
ORM	Operational Risk Management
PDCA	Plan Do Check Act
PESTLE	Political, Economic, Social, Technological, Legal, Environmental
SME’s	Small and Medium Scale Enterprises
SPC	Statistical Process Control
SWOT	Strength Weakness Opportunities and Threats
TQM	Total Quality Management
UK	United Kingdom

CHAPTER 1

Introduction

Oil and gas companies are shifting exploration and production activities from conventional fields to offshore fields due to increasing energy demand [Li X, et al, 2016]. The World's energy consumption is predicted to grow by 56% from 2010 to 2040, from 524 quadrillion British thermal units (Btu) to 820 quadrillion Btu. Most of this growth will come from non-OECD (Organization for Economic Cooperation and Development) countries, where demand is driven by strong economic growth [Lacalle et al, 2015].

Although, renewable and nuclear energy usage are increasing at a rate of 2.5% each year, making them the world's fastest-growing energy sources, fossil fuels continue to supply nearly 80% of world energy use through 2040[Lee et al, 2015; EIA, 2016]. Crude oil and natural gas still enjoy a large demand relative to upcoming supplies such as renewables and nuclear as shown in Fig 1.

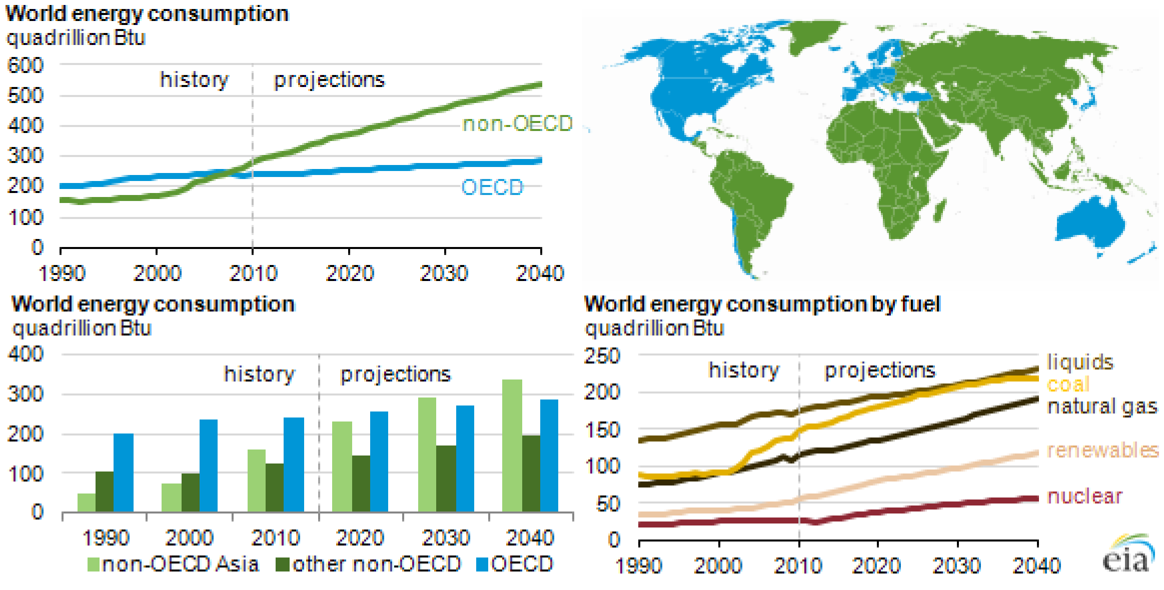


Figure 1: Snapshot of energy growth trends across the world [EIA, 2016]

Historically, conventional oil and gas production systems have had an impressive performance history, however, complex subsea systems are now being exploited in ways that were rarely experienced in previous development programmes. This rapidly increasing shift towards subsea production represents a higher level of risk exposure compared to conventional oil and gas operations. Subsea systems present a number of technical challenges because when normal technical systems are installed underwater, every traditional knowledge of material properties apparently vanishes. Due to the roughness and often remoteness of the marine domain, offshore production has experienced higher-lost-time incidents (LTI) and Total Recordable incidents than onshore drilling for instance. The fact that over 318 offshore accidents have occurred between 1970 till date is just a major indicator that offshore risks pose a lot more danger to efficiency, profitability and safety of offshore operations [OGP, 2010]. More recently, the mismanagement of risks in the arctic waters led to the Dec 2012 accident offshore Alaska; which attracted a fine of $12million dollars at a time of oil price slump [Sweet, 2015]. This is an indication that a potential operational risk may not only raise just safety and environmental concerns but also generate serious long-term economic consequences. Therefore, adopting a reliability-based approach can offer practical steps for forestalling and overcoming these risk challenges by ensuring that tolerable ranges of target reliability are achieved throughout an asset's operational life [Kolios et al, 2012].

There are enormous valid reasons for embarking on this research. In subsea oil and gas drilling and production, many of the methods have a reactive approach rather than predictive approach for risks facing subsea operations based on available literature. The existing industry standards such as the ISO 31000, the API 17N RP and the ISO proposed very robust suggestions and frameworks for risk analysis. However, people's perception of risks, affective reactions to the risk, and perceived need to prepare for it still seems somewhat immature across the subsea industry in contrast to industries such as finance and nuclear. Production assurance, risk and asset reliability broadly considers the risks in an operating system and proactively proffers robust solutions to eliminate imminent dangers in a system for business continuity [Zafra-Cabezaa et al, 2007, Torabi et al, 2016]. Operational risks in a conventional process industry, refer to those risks which originate from inadequacies or disturbances within the operational processes of an organisation [Wang et al 2016].

In the past, reliability and risk management were passively implemented either by reliance on risk transfer options such as general insurance or detective options such as safety devices, fire extinguishers, alarm systems and protective gears in order to minimise losses [Sadgrove, 1996]. In the subsea industry where technical complexity and operational variations are rife, there is no doubt that these strategy are merely reactive rather than preventive, thus, the need for a broad-based, diligent and preventative approach for managing subsea technical reliability and operational risks [Haugen et al, 2016].

Inquisitive minds may ask ‘What real value does reliability and risk management add to production assurance and profitability of a subsea firm?’ In response to that, from an operational viewpoint, subsea oil and gas firms make profits from revenue which comes from total sales minus the costs of sales. A high cost to sales ratio means that a low profit margin or complete loss is inevitable. This implies that risk, reliability analysis and a good production management model adds measurable economic value to an organisation by minimising the potential economic losses associated with unprecedented asset failures and unsatisfactory market positioning.

More critical minds may further ponder on: ‘What is the essence of researching subsea operational risks when the risks that accrue in a North Sea oilfield is probably different from the one in West Africa?’ Indeed, regional risk dynamics and operational challenges vary from company to company and from location to location, thus there is no *one size fits all* approach. This study does not argue that; rather, it attempts to reveal some of the areas where these risks may appear within a system, while suggesting an integrated approach for quantitatively and qualitatively addressing them from a predictive viewpoint. It is interesting to know that risk management research has been applied to various economic and subsea assets with tangible improvement in efficiency recorded in these systems [Yang et al 2016].

In a typical subsea production setting, key operations are those internal processes which directly impact production and efficiency. Lewis (2003) suggested that, internal risks, spring up from production capacity plans, information technology, supply chain, process system, human influence, and control systems. This suggests that operational risks emerge from the complex interaction between process, people, products or assets [Popov et al, 2016]. In a subsea environment this could mean time to repair, reliability of equipment, safety, environmental issues, competence of subsea operative or cost efficiency.

In the course of this research, various articles are explored for a good understanding of the nature of operations risk, technical reliability requirements and optimization. Subsea field development case studies on well production forecasting, artificial lift selection, pump-pipe efficiency evaluation, risk calculation and asset accelerated life testing were numerically analysed with the aid of stochastics, physics and software models. Thereafter, an investigation is carried out to find out how subsea production companies address subsea risk and reliability management. This is subsequently followed by the proposition of an integrated model and recommendations for the best practice based on the research findings.

1.1 Statement of the Problem

Many offshore accidents occur due to lack of risk culture and inadequacy of many of the existing risk or reliability assessment approach to properly address operational risks from both technical and enterprise-wide viewpoints. There is an urgent need for adopting an integrated reliability-based model that addresses both technical and enterprise risks in order to improve efficiency, profitability and safety in subsea oil and gas production.

An uncontrolled explosion caused the surge of water, mud, oil, gas and other toxic materials to rush out of the drilling riser on a semi-submersible vessel at approximately at 5000ft of water in the Northern Gulf of Mexico, offshore the coast of Louisiana on April 20th, 2010. This disaster killed 11 workers and 4 billion barrels oil leaked into the sea for 87 days [Christou et al , 2012].

‘On March 7, 2016, two kilometres of pipe that connects an offshore drilling rig to a wellhead deep under the ocean broke off and sank in a storm off Nova Scotia's coast Saturday, prompting concerns from an advocacy group over the risks of deep-water accidents caused by harsh ocean conditions. Based on that, the Director of the Clean Ocean Action Committee, said the incident is a reminder of the enormous power of huge offshore waves on the Scotian Shelf — and the risks of an offshore accident in one of North America’s most productive fishing grounds. “It’s another indicator to us that we need a regulatory regime that makes sense, and … basically takes notice of the fact we’re at the edge of our technological ability,” he said in a telephone interview’’ [Turton, 2016].

Similarly, on 10 August 2011, an oil leak was reported from the Garnet F field resulting from the failure in a subsea flow line, 176km east of Aberdeen (Department of Energy & Climate Change, 2011). Based on an initial investigation by Health and Safety Executives, it was revealed that an assessment of the safety management system for the leaking pipeline was due in 2008 but was not conducted before the incident [Ramasamy et al, 2015].

When a subsea system or asset is submerged into the marine environment for a long time, many traditionally known properties about material behaviour tend to vanish because these assets get battered by myriads of risks and reliability factors which stress-out the production assets and shorten their life-span resulting in economic losses and fatalities sometimes. Today, the pressure is to move from a reserved, narrow and silo-based approach to a cross-disciplinary, organisation-wide analysis of uncertainty [Subramaniam et al, 2011, Aven et al, 2014, Wu et al, 2016]. In view of this, a handful of regulations, standards and policies have been developed to help subsea operators towards systematic management of the inherent risks in their systems.

The problem is not just the scarcity of user-friendly integrated Quantitative Risk Assessment (QRA) models for analysing both the technical reliability and the operational risk management in a subsea oil and gas production lifecycle. The standards are either highly generic or too polarised on various stand-alone basis and not clear on implementation requirements. This is part of the gap which this research bridges.

In order to understand the complexities of system failure due to inadequate risks and reliability analysis program, it is important to develop a whole-system model consisting of physically tested mathematical models and validate them through case studies to determine the various failure modes of a subsea technical and operational system plus their severities. The proposed methodology is an aggregated mix of numerical evaluations and specialist computer simulations as established in each of the case studies. Data was obtained from a range of sources including questionnaires, interviews, industry field data, and OREDA handbook. These reflect the enhanced attributes of the over rall model.

1.2 Research Aim and Objectives

This techno-economic research seeks to develop an integrated model for subsea risk, reliability and production analysis and management. To achieve this overall aim, the research focuses on identifying the key risk vulnerabilities in the operations of a subsea production, areas of inadequacy in existing methodologies for risk management, and the challenges faced by subsea production companies in managing these uncertainties so that an enabling optimisation solution is developed.

The main objectives of this research are;

- Examine the strengths and weaknesses of the existent models and also measure the risk and reliability implementation levels in industry.
- To propose a method for selecting the optimal pump-pipe option for subsea fluid lift based on overall system efficiency.
- To develop a model for asset reliability analysis and optimisation by incorporation a corrosion covariate stress on Weibull distribution of MTTF data.
- To propose a risk severity matrix method which considers and iterates multiple risk influential factors (RIF) with basic operational factors.
- To develop an integrated model for the implementation of risk and reliability management.

1.3 Structure of Thesis

The structure of this thesis is arranged as follows.

Chapter 1: Introduction. This is the introductory chapter of this work. The research motivation, research aims and objectives were explicitly declared as well as the research focus and scope. The relevance and importance of the research were also highlighted in this chapter.

Chapter 2: Literature Review. This chapter provided considerable insights on the research topics. It contains an extensive literary review on the definitions of risk, methods for asset and operations risk management and reliability of subsea production firms. Discussion on the current standards for managing these risk sources was also presented as well as the benefits. This chapter also contains information on the types of approach being currently used for subsea risk and reliability analysis. Popular risk management frameworks such as API 17N RP, DNV

306 OSS, COSO-ERM framework, ISO 31000 were duly discussed. A critical analysis of the strengths and weaknesses of the framework was presented plus an update on the current challenges experienced in risk management globally. Thereafter, a concise summary was provided leading to the development of the research question.

Chapter 3: Research Methodology. This is the chapter where the research question was declared. The type of data to be gathered, the methods of gathering data and the reason for each choice of approach was discussed and justified. The analysis approach for data collected was also highlighted. The rationale for the data gathering approach and analysis were all explained in this chapter.

Chapter 4: Reliability Analysis and Optimization of Subsea Gas Compression System. This chapter describes the development of a novel Weibull Corrosion Covariate model which was applied to a Subsea Gas Compression System. The baseline OREDA Mean Time to Failure (MTTF) of the system components were stressed with factors of CO2 fugacity, temperature and time and pressure. To optimize the system, it was decomposed using Reliability Block Diagrams into its 39 sub-components. An enhanced Fusell-Vesely analysis was applied to determine the failure mode of each sub system and the amount of life needed to meet optimal reliability index targets. This will help firms in predicting how assets would behave in a subsea environment based on physical and statistical stress forces for deployment of adequate controls.

Chapter 5: Efficiency-based selection of Artificial Lift Systems for Production Assurance. This chapter presents an enhanced methodology and guide for choosing subsea multiphase pump-pipe system based on factors of power requirements, pipe diameter, costs and overall efficiency. First, it contains the enhancement of a Hubbert forecast model which was used to predict capacity of production. Nodal fluid flow analysis is then applied to subsea pump configuration to compare two popular pumps, an Electrical Submersible Pump (ESP) and a Progressive Cavity Pump (PCP) in terms of flow output, efficiency, power needs and pressure drop. Using fluid mechanics models for the design of flow rate and velocity and efficiency relationship is developed. This is applied to the pump-pipe case and the efficiency index proves that the ESP gives a higher volumetric efficiency in deep water, supporting the reason why it is popular in reality. Recommendations and advice were also provided so that subsea production companies can tackle field development challenges based on the quantitative analysis with due consideration to cost.

Chapter 6: Risk Severity Analysis by Matrix Method based on Historical Events and Risk Appetite Analysis. This chapter contains a risk severity analysis based on historical components of frequency and magnitude. Nine risks at nine subsea drill spots were analysed using a matrix analysis consisting of Risk Influencing Factors (RIFs), magnitude and frequency. The event magnitude was generated by a Poisson distribution and the frequency mean was obtained by a lognormal distribution of events mean. The risk severity was derived from the product of the two matrices.

Chapter 7: This chapter provided the results and analysis of the survey carried out to discover the industry awareness, trends and implementation appetite of subsea reliability engineers and operators

Chapter 8: Research Synthesis: This chapter contains in-depth discussions and recommended solutions based on the inference from the entire research.

Chapter 9: Conclusion. This chapter provided the formal summary and justification of the research. The strengths of the research and the recommended future research were also highlighted.

CHAPTER 2

Literature Review.

This chapter provides a comprehensive review of state-of-the-art in research and industry practice related to risk, asset integrity and reliability with a focus on subsea oil and gas production system. It discusses subsea production and how to determine production targets based on historical data. It explores some of the existing methodologies for ensuring production assurance based on reliability and particularly operational risk analysis. It also critically reviews the various methods for reliability and enterprise-wide risk assessment and management. A critical analysis of popular risk management and reliability models was performed; probing along their pros and cons followed by an audit of the most recent risk challenges. This set the stage for the identification of knowledge gaps and the consequent research questions. Table 1 links to the structure of the literature review with the rest of the thesis.

Table 1: Structure of the Literature Review

No	Literature Review Title	Refers To Chapter
2.1	Subsea Production and Reliability	4
2.2	Production Assurance and Artificial Lift Selection	5
2.3	Advances in Reliability Analysis Strategy	4
2.4	Risk Management	6, 7

2.1 Subsea Production and Reliability

Subsea Engineering is a specialised area of engineering which deals with the design, operation and maintenance of the underwater components and systems used to produce offshore oil and gas. Figure 2 is a trend of offshore production over the last 50 years.

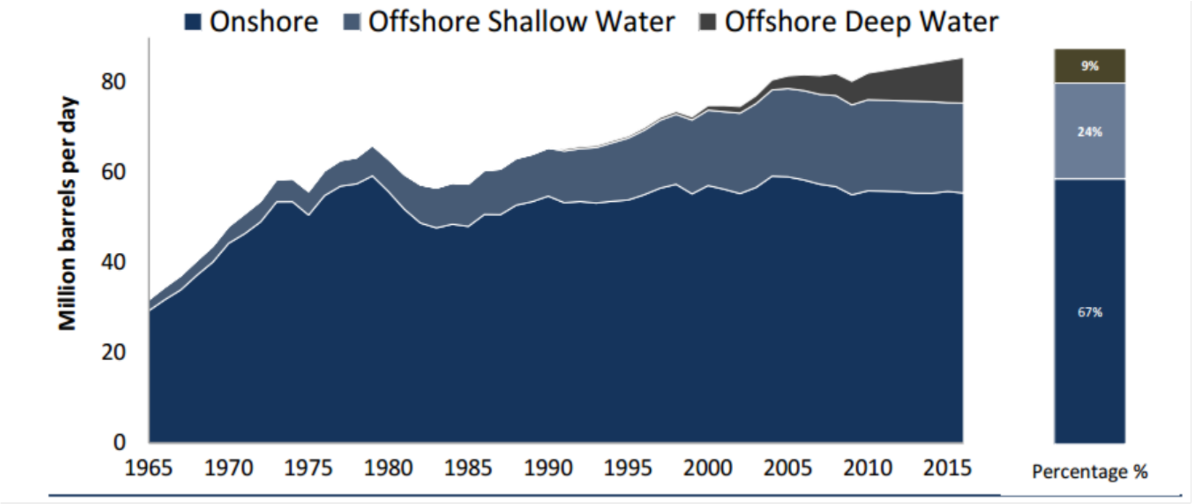


Figure 2: Expansion of Subsea Oil and Gas Production (Kohl, 2014)

The key benefits of subsea production are as follows,

- It offers a cost-effective solution in terms of Capital Expenditure (CAPEX)
- It reduces operational costs (OPEX)
- It is safer to install the components closer to the well.
- It improves production and project value.
- It enables low CO_2 emissions due to lower power consumption.
- It preserves marine life due to less disposal and disturbances at sea
- Process is safer due to unmanned operation.
- It facilitates the transport of well stream over long tiebacks.

The core of this research is centred on ensuring subsea production assurance through risk-based proactive methods. Figure 3 shows the distribution of subsea technology across the world. The key considerations for a typical subsea project focuses on;

- What to <u>Produce</u>? - Production Forecast
- <u>Technology</u> to produce it? - Process Capacity Plan
- How <u>Reliable</u> is it? - Asset Reliability
- How <u>Safe</u> and Sustainable is it? - Risk
- What does it <u>Cost</u> to run? Cost- efficiency

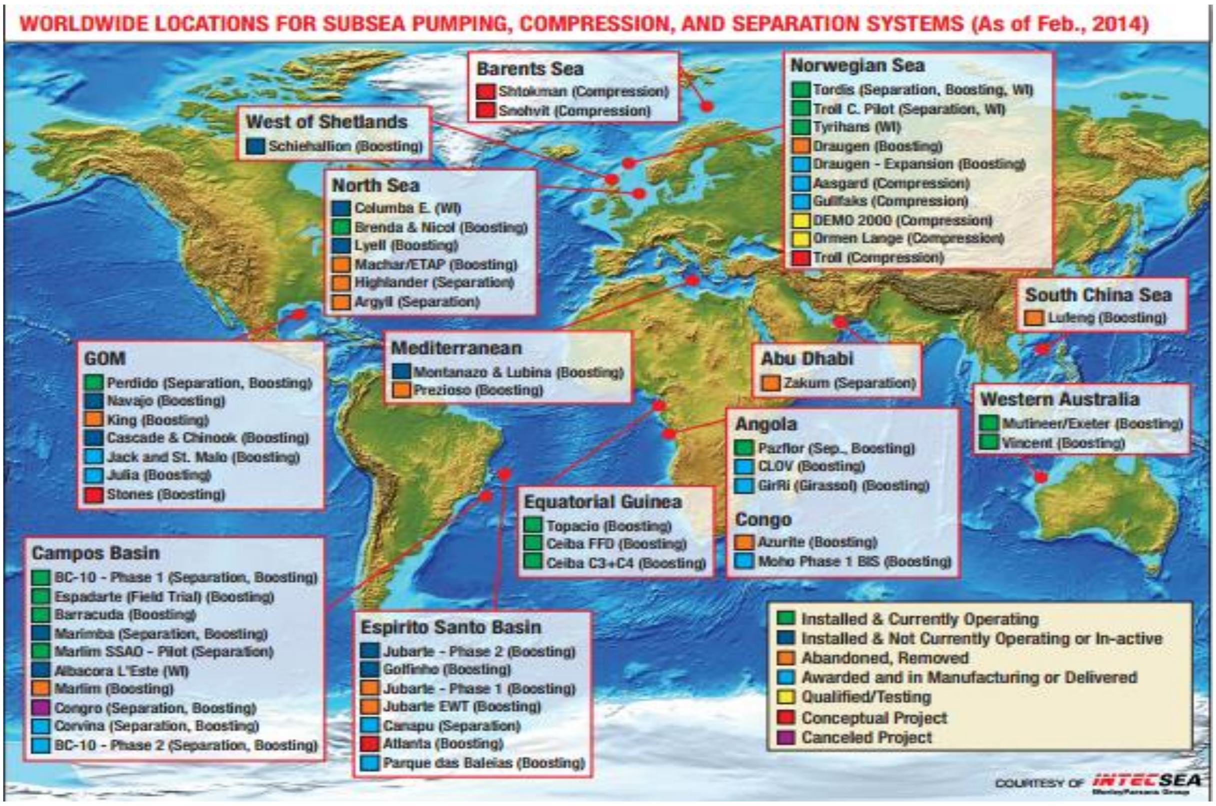


Figure 3: Distribution of Subsea Systems across the world [Intersea 2014]

2.2 Production Assurance and Artificial Lift Selection

During the production life cycle of an offshore oilfield, there comes a point where natural reservoir fluid pressure drops so low that artificial lift becomes inevitable for crude oil to flow from well head through the subsurface to the topside for further processing or storage [Huacan 2014]. Over the years, it has become a necessity to make adequate contingent strategy for recovery of reservoir fluid during the operational life of a field. In subsea engineering circles, these technical solutions commonly referred to as artificial lift methods or enhanced recovery methods involve the use of subsea pumps, compressors and valve controls in a range of configurations for fluid pressure boost [Mitra, 2012].

With artificial lift solutions, ageing deep water reservoirs which are ordinarily abandoned due to high back pressure are further depleted thereby improving the economic value of an oilfield significantly [Bai, 2012]. In fact, experts claim that modern pumps can perform impressively at tougher depths of up to 15000ft and temperatures of up to 232℃°C [Bates, 2004]. A well-informed capacity plan and a robust optimization strategy for production life of an offshore oilfield facing declining pressures and tough subsea conditions are essential for enhanced profits, efficiency and safety on subsea oil fields.

One complex challenge in subsea field development is the ability to decide which pump-pipe system to install and ensuring that flow rates correspond with production demands, pipe capacity, cost and overall efficiency variables. This requires an efficiency evaluation using a range of parameters including subsea temperatures, costs, risks, expected flow rates and of course reservoir properties. Unfortunately, not many studies have specifically provided a time-saving analytic method for evaluating efficiency in subsea oil and gas with respect to the mentioned parameters. To a large extent, this work is the result of an exiguous furtherance of the works of [Shadizadeh,et al 2009; Takacs 2012; JOGMEG 2012; Asim et al 2016] with new originality made; through the incorporation of artificial lift pumps placed at new depths, analysis of overall flow system efficiency, and consideration of costs of various pipe diameter-and pump system in the subsea domain. A new guidance is further provided on the selection of artificial lift and the procedure for evaluation of least-cost option for supporting pipe network. The costs incurred during a system overhaul for a pump fix at mid-life of field or mismanagement of flow as in the case of Piper Alpha in 1988 and Ekofisk B 1977 accidents [Christou 2012] could have been minimized by systematically predicting production performance at project kick-off.

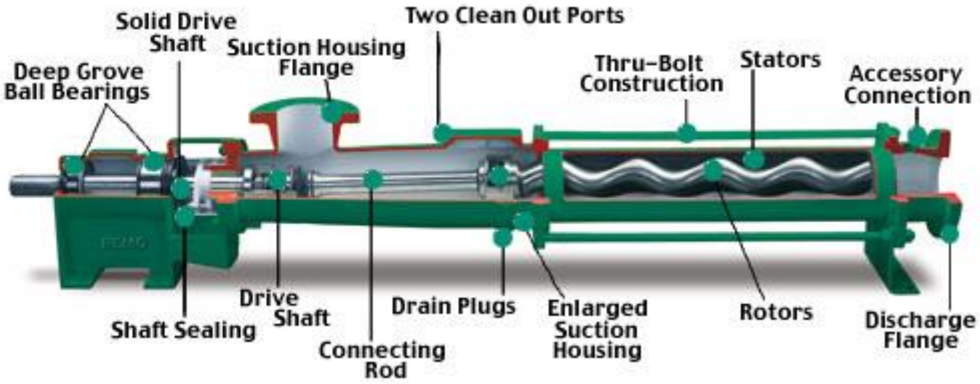
A number of stand-alone contributions have been made to address efficiency and capacity planning. To forecast oil and gas production, Ebarhimi et al [2015] presented a variance of the Hubbert Peak Theory with consideration for multiple influential variables such as new technology, shocks and production profile. The empirical success of the Hubert Model was also enhanced by Benes et al [2015]'s *a priory* views which considered a linearized Hubbert model and its relationship with oil price wherein an increase in global oil price increases oil production. Efficiency and least cost principles were studied by Ramana et al [2009] wherein efficiency, demand for power and cost of a range of power infrastructure were modelled for selecting the optimally efficient option.

Willersrud et al [2013] proposed a non-linear predictive control model for short term optimization of oil and gas facilities after investigating unreachable set points and infeasible soft constraints. Ribero et al [2016] improved on it by investigating the effect of efficiency on separators, energy loss and friction. Vieira et al [2015] carried out theoretical study of the various pressure losses in order to predict the actual head by an ESP pump, considering various flow phases. Nian et al [2015 proposed a propitious inversion method for evaluating the flow rate of a production well, the heat capacity developed using temperature data and a heat transfer model. Mohammadzaheri et al [2015] proposed algorithms based on artificial neural networks for estimation of head, brake horse power and profitability of Electrical Submersible Pumps (ESPs) for gaseous fluids.

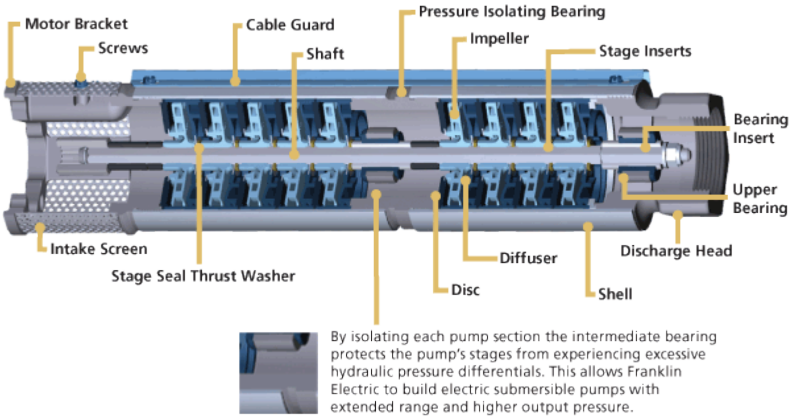
Xinfu et al [2011] suggested that a proper pipe-pump selection process must consider four primary components of the pumping systems which consist of well inflow performance, pump setting depth, water production rate, and rod string design. The components of the system are defined as a function of these four basic design parameters.

Meanwhile, Vogel [1968] was the first to suggest the Inflow Performance Relationship (IPR) technique for the prediction of flow output in vertical wells, more improvement was done by Lik [2007] to predict flow performance in saturated reservoirs. The works of Childs [1962] and Stepanoff [1957], Abdelaziz and Shen [2012] suggested a step-by-step approach for the design and optimization of cold-climate heat pumps wherein optimal designs for two different systems were discussed and analysed. It was discovered that optimization flexibilities of a system play a very significant role in the process of system design.

Ventrone et al [2000] put forward a striking methodology for the prediction of the whole head-capacity curve and the efficiency capacity curve of a turbine provided the geometrical parameters and the performance curves of a given pump are known. Even though the method appears smart it may not be easily applied without knowing the geometry of the system and in this regard it is useless for a cost-focused system designer. The subsea production system illustrated in Fig 4 shows a cross-section cut through two subsea pumps.



PCP Pump Section [Bachin, 2015]



By isolating each pump section the intermediate bearing protects the pump's stages from experiencing excessive hydraulic pressure differentials. This allows Franklin Electric to build electric submersible pumps with extended range and higher output pressure.

ESP Pump Section [Frank 2015]

Figure 4: Pump Cross-Section

2.2.1 Subsea Artificial Lifts

Artificial lifting is the process of adding energy to a stream of well fluid in order to charge the fluid with more pressure to achieve higher flow outputs. Subsea artificial lifts have continued to play a crucial role in resolving the flow assurance challenges encountered at subsea fields [McAllister 2014; Mohammedzaheri 2016]. With recent improvement in technology, lifting costs have been decreasing due to increasing availability of components that offer enhanced chemical resistance, lower power demands and certainly high reliability [Fleshman 1999]. However, not much is yet known about the relative efficiency, cost and risk profile of two popular artificial lifts; Progressive Cavity Pumps (PCP) compared to Electrical Submersible Pumps (ESP) for subsea oil and gas production.

Progressing Cavity Pumps (PCP) are reciprocating positive-displacement type of pumps consisting of a piston fitted with special valves which facilitate the displacement of a fixed quantity of fluid into the bottom-hole tubing and in turn discharges at the wellhead. PCP is a relatively recent artificial lift technology compared to others. It is not considered complex technology even though it is mainly used in lifting heavy oil [Chen et al 2013]; however, its application is sometimes confusing and misleading resulting in poor performance and low-efficiency operations [Nguyen et al 2014]. The guidelines for the deepest subsea well pump yet, an API 675 positive-displacement and reciprocating subsea pump was recently launched at the Offshore Technology Conference 2014 conference to enhance productivity in the harshest of existent subsea wells [World Pumps 2014].

Flexibility is a key consideration when choosing pumps for offshore operations and an electrical submersible pump (ESP) seemingly performs well. An ESP refers to a dynamic–displacement centrifugal pump whose pump displacement rate depends on the pressure head generated, and is becoming a popular option for offshore application [Hua et al 2012]. While Fig 5 shows that its usage trend is on the rise across the globe as more deep water and arctic fields are being explored across the globe, Table 2 shows that both ESPs and PCPs can be applied offshore. Modern models of ESP are auto-dynamic, re-adjust displacement pressure in line with fluctuating reservoir pressures and displace both gas and liquids at impressive high flow rates and pressures.

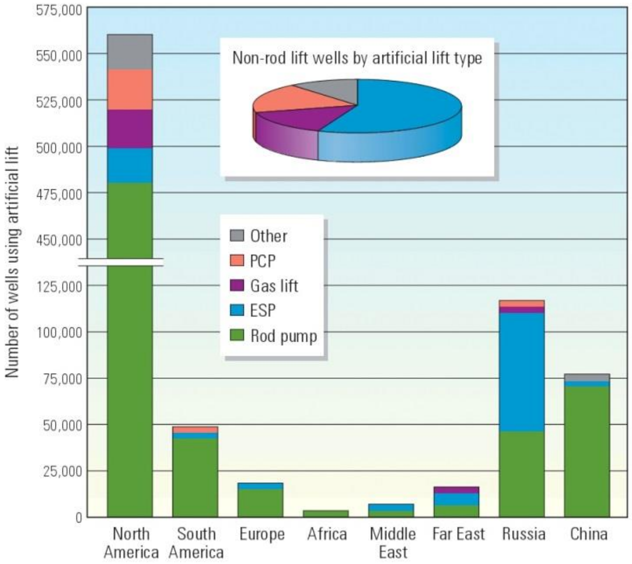


Figure 5: Artificial lift utilization across the world [Bates 2004]

Table 2: Brief Comparison of PCP against ESP

Artificial Lift Pump	**Progressive Cavity Pump (PCP)**	**Electrical Submersible Pump (ESP)**
Displacement Type	Positive displacement	Dynamic Displacement
Operating Temperature	100-500	100-400
Overall Efficiency	Pulling Rig/Workover	Pulling Rig/Workover
Maintenance	45-60	35-60
Gas Handling	Gas or Electric	Electric only
Depth	Difficulty at great depths	Less difficulty
Offshore Application	Applied offshore especially at heavy oil wells.	Unlimited. It can lift multiphase fluids but there is risks of corrosion over time.

2.2.2 Nodal Analysis

Nodal analysis technique, a method originally developed by renowned Dutch Engineer, Gilbert, is one of the methods that is currently widely used to comprehensively analyze a given oil production system [Gilbert, 1954]. It usually consists of splitting a given system at certain points known as nodes and evaluating the flow conditions at each half, with an overall aim of combining all components of the production system of various wells in order to estimate petroleum production rates and optimize configurations of the production system [Takacs 2012].

While Gilbert laid the foundation for systematic analysis of production rates with his work on gas-liquid ratio control, his postulation at the time was largely insufficient because it lacked refined correlations for reliably modelling fluid-lift or inflow performance in either vertical, horizontal pipes and network of subsea pipes with a processing equipment. Years later, further work by Mach et al [1979], gave rise to what we know today as Nodal analysis.

Typically, nodal analysis on a flow line point is carried out by plotting the IPR and TPR curves, and graphically locating the solution at the point where the two curves intersect [Guo et al, 2007]. However, sophisticated software tools lessen the task by applying the same nodal principle across an entire flow system to evaluate the average flow output, pressure and other parameters of interest.

This research sheds more light on the application of a graphical nodal analysis approach for the optimization of a subsea petroleum production system. The proposed model is original in a number of aspects. Starting from catalogue information and using design techniques [Makinde 2012, Fleshman 1999], it computes a virtual geometry and then it calculates fluid dynamic losses. For obvious economic reasons, the flexibility of nodal approach reasonably thumps that of conventional numerical solutions because an engineer can readily observe the big picture and the effect of alternating the oil and gas production parameters. More importantly, the engineer can investigate trends and compare hidden patterns such as velocity drop, costs, material costs, throughput and efficiency in order to save costs in far less time than conventional pipeline flow simulations can offer.

2.2.3 The Subsea Compression System (SCS)

The emergence of subsea gas compression technology has been one of the most significant technology advancements in the offshore oil and gas industry. The first of its kind of project was planned to take off in 2015 at *Asgard* field Norway [Terdre, 2008]. This undoubtedly represents a technological forward leap by the upstream industry as it holds huge potential for further improvement in field recovery rates in marginal fields.

Subsea compression refers to the process of increasing well stream pressure by means of a compressor located underwater [Henri et al, 2010]. It is a crucial part of the ongoing global strategy to eventually run full-fledged petroleum factories underwater in order to save cost, reduce human-machine contact and also accelerate oil recovery rate.

The concept is predicted to be more environment – friendly with lower risk since it is unmanned unlike platform based solutions [Fantoft, 2005]. Conventionally, gas is separated from well stream, compressed at topside and re-injected to well, flared or tapped off [Kennedy, 1993; Bai, 2005]. The new technology eliminates the need for topside compression as it separates and compresses fluid straight out of the well and delivers directly to the storage or processing facility.

According to its design, the compression station will be located closer to the well on the seabed thereby requiring lower inlet pressure and less overall cost for fluid lift [Berg, 2010].

A typical subsea compression system consists of three main sub-systems: the process system, the HV powers system and the control system [Berg, 2010]. The sub-systems can further be split into several components which interface with one another to make a complete functional production system.

Compared to 1 year for a topside facility, the average maintenance interval for a subsea compression system is anticipated to be 4-5 years [Aker, 2014]. This imposes a challenge to design and development of the hardware with significantly improved system reliability. The keen interest on reliability of the SCS further stems from the fact that vulnerable units of the system might require more caution in terms of design, installation and maintenance to ensure high availability which is paramount for a profitable operation.

Field experiences of failure from existing subsea technologies suggest a significant impact on both costs and schedule of operations for oil and gas production firms [Skogdalen et al, 2011]. The new model proposed in this research directly addressed the issue by predicting the reliability of the components in a realistic operational environment. Experience has shown that comprehensive tests alone will never be the same as having the unit working subsea for a longer period. This is because field reliability performance is not usually modelled into the reliability feedback loop but reliability can be achieved and lifecycle reliability simulations by taking into consideration, the boundary conditions of the operating environment [Gao et al, 2010].

2.3 Advances in Reliability Analysis Strategy

The huge loss and sanctions experienced in the 2010 *Macondo* oil spill due to the failure of Subsea Blow-out Preventer, the 2011 *Bonga* incident and a host of recent offshore failures has sparked accelerated efforts towards improvement of reliability, risk management and asset integrity for subsea systems [Skogdalen et al, 2011; Cai et al 2013; Vadachalam, 2016].

An investigation conducted by the UK Health and Safety Executive [HSE, 2014] indicated that nearly 80% of risk posed to offshore workers emanate from process-related failures. These failures which often cause accidents, downtimes and serious economic losses emanate from the complex interaction between human factor and technical factors which cause approximately 70% and 30% of offshore incidents respectively [Cai et al, 2011].

With an increasing appetite for subsea processing installations, risk exposure could even be higher due to lack of standardized reliability data and the fact that underwater assets are exposed to additional stresses brought about by dynamic influencing factors of the sea when deployed to the marine environment [Bai et al, 2012; Vedachalam et al, 2015]. This justifies any study which seeks to understand the equipment failure behaviour in subsea conditions to ensure maximum uptime. The highly specialized subsea sector is not exactly known for standardized asset life cycle reliability procedures [Antonsen et al, 2012] because there seems to be a lope-sided focus on the technical reliability qualification at manufacturing stages of subsea modules by several scholars; whilst appearing to neglect lifecycle asset reliability especially during the operational stages where the intertwine between human, equipment, environment has a great influence on asset performance [El-ladan et al, 2012].

Although risks and failure cannot be completely eradicated from any system, they certainly can be controlled through enhanced risk management strategies throughout the lifecycle of the project. As the world's first subsea compression system - a joint industry project is currently underway at the *Asgard* field offshore Norway and planned to commence operations in 2015 [Lima et al, 2011, Vedachalam et al;,2014], major concerns raised by stakeholders bother on reliability, corrosion and production assurance due to past experiences and losses encountered [Nelson, 2009].

This study presents an enhancement of a concept known as Accelerated Life Testing (ALT); an analysis procedure whereby basic system failure data is subjected to a high level of operational stress (covariate) and used to forecast the behaviour of a system in certain situations [Dorner, 1999]. The new approach which adopts a two-prong methodology for both technical and human reliability analysis consists of further development of the works of [Zhang et al, 2014; Barabadi, 2014; Sklet et al, 2006; Bai, 2005; Hassani et al 2014; Kaczor, 2016] wherein important contributions were made on Weibull-based covariate relationships for technical reliability analysis and human factor analysis respectively.

Deep water production hardware are exposed to high CO_2 pressure and temperature conditions which directly affect the degradation and performance of such materials [Zio et al, 2007]. At temperatures below 5°C and pressures much higher than 7.38 MPa, CO_2 could be in its supercritical state. In the absence of water, supercritical CO_2 is not corrosive, however, under normal deep water production operations, water is always present. When CO_2 dissolves in water, carbonic acid (H_2CO_3) is formed which significantly increases the corrosion rate of carbon steels and other materials. The mechanisms of CO_2 corrosion under supercritical conditions do not change compared to those identified at lower partial pressure [Lund, 2000].

The behaviour of a subsea system is better understood from a system reliability viewpoint [Jablonowski et al, 2010] which may connote a reliability study on equipment availability times, an asset integrity assessment, a hazard and operability (HAZOP) study dealing with operability of a system or even a profitability analysis of a system in terms of production capacity and revenue appraisal. In other contexts, it could imply Net Present Value (NPV) of a project, economic and management measures.

At the forefront of reliability analysis techniques is Monte Carlo's simulation which has been widely used over decades to quantitatively capture the realistic multi-state dynamics and stochastic behaviour of components and systems in reasonable computing times [Norris et al, 2016; Lin et al, 1998].

Lund, [2000], developed a statistics-based dynamic model for analysing offshore petroleum projects considering a number of uncertainty factors. The model incorporates several types of flexibility such as drilling options, uncertainties and capacity expansion uncertainties. A case study was carried out using the model and it shows that flexibility in capacity improves a project's economic value especially when there are many uncertainties surrounding the offshore reservoir. Unfortunately, considerations for human error estimation were not considered in the proposition.

Jablownosky et al [2010], modelled subsea reservoir uncertainty and measured the value of flexibility of assets for various capacities that could be expanded in the future in order to maximize the project's net present value. The major deficiency of the proposed model was its lack of explicit consideration for operational safety in a subsea scenario as it largely focused on the economic aspect of the oil field. Norris et al [2016], incorporated physical parameters into risk analysis by coupling laboratory-derived probabilistic nucleation model with existing deterministic calculations for hydrate growth.

The works of Lin [1998] and Lin [2008] suggested flexibility models for deep water oil field systems which were simulated using Monte Carlo's model to determine the value of specified flexibilities under the uncertainty conditions of reservoir and production capacity. The models did not address the severity of risk influence on CAPEX and OPEX in significant contrast to Lee et al [2016] wherein a design procedure for offshore installations life cycle cost analysis under various environmental load stresses was presented.

Chen [2016] developed a stochastic methodology for structural reliability analysis of a Floating Production, Storage and Offloading (FPSO) hull girder using an enhanced Smith Method. The model incorporates the severity impact of still-water bending moment, wave-induced bending moment and corrosion propagation mechanism. To understand wave-structure interaction of offshore structure and highlight lessons for reliable designs, Tao et al [2009] performed a classical parametric study on a three dimensional short-crested wave with a porous cylindrical break-water based on linear potential wave theory.

Leira et al [2016], suggested an enhanced Monte Carlo method for reliability analysis of pipeline systems facing multiple corrosion defects. The method presented failure analysis and frequency estimations of a corrosion-based failure but did not advise on optimisation of the local corrosion induced failure.

Choi et al [2016], developed an enhanced method based on fault-tree analysis for reliability and availability assessment of seabed storage tanks. The work suggested underwater storage tanks for subsea production and proposed a four-step procedure for defining system boundary, collection of reliability data, constructing a reliability tree and estimating the reliability of the subsea tank.

Thies et al [2016] applied accelerated testing by exposing static submarine power cable, fitted with an articulated pipe bend restrictor, to mechanical load regimes exceeding the allowable design loads in order to provoke accelerated wear and component failure in order to improve its design and operational life curve.

Lee et al [2016], developed a pragmatic model for determining the optimal load tolerance and reliability of a newly developed offshore asset based on return periods on environmental loads of waves, currents, and winds. The model is distinctive because it established a relationship between expected load and structural reliability and also applied a probabilistic procedure for estimating capital expenditure and risk expenditure based on load tolerances. Similarly, Vedachalam et al, [2015] modelled and analysed the reliability of a long step-out subsea boosting system using the fault-tree-analysis method and further recommended optimisation of some of the components such as the seal by means of pressure compensation technique.

Kolios et al [2016], developed an enhanced TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and applied it for decision making on reliable structural configuration for offshore wind turbine support on the basis of stochastic data from experts and associated weighting. Human reliability in offshore operations was similarly addressed by Akyuz et al [2016] using an enhancement of the human error assessment and reduction technique (HEART) which incorporated, interval type-2 fuzzy sets in order to override more of the uncertainty of experts' judgement and expressions in decision-making.

In a bid to enforce reliability practice across the subsea industry, ISO 20815 standard stressed the need for representation of stochastic variations related to lifetimes and restoration times using probability distributions while AP1 17N RP provided a structured approach which organisations can adopt for management of uncertainty throughout project lifecycle [Emmet et al, 2012].

Modelling complications are encountered when process variables such as temperatures, mass flows, pressures, affects the probability of occurrence of the events in resonance with human and organisational influence [Norris et al, 2016; Zoe, 2009; Anthonovsky, 2016].

An accelerated life testing (ALT) reliability analysis is meant to help operators ascertain the difference between the reliability warranty values suggested by the manufacturers and the realistic asset performance [Naseri et al, 2016] being that risk influencing factors such as seabed temperature of 5℃ at 4000 meters of depth, PCO_2 fugacity, and pH which are prevalent and are major agents of asset degradation at seabed need to be considered. Unfortunately, literatures on reliability of subsea compression technology are barely available at this time due to the nature of its very recent development. This perceived vacuum inspired this work whose main aim is to propose an assessment model that links failure distribution to influencing covariates using Weibull analysis; in order to forecast asset survival rate and reliability.

This research combines the statistical confidence bounds of a two parameter Weibull model and a covariate model to create a new reliability model technical failure assessment, this study demonstrates that the lifecycle operational requirements of a subsea system can be understood and improved by analysing the effect of a corrosion stress on a Weibull failure data in addition to fuzzy scaling of human and operational barriers. A case study on a subsea compression system was used to demonstrate the applicability of the model. The poor reliability of a subsea system can be optimized by breaking down component systems using Reliability-Block-Diagrams (RBD) and prioritizing the components based on Fusell-Vesely reliability importance.

2.3.1 OREDA and Accelerated Failure Testing (AFT)

Offshore Reliability Database (OREDA) is a unique data source of mean failure rates, failure mode distribution and repair times for equipment used in the offshore industry from a wide variety of geographic areas, installations, equipment types and generic operating conditions between year 2000 and 2009 [OREDA, 2009]. OREDA is a joint industry project for the aggregation and storage of equipment failure times and associated data. With over 17000 equipment units of subsea oil and gas equipment recorded up to date, there is no doubt that it is indeed the largest data bank for offshore equipment at present.

Ideally, real historical failure data are the most suitable for reliability modelling. Unfortunately, such data only become available towards the end life of a system and that justifies the use of OREDA values for MTTF in place of real field data. This means that OREDA may not be completely relied upon for accurate prediction of failure times of emerging technology and components which have little or no historical records but could be used for failure prediction.

It is true that the latest version of OREDA consists of some consolidated failure data based on subsea-based installations. However, OREDA handbook reports the parameters of the hazard rate and average active repair time of a variety of the equipment units installed on offshore oil and gas platforms operating mainly in the North and Norwegian Seas. These areas are considered the base areas and are often used as the baseline. [Naseri et al, 2016]. Whilst OREDA is a very useful book due to its massive database, it hardly does report full comprehensive data for other areas across the world where substantial new subsea production activities have been carried out in offshore fields with harsh weather conditions. More specifically, OREDA data only consists of various failure rates (MTTFs) of selected subsea components. From a reliability perspective, these data are far from sufficient for the prediction of overall failure rate since it does not tell much about the cumulative failure rate and reliability of the entire system at a given time. The various parts fail at their mean lifetimes, therefore the comprehensive analysis reported in this work is a crucial step forward to identify those critical parts for enhancement

As part of the effort to address the gap, the system analysed in this thesis is for the West African Offshore environment with the covariate physical conditions being incorporated into the Weibull model of OREDA data in order to predict realistic failure time of the asset.

MTTF is the mean of distribution of a product's life calculated by dividing the total operating time, accumulated by a defined class of components within a given period of the total number of failures in that time period. It must be noted that it is based on a statistical sample and is not intended to predict any one specific unit's reliability, in order words, MTTF is not a necessarily warranty statement but manufacturer's statistical prediction devoid of usage environment variations. Table 3 shows some of the data sources which are used for reliability analysis.

Table 3 : Table of Various Reliability Data Sources

Various Reliability Data Sources	Focus
CCPS Guidelines for Process Equipment Reliability Data, AIChE, 1989	Process Reliability
EiReDA - European Industry Reliability Data	Both and Mechanical and Electrical data of mainly nuclear plant components.
EPRD - Electronic Parts Reliability Data (RIAC)	Mainly components in nuclear power plants
Subsea Master Exprosoft	Many data for with enabling software tools for analysis. : Components in subsea oil/gas production systems
Failure in the electro-power supply system	Power System In Norwegian
FIDES	Mainly electronic components
FMD-97	Failure Mode/Mechanism Distributions (RIAC)
GIDEP	(Government-Industry DataExchange Program)
Handbook of Reliability Prediction Procedures for Mechanical Equipment - Mechanical equipment - military applications	Mainly for military and high precision designs
IEC/TR 62380 Reliability Data Handbook	Universal model for reliability prediction of electronics components, PCBs and equipment
IEEE Std. 500-1984	IEEE Guide to the Collection andPresentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear Power Generating Stations
MIL-HDBK-217F	Reliability Prediction of Electronic Equipment
NPRD-95 Non-electronic Parts Reliability Data (RIAC)	
OREDA - Offshore Reliability Data	Specifically for offshore oil and gas data
PERD - Process Equipment Reliability Data(AIChE)	Process equipment
PDS Data Handbook	Reliability Data for Process Control and Safety Systems (PDS)
EXIDA	Safety Equipment Reliability Handbook (exida),
SPIDR	System and Part Integrated Data Report (System Reliability Center)
Telecordia SR-332	Reliability Prediction for Electronic Equipment (Telcordia Technologies)
T-Book	Reliability Data of Components in Nordic Nuclear Power Plants (ISBN 91-631-0426-1)

In AFT, the covariates act multiplicatively at the failure time by some constant, so its effect is to accelerate or decelerate failure time. This assumption provides a physical or chemical interpretation for the effect of covariates on the failure time. Hence, the AFT can be more appealing in many cases due to this direct interpretation [Gao et al, 2010]. Furthermore, unlike proportional hazards models, the regression parameter estimates from AFT models are robust to omitted covariates, and they can be used to quantify the effect of time-dependent covariates. Such induced stress normalizes the data set and makes it suitable for stochastic analysis and prediction of reliability.

System failure data are usually gathered from historical performance archives, but in practice, these data are insufficient and do not reflect the real operational conditions of its purposed domain [El Abassy et al, 2014].

In further attempts to account for these life cycle conditions, a number of numerical models consisting of life-covariate relationship such as the Arrhenius model, Proportional Hazard Model (PHM), Eyring model Extended Hazard Regression, Inverse Power Law had been seen to provide acceptable results [Nelson, 2009]. Reliability analysis had been carried out using experimentally or field-sourced failure data and applying predictive models in order to extrapolate results of system reliability beyond the given data range [Goode, 2016; Volk et al, 2004; Barabadi et al, 2011; Barabadi et al, 2014, Tsoukalas, 2016; Gómez Fernández, 2016; Chiaccio, 2016; Peng et al, 2016; Naseri, 2016; Gao, 2016]. For example, in PHM, the operational conditions are considered to be a covariate, such that the reliability of the system is a product of time and covariates. The covariate acts multiplicatively on the threshold hazard rate by some constant [Zhang et al, 2014].

The major limitation of asset life covariate models such as PHM is that it usually has many assumptions which are not applicable in many real world cases. It can only be applied to time-independent covariates; notwithstanding, it is still the most frequently used due to its simplicity and commercial application [Barabadi, 2014].

One of the most important applications of AFT is analyses of failure data whereby collected data is subjected to high level of operational stress (covariate) is used to predict the behaviour of a system [Tsoukalas, 2016, Naseri, 2016].

The analysis of ALT data consists of (i) selection of an underlying life distribution that describes the system such as Weibull analysis (ii) incorporating a life-covariate relationship development. The first step towards AFT is understanding the operation mechanism of the system. Accelerated life testing (ALT) is a procedure that exploits the fatigue properties of materials to aid in the design and validation process (Lawless, 2003). The general trend is to use ALT as a method to demonstrate the suitability of a particular design and/or system for field usage. Another useful application for the ALT data is to aid in determining the effect of operating a system outside its original design conditions. Generally, this allows the development of reasonably accurate estimates of life when operated at higher loads.

This is done in order review the various components that make up the system and their failure mode through data collection. Failure data is sourced from a combination of expert opinion, archived reliability databases or manufacturers' prediction about equipment failure times. In this work, failure data values were obtained from OREDA data bank while failure modes were obtained from expert opinion using interviews and short questionnaires.

Due to the fact that Accelerated Life Testing has to be designed and performed in order to generate the failure behaviour of the whole system, it may involve performing Weibull analysis on the collected failure data to determine the model parameters 'α' the scale parameter and 'β' the shape parameter of the data. These parameters are then integrated into the covariate expression generated from a corrosion profile of subsea hardware and the exponential of the new model gives the hazard rate and reliability of the system.

To verify the appropriateness of the ALT reliability model and check its validity, a number of methods are used in several ways, however, the most common way of doing it is by using the quartile-quartile plot. A straight line through the origin of the Kaplan-Meier estimated values for failure data indicates that AFT model is alright.

2.3.2 Weibull Modelling

The reliability distribution of the subsea processing system can be effectively modelled after a two- parameter Weibull distribution together with a certain life covariate parameter. Weibull distribution is one of the most widely used lifetime distributions in reliability engineering.

Arguably, there are a number of methods for modelling failure rate. These include Weibull, log-logistic, gamma, log-normal, exponential models (Lawless, 2003). All of them are acceptable dependent on data set distributions, however, Weibull two-parameter modelling was the made the choice baseline model because it offers best fit plot for failure data; in contrast to others in the list which are usually associated with some form of skewness making them more suitable for queuing theory data modelling (Ebeling, 1997). The two parameter Weibull was chosen because it accommodates distributions with zero values while the 3 parameter Weibull distribution does not have accommodation for zero lower bound which implies that for failures less that the lower bounds, there is no chance of failure. The third parameter (location) is often used when data point do not fall on a straight line but a sharp concave or convex curve. The two- parameter Weibull distribution can take on the characteristics of other types of distributions, based on the value of the shape parameter. It is often used for modelling data sets containing values greater than zero, such as failure data.

In Engineering, Weibull analysis can make predictions about a product's life, compare the reliability of competing product designs, statistically establish warranty policies or proactively manage spare parts inventories, to name just a few common industrial applications (Mohammad et al, 2014).

In academic research, Weibull analysis has been used to model diverse phenomena such as the length of labor strikes, AIDS mortality and earthquake probabilities and several other probabilistic events (Nakhaee et al, 2009; Hristopoulos et al, 2014). These prove that Weibull modelling is a robust tool for failure analysis.

Table 4 shows the various categories of techniques and tools for reliability and risk analysis.

Table 4: Reliability Analysis Techniques

	ANALYSIS TECHNIQUES FOR RELIABILITY
1	**Fault Tolerance**
	Parts De-rating and Selection
	Stress-Strength Test
2	**Methods for Architectural Analysis and Dependability**
	Bottom-Up Method
	Event Tree Analysis
	Failure Mode and Effects Analysis
	Failure Modes, Effects and Criticality Analysis
	Hazard and Operability Study
	Top-Down Approach
	Fault Tree Analysis (FTA)
	Artificial Neural Networking, Fuzzy and Bayesian Systems
	Markov Analysis
	Petri Net Analysis
	Truth Table (Structure Function Analysis)
	Reliability Block Diagram
3	**Methods for Estimating Reliability Parameters of Basic Events**
	Failure Rate Prediction
	Human Reliability Analysis
	Statistical Reliability Method
	Software Reliability Method

2.3.3 Asset Integrity Management

Asset integrity could be described as a situation whereby an asset performs its designated function effectively and efficiently while sustaining its operations and processes in such a way that there is no harm. (Khan et al, 2016). Asset integrity ensures that subsea production facilities are designed in compliance with regulations and specified safety standards without undermining operability, safety, availability and maintainability (Ramasamy, 2015).

The main aim of asset integrity management is to make sure that subsea oil and gas operators safely abide by all regulatory policies and standards; both local and international which are designed based on best-fit industry requirements and regulations; this enables the equipment to remain fit for purpose, reliable and operational under designed threshold. Many subsea oil and gas firms employ an asset integrity strategy at various phases of an asset lifecycle which may consists of design, installation, commissioning, operation and decommissioning stages.

The operational stage of an asset often requires routine reappraisals for additional retrofits in terms of processes and equipment because asset failure frequency tends to increase after initial design life. A number of research have been performed on asset integrity with focus on oil and gas offshore.

Baby (2008) suggested that an assets operational integrity is directly linked to technical barriers of the system such as required experience, appropriate knowledge, competent manpower adequate manning and reliable data for decision making during an assets' lifecycle.

Khan (2016) argued that predictive maintenance is always more effective and recommended that material deterioration and associated cost be modelled in terms of a time- dependent stochastic process as it prevents failure uncertainties.

A Bayesian method was proposed by Zarei et al (2016) incorporating new information such as near misses and mishaps and using algorithm to map the risk. Though the method is robust, it appears static and seems inadequate for complex situations. The Fuzzy Multiple Criteria Decision Making (MCDM) developed by AlNajjar et al (2003) for evaluating a mix of approaches and selecting the most adequate maintenance approach presented a well-structured method for integrity management strategy selection. Bevilacqua et al (2005) applied an enhanced Analytical Hierarchical Process (AHP) for asset failure rate and integrity optimization.

El-Abbasy et al [2014] designed a condition assessment and prediction model which is used to analyse expected deterioration curves for offshore oil and gas pipelines while Ossai et al [2016] applied Markovian analysis on the operational parameters and pit depths of pipelines in a way that predicts crack initiation times for various corrosion rates. Lundteigen et al [2009] outlined a new approach which incorporated Reliability, Availability and Maintenance and Safety (RAMS) into the life cycle of an assets operating at high pressures environments.

Aven [2016] buttressed that the future of risk and integrity management would be based on balanced risk-based approaches, cautionary/precautionary (robustness, resilience, adaptive), and discourse-based approaches. The review was a suggestion for mixed decision making approach that entails both quantitative, probabilistic and non-probabilistic concepts.

The contribution by [Netto et al, 2013], presented a subsea flexible pipe integrity management tool which is based on data enveloping analyses (DEA). This allows linear programming to maximize relative risk by coupling subjective weights of input for the main observed failure mechanisms with objective expected failure modes.

A comprehensive approach was put forward by Rahim et al [2010] suggesting a Cause-Effect-Action-Outcome chain analysis using a 5C integrity model which consists of Competence, Compliance, Communication, Collaboration and Control.

A more robust framework for asset integrity will be useful for achieving the goal of ensuring that assets meet their full life cycle usage requirements or intention. Subsea asset integrity framework requires the systematic and continuous monitoring of activities from concept selection, detail engineering, procurement, manufacturing, construction, installation, commissioning, operation, inspection and maintenance to meet asset integrity objectives.

2.4 Risk Management.

Risk management is the systematic application of policies, procedures, methods and practices to the tasks of identifying, analysing, evaluating, treating and monitoring risks' (BS 6079: 3-2000). Operational risk in a subsea environment refers to the probability of misfortune within a subsea asset and these include safety concerns, explosions, environmental danger, loss of production, and associated costs [Okoh et al, 2016]. In practical terms, it refers to those sub-set of risks which are usually generated by the Assets, People, Processes, Products.

According to Burduk et al, (2006), the effectiveness of a risk management program hugely depends on a firms' ability to identify the inherent hazards in its systems, the situations that can generate them, the vulnerable areas of uncertainty, and whether it can exercise control over these risk generators.

Many times, operational risk management is formally implemented by the adoption of defined risk management standards, guidelines or policies. Whilst there exists a range of specific risk management approaches and standards at the moment for subsea application, the risk analysis process itself consists of a number of well-defined steps which are broadly the same across all available risk management guidelines. A close look at the structure of most risk management approaches takes after the PDCA flow diagram which is further broken down to the Fig 6.

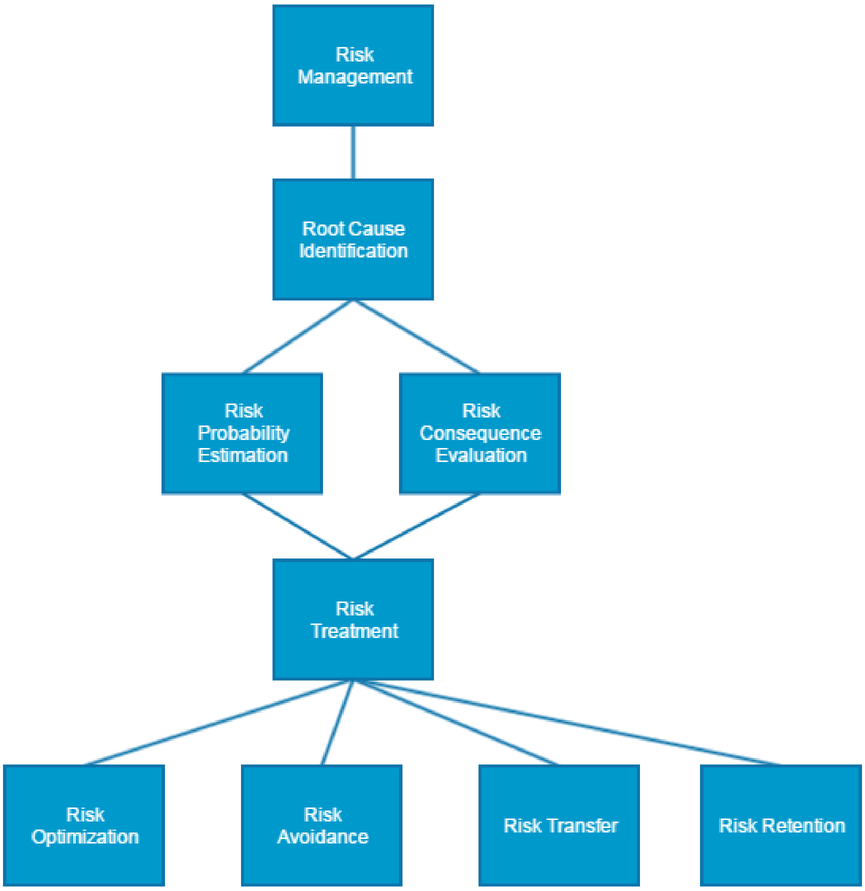


Figure 6: Basic Risk Management Procedure

Identification of the risk source involves unravelling the root causes in order to make proper plans for treatment. Risk estimation is another vital part of the risk management process because it helps to quantitatively and qualitatively predict the certainty associated with a risk's manifestation as well as its magnitude (Okaabe et al, 2009).

There are several methods for quantitative risk analysis which may include Monte Carlo simulations, Poisson distribution, Pareto distributions, Log normal distributions, gamma distributions (Chiaccio et al, 2016, Tsoukalas 2016) and several other stochastic approaches which are used to model and predict the possibilities and impacts of a risk or group of risks.

Whilst, these statistical estimates help to model and predict risk, they all have their peculiar strengths and limitations because they are actually mere guides for estimates and assumptions, which may not be exact with reality. All the methodologies have their pros and cons, but Monte Carlo simulations seems to be quite flexible and effective because it makes it easy to understand many risks variable; once the parameters and scatter plot are created (Okabe et al, 2009).

Risk controls are the strategic responses deployed towards an identified risk based on the results from risk identification analysis and predicted severity on a firms' short-term or long-term objective [Vinnem et al,2016]. A firm could either; exploit the risky situation with some positive expectation, avoid the risks, transfer the risks or accept it while communication is maintained throughout the whole process as duly pointed out in Fig 6.

For many centuries in the past, risk management was traditionally done by experience, guesses and feel. Although the approach worked in certain cases, it was found to be broadly ineffective as proved by the huge losses encountered by firms towards the end of the last century (Williams et al, 2006).

Risk-based evaluation analysis have been utilized to determine the optimal repair or replacement times of subsea process equipment, hinged on the likelihood and consequence of failure caused by time-dependent degradation mechanisms [Thordi et al, 2013].

Aven, Sklet [2006], developed a method for barrier and operational risk analysis of hydrocarbon releases by combining qualitative and quantitative data to predict platform specific hydrocarbon release frequency. Similarly, Shafiee et al [2015], presented a Multi-Criteria-Decision-Making (MCDM) method which is based on Analytic Network Process (ANP) method for choosing the best risk mitigation strategy for offshore wind assets.

The risks in an offshore production environment can be modelled and analysed in terms of monetary value per cycle of operator to determine whether a predicted risk exceeds a predefined target risk tolerance [Aljaroudi et al, 2015]. Although limit state approach was applied to determine the probability of failure for a pipe however, the methodology did not consider human influence on risk vulnerability.

Li et al [2016], presented a concise review of the current situations and risk impacts of offshore oil spills, as well as the policies and technologies in offshore oil spill response and countermeasures. The increasing risk of oil spills in the northern regions from the expansion of the Arctic Passage was addressed with specific recommendations.

A methodical approach based on operational procedures and numerical analyses of allowable operational risk limits in sea state has been applied to identify critical events and decide the corresponding semi-probabilistic response parameters during the planning phase of offshore installation [Acero et al, 2016].

Hughes et al [2016], developed a very interesting method which combines qualitative and quantitative data to measure, analyse and potentially improve a system's energy security based on well-known properties of events such as the frequency of occurrence and expected stress and that of entities such as flows, time-to-recover, and stress-tolerance.

Haugen et al, [2016], provided a brilliant discussion on the concept of *black swans* and stressed that it is better to be aware of events which may come as unprecedented surprises, and create uncertainty in risk assessment process. [Li X, et al 2016], presented a Bayesian-based quantitative risk analysis method which was used to model cause and effects relationships of uncertainties surrounding a subsea pipeline.

Johannessen et al [2015], studied the high-risk work involved in subsea operations and provided in-depth insights on how the subsea operators can readily respond to disruptive events by balancing of organisational structure and flexibility through informal leadership redundancy. The recommended approach encouraged the decentralisation of silo-structured risk management strategy and the implementation of risk management at the grassroots level of an organogram for efficient operations.

In several subsea oil production companies, there are no specific rigid rules for managing operational risks but information gathered from available literature depicts that risk management initiatives are maximized through the application of any of the category of broad approaches under-listed.

- The Enterprise- Wide Risk Management Approach (ERM)
- Generic Risk Management Approaches
- Stand Alone Approaches.

2.4.1 The Enterprise-Wide Risk Management (EWRM)

Enterprise-Wide Risk Management is the process whereby an organisation's top management and other distinguished persons involved in strategy setting across an enterprise; put up certain strategies for managing risk within the firm's risk appetite and drive the firm towards realizing its corporate objectives. (Steinberg et al, 2004; Lam, 2014).

According to Gupta (2006), Enterprise Risk Management (ERM) is rapidly emerging as the powerful tool which helps in making better decisions across the organisation as regards risk identification, measurement and treatment. A candid example of an ERM framework is the COSO-ERM framework that was designed by the Committee of Sponsoring Organisation of the Treadway Commission (COSO) in a bid to encourage and enhance the ability to manage internal risks in industrial systems. According to Samson et al (2008), this well-structured framework is the most widely adopted and utilised approach for risk identification, assessment and mitigation of risk. It further stresses that most of the other risk management are either enhancement of this original format or simply sprung out of it.

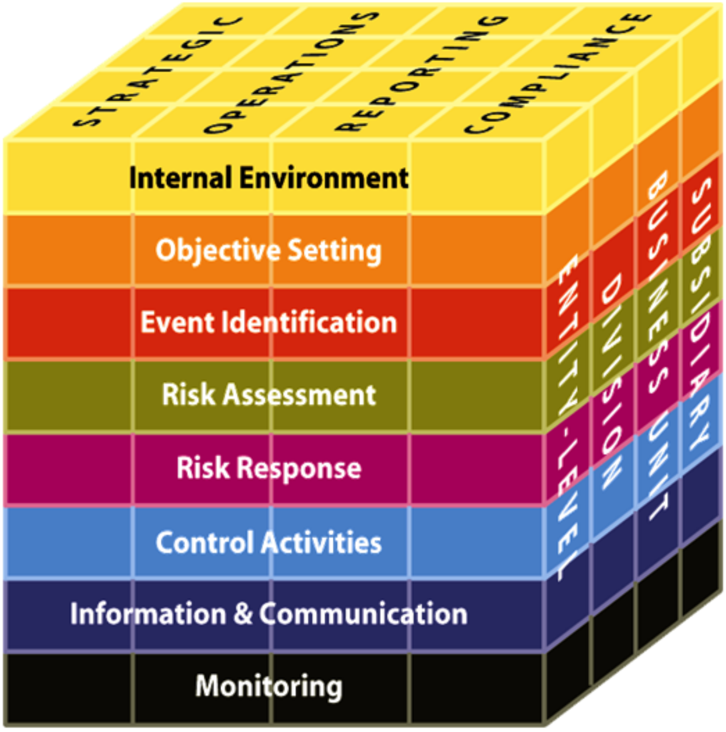


Figure 7: ***The COSO Enterprise Risk Management Cube. (COSO, 2004).***

Fig 7 depicts the ORM system framework which contains the synchronisation of three different divisions. The framework is categorised into three main divisions A, B, C.

(A) The first division focuses on the following elements of an organisation as discussed in detail by [Moeller, 2011]:

- Strategic – Deals with goals and missions of the organisation.
- Operations- Allocation and utilisation of resources.
- Reporting – Special focus on reliability of data.
- Compliance- focuses on laws and regulations (Steinberg et al, 2004).

(B) The second division focuses on the application of risk management based on the complexity and of the organisation by categorising into the following:

- Subsidiary
- Business unit,
- Division
- Entry level.

(C) The third division focuses on the actual implementation process of the COSO framework which consists of the following eight interrelated steps: [Tricker, 2015]

- Internal Environment: This refers to a philosophical approach whereby risk culture and risk appetite, culture and awareness is established in an organisation.
- Objective setting: refers to the establishment of a well-structured strategy guiding the setting of a firm's objectives.
- Event Identification: Identification of the internal and external factors that bring risks and opportunities in a firm.
- Risk Assessment: The process in risk management whereby the possibility of a risk occurring and its impact is determined.
- Risk Response: The process of determining the tolerance level for a risk by deciding whether to avoid, accept, reduce, or share the risk.
- Control Activities: The application of procedures and policies in order to ensure that appropriate action is taken.
- Information and Communication: This refers to the dissemination of information concerning risk management whereby information move up down, across and through the entirety of the firm.
- Monitoring: Routine monitoring of the applied process and modifications made if necessary (Steinberg, 2004, COSO, 2004).

In practical terms, COSO-ERM framework was designed to help manage the risks across various sectors of any organisation for strategic enterprise wide risk management. Lam [2014] noted that the advantages of ERM includes organisational effectiveness, improved risk reporting and business performance. After pondering on the third division of the cube (implementation phase), it is clear that the implementation procedure closely relates to the robust Deming's Plan-Do-Check-Act (PDCA) cycle as shown in Table 5.

Table 5: ***The Relationship between COSO Framework and PDCA Cycle***

Stage	**PDCA Cycle**
• Internal Environment • Objective Setting	PLAN
• Event Identification • Risk Assessment	DO
• Risk Response • Control Activities	CHECK
• Information and Communication • Monitoring	ACT

Interestingly, many researchers have criticised the COSO-ERM approach citing that the cube is overtly confusing, failed to give adequate and specific advice concerning operations management and had the following fault lines; (Gates, 2006, Andersen 2006):

- It seems to have a lot of flavour for financial risks thereby neglecting technical risks.
- It did not clearly extrapolate risk discussions to strategic levels as par being proactive.
- It did not provide a two-way top to down and bottom to up approach with full support from top management.
- It failed to produce a wholesome view of enterprise in order to trap a variety of risk throughout the firm.
- Failed to give practical advice and does not treat risk pro-actively hence could be misleading

In industries, top management have expressed their dissatisfaction towards the COSO ERM framework by considering it too detailed, non-value adding hence little need to waste time and resources on such an activity. A survey by Beasley et al (2010) found that 41% of the companies believe the cube is theoretically sound while 25.4% declared that it is too complex, failed to address the core operational needs and causes negative reaction to the use of the framework. Notwithstanding the report, it is still the most widely cited, adopted and utilised approach for identifying, assessing and mitigating risks. At this stage in this research, it is quite early to argue about the efficacy of COSO-ERM framework in handling operational risks. Therefore, later on in this work, we shall investigate and discuss the efficacy of COSO – ERM and its application towards risk management via a survey.

2.4.2 The Generic Risk Management Frameworks

Many generic risk management approaches have been used in the past when risk management became an issue of concern. Currently, the most popular ones are the ISO 31000 and the AZ/NZS 4360.

The AS/NZS 4360:2004 is basically an Australian standard for management of risk. According to Rasmussen et al (2007), its approach is more flexible and mature than older standards such as the COSO ERM. It is viewed as an approach which provides considerable resources for managing different risk scenarios. It is achieved by focusing on both external and internal factors of risk, with priority given to stakeholders through proper consultation and communication. A major flaw detected in the standard is in the preface where it was mentioned that the standard applies to both opportunities and threats. That is a confusing statement and there was no further explanation pertaining to this in the body of the standard details as pointed out by Razz et al (2005).

A very popular approach is the ISO 31000: 2009. It is a general guideline developed by the International Standard Organisation to be used by public, private, groups, individual and communities for management of risk. Unlike other ISO standards, ISO 31000 is not a certifiable standard, but provides guidelines regarding strategic management of risks in an environment. It was designed to take into account the various needs of a company in terms of objectives, operations, projects, products and services and all the inter-related tasks (ISO 31000, 2009). It is also hinged on the PDCA ideology whilst combining several best aspects of the other existing risk management, such as the Canadian CSA Q850, Australian AZ/NZS 4360 and the COSO framework which makes it relatively comprehensible compared to the others (Hortreed, 2010). Even though, the implementation is carried out across the entirety of an organisation, the core responsibility of RM lies on the shoulders of two or three persons of which one is a chief risk officer. Though these titles are important in a subsea production firm, it could be seen as promoting the much dreaded silo-based approach which often does not allow other employees to learn or participate actively in the risk management process. The job of risk custodians is to always enforce, review and embed risk culture within the organisation.

ISO 31000 lays particular emphasis on the following areas:

- Application of risk management in all decision making
- Continual Improvement
- Full accountability for risks from top management to the bottom

- Continual communication
- Full integration into the organisations' governance structure

(ISO 31000:2009).

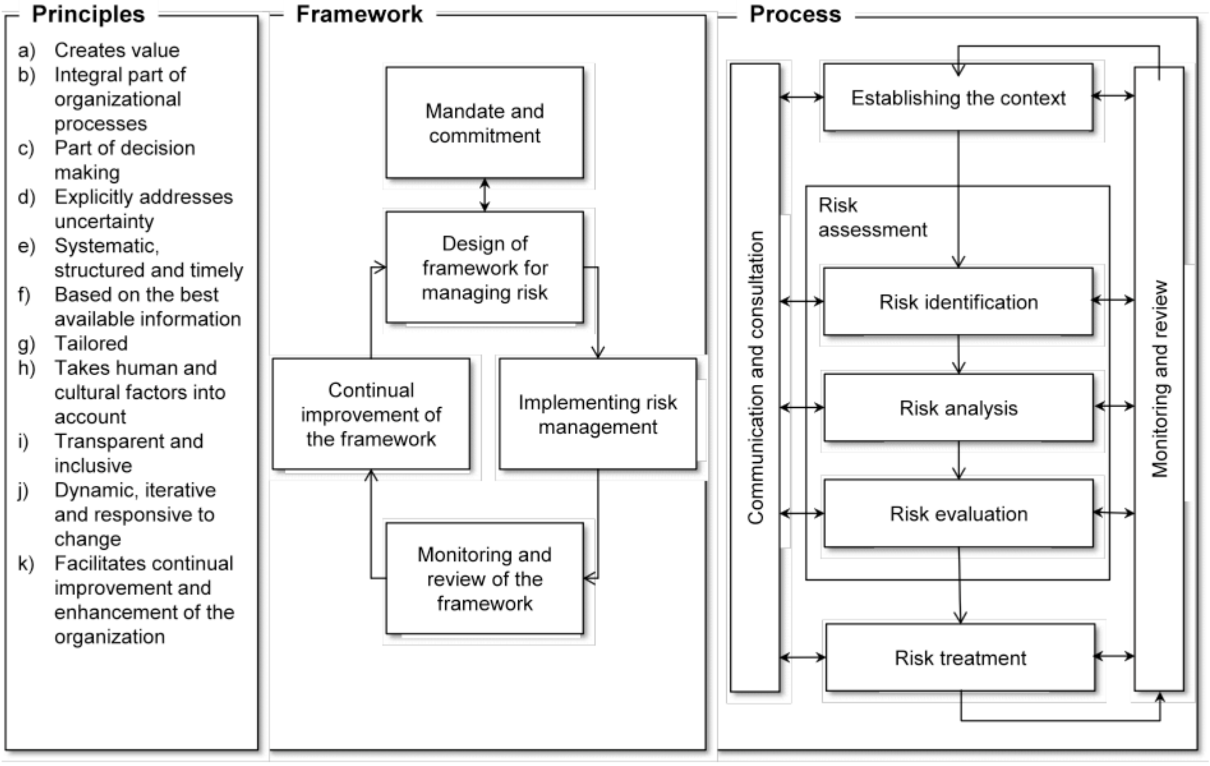


Figure 8***: ISO 31000 Risk Management Model (ISO 31000 Standard, 2009)***

From the diagram presented in Fig. 8 and from the contents of the ISO 31000 document, the ISO 31000 explicitly supported the following:

- Risk management should be known by the key decision makers in the organisation and adequately applied during decision making.
- It supported that top management should be committed towards risk management by making sure the procedures are embedded in governance and organisational activities.
- Linkage between risk management and information flow through information technology as an essential part of risk management.
- Professional trainings and establishment of audit teams and boards as custodians of the risk framework and the register helps to embed risk culture across an organisation. (Hortreed, 2010, Banks, 2012).

The ISO 31000 standard is comparatively clearer than the cuboid COSO framework. Experts have expressed optimism about the robustness of ISO 31000; suggesting that it is more robust than COSO ERM and AZ/NZS 4360 because it provides systematic, logical and quick instructions and as such well-balanced in terms of scope [Tsiouras, 2015]. A study conducted by the ISO 31000 professional body discovered that 40% companies develop their own in-house framework while 36% of the sample population use the ISO 31000 (ISO 31000, 2012). This issue shall be re-visited later on in later chapters.

It is quite true that some of the risk standards mentioned are either project specific, operation focused or enterprise wide focused, but that does not suppress the fact that they are basically generic in outlook and are not specifically designed for the subsea production industry. Interestingly, a closer examination at all the frameworks discussed shows that they all took after the outline as the Deming's PDCA cycle, suffice to say they took their roots from the much effective management cycle.

Apart from the major strong points and remarks made in the table above, a number of slight differences were found amongst the risk standards. For instance, in the terminologies used, some of the frameworks used the words 'risk evaluation' or 'risk estimation', while others simply say 'risk analysis' meanwhile they all stand for risk analysis in the process. There were also differences in the definition of risk; some standards defined it as 'threat' or 'hazard', while other defined it as a possibility of both 'threats' and 'opportunities'.

A close look at the framework suggested by COSO, and ISO 31000 bodies readily shows some remarkable similarity between the two standards in terms of implementation structure. Both presented an integrated, step-by-step, generalist approach for the management of risk. A review of both standards indicate that, ISO 31000 was developed from the best aspects of the COSO ERM and AZS 4360: 2004. Results from a survey indicated that most risk practitioners showed that 52% of the population preferred the ISO 31000 against 15% who opted for the COSO ERM framework [Marks, 2012]. The points highlighted by the respondents is shown in Table 6.

Table 6*: Comparison between ISO 31000 AND COSO-ERM framework*

The COSO ERM Framework	The ISO 31000 Framework
• It is comprehensive and has stood the test of time. • Is the standard that has been adopted by their regulators? • Their organization previously adopted it. • It leads to the COSO internal control framework. • It has a better discussion of risk appetite. • It is stronger on corporate governance. • There is a better linkage to strategies and objectives	• Easier to understand and explain to others. It is user-friendly. • Written by practitioners instead of accountants and auditors • Clear, logical, intuitive, and practical • A better 'how to' guide, easier to use when implementing risk management • More focused on risk and less on audit and controls than COSO • Represents best practice and the collective wisdom of global risk leaders. • Flexible, less prescriptive, easily tailored. • Has a top-down approach to risk management

Unfortunately, among all risk frameworks reviewed, none provided specific advice regarding the role of human aspects in implementation of risk management and its contribution to its effectiveness. The human aspects include issues such as human reliability, bias, training and awareness, the role of top management and stakeholders. Incorporation of these aspects would have made these standards more user-friendly, practical and easy to adopt. The most pressing issue about the framework is its generalist tone which makes no mention of any key areas to be considered for application. In doing so, it failed in its capacity to provide adequate information which can pose a serious challenge to its potential users (say a subsea production firm) whom may find it difficult deciding how and where to apply risk management frameworks in their various systems.

Furthermore, majority of the standards except ISO 31000 did not emphasize the need to routinely examine the effectiveness of the risk framework implementation and the need for noting the lessons learned for continuous improvement. It would have been more valuable to have clearly stated the 'Dos and Don'ts' plus possible challenges and limitations to be encountered when adopting any of the risk standards, code or recommended guideline.

Finally, it was observed that all the risk management frameworks take after a basic procedure which normally starts with risk identification, risk analysis and risk treatment irrespective of variation in the sub activities contained in these three basic processes. A commendable attempt was made in the new ISO 31000 which stressed much on risk appetite and communication. Meanwhile, some informal sources have highlighted that a supplementary standard; a possible ISO 31001 is currently being developed to address more lapses in the previous ISO 31000 in terms of application.

2.4.3 Subsea Risk Management Based On Stand-Alone Systems Standards.

The spate of rapid globalisation and continuous increase in market competition has continued to pose a serious challenge to organisations with respect to their management practices. In response to this, the International Organisation for Standard (ISO) and several other national standard institutes have developed a few management standards for regulation of specific aspects of the subsea production chain which may include quality, environment, occupational health and safety, business continuity and many more.

Risk management could be managed quite subtly, but effectively through adherence to some well-defined international, national, industry-specific and operation specific standards and policies. Within the past couple of years, a lot of companies use a company-tailored standard which consists of a combination of several management or regulatory standards such as environmental standards, occupational health and safety standards, quality standards and some undocumented company specific standard to suit their needs. In the context of this research, these systems are termed ‘Stand Alone’ systems because they often focus on a subset of operational activity, in other words, they are less integrated. The standards include:

DNV 306 OSS: Verification of Subsea Facilities

The standard was designed for subsea engineers to focus on reducing risks in a pipeline, riser and subsea facilities and thus reduce risk at optimum cost. The document contains detailed risk-based guidelines for the selection of appropriate verification scopes for subsea systems. One of the key strengths of the DNV 306 OSS is its combination of simplified analysis, inspections, quality controls and test to mitigate the risk of asset failure during operation. The major focus of the DNV standards include

- Structural and pressure containment design reviews
- Flow assurance design review
- Process safety and control system design review
- Type of independent calculations required
- Fabrication requirements
- Installation requirements
- Commissioning requirements.

The major con of the guideline is its apparent neglect for human factors and enterprise risks even though there was a mention that risk is not only related to physical failure modes, but also to operational errors, human errors and so on. For some risks the functional failures or physical failure modes contribute less than 20% while more than 80% of the risk relates to other devices (DNV OSS 306, 2004). It did not clearly discuss how any tool, statistical or otherwise could be used to trace organisational risks and whose responsibility it is to manage and chart-out these risks.

API 17 RP N: Subsea Production System Reliability

The main aim of the standard is to identify the best practice and enhancements needed for the management and assessment of subsea reliability, technical risk and operational Integrity in the Subsea industry [Strutt et al 2014; API 2009]. It is also intended to present a guidance on management practices and tools to assess, optimise, manage and meet safety, environment and production goals.

Its aim is to identify improvements to the alignment of reliability and integrity management activities during design and operational stages. There are two key major strengths of API 17RP N. Firstly, it provides an update section on the use of Technology Readiness Level (TRL) in qualification of new technology, and it is highly integrated with standard ISO 20815 – the production assurance standards for petrochemical companies, which is a very robust standard that has been in use for a longer period of time in the oil and gas industry. Other advantages include;

- The API 17N schema provides a prepopulated network with links to key performance specific networks (with appropriate notation)
- Using principle of modular Global Safety Network.
- Gives structure to the application of API 17N reliability activities
- Provided dashboard for monitoring status of current activities and managing documentation
- Provided templates for supporting evidence and assurance documentation
- Facilitated creation of assurance reports (plugin) for operators, investors and regulatory bodies dynamic link to supporting evidence such as the FMECA and qualification plan.

However, it did not adequately discuss the reliability assessment of emerging subsea assets due to lacking of proper historical data. It could have provided advice on the kind of stressed stochastic analysis that may be needed to predict reliability performance of subsea systems in water.

ISO 20815: Production Assurance and Reliability Management

According to the ISO 20815 standard, the petroleum and natural gas industries require large capital investment as well as operational expenditures ISO 20815 [2012]. The profitability of these industries is dependent upon the reliability, availability and maintainability of systems and components that are used. Therefore, for optimal production availability in the oil and gas business, a standardized, integrated reliability approach is required. The concept of production assurance, introduced in this International Standard, enables a common understanding with respect to use of reliability technology in the various life-cycle phases and covers the activities implemented to achieve and maintain a performance level that is at its optimum in terms of the overall economy and, at the same time, consistent with applicable regulatory and framework conditions.

This international standard designates 12 processes out of which seven are defined as core production assurance processes. The remaining five processes are denoted as interacting processes and are outside the scope of this International Standard. The interaction of the core production-assurance processes with these interacting processes, however, is within the scope of this International Standard as the information flow to and from these latter processes is required to ensure that production-assurance requirements can be fulfilled.

DNV 0002: Subsea Integrity and Reliability Management

The RP (DNV GL-RP-0002 ‘Management of Subsea Production Systems) is the result of a two year joint industry project (JIP) involving DONG Energy, FMC Technologies, GDF Suez, Norske Shell, Statoil, Talisman, Petroleum Safety Authority and Norwegian Oil and Gas. The JIP project explored the typical failure modes of existing subsea equipment and how the integrity of subsea equipment could be managed.

The recommended practice has been developed to provide guidance for operators and suppliers for the establishment and maintenance of an integrity management system (IMS) for subsea production systems. A description of the overall IMS with the core integrity management process (IMP) is provided respectively considering the IMP in a lifecycle perspective. It further describes the four main activities that form the IMP and gives recommendations on how to establish and maintain integrity by carrying out these activities: [DNVGL-RP-0002, 2014]

A. Threats and failure modes
B. Risk assessment and IM planning working process
C. Recommendations with regards to corrosion and erosion.
D. D: Integrity reporting template.

Failures in subsea production systems can arise from inadequate design, manufacturing or installation. In operation, material degradation as well as structural threats, natural hazard and operational threats, might cause failure of the system. The standard demonstrated that information management and documentation is a particular challenge and organisational interfaces can also impede clear communication and exchange of operational data across operators' organisations.

The subsea industry is challenged by high cost levels and complexity therefore integrity management is not only a matter of operational control on a daily basis, it should start from the outset of the design phase and continue through the entire life span of the system [Turander, 2014].

American Bureau of Shipping (ABS) Guidance Notes: ABS is one of the largest classification society in the world. The standard is termed risk assessment applications for the marine and offshore oil and gas industries. It suggested many positive recommendations for risk management in the offshore industry. Firstly, it presented a distinction between broad focused risk analysis and narrow focused risk management and methods for selecting the best fit method for a case. It provided a clear overview of many widely recognized risk management tools such as FMECA, FTA, ETA Bayesian and many others. The key advantage of the standard is that it is written in a clear and simple language which is easy to understand. It also incorporates the merits of deterministic and prescriptive regulatory requirements based mostly on experience, testing programs and expert judgment. [ABS 2000]. ABS rules and guides contains over 254 publications for various aspects of offshore oil and gas production ranging from subsea pipelines, to human factors and safety assessment.

BS OHSAS 18001 is an international management standard for management of occupational Health and Safety risks (OHS). It provides a structured framework for identifying, prioritising, evaluation, treatment and monitoring of OHS risks. It was designed to help protect workers, customers, and the public from health hazards and it can be applied to all categories of subsea organisations ranging from small, medium and large enterprises. It has been viewed to be compatible with ISO 9001 and 14000 (British Standards Institution, 2008).

IEEE 1540-2001: This standard was developed by the International Electrical Electronics Association; a United States-based organisation whose standards and frameworks have often been adopted and used internationally. Besides advocating for the normal risk identification, assessment and treatment processes, it laid special emphasis on the need for adequate communication with the organisations' stakeholders in the risk management process (Razz et al, 2005).

IEC 62198: 2001: This standard was established by the International Electro technical Commission (IEC). It is a standard for managing risks in projects and operations containing a technological content. Its main emphasis lies on the need for communication across the various disciplines involved through risk reporting and treatment (Razz et al, 2005).

BS 6079:3-2000: This is a British Standard for project risk management released in the year 2000. Its major strong points include the emphasis on stakeholder analysis and alignment of risk management measures towards business objectives and strategy (Razz et al, 2005).

CAN/CSA Q850-97: This emphasises the importance of communication at all stage in the process, including close proper communication with all the stakeholders. In the UK, most of these standards are often used as supplementary "stand alone" standards.

2.4.4 Global Outlook on Reliability and Risk Management.

A study was carried out on 450 risk practitioners and business executives in 31 major industries across the globe by issuing questionnaires and conducting interviews on risk practitioners and business executives across a wide range of companies including energy firms globally. The survey exposed mostly the current trends as regards the current practice of risk management in many industries [Accenture and Oxford, 2013]. One of the key findings of the study is that risk management is increasingly being integrated with the rest of the organisation on an organisation-wide basis for decision making.

Firstly, it was observed that most companies valued risk management more than they valued it in 2011 with 46% highlighting operational risks as a key external pressure and energy firms ranking operational risks among the top two key risks expected to rise within two years.

Secondly, up to 85% of the global companies surveyed considered risk management central and strategic for dealing with the growing competition and plan to enhance corporate risk handling capability through proper operational risk management. The third key information in the report is that 62% of the respondents from energy firms confirmed the adoption of Enterprise Risk Management program while 21% confirmed that none is being applied at their firms but there is plan to adopt a risk program in 1-2 years. Meanwhile, a similar survey conducted by ISO revealed that only 40% percent of companies manage their risks in-house (using self-tailored frameworks) while other companies manage risks with any of the local or international standards [ISO 31000, 2012].

'*In terms of unsafe practices and conditions, there is zero tolerance on such risk," notes RK Mehra, Head of International Trade and Risk Management at Bharat Petroleum, one of the largest state-owned oil and gas companies in India. "I have been working for 25 years in resources, and there has been a night-and-day change in the focus on risk," agrees Accenture's Mr. van 't Noordende. "Risk incidents today impact your 'license to operate,' and if you have a bad enough incident, you can be shut down*' [Accenture and Oxford, 2013].

Even though the majority of companies use one form of risk management program or the other, the data gathered from risk respondents indicated that a number of challenges has been encountered in the implementation of risk management so far. Among all the risk types being investigated, operational risks were found to constitute a very high proportion of the risks posed to the companies.

The challenges encountered are highlighted below:

- The magnitude and size of risks are increasing: Among the major concerns expressed by executives is the continuous and rapid pace at which risks emerge and change its forms and the corresponding change in regulatory requirements. Inflexible company policies, lack of risk culture, structure and governance could be blamed for this.
- There is insufficient proactive engagement of the organization with regulators and governments and this brings about lack of an integrated risk culture and reform by business units or senior management.
- Organisational silos are preventing effective integration of risk management structures and responsibilities: Up to 46% of the executives surveyed expressed that operational risk management is only somewhat integrated into company systems while 50%

expressed that risk operational risk management. ‘somewhat’ here means averagely. Firm’s structural and governance structure is to be blamed for inability to integrate with other risks for effective operational risk management.

- Lack of skilled staff to develop the right analytical models and the difficulty in embedding risk analytics in management processes..
- Cost reduction and alignment of risk management with business strategy are ongoing executive concerns: This was rated the most challenging concern by 40% of the risk practitioners. This challenge is justified because the ultimate aim of risk management is to forestall and reduce unnecessary costs thereby saving money for the organisation save.

2.5 Research Gaps and Summary

- Many of the existing reliability standards are either too broadly advisory or have gaps for reliability assurance of emerging subsea oil and gas technology.
- OREDA data is not sufficient for application at other areas. At subsea, material become too vulnerable due to extreme stresses from temperature, pressure, pH, corrosion and human factors which force the assets to degrade sharply, fail, explode or even cause deaths. Ideally, real historical failure data are the most suitable for reliability modelling. Unfortunately, such data only become available towards the end life of a system and OREDA data only contains conventional data which were gathered from the North Sea and as such may not apply to the Arctic or West African offshore.
- Many of the existing methods for reliability prediction considered either only the impact of a single element such as temperature or cost or current load on the marine facilities. This research considers temperature, pressure,Co2 fugacity simultaneously within a corrosion profile model used as covariate stress ON basic failure data from OREDA. This is presented in chapter 4.
- Offshore reliability database (OREDA) only listed the Mean Time to Failure (MTTF) of individual subsea components but did not explicitly advice or consider the cumulative failure times of the components at system level. This is investigated in chapter 4.
- There is need to measure how the subsea industry implement *reliability and risk standards comprising of standards such as* API, ISO, and DNV codes on risk, reliability

and production assurance respectively. A survey was conducted and presented in chapter 7.

- Availability of practical methods for the selection of the right pump and pipe configuration based on expected flow output and cost, power requirements is still challenge and this is addressed in chapter 5.
- Quantitative estimation of multivariate risk in the subsea oil and gas industry is still a huge challenge and this was further investigated and a method proposed in chapter 6.

This chapter provided a basic understanding of how reliability, asset risk and integrity affect subsea production assurance. Definitions of risk from various authors were reviewed before narrowing down to the meaning of operational risks and its forms of manifestation in subsea production companies. Operational risk in the context of this research refers to those risks arising from the internal systems of subsea oil and gas firms.

Several modern technologies for exploiting underwater hydrocarbons are being designed and deployed in deeper waters where they are faced with many harsh physical elements which may shorten their lifespan. The reliability of a subsea asset could be improved by modelling and considering several risk factors to prevent unprecedented failure, fatality and economic losses. An analysis method known as accelerated life testing has been shown to give more realistic results for equipment performance. Pumping and boosting of fluid from underwater reservoir to topside has also proved to facilitate oil recovery, however, the selection method for the best option is still unclear. These will be investigated in the next few chapters and a new methodology proposed.

A comprehensive discussion was presented about the key areas in subsea production operations in accordance with available literature and the frameworks for risk management was extensively discussed and analysed. Consequently, the most commonly used risk management approaches; categorised into the generic approach, the enterprise wide approach and operations management systems approach were reviewed alongside their applications. The literature reviewed shows that many firms that practise risk management, either choose from any of the fore-mentioned standards or develop one to suit their operations and targets.

Recent risk reports were reviewed in order to pin-point the current trends and challenges facing organisations in terms of managing risks in operations. The core message emphasised in the literature was identification of the key risk areas and an analysis of the strengths and weaknesses of risk management frameworks and also identification of the current challenges in the operational activities of subsea production companies. Based on the literature review, the following issues can be summarised as:

- The increasing volatility and growing complexity in business operations makes risk management critical and central to all industries operating in today's business world.

- Awareness of practitioners and organisation’s governance structure has a big role to play for the success of risk management.

- Although heightened awareness about risk management exists, critical exposures persist due to poor understanding and poor implementation. Hence, the benefits of enhanced risk capabilities are yet to be fully realized.

- The failure to link up operational risk management with the key operational activities is like ‘leaving money on the table’ which eventually causes the failure to achieve high performance.

- Effective risk management requires an infusion of risk culture, risk alertness, decentralisation of the silo-approach and an integration with other risks because operational risk is not exhaustive. It takes different forms and changes from operation to operation irrespective of the fact that there are key areas where they normally occur. A top-to-bottom approach is most suitable for improved results.

- Subsea companies still face implementation problems with risk management, regardless of whether they use standardised ‘integrated systems’ or ‘stand-alone’ systems which prompts more companies to adjust the risk management approaches being used by tailoring to their own peculiar systems.

In order to ascertain the validity of the mentioned points, recent information from a sample population of subsea companies shall be captured and analysed so that the various details discussed in the literature review can either be confirmed or discarded and possible new discoveries made about status of operational risk management practice in Subsea companies. The next chapter discusses the strategy with which the data collection would be achieved.

CHAPTER 3

Research Methodology

In this chapter, the methodologies and procedures employed in the course of this research were explicitly described as well as the reasons behind the choices made. This chapter also goes as far as describing the type of data collected, how they were collected, from whom they were collected and how they would be analysed. The core methodologies applied in the thesis was meant to take care of subsea asset lifecycle. Firstly, the reliability and optimization model for a subsea asset is developed from the combination of 2-parameter Weibull model and corrosion profile covariate to generate an Accelerated Life Testing model. Human reliability is analyzed using an enhanced BORA method. Secondly, Hubbert oil production prediction method was enhanced for determining production targets at pre-feed phase of project and the impact of artificial lifts on the economics of subsea wells facing hyperbolic decline in flow rates and pressure was examined. An efficiency-based methodology based on nodal analysis was then developed for the comparison of optimal design of subsea pipe-pump network with special considerations for parameters such as flow rate, pipe diameter, efficiency and pressure drop. Surveys were run to discover the trends with subsea risk practice in the subsea industry. Finally, a stochastic method for evaluating risk severity as a product of multivariate event magnitude and frequency was developed. All these methodologies were built into an integrated model for subsea production assurance and asset reliability management.

3.1 Research Rationale

The main reasons for starting the doctoral research project was to:

1. Acquire and propose advanced and up-to-date knowledge within areas of; Subsea asset reliability and production assurance management.
2. Be able to develop and apply new methods for reliability analysis.
3. Enhance research skills involving cradle to grave management of subsea research projects,
4. Writing of coherent scientific articles and articulate communication of research results.
5. Propose and contribute beneficial new concepts and methods to existing body of knowledge.

6. Develop further international and local networks with reliability, project management, industrial engineering, management and production engineering experts. The overall approach for meeting these objectives are outlined in the following sections.

3.2 Research Questions

1. Can a method proposing an *enhanced QRA model* scope (which includes the supporting processes) adequately address the usefulness of reliability and risk simulation as a management tool in the context of the development and implementation of subsea production systems?
2. What are the main *physical and operational stresses* that affect the reliability of a subsea production plant in a given location?
3. How can the overall efficiency of a *subsea lift pump system* be predicted considering the limitations of technical specifications such as power, diameter, pressure drop and cost?
4. How do subsea companies respond to *reliability and implement standard* API, ISO, and DNV codes on risk, reliability and production assurance respectively.
5. Does *organisational operational risks* in the subsea sector really influence uptime or downtime?
6. How can *production assurance* be ensured in depleting subsea wells.
7. Does the size of a company affect the *implementation strategy* of risk and reliability management?

3.3 Research Type

This study can best be described as a hybrid of explanatory and descriptive research. According to [Adler et al, 2015], a descriptive research allows the researcher to describe a phenomena, a group, attitude or events with keen focus on structure or attitude; often with the aid of some statistics. In line with the description, this research seeks to investigate the practice level of risk and asset reliability management across the subsea production sector and also use case studies which contain rigorous and detailed examination of a single case with an underlying assumption that the case represents many other such cases [Thomas, 2011]. An explanatory research is a research that attempts to find the cause and effect relationship about a phenomenon which could lead to hypothesis or theory generation. It justifies the reliability modelling.

These methods were chosen over other methods because the target environment for survey data was not controlled, survey-interviews were not open-ended, and the interview data being sought was not highly detailed (causal variables and confidence intervals) as obtainable in experimental, and explanatory methods respectively Production assets reliability and failure analysis were investigated with an explanatory philosophy in mind to establish cause and effect.

The overall aim was to obtain authentic and systematic data which could be used in averages, frequencies, consubstantial statistical predictions and develop best practice integrated model.

3.4 Research Approach

The research entails a mixed approach consisting of qualitative and quantitative approach. Both deductive and inductive reasoning were applied at various stages in this research starting by developing concrete empirical evidence from OREDA, literature among other sources – a deductive approach; model developments/case studies and statistical analysis of the survey-interview results before generalisation of the patterns found; based on the observation. The application of this sort of reasoning is justified considering the fact that the literature review was made up of abstractive observations of the key issues with subsea production management, whilst other technical data about equipment failure such as the OREDA data, had defined statistical forms. An inductive approach offers a good dose of flexibility with regards to the research outcome which may or may not agree with the initial premises and at such generates general conclusions or theory while a deductive reasoning requires narrowing down from general conclusions to specifics particularly statistical and empirical answers [Flick, 2015; Adams et al 2015]. Both approaches helped the researcher to properly investigate the contributions of metrics such as subsea temperatures, cost and pressure on asset life. They also helped in analysing key risk influencing areas in basic operations of subsea production and developing a tentative hypothesis whilst exploring the efficacy of the dominant risk management standards. These led to the consequent proposition of a better production assurance model for subsea oil and gas production companies.

3.4.1 Research Strategy

Research strategy is the systematic procedure, sequence and the research techniques employed in carrying out a research (Barbie,2010). It is an expression of justification for the decisions made towards planning the research work. The details and justification for the strategy is presented in Table 7.

Table 7: Research procedure

S/N	Steps	Area of Focus
Stage 1	The Theoretical Foundation	Literature reviews identifying Patterns, Challenges and State-of-the art
Stage 2	Research design	Design of data needs,
Stage 3	Data collection methods	Quantitative and Qualitative Approaches| This included primary and secondary data
Stage 4	Execution	• Target audience selection and choosing of sample size • Questionnaire design • Launch of survey • Follow up on respondents • Review of data collected/discard of inappropriate ones
Stage 5	Modelling and Data Analysis	Model development and interpretation of data
Stage 6	Validation	Testing of results through case studies, presentation to conferences, and journal submissions.
Stage 7	Final thesis write-up	Aggregation of all original research work done into a concise and comprehensive thesis

3.4.2 The Theoretical Base.

The theoretical base refers to the literature reviews which formed the foundation for this research as proved by elaborate subsea production management issues discussed. The theoretical part was not only meant to expose the contemporary methods for reliability analysis and risks in operations for subsea production companies but to also critically appraise the major risk management standards, technical and non-technical, thereby effectively fulfilling the objectives of this research work. The research question was developed at the end of the literature review and it focuses on what causes subsea assets to fail and how subsea production organisations respond to whole-system risk management in production operations.

3.4.3 Research Design

Research design refers to the logical structure used by the researcher to answer the research question and justify whatever had been done in research to reach valid conclusions. Since the research question has been declared, the next step is to determine the type of data which would be gathered and analysed in order to deduce conclusions. This research made use of both primary data and secondary data. The combination of both primary and secondary data was aimed at getting a robust and reliable data about operational risk challenges as encouraged by Mattews's (2010).

3.4.4 Primary Data.

The primary data was obtained from interviews and questionnaires at various intervals during the years of the doctoral research. The main questionnaire in chapter 7 was a web-based questionnaire which was designed and distributed in order to gather more recent, reliable and data from respondents who are very familiar with subsea oil and gas and risks management, to assess the current Reliability, Asset Integrity Management and Operational Risk Practices in their various industries, the critical operational risk areas, awareness level of risk, reliability and integrity standards, and personal opinion about success factors for production assurance. The use of questionnaire was selected because it is comparatively convenient, less expensive, has wider reach, and offers greater level of anonymity (Adams, et al, 2015, Kumar, 2005). In addition, the researcher believes that the response would have a higher degree of accuracy because people seem to give even highly sensitive information when their identities are unknown and there are less physical contacts. The extraction of primary data using questionnaires was also intended to enhance the originality of work rather than relying solely on historical data. The smaller questionnaire type structures were also used in Chapter 4 to gather data on human reliability.

3.4.5 Secondary Data

The secondary data used in this research was gotten from reviews of articles, journals, books, internet sources and publications from various authors. The secondary data came mainly from OREDA handbook because the reliability data was meant to compliment the primary data earlier mentioned since it treated the issue of asset failure from a broader perspective involving a larger sample population. The use of secondary data was further justified by Hair et al (2007) who expressed that secondary data is used to compliment a primary data thereby minimising the time spent in gathering the raw data for the sake of justifying the research appropriately.

On critical review, it was found that even though the secondary data contained information about risks on a broad level, it contained very little information with regards to the realistic information on subsea production industry which informed the decision to obtain some primary data.

3.4.6 Data Collection

There are two known systematic approaches for data collection in empirical social research. They are the qualitative and the quantitative approaches. A quantitative data-gathering technique is a method which is generally concerned with counting and measuring a phenomenon through structured observations, questionnaires, structured interviews and content analysis of documents (Blaikie, 2009). On the contrary, a qualitative method is the one which is more concerned with producing discursive descriptions and exploring social meanings and interpretations through participant observation, in-depth interviews, oral histories and even content analysis of document. Even though these are two distinct approaches; Miller et al (2003) stressed that researchers can combine both quantitative and qualitative approaches in either series or parallel as deemed fit for sourcing of data.

3.5 Quantitative Data

In this research, both qualitative and quantitative approaches were utilised to gather the data. The combination of both qualitative and quantitative methods were used during the course of this research. The author carried out extensive review of existing literatures and industry reports in order to broadly understand the major asset risks in subsea production operations and their effects plus an assessment of the capabilities of existing methodologies and standards for their management.

OREDA data was also stressed statistically to develop an Accelerated Life Testing model based on the numerical robustness of a Weibull Corrosion Covariate stress. This helped to analyse and optimize a Subsea Gas Compression used as case study. Thereafter, an enhanced Hubbert model was used to predict oil production in an offshore field for capacity planning. Nodal analysis was then applied on configurations of multiphase pumps for multiphase lifting from a subsea well. This was further analysed for the selection of the most efficient option based on power requirements, pressure differential, pipe diameter and cost efficiency.

Furthermore, a Monte Carlo-style method was proposed to analyse the risks on a Subsea Drill Rig based on historical information. Structured questionnaires were distributed in order to amass expert opinions on the challenges being experienced in industry in terms of subsea risk, reliability and production management. The questionnaire method was used as a validated research tool because it was the most convenient way to collect information from a fairly large number of people in industry or large population.

The work scope mainly deals with the following concepts which overlap and were often interchangeably used in the thesis

- Subsea Asset Reliability and Risk
- Operational Risk Management (ORM)
- Production Assurance

The focus is enhancing production efficiency, mitigating losses and enhancing firm's profitability in a subsea production setting. The target is process improvement of subsea systems performance. All the sub-models developed in the chapters were assembled into an integrated model for subsea asset reliability, risk and production assurance.

3.6 Qualitative Data

On the other hand, the qualitative data used; consisted of literary reviews. It provided very broad details and critical analysis of asset reliability and risk management standards policies relating to the operational aspects of subsea production firms. It also contained various scholarly views as relates to the key areas gullible to operational risks. At literature review, the author identified some of the key challenges affecting subsea operations risk management and decided to develop research questions which led to an investigation on subsea companies to discover trends in the practice of operations risk management, reliability and general asset integrity. The qualitative data was gathered with the aid of a well-structured questionnaire which aligns with the quantitative approach while the secondary data was made up of qualitative analysis of a published document. The choice of a quantitative data was informed by the need to focus on and measure the opinions of the respondents about the problems facing risk management in operations of subsea production companies in order to make conclusions and generalise the result for the firms. Both qualitative and quantitative data were critically and statistically analysed respectively, to derive the conclusions and recommendations made at the later part of this work.

3.6.1 Target Population and Sample Size Selection

The study population of this research has been identified as the West Africa subsea production companies because it is a deep water region and has one of the major hot spots for many of the subsea technology being developed. Therefore an opinion from experts in the region could be used to understand technology gaps and needs. Sampling is the selection of a few from a larger group to become the basis for estimating or generalising the dominance of an unknown chunk of information (Kumar, 2005). Recalling the initially stated research objectives and the research question, the focus sample size was established to include small, medium and large scale West African subsea oil and gas production companies. The inclusion of small and medium scale companies was borne out of the discovery that even SME's employ formalised methods for strategic planning whilst maintaining high flexibility due to their small size; in response to change in their environments (Gibbons et al, 2005).

Due to the enormous population of subsea production companies, the world wide web was chosen as the best way of capturing meaningful data from the research target population. The sample population was gotten from '*LinkedIn*'; a professional social networking platform where professionals from all works of life meet to exchange ideas pertaining to their respective fields. A search was made on Linked with the words '*Subsea Engineering, Asset Reliability and Integrity, Operational Risk Management*'.The questionnaire was posted to a forum for subsea engineers and asset integrity experts with over 20,000 active members altogether.Distributing questionaire using the questionnaire on *'LinkedIn'* was deemed best fit for capturing opinions from the target population because it was the most convenient, genuine and relatively fast way of getting useful information from West African risk management and subsea firms.

3.6.2 Questionnaire Design

Questionnaires are one of the most widely used research methods and involves the formulation of precisely written queries for respondents whose views are needed to understand an attitude or behavior [Blaxter et al, 2010; Creswell 2014]. In academic circles, it is seen as a very convenient strategy for getting a wide-range of opinions about a phenomenon. While there is nothing like an ideal questionnaire , some basic guidelines regarding wording and laying out of questionnaires were well adhered to in accordance with Blaxter, et al (2010) during the development of the questionnaire.

Questionnaires have always been used in operations strategy researches as well as other social researches. The core contents of the questionnaire was mainly developed out of the theoretical backgrounds of this work; with the intention of either confirming the assertions in the literature review or discovering new trends. The questionnaire was well-structured questions with inbuilt choice of answers.This was considered proper because, it made the survey easier for the respondents and also allowed the researcher focus on a limited number of variables considering the scope and time frame of the research.

3.6.3 Ethical Consideration.

Ethics refers to an attempt to formulate codes and principles of moral behaviour for the conduct of social research (May, 2011). Ethical policies are established to guide researchers in ensuring that the privacy of the respondents is not abused in any way. The British Sociological Association code of ethics states that 'Guarantees of confidentiality and anonymity given to the research participants must be honoured, unless there are clear and overriding reasons to do otherwise (British Sociological Association , 1996). Bearing the above rule in mind during the questionnaire design, no part was designed to get personal details of the participant. The introductory instructions to the survey clearly assured respondents of guaranteed anonymity and confidentiality of their responses during and after the dissertation life cycle. The intended respondents were also meant to understand that completing the survey is quite optional.

3.6.4 Pilot Testing

A pilot test refers to a pre-test which is used to gauge the reaction and response rate of the intended population sample. According to Neuman (2011) pilot tests are designed to allow the supposed subjects uncover certain aspects of the survey that needs refinement as well as help the researcher deduce the threats to the validity of the survey/interview so that they could be avoided.

For the pilot test of the questionnaire, an informal piloting approach as recommended by Blaxter et al (2010) was first applied to this work. This was carried out by sending the survey to five senior experts in the area of asset integrity and technical risk.The response rate was above 100% in a matter four weeks. Some of the experts offered recommendation on how to tweak some of the questions to get better results. These comments boosted the researcher's morale and indicating that the questionnaire made sense.

3.6.5 Questionnaire Launch

An introductory note explaining the purpose of the survey-interview, intended audience, contact details and an anonymity assurance statement was affixed to the survey and made available to experts in the field via the online platform '*LinkedIn*'.

The web based approach through the use of '*LinkedIn'* was chosen in order to gather as much responses as possible for sound data analysis bearing in mind that response rates of questionnaires have been known to be relatively low, especially when there is no sort of incentive for the respondents (May, 2011). Questionnaires are known to have a wider reach and ensures anonymity of the respondent which probably helps to get their innermost opinion about risk influencing factors in their respective companies.

Overall, a total of 82 responses were gotten within a six month period. At this point, the sample gotten was found to be 33% of the initially projected sample size of 250. At this stage, the author deemed the sample size fit for analysis considering the time constraints and the fact that

Visser et al. (1996) discovered that surveys with response rates closer to 20% were found to be more accurate than the ones with about 60% response rates.

Holbrook (2007) also expressed a similar view after evaluating a national survey with response rates ranging between 5% to 50% and discovered that the lower rates were just negligibly less accurate in terms of statistics.

3.6.6 Data Entry And Analysis Approach.

The data collected were analysed using a range of parametric analysis approach. The parametric analysis consisted of running exponential regressions, descriptive statistics and factorial analysis and to interpreting the survey-interview. Parametric analysis is a robust and stronger statistical approach towards data analysis because it allows inferences to be made about the parameters of a distribution (Cox, 2006; Gupta, 2014). Parametric analysis was applied to this work as evident in the defined distribution such as Weibull among others and informed by technical equipment failure times, others had to do with fluid flow details, risk severity and respondents opinions concerning risk management practice across the focus subsea production firms.

The questionnaire data was interpreted by taking the '*means*' of the responses across the sample, represents respondents' opinion regarding a question. For instance, testing the responses of small scale industries and large scale against their views on occupational/safety risks based on an earlier hypothesis.

3.6.7 Validation And Reliability Of Research

The validation of the Weibull reliability model was performed using a cox regression model. Appropriate discussions were provided for the severity and least cost models in subsequent chapters. The raw survey data were processed straight away without censoring. The internal validity of the research is balanced because procedures used in the research identified and measured what they were supposed to measure – equipment behaviour in subsea domain and operational risk influencing factors. The external validity also stands because the proposed model and methodology for reliability and risk assessment can be generalized beyond the immediate study based on the results obtained from the case studies and survey. Content and criterion validity shows that all the analysis were related to the outcome, however, due to time constraints the results and propositions had not been tested in many more case studies.

Reliability of research refers to the probability of achieving the same result using the same methodology by another researcher elsewhere. In this study, well-proven and universal empirical data from OREDA handbook was used, proven physical relationships were also integrated in the mathematical formulations for reliability performance analysis of subsea assets. Furthermore, the data collection, analysis and model development followed a clear logical sequence which conforms to the required research. Validation of the reliability model was done using the Cox model of proportionality as shown in Chapter 4.

3.7 Summary

The essence of this chapter was to provide insight into the research methods that apply to the Research. Full details of the research strategy were presented, and justification was given for each choice made. In summary, the Weibull covariate model developed was validated using a case study for subsea compression system. Efficient and least-cost configuration of subsea pump-pipe system was validated using a combination of computer software-*pipesim* and deterministic physical calculations. A stochastic method was developed for evaluating multivariate risk based on severities of event magnitude and frequency and also validated using a case study based on a drill rig.

Primary data was gathered from surveys while the secondary data was collected from OREDA database and literary reviews. The target population is subsea production firms and the research question aimed to find out how ORM is being practiced.

Limitations were identified in the cause of data sourcing, however, these did not hinder analysis of the data. In conclusion, the research strategy applied to this research is a significant fresh addition to existing knowledge because it proposed a systematic way of identifying risks, evaluating reliability and ensuring that adequate risk controls are applied to the critical failure modes of a subsea system whether human, operational or equipment risk.

CHAPTER 4

Reliability Analysis and Optimisation of Subsea Compression System facing Operational Covariate Stresses.

The scarcity of field-sourced reliability data for many of the new and emerging subsea technology coupled with the rough conditions of the subsea environment raises serious challenges for accurate prediction of reliable operating windows for subsea assets. This chapter highlights the current industry practice with regards to accelerated failure testing (AFT) and proposes an enhanced Weibull-Corrosion Covariate model for reliability assessment of a system bound to face operational stresses.

The newly developed reliability model is applied to a case study of a Subsea Gas Compression System planned for offshore West Africa to predict its reliability index. System technical failure was modelled by developing a Weibull failure model and incorporating a physically tested corrosion profile as stress in order to quantify the survival rate of the system under additional operational covariates such as marine pH, temperature and pressure. Using Reliability Block Diagrams (RBD) and enhanced Fusell-Vessely formulations, the whole system was systematically decomposed to its sub-systems in order to analyze the reliability importance of each component and optimize them. Human reliability was addressed using an enhanced barrier weighting method on data recorded from interviews. A rapid degradation curve is obtained on a subsea system relative to the base case when subjected to a time-dependent corrosion stress factor. This indicates that subsea system components failed faster than their Mean time to failure (MTTF) specifications from Offshore Reliability Database (OREDA) and manufacturers as a result of cumulative marine stresses exertion. The case study demonstrated that the reliability of a subsea system can be systematically optimized by modelling the system under higher technical and organizational stresses, prioritizing the critical sub-systems and making befitting provisions for redundancy and tolerances.

4.1 Methodology

In the proposed reliability analysis model, it is assumed that subsea equipment or systems installed in the marine environment are subject to corrosion-induced degradation and human factor impact. A Weibull hazard rate relationship is derived and merged with a corrosion profile expression to produce the new reliability assessment model. Human and operation reliability are also evaluated using a barrier analysis method. Reliability analysis starts from definition of targets; however, actual quantitative assessment involves the following distinct tasks.

- Derive formulations for selected reliability assessment method.
- Calculate the basic scale and shape parameter of the failure data.
- Determine the Corrosion profile and Corrosion Weibull Reliability Index.
- Decompose system using Reliability Block Diagram and evaluate failure frequencies.
- Optimize system by analysing Fusell-Vesely reliability importance of components based on failure frequencies and achievable reliability.
- Evaluate human-factor reliability using Barrier and Operational Analysis (BORA) method.

The flow chart in Fig 9 shows the process of reliability analysis adopted for this work

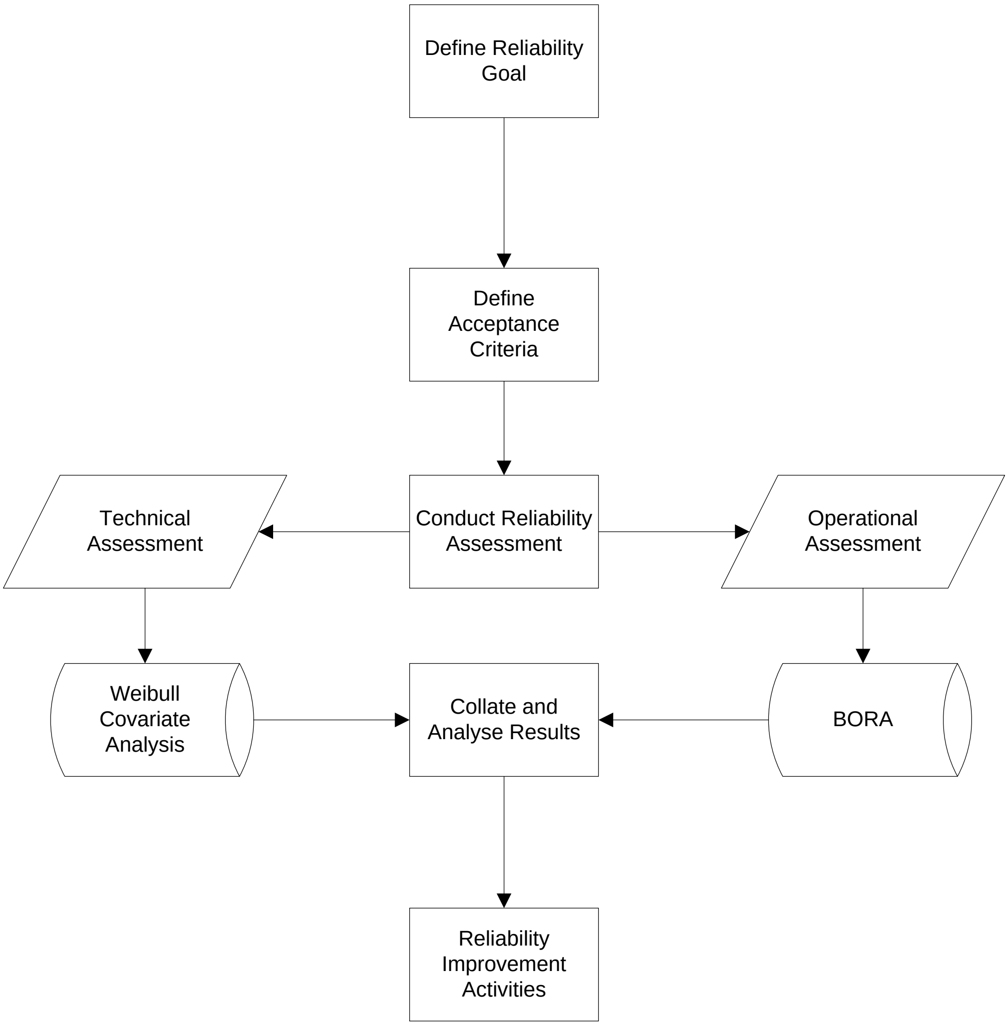


Figure 9: Flowchart of Reliability Assessment Process.

4.1.1 Mathematical Formulation of Weibull Hazard Rate Model.

The basic Weibull model assumes that the family of the equation has two parameters where a basic failure rate of a distribution can be expressed as [Dorner 1999; McCool 1970]. Weibull unreliability can be expressed as,

$$Q_{(t)} = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{1}$$

The function can be linearized to appear in the form of $y = mx + c$ in order to obtain and understand the regression wherein the constant α represents the scale parameter which is often termed the characteristic life of a system because it rates the time variable t and constant β representing the slope of the distribution as it determines the shape of the rate function.

The principle is such that if β is greater than one, the rate function increases with *t*, whereas if β is less than 1 then the rate function decreases with *t*. When β = 1, the rate function is constant and assumes an exponential distribution.

$$\ln\big(1 - Q(t)\big) = \ln\left[e^{-\left(\frac{t}{n}\right)^{\beta}}\right] \tag{2}$$

$$\ln\big(1 - Q(t)\big) = -\left(\frac{t}{n}\right)^{\beta} \tag{3}$$

$$\ln(-\ln(1 - Q(t))) = \beta\left(In\left(\frac{t}{n}\right)\right) \tag{4}$$

Stochastically, the first failure can happen before the expected number of failures reaches 1, thus the need to select an appropriate benchmark time between failures. Given a population of *n* components, with each possessing the same failure density f (t), the probability for each individual component failing by time F(t_m) is

$$F(t_m) = \frac{N(t)}{n} \tag{5}$$

Denoting the failure probability value by φ, the probability that certainly *j* components failed and ($n - j$) did not fail at time t_m is

$$P\lfloor j; n \rfloor = \binom{n}{j} \varphi^{j}(1-\varphi)^{n-j} \tag{6}$$

It then follows the *Median Rank* which is the probability of *j* components or more failing at the time t_m is given by Benard's approximation equation for median ranks. [Dorner, 1999], where *j* represents the column rank or failure and *n* is the sum of failed components being considered.

$$F(t_m) = \frac{j-03}{n+04} \tag{7}$$

This is also known as the median rank formula.

On deriving the natural log of the two sides and negating, we get

$$\ln \frac{1}{1-\frac{N(t)}{n}} = \left(\frac{t}{\alpha}\right)^{\beta} \tag{8}$$

Then taking the natural log again, we have

$$\ln\left(\ln \frac{1}{1-{}^{N(t)}\!/_{n}}\right) = \beta \ln(t) - \beta \ln(\alpha) \tag{9}$$

To illustrate the equations, assume a population of *n* has 100 components (at time $t = 0$), which has been in continuous operation. Assuming the first failure occurs at a time $t = t_1$, then the estimated number of failures at the time of the first failure equals 1 [Dorner, 1999]. This means that $F(t_1) = N(t_1)/n = 1/100$.

Then by setting y = $ln\left(\ln\left(\frac{1}{1-Q_t}\right)\right)$ and $mx = \beta \ln(t)$ and C = $\beta \ln(\alpha)$

As an extension to the basic Weibull model, a regression analysis on failure data proposed by [Wells, 1996] gives model parameters of shape (β), scale (α) and intercept (*b*) which are used to estimate the hazard rate. The survival rate of an item is a measure of the probability of an item not to fail at about a specific time *t*, in the presence of a covariate factor *c*, provided it has been available up to time *t* [Kumar et al, 1994].

Hence the hazard rate considering the covariate factor *c*, is defined as [Wells, 1996]

$$S(t,c) = \lim_{\Delta c \to 0} \left(Pr \frac{(t \leq T < t + \Delta t | T \geq t, c)}{\Delta t} \right) \tag{10}$$

If *t* represents time to failure. Then the hazard rate can be expressed as

$$S(t,c) = S_0\big(t\omega(c\alpha)\big)\omega(c\alpha) \tag{11}$$

where $c\alpha = c_1\alpha_1 + c_1\alpha_1 .... c_r\alpha_r$, and α is the regression coefficient of the corresponding *r* covariates. It then follows that when $\omega(c\alpha) = 1$, the covariate factor $c = 0$ and Equation (10) will give the hazard rate $S_o(t)$ [Misra, 2008].

The function $\omega(c\alpha)$ can represent a wide range of functions, although it is considered an exponential function made up of product of the regression coefficient and the covariate.
Since the reliability assumes a Weibull distribution, the hazard rate in the presence of covariate can be expressed as

$$S(t,c) = S_0 \left(\frac{\beta}{\lambda}\right)\left(\frac{t\omega(c\alpha)}{\lambda}\right)^{\beta-1} \lambda(c\alpha) \tag{12}$$

where λ and β are scale and shape parameters in the order laid out.

If $(\lambda/\omega(c\alpha) = \theta(c\alpha))$, the hazard rate can be rewritten as

$$S(t,c) = \frac{\beta}{\theta(c\alpha)}\left(\frac{t}{\theta(c\alpha)}\right)^{\beta-1} \tag{13}$$

4.1.2 Model Formulation of the Weibull Corrosion-Covariate Stressor

The corrosion covariate profile entails physical parameters such as marine pH, temperature and CO_2 pressure which are the key forces that affect an asset wear-out curve based on corrosion. The effects of corrosion whether external, internal or uniform are widely known to cause wear-off and leakage. The extrapolation of regression analysis results beyond available data range requires accurate, justified, and tested covariate-life models [Naseri, 2016]. To model the system in full water-wet condition, the Norsok's Corrosion profile model was adopted and merged with the developed Weibull hazard expression guided by the principle of Arrhenius reaction model for accelerated life reliability analysis.

The Norsok corrosion model was chosen as the covariate factor because an increase in the CO_2 partial pressure usually results in a drastic increase in the corrosion rate, a behaviour that is enhanced with temperature and causes the major degradation (failure) of both steel and non-steel units of the subsea compression system. It is a reliable physical relation developed, tested and proven to represent the oxidizing and corrosive impact of physical factors such as (CO_2) partial pressure, temperature and flow [Naseri, 2016].

The corrosion profile relationship for a deep water asset located in a zone with temperature 5℃ can be estimated using;

$$v = K_T \times F_{CO2}^{0.36} \times F(pH)_t \tag{14}$$

where K_T = Temperature Constant

FCO_2 = Fugacity of CO_2 pressure

$F(pH)_t$ = Fugacity of pH

The Arrhenius asset life model is governed by the principle that life of a system is directly proportional to the inverse reaction rate. The Arrhenius equation is given by [Misra, 2008].

$$L(V) = Ce^{\frac{b}{v}} \tag{15}$$

L signifies a quantifiable life measure while *V* stands for the covariate factor, developed for thermal-corrosion related variables in absolute units. *C* and *b* represent model parameters which can be calculated from analysis of variance of data.

If scale parameter is regarded as a function of the covariate, then hazard rate, *h* becomes,

$$h(t,v) = \frac{\beta}{Ce^{\frac{b}{v}}}\left(\frac{t}{Ce^{\frac{b}{v}}}\right)^{\beta-1} \tag{16}$$

Since temperature profile could give a life measure, it also makes sense for a corrosion profile stress to be part of the life covariate functions. On substituting the corrosion profile variable *v* into the survivability equation, system hazard rate under the influence of corrosive stress becomes,

$$h(v,(t)) = \frac{\beta}{\alpha e^{\frac{b}{(v)}}}\left(\frac{t}{\alpha e^{\frac{b}{(v)}}}\right)^{\beta-1} \tag{17}$$

Reliability can thus be expressed as,

$$R\big(v,(t)\big) = e^{-\left(\int_0^t \frac{e^{\frac{b}{(v)}}}{\alpha} dt\right)^{\beta}} \qquad (18)$$

Reliability can also be expressed as a function of the hazard rate as;

$$R = 1 - h \qquad (19)$$

4.1.3 Decomposition with Reliability Block Diagram (RBD) and Optimisation

Reliability analysis with block diagrams is an evaluation method which is used when a system is being evaluated based on the contribution of each component to failure. (Fig 2). It is used to represent the complex connections and reliability interactions of the system's components.

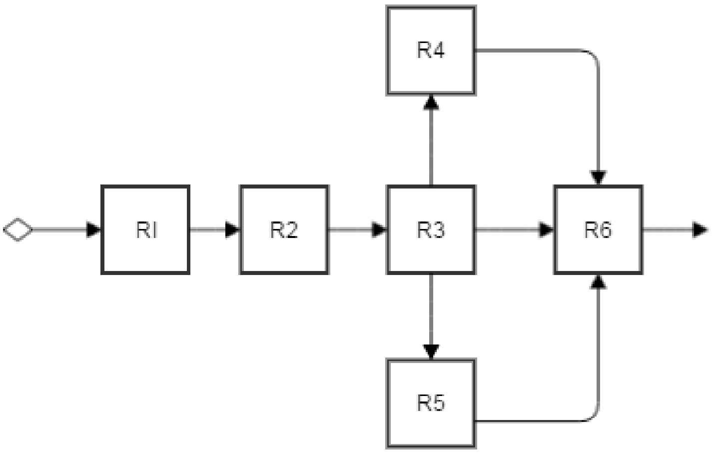


Fig 2: A typical system with both series and parallel relationships.

4.1.4 Reliability Optimisation

To develop an optimisation model, consider a system with *x* amount of components and the target is to apportion reliability improvement to meet reliability without over-designing certain components to the detriment of other critical ones to minimise cost. A concept known as ALARP (As Low as Reasonably Possible) is applied.

Optimality factor: The optimality factor is the ratio of targeted reliability index for a system and its Weibull-corrosion covariate reliability index multiplied by the failure time or basic

Mean Time to Failure (MTTF) of a system.

Mathematically, Optimality factor (O_F) is,

$$\frac{(MTTF)\ \text{X}\ (\text{Target Reliability})}{Weibull\!-\!Corrosion\ Covariate\ Reliability\ Index} \tag{20}$$

Reliability Importance: The reliability importance (I_R) of a system is defined as the ratio of system reliability (R_S) to minimum reliability value (R_I). It refers to the criticality a certain component exerts on overall reliability. Mathematically, Reliability Importance (I_R) is expressed as [Mettas, 2000, Feng et al, 2016].

$$I_R = \frac{\partial R_S}{\partial R_I} \tag{21}$$

The Benchmark Minimum Failure (Minimum MTTF): This is the product of the optimality factor and the reliability importance of a component. It is an expression that is used to arbitrarily extract resources from the over-designed components and evenly add to the under-designed or early failure ones. Two assumptions are made when evaluating the minimum time to failure.

- An assumption that if a component's life expectancy is more than three standard deviations beyond the statistical control limits (especially if beyond upper control limits) of the unstressed failure distribution, then the excess life would be extracted from the over-designed component and evenly shared among less reliable components within a sub-system.
- If the reliability importance of a component is 0 or less than 0.1, the minimum time to failure remains the same as unstressed failure data. (See Table 5)

Optimal Time to Failure (Optimal MTTF): This is an expression that is derived from by dividing-up the extracted life values obtained from over-designed among other components, thereby optimizing and extending its life to failure.

4.1.5 Human-factor Analysis.

Several investigations into offshore mishaps show that technical, human, operational as well enterprise-wide factors contribute to accidents. Despite all these, many works on quantitative risk analysis of subsea system focus just on the technical reliability of the systems thereby neglecting the influence from humans [Vinnem et al, 2005]. Several models have been propounded for Human reliability analysis. These include, methods such as Technique for Human Error Rate Prediction – THERP, Human Error Assessment and Reduction Technique – HEART, Success Likelihood Index Method Multi-attribute Utility Decomposition – SLIM-MAUD and more recent techniques which are often referred to as second generation, or advanced methods such as Cognitive Reliability and Error Analysis Method – CREAM, Standardized Plant Analysis Risk Human Reliability Analysis – SPAR-H, Information, Decision and Action in Crew context – IDAC, in addition to probabilistic ones such as Bayesians models [Cai et al, 2013; Vedachalam, 2016] , Organisational Risk Influence Model-ORIM, Model of Accident Causation using Hierarchical Influence Network-MACHINE. The major challenge is that many of these models were not particularly designed with reference to offshore risk inputs and industry average occurrence rate of those accidents [Sklet et al, 2006, Nsimah et al, 2016].

The method employed for human factor analysis in this chapter is a simplification of the Barrier and Operational Risk Analysis (BORA) model by [Sklet et al, 2006] which is a very comprehensive framework for modelling and optimising barriers on offshore production installations. The introduction of severity measure in this paper is a major enhancement of the BORA methodology because it readily compares and presents the monetary consequence of impeding system risk. Industry average probability was decided by calculating the mean of participant’s rating for each category. The status of these factors for the specific oil field was also obtained in the same manner.

A Risk Influencing Factor (RIF) template was designed to collect rate and code human factor data. It comprises of five categories of human factor risks which relate to Personnel factors, Task factors, Technical elements, Administrative and Operational Philosophy. No special root cause event was modelled in this work; rather a generic exposure to human factor risk was quantified alongside the severity implication across the whole system. The technical element will embed the stressed reliability index that is generated from the initial Weibull corrosion covariate expression.

In line with BORA recommended approach, the formula for calculating the revised Risk Influencing factor $P_{(rev)}$ is given by [Vinnem et al 2005].

$$P_{(rev)}(X) = P_{ave}(X) \sum_{i=0}^{n} W_i Q_i \tag{22}$$

where $P_{ave}(X)$ represents the industry average of probability of occurrence of an event X, W_i is the weight allocation of the Risk influencing factor and Q_i represents an actual measure of the status of Risk influencing factor at field. The severity of the Risk Influencing Factor (RIF) is ranked on a scale of A to E with A (representing outstanding practice in Industry) to E (Worst practice in industry) where C corresponds to industry average. Table 8 summarises all the input data, rating system and weights applied to the risk influencing factor and the adjustment ratio.

Table 8: Risk Factor Code Table

Risk Factor Rank (Q)	Code for Risk Factor (Q.Code)	Meaning	Revised Probability (Prev)
A	1	Good performance	0.00-0.15
B	2	Best Practice	0.16-0.25
C	3	Industry Average	0.26-0.35
D	4	Below Industry Average	0.36-0.45
E	5	Bad Practice	0.46 - 1.00

The modification factor (MF) depends on the product of allocated weights (W_i) and rated event probability (Q_i).

$$MF = \sum_{i=0}^{n} W_i Q_i \tag{23}$$

The weights are applied relative to the importance of each factor on scales 0.2, 0.4, 0.6, 0.8 and 1.0; where 0.2 means the least importance/influence and 1.0 meaning the utmost importance. Event probability (Q) is rated using a scale of A-E as shown in Table 8. The true value for the technical reliability index obtained from the new model is weighted together with the interview data obtained from survey for all factors in each category.

4.2 Case Study

The purpose of this case study is to demonstrate the applicability of the new model developed in Section 4.1 for reliability analysis and optimisation of a subsea compression system.

4.2.1 Description of the case

A major oil and gas firm wants to conduct a reliability assurance analysis on a subsea gas compression system proposed for the installation at the Escravos field off the coast of Nigeria, West Africa. The target reliability is 95% for the initial 300 days. To support decision making processes, the firm had requested for a numeric quantity of the subsea system's survivability under operational stresses. The system which is directly synchronized with power units, a process system and control system is meant to take reservoir gas from the wellhead, through the compression system to a centrally positioned FPSO. The compression unit does the mechanical job of compressing well fluid while the power units provide electric power for the entire system. The control system conveys and receives sensor signals between the Subsea Engineers on deck.

4.2.2 Case Analysis -Weibull-Corrosion Covariate Reliability Analysis

The MTTF column of each component of the subsea compression system in table 9 seems to readily show the failure times however it is imperative to carry out a more detailed analysis to determine the systems contribution or insufficiencies towards 95% reliability target at a certain defined time. Majority of the failure data were obtained from OREDA [55]. Prior to the regression analysis of the MTTF data, some adjustments were performed to make the distribution a Weibull distribution. Firstly, the failure data is ranked in descending order as shown in the column 'Rank' of Table 9. The median rank for failure is then calculated to ascertain the proportion of the system component that will fail by the mean time in column MTTF.

Using the Bernard's equation for determining median rank [Dorner 1999]:

$$\frac{X-0.3}{N+0.4} \tag{24}$$

where *X* represents the column rank and *N* is the sum of failed components being considered. In this case, there are 39 components as shown in Table 9.

The median rank and MTTF are further transformed by taking their natural logs using Eq. 8 and repeated with Eq. 9; so that regression analysis can take place more efficiently. A simple linear regression analysis is performed between 'In MTTF' and ln(ln(1/(1-Median Rank) in order to obtain parameter estimates in determining the survival rate.

Table 9: Derivation of Natural logs of component failure time (t) and Median Ranks

No	SUBSEA COMPRESSION SYSTEM	MTTF	SOURCE		Rank	Rank1	Median Rank	1/(1-Median Rank	ln(ln(1/(1-Median Rank))	ln(MTTF)
	Process System									
1	Manifold Piping	3,048	OREDA		5.6	1	0.017766497	1.018087855	-4.021491042	1.7227666
2	Mechanical Connector	1,351	OREDA		6.1	2	0.043147208	1.045092838	-3.121165758	1.80828877
3	ROV Isolation Valve	1,389	OREDA		6.3	3	0.068527919	1.073569482	-2.645229481	1.84054963
4	EI Isolation Valve/Actuator	1,489	OREDA		7	4	0.093908629	1.103641457	-2.316530606	1.94591015
5	Check Valve	162	OREDA		8.1	5	0.11928934	1.135446686	-2.063362471	2.09186406
6	Scrubber	50	OREDA		9	6	0.144670051	1.169139466	-1.856182932	2.14006616
7	Scrubber Level Detector	98	Tracerco		24.5	7	0.170050761	1.204892966	-1.679910065	3.19867312
8	Magnetic Bearing System Compressor	27	S2M Report		27	8	0.195431472	1.242902208	-1.525790316	3.3068867
9	Compressor	9	OREDA		32	9	0.220812183	1.283387622	-1.388283692	3.4657359
10	Electric Motor(Compressor)	5.6	Aker Solution		38.7	10	0.246192893	1.326599327	-1.26365639	3.6558396
11	PSD Sensors	124	OREDA		41	11	0.271573604	1.3728223	-1.149267807	3.71357207
12	Flow Meter for Anti Surge Control	650	OREDA		43	12	0.296954315	1.422382671	-1.043177384	3.76120012
13	Anti Surge Actuator	228	Aker Solution		50	13	0.322335025	1.475655431	-0.943913114	3.91202301
14	Anti Surge Valve	89	OREDA		70	14	0.347715736	1.53307393	-0.850327856	4.24849524
15	Cooler	84	OREDA		84	15	0.373096447	1.5951417	-0.761506169	4.4308168
16	Condensate Pump Unit	6.1	KOP		89	16	0.398477157	1.662447257	-0.676701617	4.48863637
17	Re-circulation choke valve	32	OREDA		89	17	0.423857868	1.735682819	-0.595293163	4.48863637
18	Meg Piping	309	OREDA		98	18	0.449238579	1.815668203	-0.516753902	4.58496748
19	Pressure and Volume Controller	89	OREDA		100	19	0.474619289	1.903381643	-0.440627964	4.60517019
	Control System									
20	Top Side Master Control Station	24.5	OREDA		108	20	0.5	2	-0.366512921	4.68213123
21	Wet Mate Connector	24980	OREDA		124	21	0.525380711	2.106951872	-0.294045889	4.82028157
22	Electrical Dry Mate Connector	4424	OREDA		162	22	0.550761421	2.225988701	-0.222892112	5.08759634
23	Electric Jumpers	72022	Teledyne		192	23	0.576142132	2.359281437	-0.152735069	5.25749537
24	Junction Boxes	41	Telecordia		228	24	0.601522843	2.50955414	-0.083267372	5.42934563
25	Magnetic Bearing Control Module	6.3	S2M Report		309	25	0.626903553	2.680272109	-0.014181765	5.73334128
26	Anti-Surge Compressor Control Pod	38.7	CFD DOC		310	26	0.652284264	2.875912409	0.054838487	5.7365723
27	SCM	43	OREDA		358	27	0.677664975	3.102362205	0.124130689	5.88053299
28	UPS	8.1	OREDA		554	28	0.703045685	3.367521368	0.19406646	6.31716469
	Power System									
29	Topside Main Circuit Breaker	1116	OREDA		554	29	0.728426396	3.682242991	0.265069889	6.31716469
30	Topside Transformers	554	Vetco Gray		650	30	0.753807107	4.06185567	0.33764293	6.47697236
31	VSD	7	OREDA		675	31	0.779187817	4.528735632	0.412402847	6.51471269
32	Topside Umbilical Hang-off	358	OREDA		1116	32	0.804568528	5.116883117	0.490140445	7.01750614
33	Power Umbilical	108	OREDA		1,351	33	0.829949239	5.880597015	0.571915995	7.20860034
34	Umbilical Termination Assembly(UTA)	310	OREDA		1,389	34	0.855329949	6.912280702	0.659228202	7.23633934
35	Subsea Enclosures (Transformer)	675	OREDA		1,489	35	0.88071066	8.382978723	0.754337905	7.30586003
36	Subsea Main StepDown Transformer	554	Vetco Gray		3,048	36	0.906091371	10.64864865	0.86096109	8.02224092
37	Hv Penetrator/Dry Connector	192	Deutch		4424	37	0.931472081	14.59259259	0.986008583	8.39479954
38	Hv Power Jumper	100	OREDA		24980	38	0.956852792	23.17647059	1.145221526	10.1258308
39	Hv Wet Mate Connector	70	Deutch		72022	39	0.982233503	56.28571429	1.39387574	11.1847269

The scale parameter and the shape parameter are obtained from linear regression analysis [Wells, 1996] of In(In(1-Median Rank)) and In MTTF columns in Table 9. The coefficients obtained are $\alpha = 473.36,\ \beta = 0.47$ and the intercept -2.9.

The Weibull scale parameter (α) was obtained by substituting the b and β in Eq. (25).

$$\alpha = e^{-\left(\frac{b}{\beta}\right)} \qquad (25)$$

In line with Weibull's principles, the characteristic life α indicates the time at which 63% of system components would have failed irrespective of the value of β [Nelson, 2009]. With an assumption that MTTF is expressed in days, the results from regression analysis indicate that at 473.36 (days), the unstressed reliability of the system in the absence of any repair or replacement work would be 37%.

To check the fitness of Weibull 2-parameter modelling for analysis, a line fit plot as shown in Fig 10 between failure values and the natural log of the median is generated.

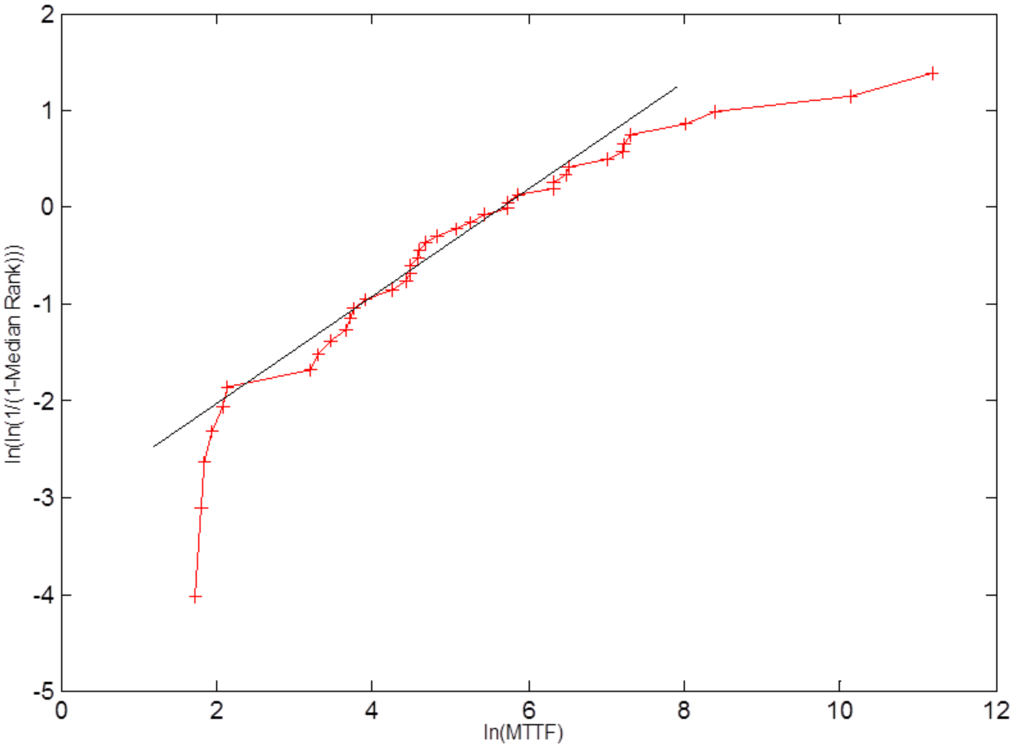


Figure 10: Line Fit plot showing fitness of data for reliability analysis

On close observation of fig 10, the fitted line has little doglegs which show that the failure modes affecting the system come from various origins [Abernethy 2006]. In the current case, these can be overlooked because such scatter plot is typical for the hydro-mechanical components. The MTTF failure data being used generates such shape parameter of the failure distribution as supported by [Kalbfleisch, 2011] proving that the straight line slope of such plot gives the shape parameter of the distribution. The plot has shown that the Weibull distribution modelling is a good choice and the generated values fit properly with theoretical values.

A regression analysis is then performed on data sets In(In(1-Median Rank)) and In MTTF to obtain the model parameters shown in table 10.

Table 10: Regression Table

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.95							
R Square	0.90							
Adjusted R Square	0.90							
Standard Error	0.35							
Observations	38.00							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1.00	39.03	39.03	325.84	0.00			
Residual	36.00	4.31	0.12					
Total	37.00	43.34						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-2.90	0.15	-19.86	0.00	-3.20	-2.60	-3.20	-2.60
1.722766598	0.47	0.03	18.05	0.00	0.42	0.52	0.42	0.52

The reliability of the subsea compression components under the influence of external operational stress was evaluated by applying a temperature-corrosion profile stressor since the basic Weibull reliability analysis only predicted cumulative failure times without due consideration of the external influential forces that could interfere and further reduce system reliability.

Values of the boundary variables were obtained from experts at the Egina field Nigeria. The temperature profile for West African waters is shown in Fig 11.

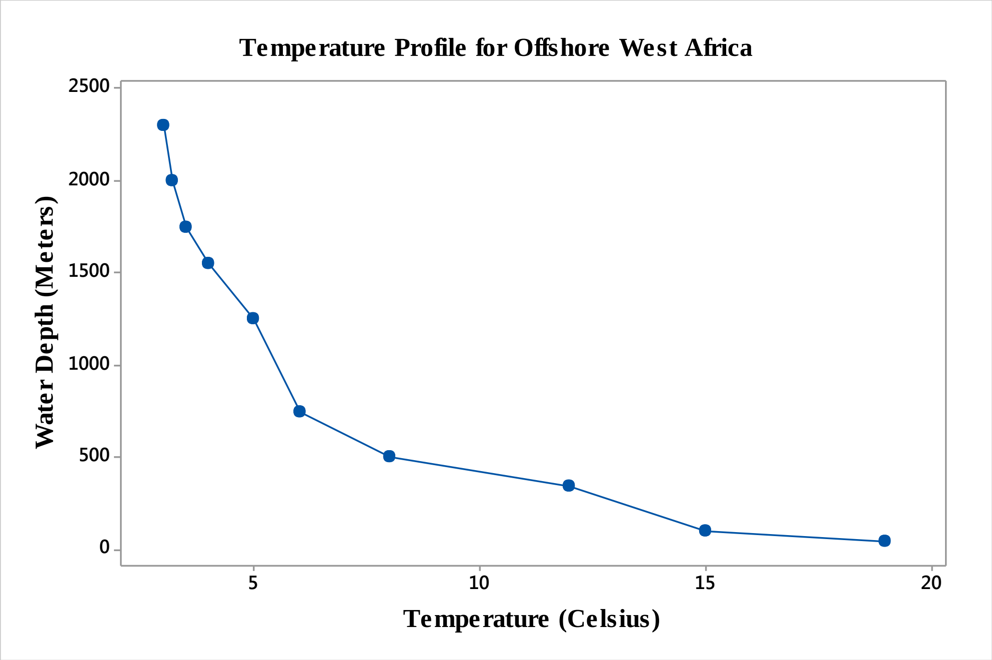


Figure 11: Temperature Profile for a West African Offshore Field [Akinde, et al 2014]

The corrosion profile, for the subsea compression system was obtained using

$$v = K_T \times F_{CO2}^{0.36} \times F(pH)_t \qquad (26)$$

If the water depth is 1500 metres, Temperature Constant at 5 degrees Celsius, $K_T = 0.42$ [Norsok 2005]:

FCO2 = Fugacity of CO2 pressure = 5840psi = 40265kPa (Field data);

$F(pH)_t$ = Fugacity of pH at West African Water at pH 9 = 0.2208 (Field data)

Therefore, $v = 11.8$.

Having generated a covariate parameter to represent the influence of marine conditions, next step is to estimate the overall reliability index of the SCS system using Eq. 27 as shown below containing the values of the shape and scale parameters derived from the failure data:

$$R_{(t,v)} = e^{-}\left(\int_0^t \frac{2.9/_{e^{11.8t}}}{473} dt\right)^{0.47} \qquad (27)$$

A stressed survival equation has been proven to be an effective method to estimate the survival function of systems with multiple component [Feng, 2016] and Table 11 shows the values for both stressed and unstressed failure data using the new failure model. The contribution to unreliability by each failure data is taken into account and as a consequence, bounds of survival functions of the system and ratings of relative importance index values can be obtained using further optimization analysis. *Reliability A* refers to the reliability of system without considering.

Table 11: Reliability Table for Basic Weibull Failure and Stressed Failure.

Model Parameters				**Without Operational Stress**		**With Operational Stress**	
			Mean Time	**Hazard Rate**	**Reliability A**	**Hazard Rate**	**Reliability B**
β -Shape Parameter	**0.47**		**30**	**0.24**	**0.76**	**0.28**	**0.72**
α-Characteristic Life	**473.00**		**60**	**0.32**	**0.68**	**0.41**	**0.59**
b- Intercept =	**-2.90**		**90**	**0.37**	**0.63**	**0.50**	**0.50**
Covariate =	**11.80**		**120**	**0.41**	**0.59**	**0.59**	**0.41**
			150	**0.44**	**0.56**	**0.66**	**0.34**
			180	**0.47**	**0.53**	**0.73**	**0.27**
			210	**0.49**	**0.51**	**0.79**	**0.21**
			240	**0.52**	**0.48**	**0.85**	**0.15**
			270	**0.54**	**0.46**	**0.90**	**0.10**
			300	**0.55**	**0.45**	**0.95**	**0.05**

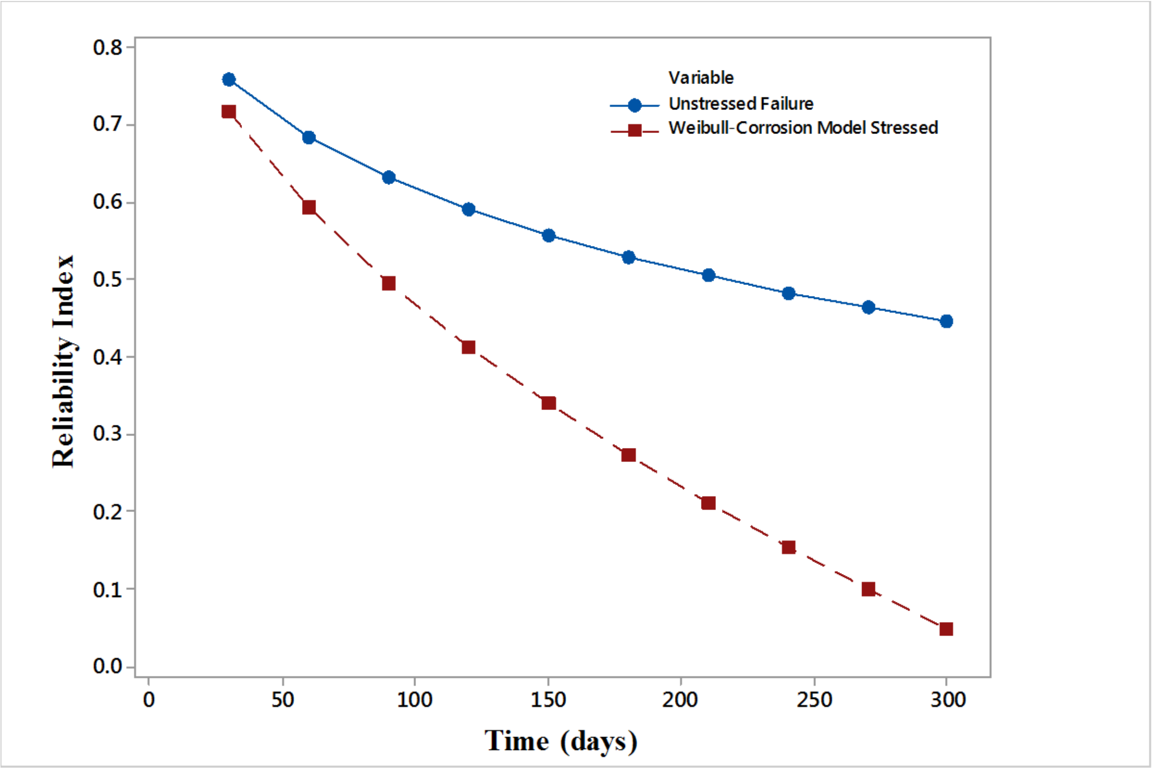


Figure 12: Basic Weibull failure vs Stressed Weibull-Corrosion failure.

The result in Table 11 and Fig 12 show the impact of marine physical conditions on failure rate. The asset-life decline curve obtained from the stressed Weibull-covariate model gave a steeper decline curve compared to the unstressed Weibull failure model. This result further confirms that a catastrophic infant mortality is imminent if the quality and redundancy configurations of the components are not improved.

4.2.2.1 Validation of the Weibull Model using Cox Regression Model.

The model is validated using the cox proportionality model which a widely used model for survivability analysis. Cox model is unable to describe the shape of the failure unlike Weibull-based models. A cox model specifies a multiplicative relationship between the underlying hazard function and the log-linear function of the covariates (Kleinbaum, 1996). A cox regression was performed on the failure data with corrosion covariate as stressor. The cox regression indicated that 62% of the components are unreliable at first failure and 38% survived and there is significant difference between the baseline distribution and the covariate regressed one as shown in the table in appendix. This corresponds with the pattern from the Weibull model applied however, cox model does not help to identify the shape of the failure curve or the failed items and that is why the Weibull based model is more suitable. The cox table is shown in appendix.

4.2.3 Root-Cause Analysis using Reliability Block Diagram.

Boolean algebra expressions defined by the MTTFs data of each component from Table 8 are used to determine minimal cut sets or the minimum combination of failures required to cause a system failure. The RBD calculates system failure frequency and unavailability based on the Vesely model. The fundamental law guiding the analysis using ITEM software used for the RBD decomposition is the Weibull failure distribution principle and an extrapolation of failure data by the Vesely theory [Jincheng, 1988]. The rationale guiding the combination of both laws is the assumption that there are no repairs thus failure is assumed as an exponential degradation curve. All failures are statistically independent. The failure rate of each subsea component is constant. After repair, the system will be as good as old, not as good as new based on the Weibull distribution model being applied. All component failures are statistically independent. The failure rate of each equipment is constant. The repair rate for each equipment item is constant. After repair, the system will be as good as new, (i.e., the repaired component is returned to the same initial state, with the same failure characteristics that it would have had if the failure had not occurred; repair is not considered to be a renewal process [CCPS 2000].

Let component failure rate be,

$$Q_i(t) = K_i(1 - exp\,[(-\lambda_i - \mu_i)t]) \tag{28}$$

$$W_i(t) = \lambda_i\,[1 - Q_i(t)] \tag{29}$$

$$V_i(t) = \mu_i Q_i(t) \tag{30}$$

$$K_i = \lambda_i/(\lambda_i + \mu_i) \tag{31}$$

where $Q_i(t)$ represents time specific unreliability of the system, $W_i(t)$ is the time specific recovery frequency of the system, $V_i(t)$ time-specific failure frequency of the system, λ_i is the time specific failure rate of the system, $\mu_i$the time specific recovery rate of the system, K is the phase of minimal cut set and t is time. More detailed derivation can be found in Jincheng [1988].

The Fusell-Vesely measurement highlights an event's contribution to system unavailability because it gives an idea on the likelihood that a system is down because a component is down. It is very important to identify those components in a system which have the greatest impact on overall system reliability. In practice, this is done by first choosing a suitable measure of component importance, calculating them for each component and then ranking the importance of components according to that measure. In this paper, a presentation is made of the various results for the power, process and control systems. This could be used to compare the relative importance of system components by calculating their Fussell–Vesely importance measures, when the components can be enhanced based on FMECA. These results help to quickly estimate optimizable components, because calculating the exact values of the component importance measures is very laborious in a large and complex system [Meng, 2000].

The RBD analysis was based on an enhanced Vesely theory which allowed the allocation of reliability capabilities to each block based on the logical failure of the system with respect to series and parallel connections. In this study, it was applied to model and decompose the system failures into cut-sets in order to visualize how the system is set-up and measure the actual faulty components so that a good logic for their optimization analysis will suffice rather than using a generic fault tree which is more suitable for sensitivity analysis without optimization details. It should be noted that it was used in a different way in the present analysis to consider the cut-sets on a node by node basis of process, control and power sub-systems. The clear advantage is that it simply allows the software to analyse the contribution of each component to unreliability.

To trace the key contributors to unreliability, the system is unbundled into its components parts using parallel and series connections as obtainable in illustrative instrumentation diagram in Fig 13.

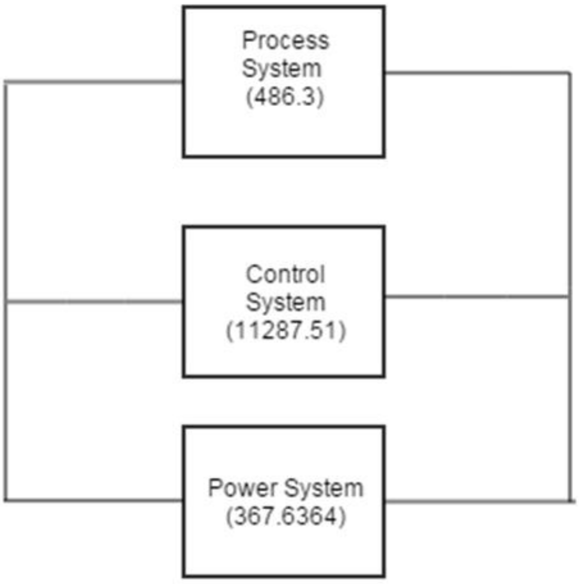


Figure 13: Reliability Block Diagram of the Subsea Compression System

4.2.3.1 Reliability Analysis of the Process Sub-System

The process sub-system is the section of the subsea compression plant where actual separation of well fluid and compression of gas occurs. An RBD diagram of the process sub-system is cut out from the main subsea compression system and calibrated accordingly with the MTTF values of Table 9. A simulation is run using ITEM Reliability Software for a lifetime of 7200 hours or 300 days and an average Meat Time to Repair (MTTR) of 7 applied to each component. The component failure data is fed to the system. 100 iterations are run on each sub-system as obtained from Piping and instrumentation drawings to determine the severity index and reliability importance of the components. This iteration is repeated for all the sub-systems. The failure severity index measures the intensity of unreliability of each sub-system.

The Failure Severity index is mathematically expressed as

$$Failure\ Severity\ Index\ (S) = T \text{ x } F_f \text{ x } F_E \tag{32}$$

where T represents Time, F_f represents failure frequency and F_E represents expected failures.

The aim of the procedure is to capture the key components that contribute to unreliability and their various reliability importance for adequate system optimization. Fig 14 shows the reliability blocks configuration into a mix of series and parallel cut-sets as obtainable in realistic configuration.

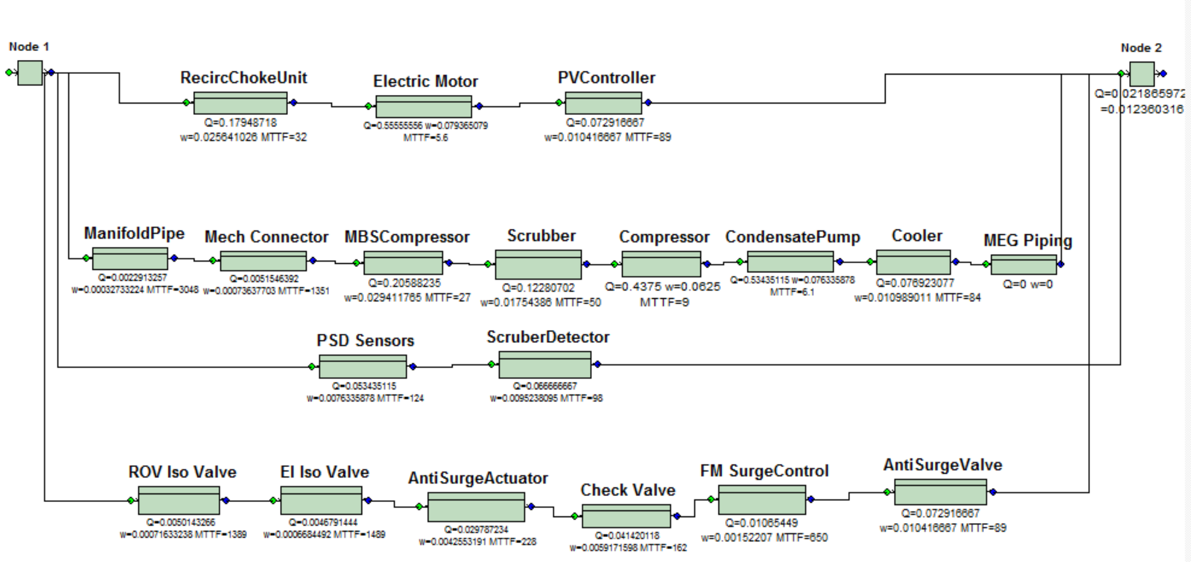


Figure 14: Reliability Block Diagram (RBD) of SCS Process Sub-System

The reliability index of the process system was found to be 0. This implies that the system is completely unreliable. The failure frequency was 12.3% and the total number of expected failures was 88.5. The risk severity factor using equation (29) is 170 which seems modest but does not count as reliable because the failure frequency of other critical components meant that the entire Sub-System has an infant premature failure.

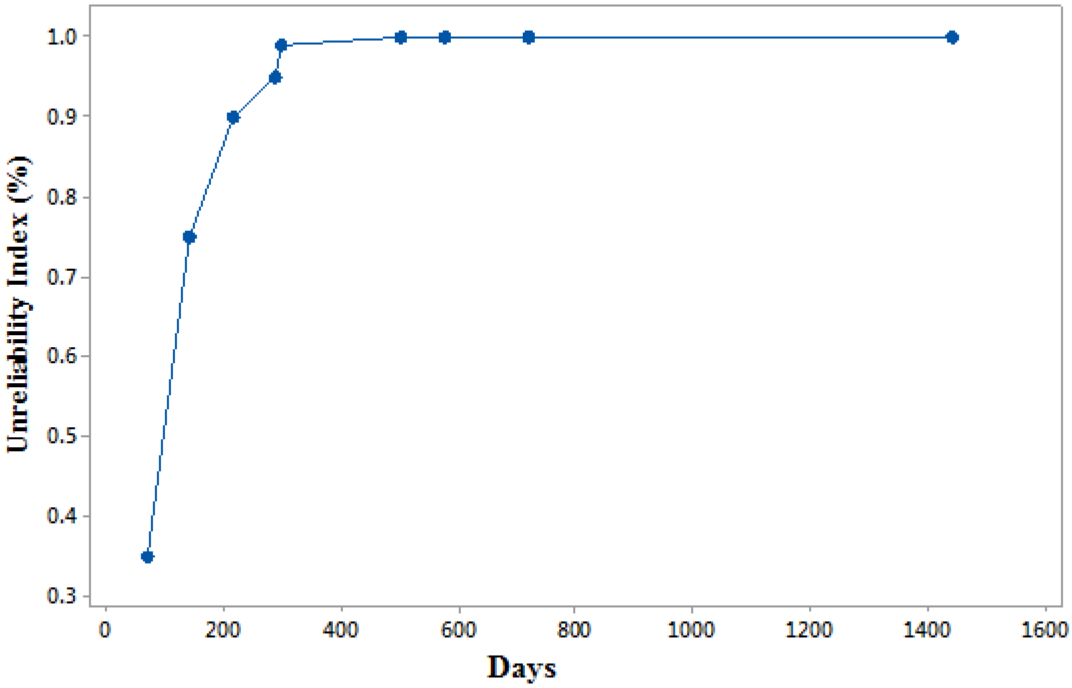


Figure 15: Time *vs* Unreliability for Process Sub-System

The time and unreliability index graph shown in Fig 15 indicates that the unreliability of the process components rapidly increases and attains full unreliability value in 288 days which significantly deviates from the pre-set benchmark of 300 days or 7200 hours. The reliability of this system in relation to target operation benchmark is zero, therefore, all the critical components need to be optimized.

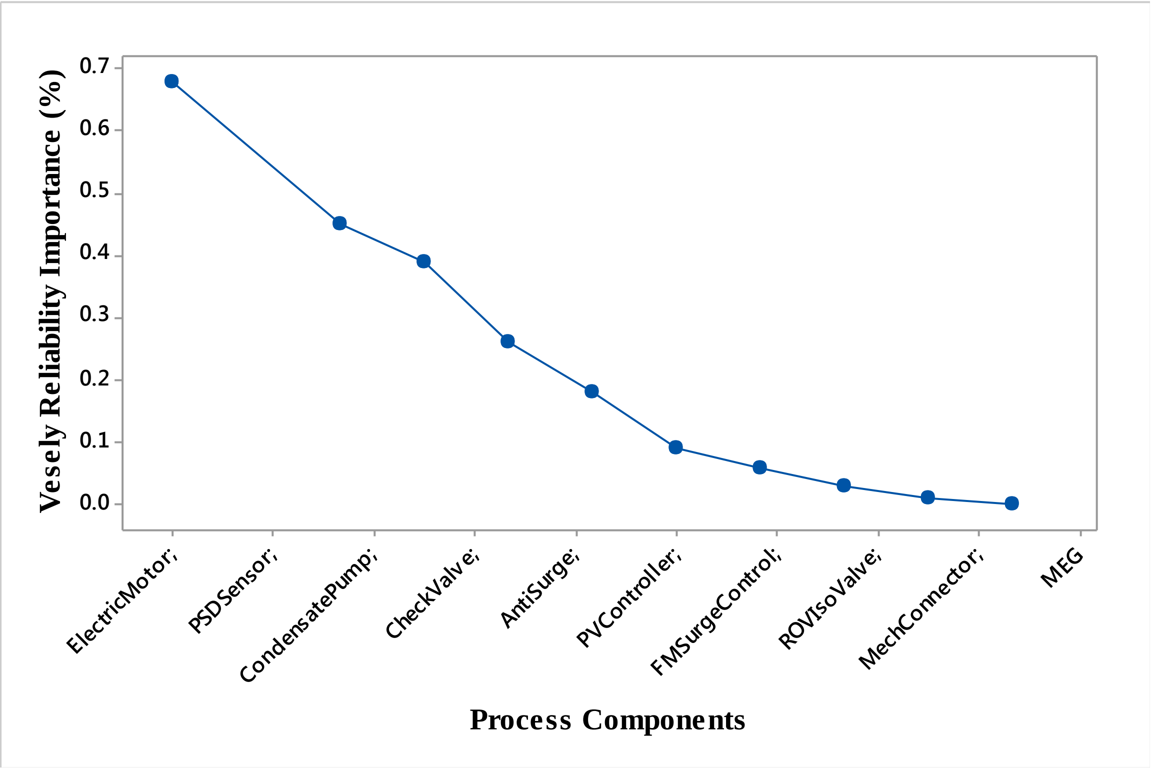


Figure 16: Reliability Importance for Process Sub-System Components Systems.

Fig 16 shows the reliability importance chart of process components. To identify the critical components which need reliability upgrade the most, another analysis is subsequently run using Fusell-Vesely's equation (FV). Fusell-Vesely Importance of the modelled plant feature (usually a component, train, or system) defines the fractional decrease in total risk level (usually CDF) when the plant feature is assumed perfectly reliable (failure rate = 0.0). If all the sequences comprising the total risk level (e.g. CDF) are minimal, the F-V also equals the fractional contribution to the total risk level of all sequences containing the (failed) feature of interest. Where F-V = 1-1/RRW and RRW is Risk Reduction Worth (RRW) [Kvassey, 2015]. Change in unavailability of events with high importance values will have the most significant effect on system unavailability.

$$Importance\ Value\ (IMP_V) = \frac{\sum Quantity\ \ of\ Blocks\ ContainingEvent}{Quantity\ \ of\ all\ cut\ sets} \qquad (33)$$

Fig 16 above shows that the Meg Piping with zero reliability importance index, Mechanical connector and Isolation Valve contributes least to unreliability while the electric motor with an importance factor of 68%, the PSD Sensor and condensate pump are top contributors to frequent failure of the process sub-system. A trade-off on cost will then guide the choice of redundancy or quality improvement to be made on the components.

4.2.3.2 Analysis of the Control Sub-system.

The control sub-system entails the auto-sensory segment which continuously monitors the overall condition of the subsea compression plant. As can be seen in Fig 17, the system is wired-up in reliability configuration and reliability analysis simulation is run through on the cut-sets.

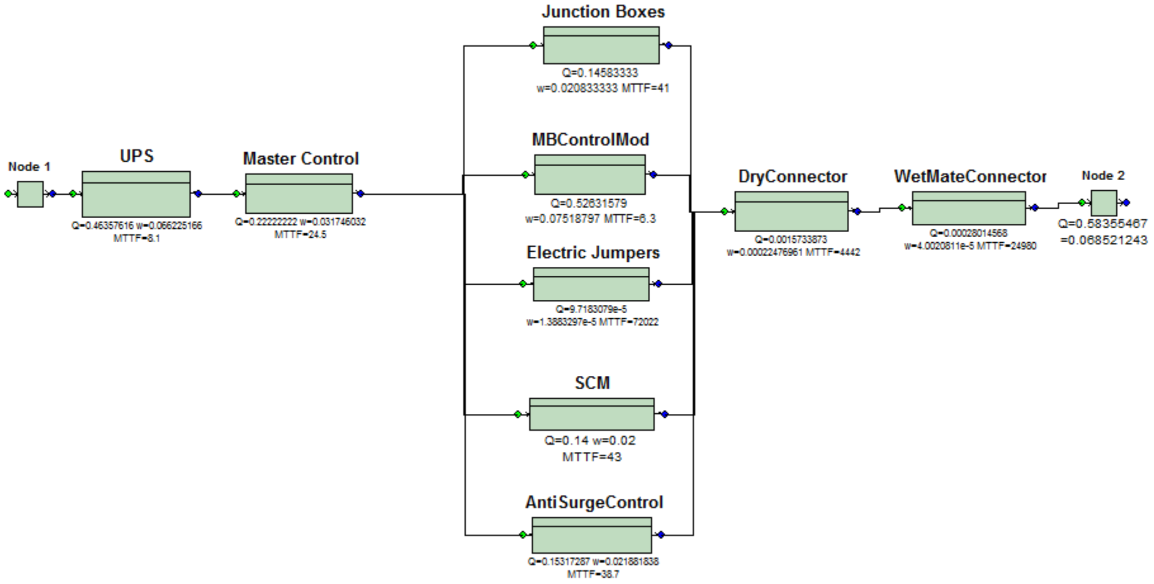


Figure 17: Reliability Block Diagram (RBD) of the Control Sub-System.

The reliability index of the control sub-system was found to be 0 with 498 failures and 4180 total downtimes. This implies that the control sub-system is completely unreliable. Using ITEM software, the failure frequency was found to be 0.0685 and the total number of expected failures was 88.5. The risk severity factor was found to be 170 which appears relatively average but ironically does not impact positively on overall reliability since the failure frequency of other critical components meant the entire sub-system has an infant failure rate.

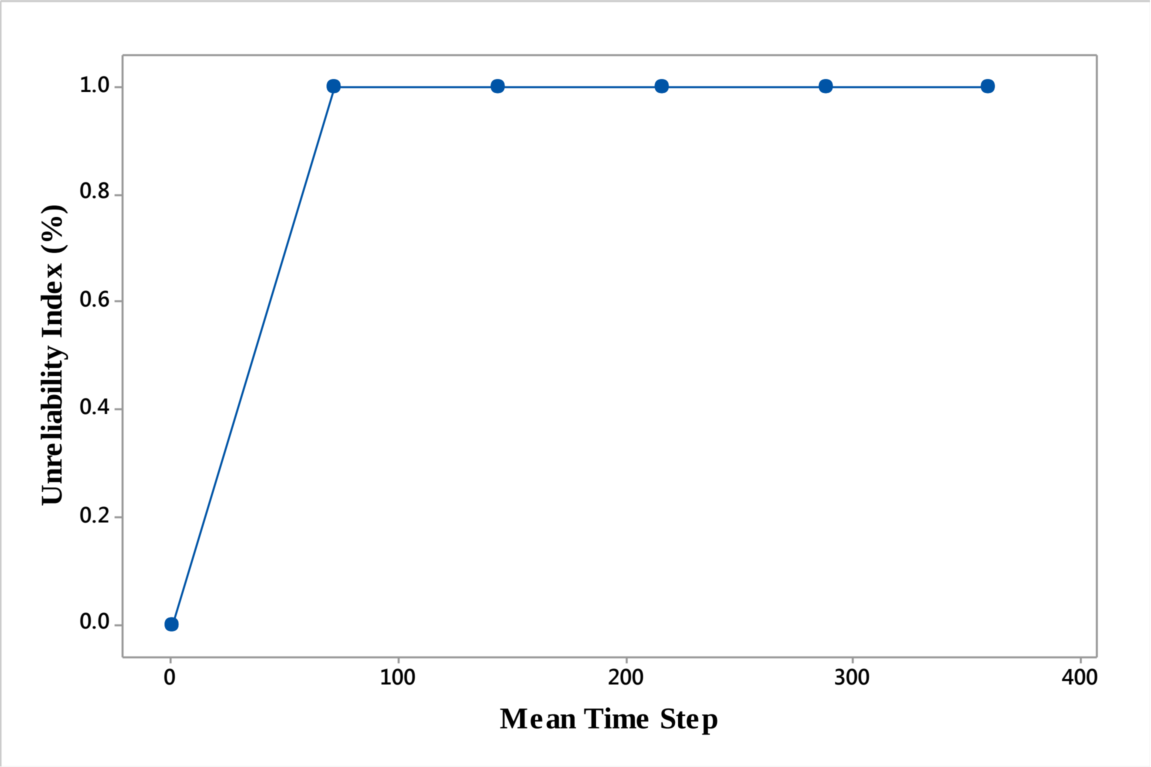


Figure 18: Time *vs* Unreliability of the Control Sub-System

The control system chart in Fig 18 appears to be the main contributor to failure being that complete unreliability was reached within 72 days. The system fails rather earlier than the benchmark target therefore a further investigation to identify the contributors is justified. Recall some components in this sub-system has the highest MTTF with Wet Mate Connector and Electric Jumpers having 24980 and 72022 MTTFs respectively according to Table 7. This analysis reveals that a high MTTF does not directly translate to high reliability rather the cumulative MTTFs together with frequency and times of failure gives better prediction of system reliability.

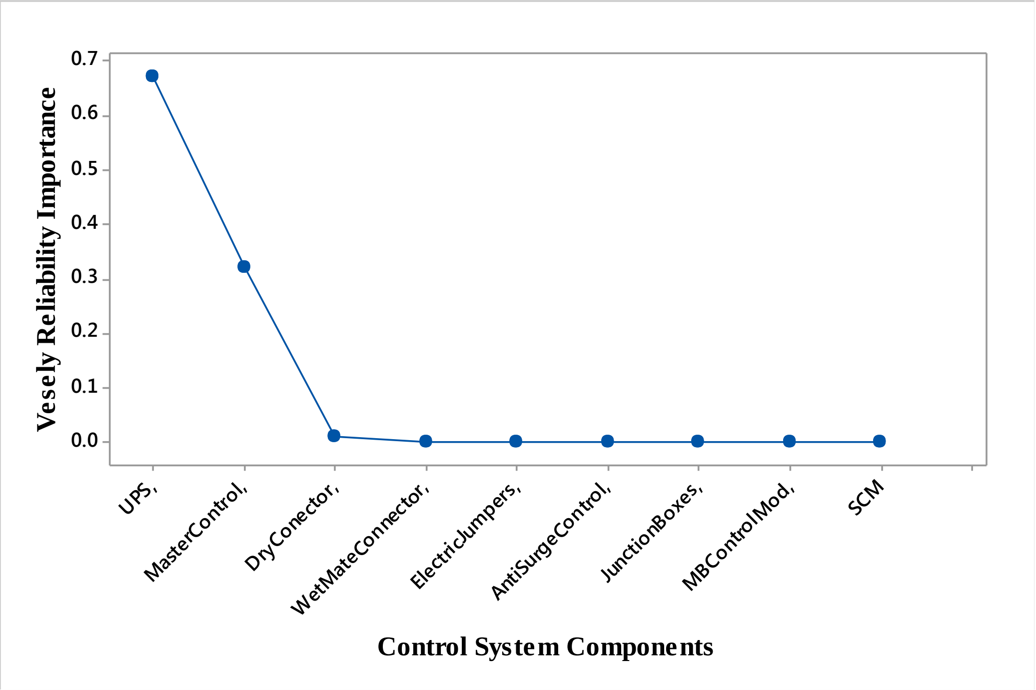


Figure 19: Reliability Importance for the Control Sub-system.

Fig 19 shows that the Subsea Control Module (SCM) and the Dry Connector did not contribute much to unreliability rather it is the Master Control and UPS that are critically important to reliability because they contribute to unreliability by 32% and 68% respectively. This implies that a significant upgrade of these two components will significantly improve the reliability of the control system cut set.

4.2.3.3 Analysis of the Power Sub-System

The power system supplies the electric voltage that runs the subsea compression system. It is an integral part of the system that runs from the top side through the umbilical cable down to the base of the ocean where the compressor is located**.** Arhenius Law and Basquin Law posited that electronic components fail due to an increased ambient temperature [Fides, 2009]. It is possible to extend the life of the power components beyond the mean MTTF using pressure protective enclosures for the power sub-components as demonstrated by [Vedachalam, 2013], however this particular research seeks to identify how the system configuration contributes to reliability and failure severity for stochastic optimisation. This implies that temperature fluctuations underwater have serious impact on the lifespan of the power sub-components. To account for this, the model law assumes a uniform fatality constant for stress based on the Weibull reliability index earlier estimated in 4.3.2. Fig 20 shows that the decomposition and of power system in series connection based on instrumentation diagrams obtained for the case study.

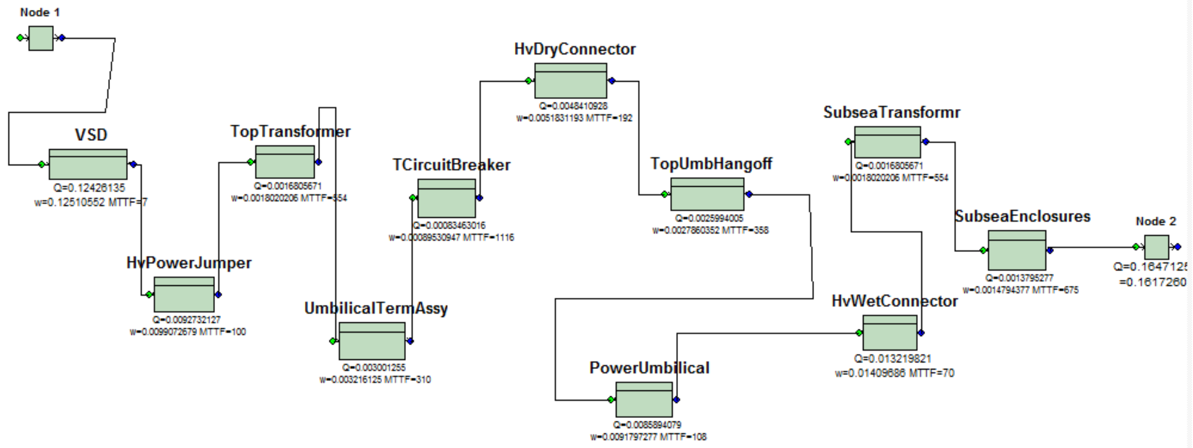


Figure 20: Reliability Block Diagram (RBD) of the Power Sub-System

Based on the RBD Fuselly-Vesely of the power system in Fig 20, the reliability index of the power sub-system was found to be 82% with 0.086 failures. The power sub-system was found to be the most reliable and of least reliability importance. The failure frequency was 0.167% for the sum of total number of expected failures was 0.176. The severity index was found to be 0.002 disregarding the fact that it had 11 cut-sets.

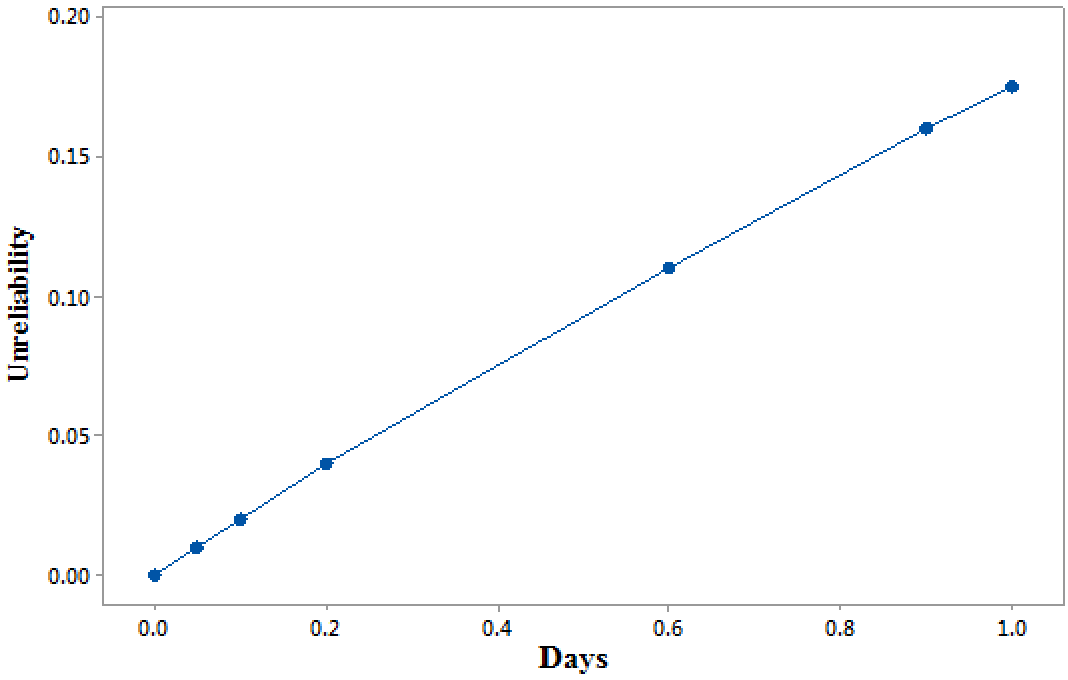


Figure 21: Time Vs Unreliability of the Power Sub-system

The power sub-system is the least contributor to failure of the whole subsea compression system being almost 99.9% of reliability was maintained further in time step than other sub-systems. Fig 21 shows that, at maximal unreliability, the system maintains a total unreliability of 0.18 in 1 time step. System unreliability is relatively low and varies almost linearly with time. The three data points on Fig 21 established a sufficient convincing trend, however, in real field applications; curve fitting may be exercised on the graph to determine the best-fit decision for reliability improvement.

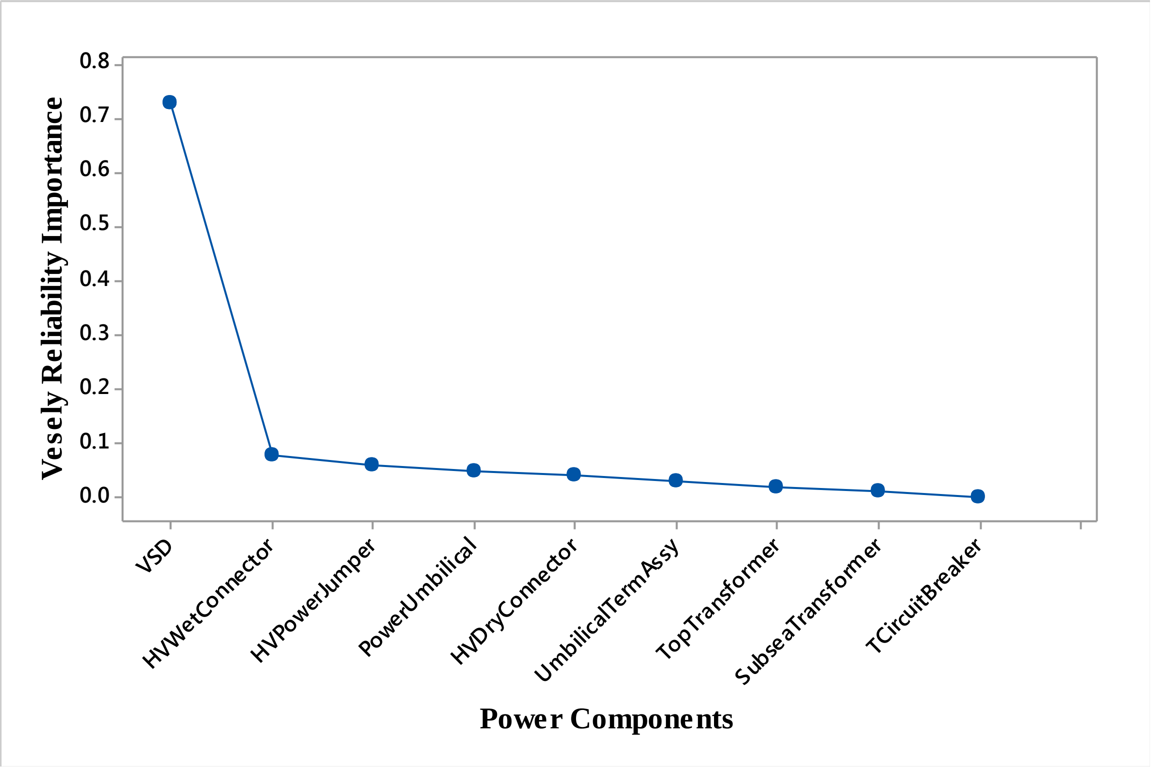


Figure 22: Reliability Importance of the Power Sub-system

The Variable Speed Drive (VSD) was identified as the critical item to be improved in the power segment. The high voltage connector may also need to be optimized because under subsea operational circumstances, the failure rate would increase. Table 12 shows a break-down of the results from sub-systems reliability assessment. It showcases the severity table of the whole system based on the Weibull analysis and Fusell-Vesely of the minimal cut sets. Minimal cut sets depend on the number of blocks in connection in each sub-system. A two-tailed F-test reveals that there is no relationship between the number of cut sets and expected failure, reliability, unreliability and failure frequency but there seems to be relationship between number of cut sets and severity. Thus, the lower the cut sets, the higher the severity. The biggest contributor to severity factor is total downtime.

Table 12: Summary Table of Sub-Systems Reliability

Subsea Compression Sub-Systems	No of Cut Sets	Unreliability (%)	Reliability (%)	Total Downtime	Expected Failures	Failure Frequency	Severity
Process System	19	1	0	156.64	88.5	0.0123	170.51
Control System	9	1	0	4180	496	0.0685	142019.68
Power System	11	0.17	0.823	0.086	0.176	0.1617	0.002

4.3 Optimisation of the Subsea Compression System

Optimisation of the whole Subsea Compression System requires a careful consideration of the Weibull-Corrosion Covariate results of Table (11) and Table (12). Since basic Weibull analysis has showed an infant mortality failure, it is imperative that the design is optimized to achieve the necessary reliability levels. Based on the requirement of 96% reliability at 300 days, a close look at the system components' MTTF indicates that that up to 25 components were under-designed while 14 were over-designed. The low survivability of majority of the individual components was responsible for the low value of β and the subsequent stress induced failure.

An optimisation of the lope-sided reliability design can be achieved by enhanced process control at the design stage and subsequent identification of reliability importance of the various components. Fig 23 shows the process control chart of the system.

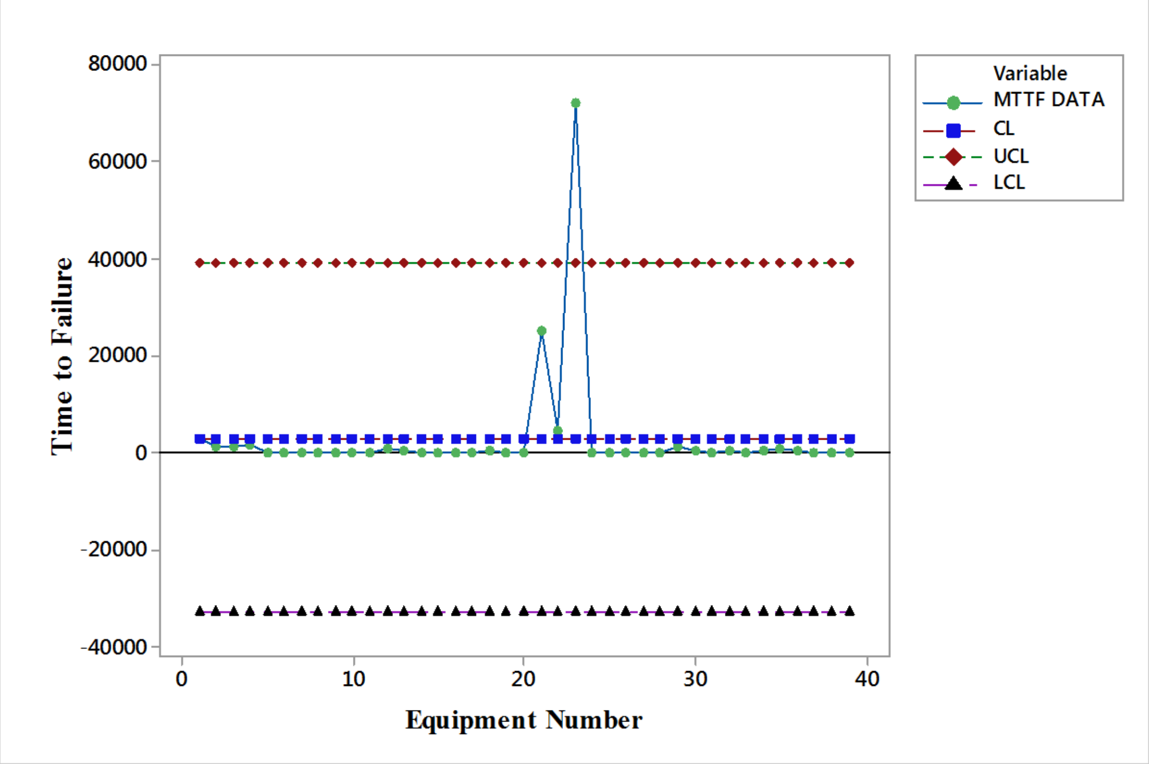


Figure 23: Statistical Process Control Chart for Design Optimisation

System optimization using control charts helps to identify design needs in a cumulative fashion. In Fig 23, it can be observed that the design violated the seven-point rule which suggests that seven consecutive data points above or below the mean indicates a problem with the process. With a mean MTTF of 2945 as benchmark, a standard deviation of the mean (CL) 2945 gives an upper control limit (UCL) and a lower control limit (LCL) of 39703 and -33182 respectively. There is then room for process-smoothing and possibly cost balancing as these will help to prevent the discrepancy resulted from either over-design or poor designs. Whole failure time of any components that fall outside of the standard limits would need to have some of its value extracted and shared out to deficient components in the distribution. This further confirms that unavailability of the subsea compression system is due to poor design and process control of individual components therefore there is a need for further analysis of the sub-systems and components to trace the key contributors to unreliability.

Table 13: Optimized Subsea Compression System

No	SUBSEA COMPRESSION SYSTEM	Initial MTTF	Optimality Factor	Reliability Importance	Minimum MTTF	Optimal MTTF
	Process System					
1	Manifold Piping	3,048	58,522	0	3,048	3,877
2	Mechanical Connector	1,351	25,939	0	1,351	2,180
3	ROV Isolation Valve	1,389	26,669	0.04	1066.752	1,895
4	EI Isolation Valve/Actuator	1,489	28,589	0	1,489	2,318
5	Check Valve	162	3,110	0.25	777.6	1,606
6	Scrubber	50	960	0.12	115.2	944
7	Scrubber Level Detector	98	1,882	0.56	1053.696	1,882
8	Magnetic Bearing System Compressor	27	518	0.32	165.888	995
9	Compressor	9	173	0.43	74.304	903
10	Electric Motor(Compressor)	5.6	108	0.69	74.1888	903
11	PSD Sensors	124	2,381	0.44	1047.552	1,876
12	Flow Meter for Anti Surge Control	650	12,480	0.08	998.4	1,827
13	Anti Surge Actuator	228	4,378	0.18	787.968	1,617
14	Anti Surge Valve	89	1,709	0.44	751.872	1,581
15	Cooler	84	1,613	0.08	129.024	958
16	Condensate Pump Unit	6.1	117	0.44	51.5328	880
17	Re-circulation choke valve	32	614	0.22	135.168	964
18	Meg Piping	309	5,933	0	309	1,138
19	Pressure and Volume Controller	89	1,709	0.11	187.968	1,017
	Control System					
20	Top Side Master Control Station	24.5	470	0.32	150.528	979
21	Wet Mate Connector	24980	479,616	0	24980	25,809
22	Electrical Dry Mate Connector	4424	84,941	0	4424	5,253
23	Electric Jumpers	72022	1,382,822	0	39703	39,703
24	Junction Boxes	41	787	0	41	870
25	Magnetic Bearing Control Module	6.3	121	0	6.3	835
26	Anti-Surge Compressor Control Pod	38.7	743	0	38.7	867
27	SCM	43	826	0	43	872
28	UPS	8.1	156	0.67	104.1984	933
	Power System					
29	Topside Main Circuit Breaker	1116	21,427	0	1116	1,945
30	Topside Transformers	554	10,637	0	554	1,383
31	VSD	7	134	0.72	96.768	925
32	Topside Umbilical Hang-off	358	6,874	0	358	1,187
33	Power Umbilical	108	2,074	0	108	937
34	Umbilical Termination Assembly(UTA)	310	5,952	0	310	1,139
35	Subsea Enclosures (Transformer)	675	12,960	0	675	1,504
36	Subsea Main StepDown Transformer	554	10,637	0	554	1,383
37	Hv Penetrator/Dry Connector	192	3,686	0.02	192	1,021
38	Hv Power Jumper	100	1,920	0.05	100	929
39	Hv Wet Mate Connector	70	1,344	0.08	70	899

Using the formulas in 4.14, Table 13 shows the optimisation of the subsea compression system to maintain 96% reliability at 300 days. The RBD decomposition of the entire system into its constituent components and analysis with pre-set algorithms in the *ITEM software* helped to analyse the contribution of each component to overall reliability. Whilst some components needed an increased MTTF, others for instance No (13), (*Electric Jumpers)* had way too much uptime life and its optimal MTTF had to be smoothened to a lower value to accommodate other deficient components. The components whose reliability importance are 0 or less than 0.1 are left untouched as seen in No (1), (*Manifold Piping)* in Table 13 where 3048 was both the initial MTTF and minimum MTTF but only increased to 3877 by taking a percentage of the extracted excess life of the Electric Jumpers.

4.4 Human-Factor Reliability Assessment

A questionnaire based on the Delphi method was developed by interviewing experts from the West African subsea sector. The questionnaire was reviewed by a reference panel to confirm its academic and ethical status. The panel was made up of engineering experts whose backgrounds were operation, maintenance, and subsea engineering.

A pilot survey was launched and little adjustments were effected on the final draft before the proper interview was carried out. The first section of the interview was designed to discover the company's main business activities, experience and technical know-how of the respondents in order to understand how the operations are shared-out within the company while at the second section, the company's subsea personnel were required to highlight its strategy for offshore system maintenance activities and the operational challenges at play. Their opinions were measured on a scale and the same questionnaire was used in order to maintain uniformity of data from participants.

Five key factors were analysed being that they are factors that affect the installation, production and maintenance stages of a typical West African oil field. Ten specialists were interviewed through phone calls. Five of the specialists work with operators, two specialists work with subsea manufacturing companies and the other two specialists work with a company providing subsea consultancy service.

Each of the specialists possess a minimum four years' experience with subsea systems and at least 10 years' experience in several engineering and management positions within the subsea oil and gas industry. Based on the respondents' profiles, the study reasonably indicated current trends and rating regarding human factor and operation indices of subsea oil and gas production practices, problems and issues in the installation.

For this case, the reliability value derived from the Weibull-Covariate analysis was fed to the slot for the technical condition/reliability system and the severity code read-off. The revised probability of failure in Tables 14 and 15 show that the most contributing Risk Influencing Factor (RIF) is the personnel factors with a 56% probability of failure and the overall least RIF is technical factors with a 29% probability of occurrence. The severity index could be transcribed into weighted financial consequences depending on pre-set benchmarks. From the results, urgent effort needs to be made towards smart resource allocation and staff scheduling in order to reduce human fatigue risks, improve occupational health and safety, and associated cost implications. Whilst the sum of Revised Probability (P_{rev}) of Influence for the technical RIFs seem to be relatively low, a look at the modification factor shows that elements such as material properties and process complexity of the system were both significantly high at 1.2, thus, requires improvement. Table 14 entails an enhanced method for human reliability assessment by quantitatively assessing the risk in a particular scenario.

Table 14: Human Reliability Analysis Table

No	RISK INFLUENCE FACTOR	RATING						
		Industry Average (Pave)	Weight (W)	Risk Influencing Factor (Q)	Code for Risk Influencing Factor (Q. Code)	Moderation Factor (MF)	Average Moderation Factor (MF Ave.)	Revised Probability (Prev)
1	**PERSONNEL FACTORS**	**0.45**					**1.25**	**0.5625**
1a	Competence		0.8	C	3	2.4		
1b	Work Stress		0.2	D	2	0.4		
1c	Fatigue Rate		0.2	D	2	0.4		
1d	Health Condition		0.6	C	3	1.8		
2	**TASK FACTORS**	**0.44**					**1.01**	**0.4463**
2a	Ergonomics		0.5	C	3	1.5		
2b	Supervision		0.2	C	3	0.6		
2c	Methodology		0.4	D	2	0.8		
2d	Time Pressure		0.8	E	1	0.8		
2e	Sufficient Work Tools		0.2	D	2	0.4		
2f	Spares Availability		0.2	C	3	0.6		
2d	Explosivity/Inflamability		0.8	C	3	2.4		
3	**TECHNICAL ELEMENTS**	**0.37**					**0.77**	**0.2854**
3a	Equipment Design		0.2	C	3	0.6		
3b	Material Properties		0.4	C	3	1.2		
3c	Process Complexity		0.4	C	3	1.2		
3d	Human Machine Interface		0.2	D	2	0.4		
4d	Maintainability		0.2	D	2	0.4		
5e	System Feedback		0.4	D	2	0.8		
5f	Technical Condition/Reliability		0.8	E	1	0.8		
4	**ADMINISTRATIVE**	**0.33**					**1**	**0.33**
4a	Work Permit		0.2	C	3	0.6		
4b	Work Safety Analysis		0.4	C	3	1.2		
4c	Procedures/Protocols		0.4	C	3	1.2		
5	**OPERATIONAL PHILOSOPHY**	**0.35**					**1.16**	**0.406**
5a	Trainings		0.6	C	3	1.8		
5b	Enterprise Feedback Loops		0.4	D	2	0.8		
5c	Communication		0.6	C	3	1.8		
5d	Regulation		0.4	D	2	0.8		
5e	Management of Changes		0.2	C	3	0.6		

Table 15: Risk Matrix Table of the RIFs

	Risk Factor	**Severity Index(Percentage)**					
		10	20	30	40	50	60
i	Personnel Factor					■	
ii	Task Factor				■		
iii	Techanical Elements			■			
iv	Administrative			■			
v	Operational Philosophy				■		

4.5 Strengths and Limitations

- The key contribution of the research is a new systematic methodology for stressing a low-stress failure data such as OREDA MTTF in order to predict a realistic failure curve and optimize an asset which has little field records but bound to face exponential covariate vectors of operational stresses afield.
- To model the reliability of a system in full water-wet condition, the Norsok's Corrosion profile model was adopted and incorporated with the newly developed Weibull failure expression by implementing the principle of Arrhenius reaction model for accelerated life reliability analysis.
- The present analysis reveals that a high component MTTF does not directly translate to high reliability, instead the cumulative MTTFs together with frequency and times of failure gives better prediction of system reliability as per first failure without consideration of maintenance.
- The motivation of the current study is due to the unavailability of any known publication which addresses the reliability and optimization of a Subsea Gas Compression System - an emerging technology that had only been launched in 2015 at Asgard field, Norway.
- Further development of the present reliability analysis method shows that the baseline reliability index of a system was stressed with statistical stress based on intended operating environment, in this case – a corrosion profile ; considering extended parameters such as subsea temperature, pressure, pH and fugacity variables, so that weak components are identified and an optimal MTTF is proposed (either increased, kept constant or decreased) for each component as shown in Table 10.

The reliability analysis conducted in this study focused on an enhanced reliability model developed for the subsea compression system. It is a simplified representation of the true system, and for practical reasons, it cannot describe all features of the system with 100% accuracy. For instance, the inaccuracies may relate to the configuration of the system and the production capacities of the system for various equipment states.

Some degree of subjectivity might have affected the weights and responses received from the interviewees on human reliability. However, the strength of the overall reliability assessment model lies in its ability to visualize the life failure data, accelerate failure life and project optimal tolerances for subsea equipment subjected to operational influences of both the marine and human factors. The corrosion-Weibull covariate model produced valid benchmark which is vital for the improvement of the overall design of the subsea compression system for longer life. Redundancies and back-up systems were not considered in this study however, the detailed statistical analysis of the system has a 95% confidence status.

4.6 Conclusion

The study reported in this chapter constitutes a step forward in advanced qualitative and quantitative analysis for assessing the reliability of the emerging subsea compression system.

- This paper reveals that a high MTTF component does not directly translate to high reliability of a system rather the cumulative MTTFs together with frequency and times of failure gives better prediction of system reliability.

- It is more efficient and time-saving to (a) identify any infant mortality (b) identify over-designed components by applying Weibull failure model and Fusell-Vesely theory to their minimal cut sets for optimizing overall reliability index based on criticality and reliability importance of components. The initial basic reliability of the system was optimized by a margin of 52% from 0.45 to 0.95 based on the confidence interval of the whole reliability analysis.

- The analysis indicates that there is no significant relationship between the number of cut sets and expected failure, reliability, unreliability and failure frequency but there seems to be relationship between number of cut sets and severity. Thus, the lower the cut sets, the higher the severity risk. However, the biggest contributor to severity factor is total downtime.

- The operational requirements of a subsea gas compression system can be understood and optimized by embedding a high operational stressor using a covariate corrosion profile on a Weibull model of component failure distribution, then reliability decomposition of the sub-components to identify the critical components and an optimization analysis based on reliability importance of each sub-component.

- Low subsea temperatures, high CO2 fugacity and pH variation has a significant impact on asset degradation rate, failure modes and frequency over a time series. Personnel factors such as competence of the operators, works stress, fatigue, stress, and ergonomics constitute the highest weight of risk influencing factors that could cause a subsea gas compression system to fail based on the geographical setting of the study.

- The new model demonstrated a significant originality in producing more realistic failure rate compared to the basic reliability models which does not consider credible external influences.

The newly developed method in this chapter combines the powerful calculative abilities of a Weibull with corrosion covariate model together with systematic decomposition of the whole system with RBD analysis, subsequent identification of the reliability importance of each component and the novel optimisation method therein.

Using well-known physical based life-covariate relationships supported by systematic operational survey and optimisation through RBD decomposition, the model provides a suitable statistical approach for achieving in-depth knowledge on inherent risks towards a system and optimization. Future work may add more stress covariates and make an in-depth focus on the relationship between the cut sets and unreliability, failure frequency and failure times.

CHAPTER 5

Subsea Oil Production and Efficiency Analysis Using Artificial Lifts and Nodal Analysis.

Front End Engineering Design (FEED) studies for determining the choice of an efficient subsea system with the least-cost is a challenge for most subsea oil field development. This paper describes how the operational life of subsea wells can be predicted, analyzed and optimized using artificial lift systems. The novelty in this paper is the proposition of a concise methodology for production efficiency evaluation and selection of optimal artificial lift and pipe systems based on power requirement, pipe diameter, vertical and horizontal pressure drops, cost of pipe system and flow velocity.

Firstly, an enhanced Hubbert method is developed and applied for determining production targets at pre-feed phase of project and the impact of artificial lifts on the economics of subsea wells facing hyperbolic decline in flow rates and pressure is examined. The principle of nodal analysis was highlighted and applied to optimize a proposed subsea production system consisting of configurations of a nominally rated progressive cavity pump (PCP), and an electrical submersible pump (ESP). The production systems were modeled in a black oil flow using software "*Pipesim*" and the production outputs were further used to carry out a least-cost efficiency analysis for optimal choice of pump-pipe production system. The efficiency-based methodology was then applied to a case study for selection of optimal design of the pipe-pump network with special considerations for parameters such as flow rate, pipe diameter, efficiency and pressure drop.

It is revealed that over 88% of overall efficiency was achieved by the Electrical Submersible Pump (ESP) compared to the Progressive Cavity Pump (PCP) of same rating which achieved only 29% in efficiency. A methodology is developed to analyze and enhance the recovery curve of subsea oil production using artificial lift, nodal analysis and optimum efficiency principle. The benefit of this work is an enabling cost-effective approach for comparing contemporary artificial lift strategies in deep water oil and gas production

5.1 Methodology

The concept of system analysis works on the principle of continuity This means that each point in the flow system has a pressure, and as well fluid flows from the underwater reservoir to the topside, a significant amount of pressure is lost through friction, bending moments and gravity [Douglas et al, 2005]. Fig 24 depicts inflow and outflow curves of a well flow.

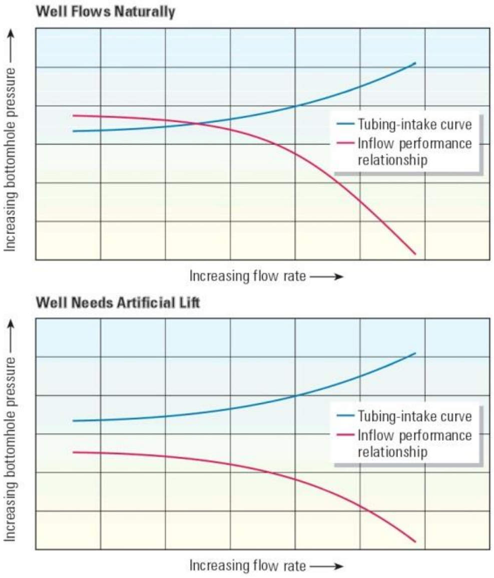


Figure 24: Depiction of inflow and outflow curves (Bates et al, 2004)

Considering the bottom-hole node of an oil and gas well, the gross pressure differential between the reservoir pressure and the topside outflow would be gotten from the difference between the average reservoir pressures at the sink minus that at the bottom hole.

Mathematically, assume that total inflow equals the total outflow when well flows naturally:

$$\boldsymbol{P_I = P_O} \tag{34}$$

Then difference in pressure is ,

$$\Delta \boldsymbol{P_T} = \boldsymbol{P_R} - \boldsymbol{P_S} \tag{35}$$

Since the total drop in pressure along the pipe consists of irregular periods of drop encountered from completion, through tubing, process equipment, wellhead and irregularities at bends in flow lines [Edgar Camargo et al, 2008]. From Eq.34, total pressure drop can also be expressed as the sum of individual pressure across the flow line.

$$\boldsymbol{\Delta P_T = \Delta P_1 + \Delta P_2 + \Delta P_3} \tag{36}$$

Depending on the details of analysis, these discrete pressure losses can be broken into further pressure losses to identify the contribution of valves, external environment and other influences on the flow line. As mentioned previously, nodal analysis interestingly offers pliancy on the analysis of any point of scrutiny across the production system in order to evaluate a behaviour of the system. Although, most analysts place the node at the wellhead or at the bottom hole [George Guthrie et al 2010]; such that the reservoir is positioned at upstream terminal and the discharge point at the topside, the node could be placed directly on the well head and any point on the flow line. Once the node point is chosen, the outflow and inflow sections of the pipe are resolved using pressure relationships.

The pressure loss in the production system varies as a function of flow rate. As a result, a reliable flow rates model could be applied to calculate node pressures for each part of the system**.** The Inflow Performance Relationship (IPR) of a single phase oil reservoir above bubble point pressure is given by Fattah et al, [2014],

$$\boldsymbol{q = J \times (\rho - \rho_{WF})} \tag{37}$$

The Total Performance Relationship (TPR) is given by the Poet-mann Carpenter model which is

$$\boldsymbol{\rho_{wf} = \rho_{wh} + \left(\rho + \frac{k}{\rho}\right)\frac{L}{144}} \tag{38}$$

The node can be determined graphically by plotting the intersection of flow rate q values against pressure values ρ_{wf}. It can also be determined analytically by resolving both equations simultaneously to give equation 39.

$$q = J \times \left[p - p_{wh} + \left(p + \frac{k}{p}\right) \frac{L}{144}\right] \tag{39}$$

While Eq. 39 provides flow rate relationship, it does not provide the productivity index which is a measure of how much a well can produce.

The IPR defined can be expressed as a function of the production rate and the reservoir pressure of an active well.

$$J = \frac{Q_0}{P_r - P_{wf}} \tag{40}$$

Mathematically, it is represented as,

$$J = \frac{0.00708 K_o h}{\mu_0 B_o \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]} \tag{41}$$

For multiphase flow in two-phase pseudo steady state, both TPR and IPR change with time because when the reservoir pressure drops under bubble point, some gas escape randomly within the reservoir and a liquid-gas ratio drives fluid production [Guo, 2007]. The Vogel correlation is applied to model TPR and flow rates.

The flow rate *q* is given by Vogel's relation [Fattah et al, 2014].

$$q = \frac{J \times p}{1.8}\left[1 - 0.2\left(\frac{p_{wf}}{p}\right) - 0.8\left(\frac{p_{wf}}{p}\right)^2\right] \tag{42}$$

and oil and gas ratio is given by

$$R_{mean} = R_S + \frac{K_{rg} \mu_0 B_o}{K_{ro} \mu_g B_g} \tag{43}$$

In this work as applicable in most real situations, the *Pipesim* software applied these correlations once set on a well system. The production rate and pressure of the system being analysed is obtained by reading-off the intersection point of the node pressure curve and the flow/production rate curve.

The point of intersection also known as operating point indicates the point of continuity and also expresses the production rate and pressure of the system. A case study has been carried out using *Pipesim*, a software tool which applies the principle of nodal analysis to evaluate production rates.

5.2 Determination of Target Production at Pre-Feed Phase.

The estimation of oil production profile at the pre-feed phase of oil and gas production projects is regarded as one of the most crucial techno-economic tasks, vital for oil recovery plan over a period of time. Production forecasts allow for proper allocation of resources, capacity planning and most importantly, continuous production assurance during asset field life.

Numerous models have been proposed by various researchers to help predict oil production at various stages of an oil field lifecycle. With varying levels of complexities, they are able to provide credible behavioral curve of oil recovery rate based on selected variables such as reservoir properties, time, energy, cost, man power and so on. Production forecast models are broadly grouped into Harmonic, Exponential and Hyperbolic models. Harmonic models such as the prominent Hubbert-type curve fitting models, may produce reasonable predictions with their linear expressions but provide little understanding of the drivers (physical or economic of oil production). Hubbert model works on the principle of Central Limit Theorem which alludes that under specified conditions, the arithmetic mean of a sufficiently large number of iterates of independent random variables, each with a well-defined expected value and well-defined variance, will be approximately normally distributed, regardless of whether the distribution is Gaussian or exponential. This model which assumes that oil production profile is symmetric is widely applied during pre-feed stages to estimate oil production capacity.

Complex models on the other hand often show oil depletion trend that is difficult to predict from first principles, such that causal explanations cannot be generated and as such barely increases our understanding of the importance of various factors on future oil production. These sort of models exhibit the asymptotic and non-linear behavior of the variables considered to give hyperbolic oil recovery decline curves.

In reality, neither the simplistic, exponential nor hyperbolic decline models can solely predict reliable production forecast for policy and decision making. It is imperative to develop a hybrid model encompassing desirable properties of both complex and simple decline model categories.

This chapter proposes a hybrid production profile modelling approach crafted from the Hubert model with a hyperbolic-exponential. This model is suitable for pre-feed studies on subsea oil field development. To this effect, a semi-complex model is imperative.

Using the Hubbert model, the estimated ultimate recovery of the oil field can be derived. The Hubbert model is described as:

$$\boldsymbol{Q = \frac{2Q_M}{1+cosh[-b(t-t_m)]}} \tag{44}$$

$$\boldsymbol{b = \frac{4Q_M}{EUR} = \frac{5}{C}} \tag{45}$$

where EUR is the Estimated Ultimate Recovery, Q is the oil production at time t, Q_m is peak production, t_m time of the peak, b and c are parameters which account for the slope of the curve and the estimated average useful life of fields, respectively.

A value of $b = 0$ corresponds to exponential decline, values of $0 < b < 1$ correspond to hyperbolic decline, and a value of $b = 1$ corresponds to harmonic decline. It is noted that values of $b > 1$ are not consistent with decline curve theory, but they are sometimes encountered.

Being that hyperbolic decline rate is the rate at which exponential decline rate starts, it makes more sense to incorporate it into the deterministic Hubbert for a more accurate result. The time at which the hyperbolic decline turns to exponential decline of a producing well could be expressed as:

$$\boldsymbol{T_{exp} = b(D_{exp} - D_1)} \tag{46}$$

where $\boldsymbol{T_{exp}}$ is the time at which the hyperbolic behavior changes to exponential; $\boldsymbol{D_{exp}}$ is exponential decline rate while $\boldsymbol{D_1}$ is initial decline rate and $\boldsymbol{b}$ is the regional hyperbolic decline constant.

Assuming that only the hyperbolic decline is the main focus and exponential decline is to be ignored, we have,

$$\boldsymbol{T_{Hyp} = b(D)} \tag{47}$$

where $\boldsymbol{D}$ is simply the average decline rate from historical data and T_{Hyp} is the time of hyperbolic decline.

If $\boldsymbol{b}$ is assumed to be equal to $\boldsymbol{D}$ for a particular country or region, then we can confidently say that

$$\boldsymbol{T_{Hyp} = b^2} \tag{48}$$

This work proposes that an imposition of $\boldsymbol{D}$ into the Hubbert equation would enhance the reliability of forecasts by exploiting the symmetric capabilities of Hubbert model as well as the hyperbolic curve for the oil reserves.

The target production for the field assuming a hyperbolic decline can be determined by incorporating the decline rate into the Hubbert equation to generate the new oil production rate model *Qnew*. The decline rate constant is raised to the power of two to give an optimum recovery rate in the presence of declining reserves. The new production target will give a higher oil production and sustained by artificial lifts in the face of reservoir pressure decline.

$$\boldsymbol{Q_{new} = \frac{2Q_M}{1+cosh[-b^2(t-t_m)]}} \tag{49}$$

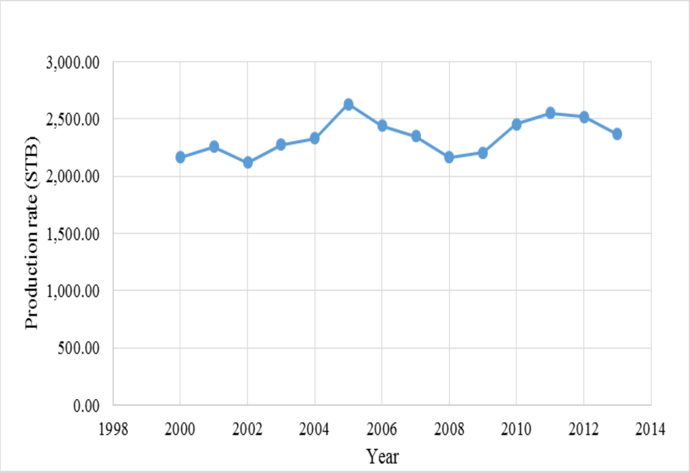


Figure 25: Historical Production Rate of Country *X*. [Indexmundi, 2014]

Given that *b* for country *X* is 0.192333 [Makinde et al, 2012], the Peak production Q_m is 2627 from Table 16 and Time of Peak production T_m is 2005 as shown in Fig 25. The new model is validated by using real oil production data obtained from [Indexmundi, 2014]. Given that *b* for country *X* is 0.192333 [Makinde et al, 2012], the Peak production Q_m is 2627.44 from Fig 25, and Time of Peak production T_m is 2005 as shown in both Fig 25 and Table 16. Substituting these values into Equation 45, we get the values in Fig 26 and Table 16.

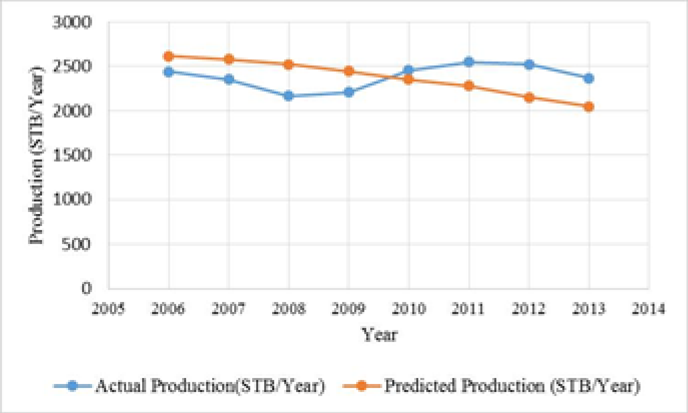


Figure 26: Graph Showing the Target Production and Prediction

Table 16: Various Prediction Methods versus Actual Output

	Actual	**Qnew**	**Hubbert**
Year	**Production in Million STB/Year**		
2000	2,165.00	_	_
2001	2,256.16	_	_
2002	2,117.86	_	_
2003	2,275.00	_	_
2004	2,328.96	_	_
2005	2,627.44		
2006	2,439.86	2,625.00	2,600.00
2007	2,349.64	2,623.00	2,532.00
2008	2,165.44	2,619.00	2,421.00
2009	2,208.31	2,612.00	2,273.00
2010	2,455.26	2,604.00	2,102.00
2011	2,550.35	2,594.00	1,966.00
2012	2,520.00	2,583.00	1,722.00
2013	2,367.37	2,570.00	1,529.00
Total	19,056.23	20,830.00	17,145.00

Table 16 shows that indeed the newly crafted model, Q_{new} could be used to predict the basis of production target for a declining reserve of country X. The results of the Q_{new} predicts a total of 20,830 barrels per year (bpy) of cumulative production for the 8 years succeeding peak production. The Hubbert model gave a much lower production of 17,145 stb/year. In essence, Q_{new} represents the upper limits while the Hubbert model estimate represents lower production limits. A more realistic forecast is obtained by finding the mean of the upper and lower limits. The *Prediction* column (mean of Q_{new} and Hubbert column) shows that the new prediction closely tallies with the overall actual production obtained from 2006 to 2013; with only 63 barrels as inventory stock.

5.3 Costing plan.

The optimization model is based on the fact that total cost involved in the design of a subsea pipeline transporting fluid is kept to a minimum. The present study makes use of the design Equations developed by (Asim, 2013) explicitly for on shore HCPs transporting spherical capsules and developing an optimal design methodology for such pipelines. The model presented is based on the principle of Integrated Resource Planning (IRP).

Integrated Resource Planning (IRP) is the process of selecting the minimum cost for providing a certain level of service or benefit. It is a robust method for analysing a given level of output which could be different combinations of two or more variable inputs. In choosing between the two completing resources, the saving in the resource replaced must be greater than the cost of resource added. The principle of least cost combination states that if two factor inputs are considered for a given output the least cost combination will be such that their inverse price ratio is equal to their marginal rate of substitution.

In this work, the IRP model makes use of equations developed by (Asim, 2013) for Hydraulic Capsule Pipelines (HCP) and Engineering Toolbox (2015). The total cost can be split into the sole cost of the pipeline and the sole cost of the fluid in it which is the oil and gas, then the cost of power. Power is usually the highest contributor to operational cost in pump-pipe flow configurations.

$$\boldsymbol{C_{Total} = C_{Pipe} + C_{Flow} + C_{Power}} \tag{50}$$

where C_{Total} is Total cost, C_{Pipe} is pipe cost, C_{Power} is power cost.

5.3.1 Cost of Pipeline

The cost of pipeline material is given by (Menon et al, 2013)

$$\boldsymbol{PMC = \frac{10.68(D-T)TLC \times 5240}{2000}} \tag{51}$$

where PMC = Pipe material cost,
L = Length of pipeline (m)
D = Pipeline Outside Diameter
T= Pipewall Thickness (m)
C = Pipe Material Cost $/ton

The pipe wall thickness can further be expressed as $T = C_c$, where C_c is a constant of proportionality dependent on expected pressure and diameter ranges of the pipeline.

5.3.2 Cost of Power

The cost of power per unit watt is given by

$$\boldsymbol{P} = \frac{\boldsymbol{Q_M} \times \boldsymbol{\Delta P_{Total}}}{\boldsymbol{\eta}} \tag{52}$$

where Q_m is the flow rate of the mixture, ΔP_{Total} signifies the total pressure drop in the pipeline transporting the oil while η signifies the efficiency of flow output and in essence the pumping system. For subsea application, the efficiency of pump should be high due to the long distances and heat loss in water. A range of 70% to 80% of efficiency is recommended. Industrial applications normally hedge the target to 60% to 70% of efficiency (Asim, 2013). In the calculation for this work, it was assumed to be 75% for the basic optimal pipe design before comparison with the flow rates results from nodal analysis of the ESP and PCP configurations.

5.3.3 Total Pressure Drop

Bearing in mind the vertical and horizontal configuration of the pipeline system, the total pressure drop in the subsea pipeline can be expressed as the sum of the major pressure drop and minor pressure loss due to fittings and bends along the pipeline. The pressure drop can be estimated using the Darcy-Weibach formulae. Mathematically, it can be expressed as

$$\Delta \boldsymbol{P} = \boldsymbol{F_D} \frac{\boldsymbol{\rho V^2}}{\boldsymbol{2}} \frac{\boldsymbol{L}}{\boldsymbol{D}} \tag{53}$$

The pressure drop in the riser can be calculated using Eq. (53) for horizontal pipes (Kiijarvi, 2011). It consists of head loss in horizontal pipe multiplied by pressure loss in the horizontal and the same for vertical riser and summed up.

$$\Delta \boldsymbol{P_{Major}} = \boldsymbol{f_v} \frac{\boldsymbol{L_p}}{\boldsymbol{D}} \cdot \frac{\boldsymbol{\rho_w Vav^2}}{2} + \boldsymbol{f_h} \frac{\boldsymbol{L_p}}{\boldsymbol{D}} \cdot \frac{\boldsymbol{\rho_w Vav^2}}{2} \tag{54}$$

where ΔP = Pressure loss

f = Darcy friction formula

L = Length of pipe

D = Inner diameter of the pipe

P = Density of the fluid

V = Flow velocity

In the same way, the minor pressure drop can be expressed as

$$\Delta \boldsymbol{P_{Minor}} = \boldsymbol{K_{lw}} \frac{\eta}{D} \frac{\rho_w Vav^2}{2} + \boldsymbol{K_{lc}} \frac{\eta}{D} \frac{\rho_w Vav^2}{2} \tag{55}$$

where η represents the number of bends and corners in the pipeline. Here friction factor can be derived using Moody's approximation tables. K_{lw} represents frictional factor.

5.3.4 Volumetric Flow Rate

According to Liu (2013) the flow rate in a pipe is defined as the volumetric flow rate as an amount of fluid is passing through the pipe per instant time due to friction losses and the relationship between the inertial and viscous forces of fluid.

$$\boldsymbol{Q} = \frac{\pi D^2 V_{av}}{4} \tag{56}$$

where V_{av} represents the average velocity of flow.

In the turbulent regime of flow, there is always a thin layer of fluid at pipe wall which is moving in laminar flow. That layer is known as the boundary layer or laminar sub-layer

$$\boldsymbol{Average\ Velocity}\ (\boldsymbol{V_{av}}) = \frac{\mu \times R_e}{\rho \times D_h} \tag{57}$$

where V_{av} is average velocity, ρ is the density of the fluid, μ is viscosity while $v = \mu/\rho$ is kinematic velocity.

A non-dimensional indicator, such as the Reynolds number, does not generally characterise the flow as a whole, but only serves as a feature chosen for the flow. The main aim of calculating the Reynolds number is to evaluate the importance of inertial effects vs viscous ones, therefore, for inertial effects, it makes sense to choose the highest density, the one of the liquid over the one for gas. The characteristic velocity should also be characteristic of the liquid phase since it is a turbulent flow with high fluid characteristics. To calculate the cross-sectional area of pipe, the formula $A = 0.785d_i^2$ is used. Where A is area and d represents diameter of pipe.

5.4 Case Study - Problem Statement

In order to demonstrate the principle of nodal and system analysis for production assurance of a subsea well, a simple case study is set up. The case demands:

- A unique demonstration of nodal and system analysis principles to determine the adequate artificial boost needed to maintain depletion of a West African offshore well with 12-year operating period.
- It is also required to estimate the efficiencies of the two pump and pipe options based on pressure drops, power demand and optimum pipeline diameter for the system.

5.4.1 Case Description

An oil and gas producer recently won a concession to produce from a marginal oilfield located offshore Nigeria for a maximum period of 12 years. The well would be tied-back to an FPSO located at a central processing station. Data about subsea flowing well with all its parameters are listed in Table 17. Well stream which contains a varying percentage of oil, and water flows from the reservoir will be transport to process facilities up to the topside where it is further processed. The fluid is expected to be served to customers at a nominal pressure of 2000 psig.

At production kick-off, the reservoir pressure supports natural flow until later in field life when the back pressure is expected to dip across the system, thereby potentially causing flow problems ranging from to low recovery, time wastage, and increased slug flow. Meanwhile, according to preliminary forecasts, Table 17 shows the expected yield from the field.

The producer has asked for an optimum plan to make maximum recovery at least cost from the field during its 12-year lease period. For the pipe design, consider Reynolds number to be 4100, temperature 130F, mean velocity to be 13 feet per second.

Table 17: Target Production

Year	Water Cut (%)	Oil Production Target (STB/d)
1	0	18,800
2	0	18,800
3	5	18,700
4	15	18,500
5	21	18,300
6	27	18,200
7	31	18,150
8	35	18,100
9	38	17,950
10	39	17,900
11	40	17,850
12	41	17,820
Total Production		219,070

5.4.2 Evaluation Strategy

The production system was set up using *Pipesim*, a steady-state simulation tool. The subsea production system was fed with the input data on Table 18 and iterated for each case. The simulation runs a calculation using pre-fed values to estimate the flow rate in standard barrels per day, the number of production years-represented by the water cut percentages and the output pressure. The calculation is based on proven differential pressure loss estimation models which are viable for different kinds of fluid flow systems.

Table 18: Input data

Design Parameters	**Values**
Tubing Diameter	10"
Reservoir Temperature	250°F
Reservoir Pressure	9000psia
Production Index	20bpd(d.psi)
Tubing Depth	10000ft
Roughness of Tubing	0.0015"
U Value of Wellbore	2.0 Btu/FWh/0F
Completion TVD	2.0 Btu/FWh/0F
Subsea Data	
Tie back distance	18,000ft
Flow line Distance	10,000ft
Water Depth	8,000ft
Riser Roughness	0.0015
Flow line Roughness	0.0015
Riser Height	9,000ft
Rod Pump	15,000 STB/d
Electrical Submersible Pump(ESP)	10,000- 19000 STB/d
Multiphase Pump(MSP)	3000psi
Fluid Parameters(Black Oil)	
Fluid Gravity (API)	30
Gas Oil Ratio	400
Gas Specific Gravity	0.64
Water Specific Gravity	1.02
Topside	
Platform Height	12ft
Fluid mimimum arrival pressure	2000psi
Minimum Arrival Temperature	100 °F

The solution node or operating point is best selected at the well perforations when the following two subsystems will result in: (a) the formation and the well completion (the well’s IPR curve), and (b) the casing string, ESP pump, tubing string plus the surface flow line [Guo, 2007]. However, in this case, the node would be placed at the topside in order to divide the entire flow system in to inflow and topside output. The performance curves of these subsystems are calculated from the two known pressures; the exterior borderline of the drainage zone and at the topside facilities. These would intersect at a point where the fluid producing rates that would develop; given a range of assumed conditions. Unlike most well-centric cases where the node is placed on the well head, the node was placed at the topside in this case so that yield would be ascertained. The flow chart in Fig 27 describes the procedure for selecting optimal pipe-pump configuration based on efficiency.

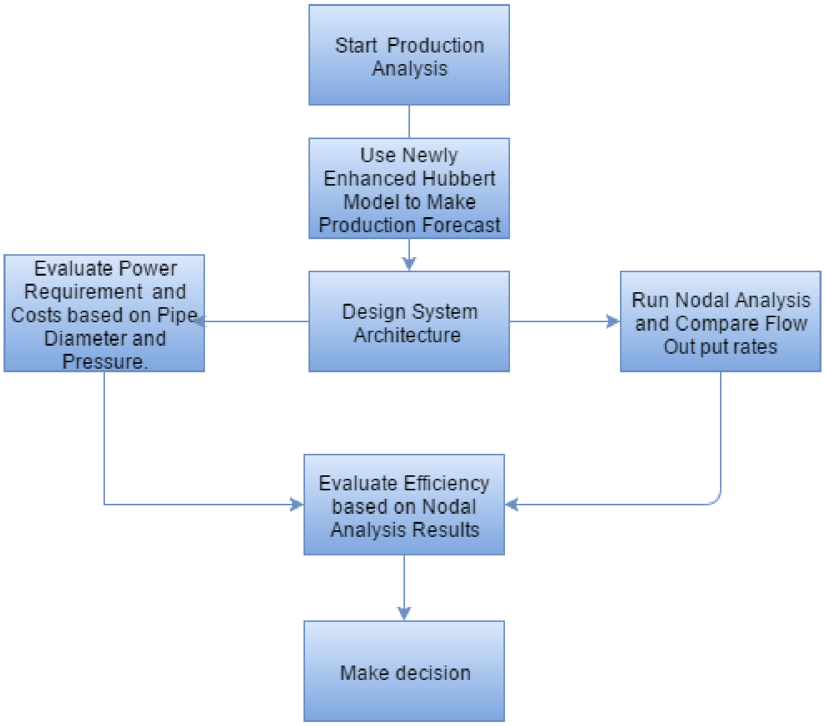


Figure 27: **Methodology Process Flowchart**

5.4.3 System Architecture Design

Pump selection is an essential part of subsea system design whereby specifications, losses and tolerance of a proposed artificial lift are evaluated based on expected pressure output. Expected pressure losses, pump discharge pressure and distance. Although these variables have been pre-coded on the software tool, it is important to express the principle guiding the selection of the pumps by using simplified relationships.

The frictional loss in the flow line of production system can be calculated by [Saleh, 2002]:

$$\Delta P_f = f \times \rho_f \times \frac{L}{d} \times \frac{V^2}{2g} \tag{58}$$

where $\boldsymbol{V}$ is the fluid velocity, L is length, d is diameter, g is acceleration due to gravity and *f* is the moody friction factor. The moody factor is a dimensionless quantity which is based on the relationship between Reynold's number, pipe roughness and the relative fluid flow in a round pipe; coupled with Darcy- Weisbach friction factor [Saleh, 2002].

Fluid velocity $(\boldsymbol{V}) = \frac{\boldsymbol{Q(STB/day) \times 5.615(ft^3/bbl}}{\boldsymbol{86400(s/day) \times (\pi d^2/4)(ft^2)}}\ \boldsymbol{(ft/s)}$ (59)

The pump discharge pressure can thus be evaluated using

$$\boldsymbol{P_d = P_S + \Delta P_f + \Delta P_{hh}(ft)} \quad (60)$$

where P_S (psi) is the wellhead pressure required to transport fluid to topside, ΔP_f is the expected frictional loss across pipe and ΔP_{hh} is the hydrostatic head due to column of fluid. To save time, the *Pipesim* software was used to select the appropriate pumps for each case with displacement pressures of 3800 psia.

5.5 Results and Discussion.

One of the key objectives of nodal fluid analysis is the estimation of the flow rate of a given process system. This aim was accomplished by the analysis of a subsea well with a 12 year production concession.

PCP and ESP fluid pumps of same capacity were placed at same down-hole depths and simulated. The ESP's dynamic performance thumbed that of the PCP's configuration with a difference of 62% volumetric efficiency and was able to achieve the overall target production for the 12 years with a surplus amount of 530 standard fluid barrels as shown in Table 19. The PCP's cumulative output of 83,812 against the production targets further confirms its limitations in terms of deep water oil production. It is still not economical since it negatively suppresses high fluid output due to its positive-displacement mechanism.

Table 19: Production Performance Comparison

Year	Water Cut (%)	Production Target(STB/d)	PCP Pump (STB/d)	ESP (STB/d)
1	0	18000	7013	18873
2	0	18000	7010	18873
3	5	18700	7010	18751
4	15	18500	7006	18513
5	21	18300	7002	18373
6	27	18200	6994	18236
7	31	18150	6988	18146
8	35	18100	6980	18056
9	38	17950	6971	17967
10	39	17900	6952	17945
11	40	17850	6944	17945
12	41	17820	6944	17945
Total Production		**219,070**	**83,812**	**219,600**

5.5.1 Case 1: Artificial Lift with PCP Pump.

Case 1 involves artificial lift flow simulation with PCP at bottom hole and multiphase pump at base of riser. The PCP as highlighted earlier is quite reliable for volumetric efficiency. The only challenge is that it might not be able to sustain boosting pressures for long periods of years without other pressure supports. PCP with multiphase pump being placed at the base of riser, well fluid will flow through flow lines to the topside supply. The multiphase pump can add 3000psi boost to the flow.

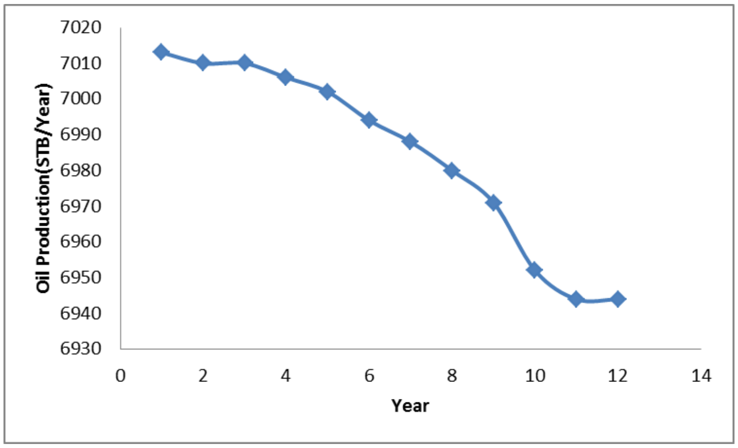


Figure 28: **Production Performance of Progressive Cavity Pump over 12 years.**

The production output in Fig 28 by the progressive cavity pump was rather not surprising because the production rates started out low and only kept decreasing by a little margin over the years. The flow output curve shows that peak mass flow rates of 7012 barrels per day was accomplished at 1st year and ended at about 6988 barrels per day on 12th day. A total of 83,812 barrels against the expected 219, 070, was made during the 12 years of production.

Although, the pump was calibrated as a 15,000 STB capacity pump, this awkward output pattern could be attributed to the limitation of the PCP in offshore water depths and wells with high water cuts. Indeed, the pumps seem to have even impeded free flow by discharging only about 6200 STB/d due to its fixed positive displacement mechanism over time. Furthermore, the API of the well fluid with the tubing dimensions could also be contributors to its low performance, thereby making the choice of ESP very appealing for deep water operations [Fleshman et al, 1999]. The target production rate was not achieved with the pump set-up.

5.5.2 Second Case: Electrical Submersible Pump Performance

System analysis of a subsea well producing an ESP Pump of 60 Hz with a capacity of 10000 STB to 19000 STB was placed at 9200ft.

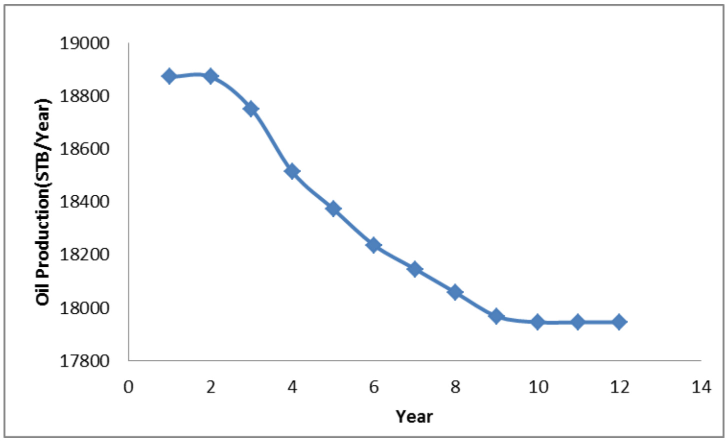


Figure 29: Flow performance of ESP over 12 years.

For the configuration with ESP pump of same capacity with PCP pump, the target production was overly met as shown in Fig 29. The output presented the best yield by yielding the production target with an excess of 530 barrels - a rise of 2% from actual targets. The nodal operating point at first year as shown connotes an operating point of 2013psi with 18,873 flow rate (Fig 29). The initial year gave 18,634 STB/day while the last year gave 18562 STB/d. In other words, the field would be maximally exploited during the period of concession by installing an ESP. This result supports the notion that electric submersible pumps supports high volume production in deep waters and has a better volumetric efficiency than the much popular rod pumps. The target production was achieved with the artificial lift configuration of the third case involving an ESP at bottom-hole and at the base of riser.

5.5.3 Pipe Cost Design

Table 20: Pipe Selection Table

OD(m)	ID (m)	Qm (m3/sec)	ΔP(psig)	Power(KW)	Cost Power(£)	Cost Pipe(£)	Total Cost (£)
0.254	0.234	12.813	137.605	23.509	35263.133	21.338	35284.471
0.203	0.183	8.184	107.614	11.743	17614.924	13.629	17628.553
0.152	0.132	4.589	77.623	4.749	7123.587	7.641	7131.228
0.105	0.085	2.190	49.985	1.459	2188.946	3.646	2192.593
0.051	0.031	0.517	18.230	0.126	188.339	0.860	189.199

Using the formulas enumerated in sections 5.3 to 5.4 of this chapter, Table 20 shows that as the pipeline diameter reduces, the cost reduces. A larger amount of material is required for large sized pipes and this increases both power and material overall costs of operating the pump pipe configuration. However, it was found that an increase in volumetric flow leads to a consequent pressure drop in the pipe system and the cost of operation. This means that an inverse relationship is established between the volumetric rate of flow and the mean velocity of flow, thus, a consequent decrease in pipe diameter results in reduced operating costs, especially power costs.

The Reynolds number was read off from as 0.015 from Moody' chart in Fig 30. Pipe length of 10,000ft was converted to meters and applied to the calculations.

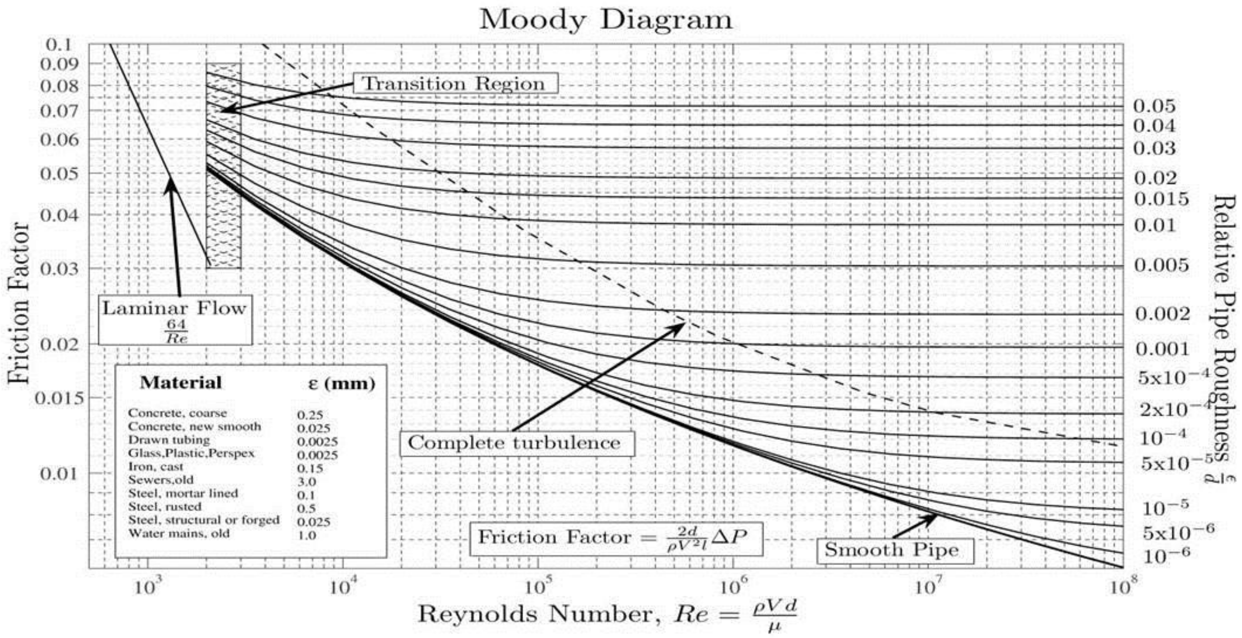


Figure 30: The Moody Chart

The efficiency is then estimated to determine overall advantage. Optimal Efficiency is calculated from Eq. (61). However, actual efficiency is estimated as ratio of flow rate given by pumps and target flow rate then multiplied by optimal efficiency obtained from the cost-efficient design. Mathematically it could be expressed as

$$\boldsymbol{Actual\ Efficiency\ (E)} = \frac{\boldsymbol{Flow\ rate\ from\ Pump} \times \boldsymbol{Optimal\ Efficiency}}{\boldsymbol{Target\ Flow\ rate}} \tag{61}$$

Table 21: Pipe-Pump Efficiency Table

ID (m)	Optimal Efficiency	Case A(%)	Case B(%)
0.234	132.0962065	44.76593663	137.967149
0.183	84.37523362	28.59382917	88.125244
0.132	47.3053313	16.03125116	49.40779047
0.085	22.57363563	7.649954296	23.57690832
0.031	5.325535263	1.804764728	5.562225719

In Table 21, the efficiency of the output of both lift systems under consideration were compared with the standard design to determine which of the cases: whether PCP pump or ESP gives better value for money in terms of capital expenditure. Since the initial *Pipesim* simulation results did not factor in inputs such as pipe size and power costs, the efficiency of the pipe diameter range is estimated for an optimum choice. Efficiency being a function of flow rate, pressure drop and pipe diameter compared against gives a general indication about the flow. The result shows that the ESP gives a better overall efficiency compared to the PCP pump. The highlighted blue strip in Table 21 represents the ideal choice. Ideal pipe diameter for the system is the 0.183m diameter based on power costs, efficiency of 88% which corresponds with industry target.

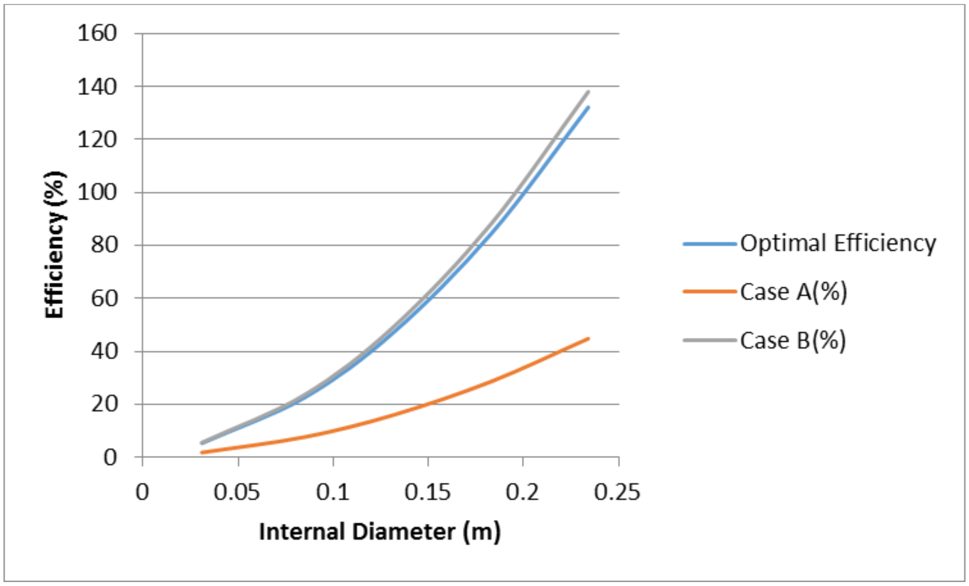


Figure 31: Comparison of the Optimal Efficiency and Pipe Diameters.

Fig 31 shows that case B, the ESP curve, matches more closely to the optimal efficiency. Pressure drop and power requirement across the various pipe diameters under consideration has a direct relationship as shown in Fig 32. As pressure drop increases, more power is needed to boost production. The optimum power consumption based on ESP which is the chosen pump is a 12 Kilowatt pump based on 107 psig pressure drop.

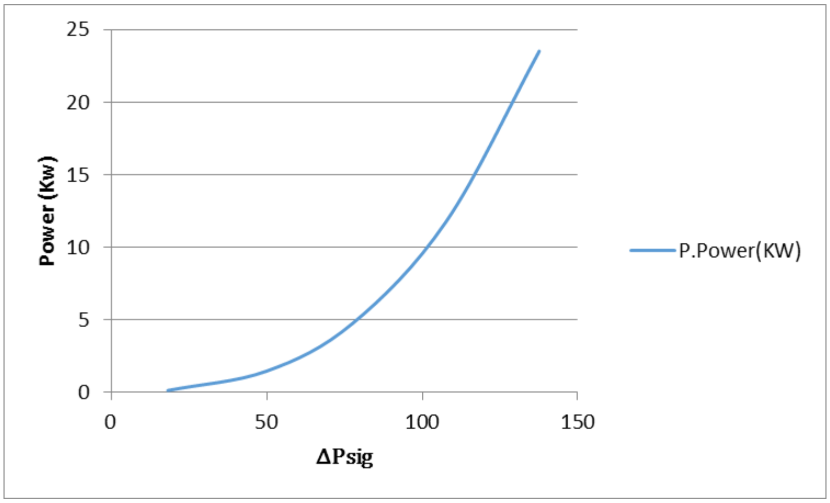


Figure 32: Power versus Pressure Drop

Fig 33 shows the variations in optimal pipeline diameter and pumping power at various cost rates. It can be seen that as more energy is required, the cost rises. As the diameter increases, more power is needed to transport the fluid through the pipeline with a length of 18000ft.

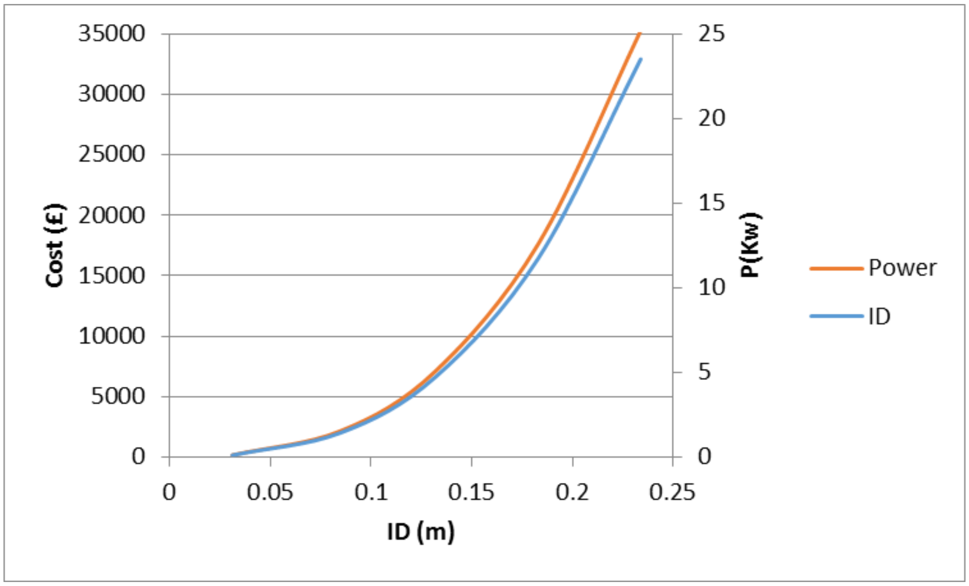


Figure 33: Variations of Optimal Diameter and Pumping Power with respect to cost.

Fig 33 also shows that the power requirement for fluid flow varies directly with pipe diameter in design. This implies that the bigger the diameter of a pipe, the more the power expended in moving fluid up or down its volume.

In contrast to many previous studies which did not estimate the overall life cycle cost of an asset, the present research demonstrated that it could be done using a combination of physical calculations and projections.

5.6 Summary

This chapter presented how system analysis can be combined with nodal analysis to make meaningful cost-efficient optimization of a well by selecting and placing appropriate artificial lifts at the right spots for production assurance. This work contributes to the existing knowledge in subsea field development by comparing the topside pressures and liquid flow rates of an ESP and a PCP artificial lift of same capacities using Nodal and system analysis. Results demonstrated that the volumetric efficiency of Electric Submersible Pumps in deep water subsea wells outperforms that of the PCP artificial lift under the same subsea and oil well conditions. While progressive cavity pumps seem to be have good cost efficiency and low operating costs, the recent spike in offshore oil production could spell a corresponding and sharp increase in ESP field application far more than even rod pumps or PCPs which do not lift as much volume.

Suggestively, the efficiency of the PCP could be enhanced by embarking on research for corrosion resistant designs, reliable components for underwater reservoirs. Perhaps a robust design configured with wear-resistant underwater gears could increase rod's compression action and consequently, high volumetric output.

In summary,

- A system made up of Electrical Submersible Pump (ESP) at bottom hole and multiphase pump at riser base can give higher flow rate and sustained pressure over longer time periods than a Progressive Cavity Pump (PCP) installed down-hole supported by multiphase pump. The study showed that production output of the ESP was better that the PCP configuration over the 12 years of production. It gave an excess of 530 STB while a shortage of 135,258 STB was recorded on the PCP.

- The pressure differential on the flow lines is very crucial for production assurance and operations safety; given that most subsea wells do prematurely become unproductive in mid-life as a result of back pressure and weak bottom-hole pressure.

- The diameter of a pipeline has direct relationship with the power requirements of the pump needed to lift fluids from a subsea well to the topside.
- As pressure drops along the pipe, efficiency reduces therefore more power in required to lift fluid.
- Water cut has a much lower impact on the production index of an ESP pump compared to a PCP. However, depth and reservoir pressure does affect both production index and flow rate.

The lessons from this study highlight the practicality and comprehensiveness of using nodal system analysis to enhanced the recovery rates in a subsea well aided by an appropriate artificial lifts. Future work in this area will focus on analyzing system behavior when separators and compressors are added to the system. There is also a need to address the failure mode analysis of both systems under same conditions and also compare the lifecycle requirements of gas lift through artificial lift which is another promising technology for subsea field development.

CHAPTER 6

Analysis of Offshore Drilling Risk Using Severity Matrix Method

This chapter presents a statistical analysis method for analysing risks facing offshore drilling. As part of the overall integrated model being developed in this thesis, the new methodology developed and applied in this chapter focuses on the use of historical risk data to evaluate the consequences of risk as the product of event frequency and event magnitude in a subsea system. An offshore drill rig which is meant to drill nine locations is used as case study.

6.1 Methodology

Assuming that an offshore drill rig is to drill nine satellite wells within a block. Each route has five key Risk Influential Factors (RIF) or characteristics, namely diameter, mean pressure, and distance, cost and temperature which could be iterated with other variables to determine the severity of risk in a system. These RIFs are made up of constant and variable data across the nine drill spots. For each risk event and drill spot, two quantities are iterated which are the number of events where that risk type occurs and the typical magnitude of such a risk. These are then aggregated to find the severities of the risk types, by spot and sum over all the spots. In a nutshell, this work hopes to propose a method which uses a 3 by 3 matrix to capture and calculate the severity of risks based on a number of co-variates.

The model assumes that sufficient historical data is available to estimate regression equations relating the frequency and the mean magnitude of each risk type to the characteristics of the routes. The resulting coefficients appear in the parameter sheet. Besides the usual constant and variable coefficients, there are also “Errors” which are pre-determined error data. When simulating either a risk frequency or a mean risk magnitude, this error coefficient is multiplied by a standard normal random variable to provide extra variability so that the calculated parameters do not lie *directly* on the regression lines. The risk frequencies then effectively become Poisson distributions’ means from the regressions while the event magnitudes are assumed to be lognormally distributed with means from the regressions and standard deviations equal to given percentages of the means. These percentages are in the "Coeff of var" column in the Parameters sheet.

To accumulate the total severity for any risk type and route, one possibility is to multiply the frequency with the typical magnitude. However, this would assume that all events for that risk type/spot combination have the *same* magnitude. A better way is to use the RiskCompound function of excel. A results sheet is set up to display summary statistics and a histogram for each risk type, and for the total of all risk types. By running the simulation, the results will come alive. A major highlight of the method is the consideration and iteration of five risk constants namely pressure, drill mean diameter, temperature, cost and distance alongside the frequency.

6.1.1 Sequence of Analysis

Step 1: The format of the function is to multiply matrices in given arrays: *array1* and *array2*. In excel, MMULT command is used where *array1* and *array2* are arrays of numeric parameters which represent matrices, and the number of columns in *array1* is equal to the number of rows in *array2*.

The resulting matrix has the same number of rows as *array1* and the same number of columns as *array2*. If that is the case, the mean of risk severity is estimated to make the next set of arrays to form a Poisson and lognormal distribution which represent the frequency and magnitude of risk respectively.

Given the two matrices representing the frequency and magnitude coefficients of the risks being evaluated:

$$\boldsymbol{Frequency\ (A)} = \begin{matrix} \boldsymbol{a_{11}} & \boldsymbol{a_{12}} & \boldsymbol{a_{13}} \ldots \infty \\ \boldsymbol{a_{21}} & \boldsymbol{a_{22}} & \boldsymbol{a_{23}} \ldots \infty \end{matrix} \tag{62}$$

$$\boldsymbol{Magnitude\ (B)} = \begin{matrix} \boldsymbol{b_{11}} & \boldsymbol{b_{21}} & \boldsymbol{b_{31}} \ldots \infty \\ \boldsymbol{b_{12}} & \boldsymbol{b_{22}} & \boldsymbol{b_{32}} \ldots \infty \end{matrix} \tag{63}$$

The product of any of the matrices is obtained mathematically in the form

$$\boldsymbol{AB} = \begin{matrix} \boldsymbol{a_{11}b_{11} + a_{12}b_{21} + a_{13}a_{31}} & \boldsymbol{a_{11}b_{12} + a_{12}b_{22} + a_{13}a_{32}} \\ \boldsymbol{a_{21}b_{11} + a_{22}b_{21} + a_{23}a_{31}} & \boldsymbol{a_{21}b_{12} + a_{22}b_{22} + a_{23}a_{32}} \end{matrix} \tag{64}$$

Since the frequencies are influenced by the statistical errors of both frequency coefficient and magnitude coefficients. It is therefore important to incorporate these into the matrix to get the statistical means which will give the standard deviation of the severities from regression iteration.

$$\boldsymbol{Mean\ of\ Frequency}\ (\boldsymbol{A_{MF}}) = \boldsymbol{f_c} + \left(\left[\begin{matrix} \boldsymbol{a_{11}} & \boldsymbol{a_{12}} & \boldsymbol{a_{13}} \dots \infty \\ \boldsymbol{a_{21}} & \boldsymbol{a_{22}} & \boldsymbol{a_{23}} \dots \infty \end{matrix} \right] \boldsymbol{R_f} \right) + \boldsymbol{E_f} \times (\boldsymbol{R_q}) \tag{65}$$

where f_c is the frequency constant,

$a_{11} \dots a_{23}$ represents the coefficients in the frequency matrix,

R_f represents the risk influencing factors,

E_f stands for error constant of the coefficient of frequency,

R_q represents the normal natural quantities for which could be 0 or 1.

The mean of frequency is converted to a Poisson distribution by *c*

$$\boldsymbol{Mean\ of\ Magnitude}\ (\boldsymbol{B_{MF}}) = \boldsymbol{M_c} + \left(\left[\begin{matrix} \boldsymbol{b_{11}} & \boldsymbol{b_{21}} & \boldsymbol{b_{31}} \dots \\ \boldsymbol{b_{12}} & \boldsymbol{b_{22}} & \boldsymbol{b_{32}} \dots \end{matrix} \right] \boldsymbol{R_m} \right) + \boldsymbol{E_m} \times (\boldsymbol{R_n}) \tag{66}$$

where M_c is the magnitude constant

$b_{11} \dots \mathrm{b}_{23}$ represents the coefficients in the frequency matrix

R_m represents the risk influencing factors

E_m stands for error constant of the coefficient of magnitude

R_t represents the normal risk tolerance level which could be 0 or 1.

The risk influencing factor could be a single value or several. If it consists of several values, then it put in the form of a single vertical matrix and worked out. In this work, five factors which include diameter, temperature, distance, cost and mean pressure were calibrated and designed values into calculation.

Step 2: The second major step is to convert the magnitude and frequency means to the form of poisson and lognormal distribution respectively. The frequency mean matrix is converted to a poisson distribution to create a discrete frequency distribution which gives the probability of a number of independent events occurring in a fixed time. In a similar manner, the means of the magnitude matrix is simulated to convert it to a lognormal distribution results. The conversion is easily done with a computer code or on excel.

Mathematically, event frequency which assumes a Poisson distribution is derived by assuming that Y denotes the number of events occurring in an interval with mean λ and variance λ. Now, if X_1, X_2, ..., X_λ are independent Poisson random variables with mean 1, then:

$$\boldsymbol{Y = \sum_{i=1}^{\lambda} x_i} \tag{67}$$

Eq 68 represents a Poisson random variable with mean λ. Then, the Central Limit Theorem can be applied when λ is sufficiently big using:

$$\boldsymbol{Z = \frac{Y - \lambda}{\sqrt{\lambda}} \rightarrow N\,(0, 1)} \tag{68}$$

For the magnitude of event which assumes a lognormal distribution, a lognormal distribution is normally parameterized by,

$$\boldsymbol{\mu = \log(m)} \tag{69}$$

μ is the mean of the log of the distribution where m is the mean.

Step 3: In most cases, the coefficient of variance can be given or estimated from historical data. The standard deviation is calculated by multiplying the matrix containing the coefficient of variance and the mean of magnitude matrix already calculated.

Step 4: The severity is calculated lastly and plotted. This severity is obtained from the product of the Poisson (frequency) and Lognormal (magnitude) distributions obtained from the previous steps. They both represent the frequency and magnitude of each risk respectively. These can be plotted on graphs to show statistical upper limits and lower limits of each of the risk event severity.

Mathematically, the severity of the risk is;

$$\boldsymbol{(S) = Y * \mu} \tag{70}$$

where Y represents Poisson frequency and μ represents lognormal magnitude.

Step 5: Determination of Failure event tree and calculation of event failure from failure rate .

6.2 Case Study

A given subsea drilling rig faces a certain amount of risk ranging from technical to man-made but these collectively has serious implications for efficient production. A data gathering survey has identified a number of risks facing a drill pipe on a rig. There are nine identified key risks and there are nine different wells facing the operation. Each well has five risk influencing constants as listed in the Table 20. They are diameter, mean pressure, distance, temperature and cost. The case tasks are:

- Determine the risks based on the magnitude, frequency and risk influencing constants.
- Determine the severity of each of the risks.
- Determine the critical failure mode of the pipeline based on the identified risks.

6.3 Analysis and Discussion

Table 22 shows historical input data obtained from an industry partner. It is used to obtain the regression expression with respect to frequency and magnitude of each risk in accordance with the probability of risk event at the drill locations of the drill pipes. Nine different risks were being analysed based on regression analysis of the frequency and magnitudes coefficients. There are nine spots to drill and each spot has five characteristics as shown at the drill pipe parameters in table 24. The means and standard deviation of the regression are computed and analysed in order to derive the values of overall severity for each risk type on the subsea drilling operation for each spot and the total for all spots. Table 22 is derived from historical input values of the frequency coefficient of these risks obtained from the region being analysed.

Table 22: Frequency coefficients table.

		Frequency Coefficients						
Index	Risk Type	Diameter	Pressure	Distance	Temperature	Cost	Constant	Error
1	Caught In,Under, Between	0.0001	0.0068	0.0029	0.0085	0.0089	0.0018	0.0006
2	Explosion, Burns	0.0014	0.0038	0.0024	0.0035	0.0090	0.0044	0.0068
3	Electric Exposure/Power Failure	0.0015	0.0074	0.0063	0.0031	0.0032	0.0032	0.0032
4	BOP Failure	0.0019	0.0039	0.0025	0.0095	0.0059	0.0041	0.0074
5	Falls from Height	0.0022	0.0058	0.0072	0.0041	0.0055	0.0058	0.0052
6	Pressure Releases/Kick	0.0027	0.0022	0.0045	0.0054	0.0034	0.0034	0.0002
7	Struck By	0.0032	0.0005	0.0038	0.0018	0.0061	0.0002	0.0032
8	Sensor Failure and Data Delay	0.0034	0.0057	0.0005	0.0034	0.0077	0.0035	0.0027
9	Drownings	0.0054	0.0010	0.0037	0.0048	0.0032	0.0056	0.0063

Table 23: Magnitude Coefficients Table.

Index	Risk Type	Magnitude coefficients							
		Diameter	Pressure	Distance	Temperature	Cost	Constant	Error	Coeff of var
1	Caught In,Under, Between	3.45	0.47	21.00	105.00	32.00	42.31	64.75	20%
2	Explosion, Burns	117.68	0.67	104.18	89.00	23.00	1.30	28.58	12%
3	Electric Exposure/Power Failure	10.09	0.92	0.30	3.00	10.00	12.19	8.22	45%
4	BOP Failure	4.75	0.58	102.26	14.00	14.00	22.38	32.78	70%
5	Falls from Height	2.09	0.11	116.52	10.00	13.00	100.14	31.50	300%
6	Pressure Releases/Kick	3.00	0.75	95.83	7.00	22.00	24.44	37.10	9%
7	Struck By	32.00	1.08	93.08	42.00	44.00	39.66	23.48	62%
8	Sensor Failure and Data Delay	39.84	0.18	3.45	34.00	38.00	23.00	91.80	35%
9	Drownings	116.32	0.61	124.76	13.00	11.00	3.23	100.10	250%

Table 23 shows corresponding values for the magnitude parameters. Table 24 shows the major risk influencing factors which are five in number. The routes of drilling have nine spot wells within the same surrounding and each one requires a different distinct mean diameter,the distance and temperature. The offshore drilling risk influence factors (RIF) are absolute values which exist in the subsea domain. The cost of each drilling spot is indicated in pounds, ranging from £10,000 to £40,000. The mean hydrostatic pressure ranges from 1100 to 1400 psi.

Table 24: Offshore Drill Risk Influencing Factors (RIF)

Offshore Drilling Risk Influencing Factors									
Drill Pipe Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Diameter (mm)	250	250	200	200	150	200	100	150	250
Mean Pressure (PSI)	1120	1000	1000	1200	1300	1400	1100	1100	1100
Distance (miles) Accesibility	3.4	3.4	3.4	3.4	3.4	1.7	1.7	1.7	1.7
Temperature (Celsius)	4	4	3	3	2	0	2	2	1
Cost (£)	20000	50000	30000	25000	20000	10000	15000	25000	40000

The first step to risk analysis according in this methodology is the computation of the means of both the frequency matrix and the magnitude matrix. MMULT excel command is used to generate the frequency mean from the product of matrices and RIFs. The Poisson distribution which represents the frequency of event on the drill system is obtained by iterating the means using the RiskPoisson command on Palisade Risk software. The event frequency is shown in Table 25. The table shows that *explosion and burns* with a frequency of 454 is the most frequently occurring event with *drowings* with drill pipe six the least being the frequent. The means and standard deviation table is attached at appendix.

Table 25: Event Frequency in Poisson distribution.

Simulation of Event Frequencies (Poisson Distribution)									
Event type\Drill Pipe	1	2	3	4	5	6	7	8	9
Caught In,Under, Between	186	452	274	231	187	99	141	230	364
Explosion, Burns	185	454	274	230	185	96	139	229	365
Electric Exposure/Power Failure	73	168	104	89	74	43	56	88	137
BOP Failure	123	299	181	153	123	65	93	152	241
Falls from Height	117	281	171	145	118	64	89	144	227
Pressure Releases/Kick	71	173	105	88	71	38	54	88	139
Struck By	123	306	184	154	123	62	92	154	245
Sensor Failure and Data Delay	161	392	237	200	162	86	122	199	315
Drownings	66	162	98	82	66	34	50	82	130

The lognormal distribution in Table 26 shows the magnitude of the events generated from the means of the lognormal distribution. At first sight, *Explosion/burns* and *Drownings* appear to have the overall magnitude of risky events respectively. *Falls from height* is the lowest event magnitude across all drill pipes. However, the table does not clearly indicate the margins by which they influence overall risk because they are dependent on the frequency on occurrence. A further severity analysis is performed to reveal hidden patterns of risk over a number of iterations.

Table 26: Event Magnitude in Lognormal Distribution.

	Simulation of Event Magnitudes (Lognormal Distributions)								
Event type\Drill Pipe	1	2	3	4	5	6	7	8	9
Caught In,Under, Between	1,505	1,448	1,276	1,370	1,245	1,429	942	1,115	1,460
Explosion, Burns	30,525	30,444	24,560	24,694	18,876	24,650	12,682	18,566	30,334
Electric Exposure/Power Failure	3,561	3,451	2,947	3,130	2,717	3,312	2,029	2,533	3,542
BOP Failure	2,212	2,142	1,904	2,021	1,842	1,964	1,314	1,551	2,026
Falls from Height	1,142	1,129	1,024	1,046	953	870	628	733	942
Pressure Releases/Kick	1,946	1,855	1,705	1,856	1,781	1,844	1,318	1,468	1,768
Struck By	9,566	9,436	7,836	8,052	6,560	8,110	4,586	6,186	9,386
Sensor Failure and Data Delay	10,199	10,177	8,185	8,222	6,249	8,253	4,214	6,206	10,190
Drownings	30,194	30,120	24,304	24,427	18,673	24,338	12,522	18,338	29,970

The total event severity table (27) shows the severity level of each risk and is derived from the product of lognormal distribution of event magnitude in table (26), Poisson distribution of frequency coefficients in table (25), RIFs in table (24) generated.

Table 27: Simulation of Total Event Severities

	Simulation of Total Event Severities									
Event type\Drill Pipe	1	2	3	4	5	6	7	8	9	Totals
Caught In,Under, Between	279,116	654,391	348,656	315,500	232,459	140,476	132,691	255,938	530,196	2,889,422
Explosion, Burns	5,633,002	13,826,078	6,723,640	5,669,857	3,494,218	2,352,218	1,765,707	4,256,321	11,052,969	54,774,010
Electric Exposure/Power Failure	257,769	577,117	304,922	276,723	199,358	141,537	114,151	222,475	480,227	2,574,280
BOP Failure	268,701	633,536	342,561	305,453	224,469	126,373	120,170		482,884	2,504,147
Falls from Height	125,589	296,637	167,685	141,896	104,999	51,685	52,129	99,162	200,936	1,240,719
Pressure Releases/Kick	138,420	320,550	178,544	163,410	126,992	69,372	70,665	128,848	245,742	1,442,543
Struck By	1,168,559	2,860,762	1,434,257	1,229,710	799,019	505,640	417,582	942,816	2,280,198	11,638,543
Sensor Failure and Data Delay	1,638,927	3,986,855	1,936,612	1,639,999	1,007,713	705,549	511,440	1,232,250	3,197,156	15,856,501
Drownings	1,903,769	4,605,922	2,264,223	1,916,760	1,172,115	830,295	607,134	1,431,472	3,733,006	18,464,695
Totals	11,413,854	27,761,848	13,701,099	11,659,307	7,361,343	4,923,144	3,791,669	8,569,283	22,203,314	111,384,862

6.3.1 Risk Severity

To accumulate the total severity for any risk type and route, one possibility is to multiply the frequency with the typical magnitude. However, this would assume that all events for that risk type/route combination have the *same* magnitude. The results sheet is set up to display summary statistics and a histogram for each risk type, and for the total of all risk types.

The histograms in Fig 34 which generated using the Palisade software shows 90% percentile of *risk spread* otherwise known as the severity of each risk event. 90% percentile was made the optimal benchmark risk value based on an 80/20 rule. A careful look at the graphs show the various disparities and values of the risk in millions after 100 iterations. The axis represents the risk severities in both millions (macro) and micro units. The values do not have any unit, however, they could be tied to cost or other relevant metrics in realistic cases. It is interesting to find out that *Drownings* severities with a standard deviation of 1,811, 510.46 was the biggest among the risk events being evaluated rather than the *Explosions* which had a higher mean value for risk index among all the events at all nine rigs. Each of the risk event can be further analyzed into more depth for adequate controls to be set up.

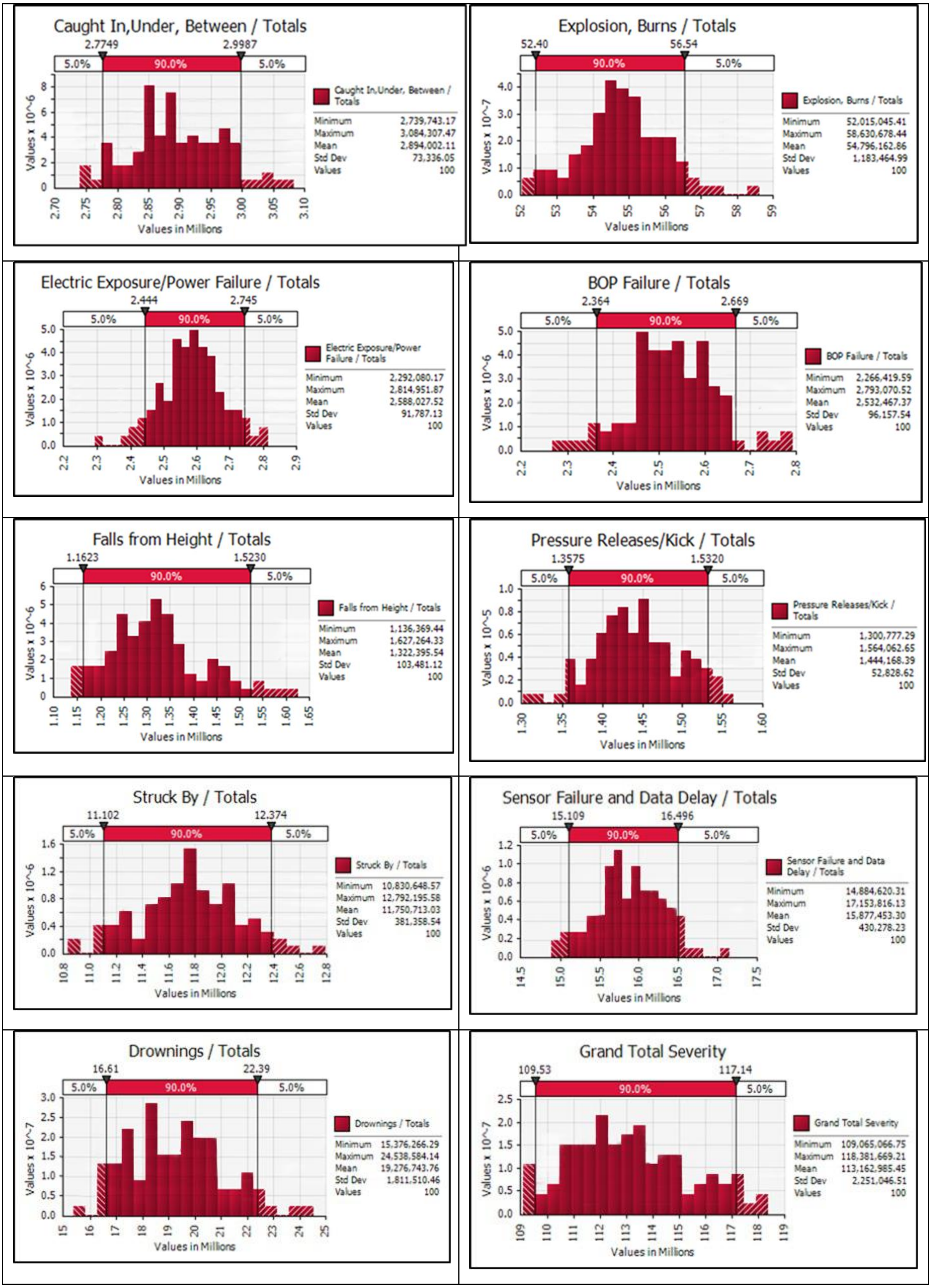


Figure 34: Chart of Risk Severities

6.4 Summary

The risks facing an offshore drill rig can be modelled and understood using a combined Monte Carlo-type and Fault Tree Analysis. The main contribution of this chapter is a robust stochastic method for identifying risk consequences based on the characteristics of a system in order to set-up adequate controls based on failure modes identified. The Monte Carlo-type simulation is used to determine event severity by iterating the covariates of Risk Influencing Factors, Frequencies, Magnitude and their respective Coefficients.

The main methods adopted in this chapter are theoretical and quantitative analysis combining on-site investigation, expert visits and computer simulation. The demand and capability of drill pipe fragility under typical system risks are systematically analysed. Pipeline overall reliability model based on internal and external dangers and on fragility is established as a theoretical basis for oil / gas drill rig system's quantitative risk assessment.

CHAPTER 7

Measuring the Practice of Asset Integrity, Reliability And Risk For Production Assurance in Subsea Production Firms.

As outlined in the research methodology, the target respondents from the survey were employees of small, medium and large-scale West African Subsea operators that are familiar with operations management, asset reliability and risk management in their respective companies. The questionnaire was designed comprising of 10 questions; some of which were mixed options for multiple choice answers, scale ratings, agreement and disagreement levels and lastly an some open-ended opportunity for comments. The structure of the questionnaire reflects the issues which have been pin-pointed in the literature review. All the questions were answered.

The survey was conducted in the West Africa, therefore all the responses shall be used to generalise respondents' opinion across the West Africa subsea production industry. Again, the total number of response is 82.

7.1 Background Of Respondents

Q1. What kind of product or service does your company offer?

The answers to this question were categorised into eight sub groups, with each sub-group representing a subsea affiliated company. This question was asked in order to obtain baseline information about the sample popluation before delving into more complex questions. Out of the 82 responses received, over 55% of the respondents were from core oil and gas firms while the rest came from support servvices such as offshore construction, consultancy and academia as shown in Fig 38.

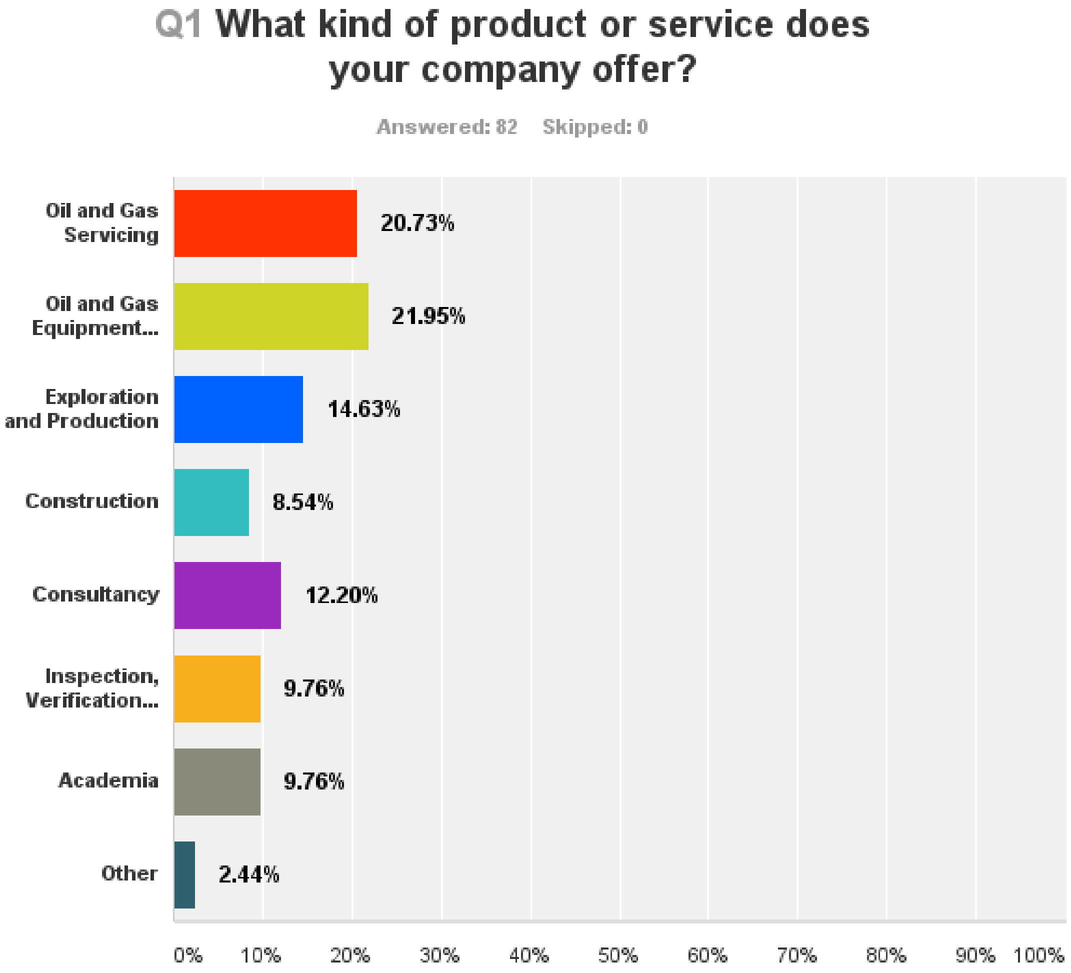


Figure 35: Industry segmentation chart

The Pie-chart in Fig 37 is showing the distribution of the industries based on respondents in the survey. The result shows a fair representation across the petroleum sector. Oil and Gas Equipment manufacturers had the highest response. It is interesting to know that their perspective on the next few questions further validates this survey since reliability is a primary focus when designing and manufacturing subsea hardware.

7.2 Role, Responsibility and Fitness for Survey

Q2. What is your role at current job?

The aim of the first question was to find out the roles of the respondents in their respective companies. It was a good way of starting the questionnaire since it is a simple question meant to further attract the interest of the intented respondent.

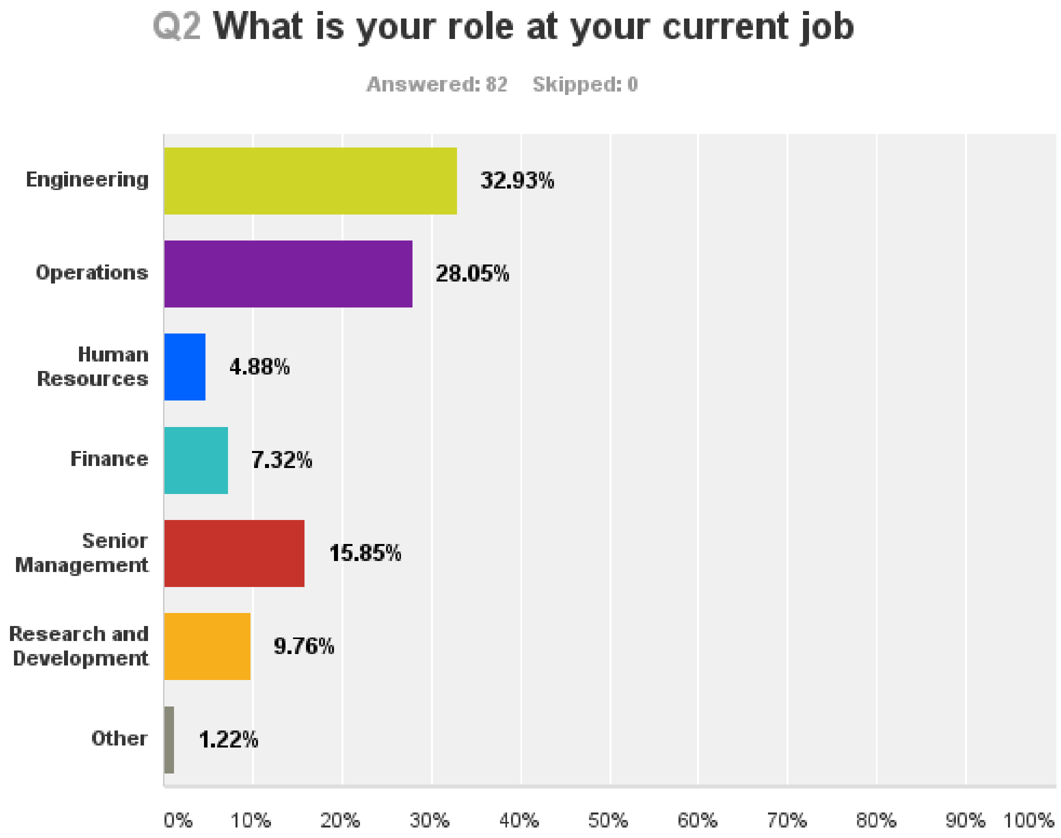


Figure 36: Distrubution of Survey Respondents.

The survey result for this question shows that majority of the respondents are in positions believed to expose them to engineering and operational actvities within subsea firms. The chart in Fig 36 shows that majority of respondents were Engineers and operational analysts making up 61% of the sample. operations and logistics who are indeed at the core of operations within their respective firms. This result helps to improve the validity of the report since majority of the respondents are key players within the operation functions of their respective subsea production enterprises. Hence, they believed to be knowledgeable regarding the operations at their firms, giving significant credibility to their responses for the purpose of this research.

7.3 Size of Participants' Organisation

Q3. What is the size of your organisation?

The objective of this question was to evaluate the size of the organisation where respondents belonged. The aim was to measure the relationship between Subsea Reliabity and Risk Analysis practice and the size of the company. The researcher was faced with the option of choosing between the two commonly used indicators for measuring organisation size, which are: annual total revenue and number of employees. The best indicator for measuring the size of the firms was the employee size chosen. The annual turn-over was not used as an indicator because it does not seem to directly affect the implemetation of Reliability and Risk practices in the companies.

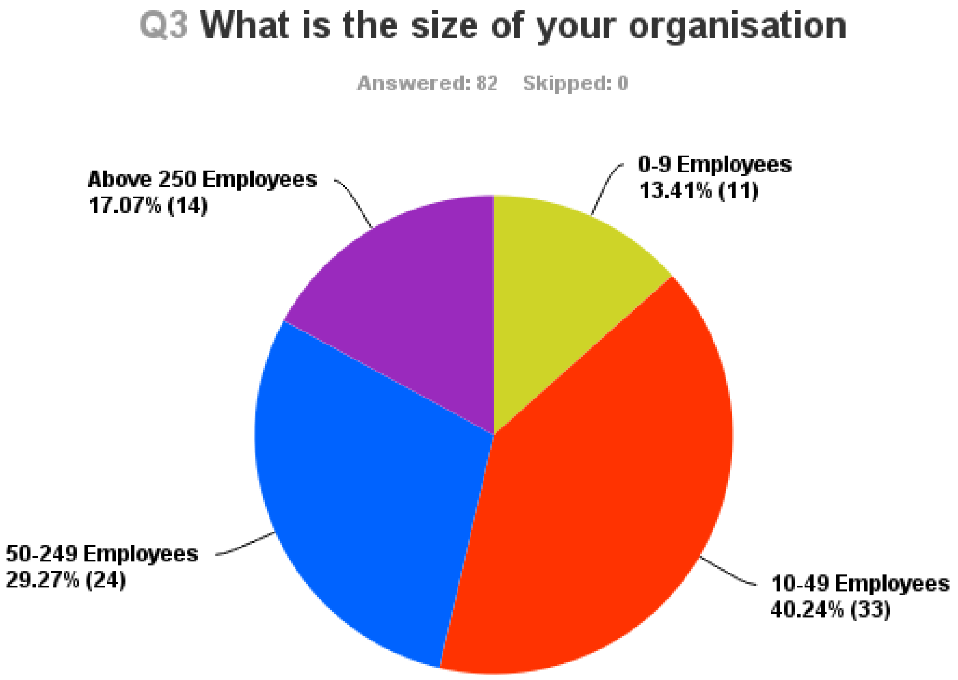


Figure 37: Bar chart showing the sizes of respondents' organisations.

There is normally distributed job roles with the majority for the medium-sized companies and less condensation on small and large sized companies. The sizes were divided up into small, medium, large and mega companies based on the sizes as shown in Fig 37. Out of 82 responses obtained, the biggest response 40.24% was from medium sized companies where from large and mega-scale companies jointly accounted for 46.34% of responses.

Fig 37 indicates that there is a significant amount of awareness about Subsea Reliability and Risk across all sizes of industries irrespective of its size. It could be inferred that the awareness or subsea risks and reliability concerns is not limited by the size of an organisation in accordance with the discussion cited in the literature review.

7.4 Adherance to a defined regulatory standard.

Q4. Do you think your organisation adheres to a defined standard for preventing downtimes from technical and operational risks?

The question was meant to measure if the organisations practice any form of risk management regarding their operations. This would help to explore how well risk management standards are recognised and utilised among the population.

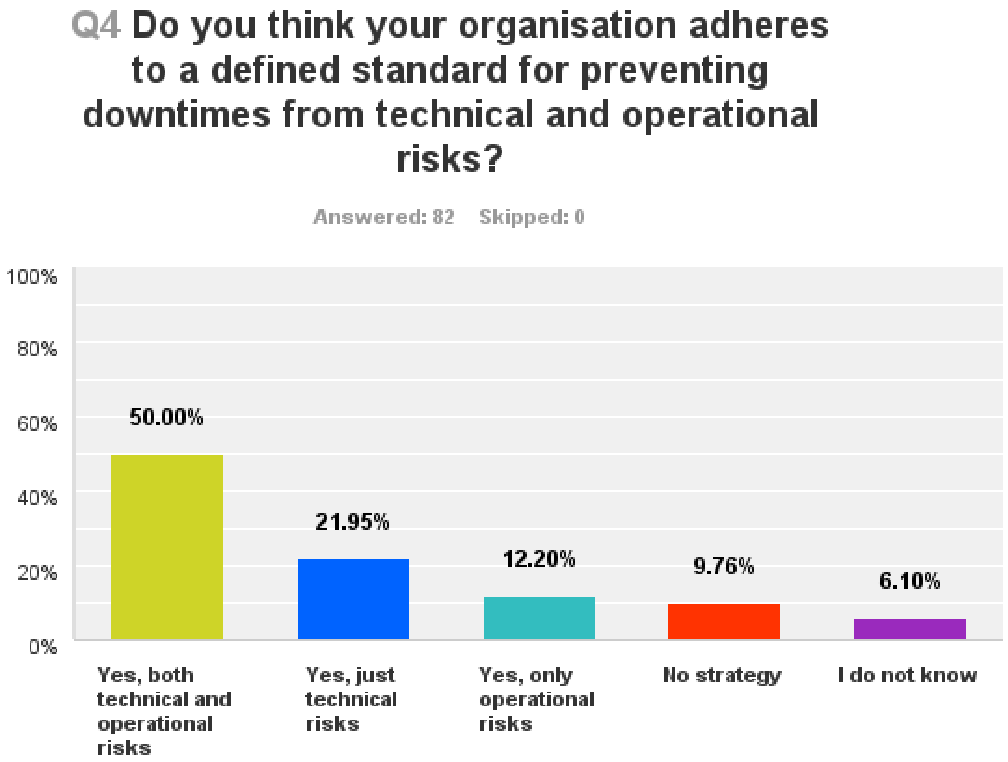


Figure 38: Distribution of organizations with and without risk management strategies.

The chart in Fig 38 shows that 92.15 % of the the surveyed respondents indicated that their organizations had an some form of standard for controlling risks. Half of total respondents had both technical and operational risk standards in th firms. Only about 16 % do not adhere or know whether were their organisations had no provisional standards for asset risks and reliability management.

Using **Chi squared** test of independence, the question of whether the organization adhere to a defined standard and to what extent is not independent. It is dependent on *product or service company offer*, *Role in current job* and whether *implementation of recognized Standards* adds economic value and size of company at 10% confidence level.

The inference here is that majority of the subsea operating firms have one form of strategy or the other for ORM, while a few others do not have any strategy in practice. This does not necessarily mean that the strategies are the formal ISO or API or similar standard. It could be formal as well as internally created stand-alone ones but one thing is clear, majority of the companies are making effort to control offshore risks.

7.5 Value Perception of Risk and Reliability and Production Assurance Regulations

Q5: Do you think that the implementation of any recognised Standards for Subsea Risk,

Reliability and Production Assurance adds economic value to the company. The aim of this question was to discover respondents' opinion on how they regard the value of subsea risk and reliability regulation as an essential tool for competitive advantage. It was done in order to assess the risk awareness level and culture among the population. The responses are shown in Fig 39.

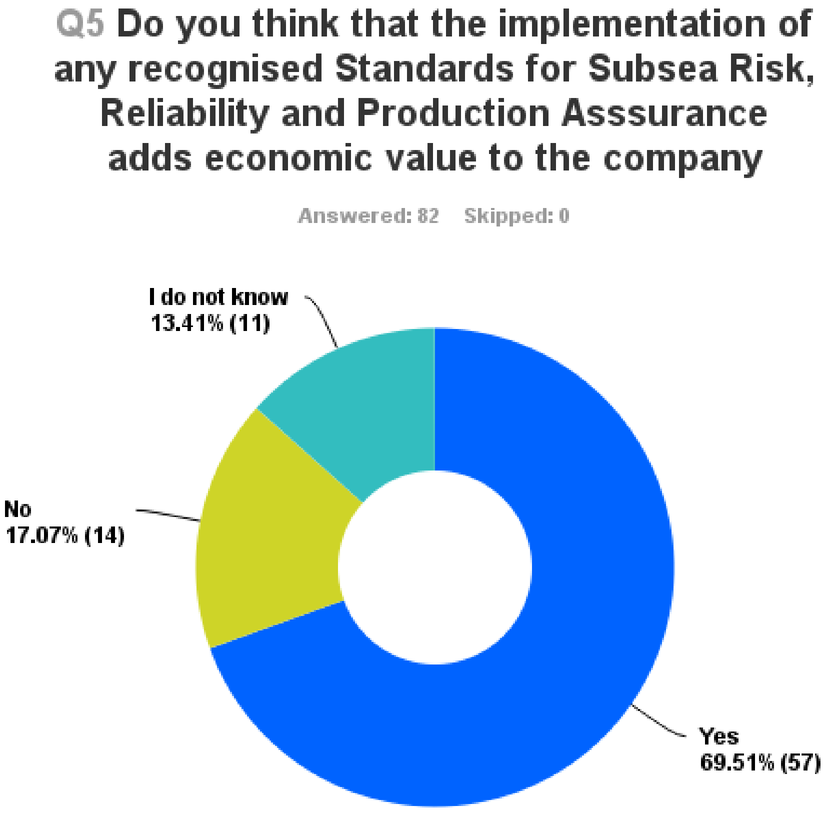


Figure 39: Recognition and Awareness Chart

Almost 70% of the respondents think that implementation of recognized Standards adds economic value while 17% do not believe so.

Using **Chi squared test** of independence, implementation of recognized Standards adds economic value is not independent, it changes with respect to; *product or service company* *offer*, *Role in current job* and as mentioned earlier *adherence to a defined standard* for preventing downtimes at 10% confidence level.

7.6 Implementation Preferences for Regulations and Standards

Q7. Which of these standards does your organisation implement to manage risks, system reliability and production assurance?

This question was informed by the literature review in the sense that certain companies use discrete 'stand-alone' frameworks for managing risks, while other use integrated approaches by applying various risk management standards. The aim of gathering this data was to get a sense of the preferences of the population in terms of the most popular subsea risk regulations. Respondents were asked to select as much possible correct answers/choices as possible.

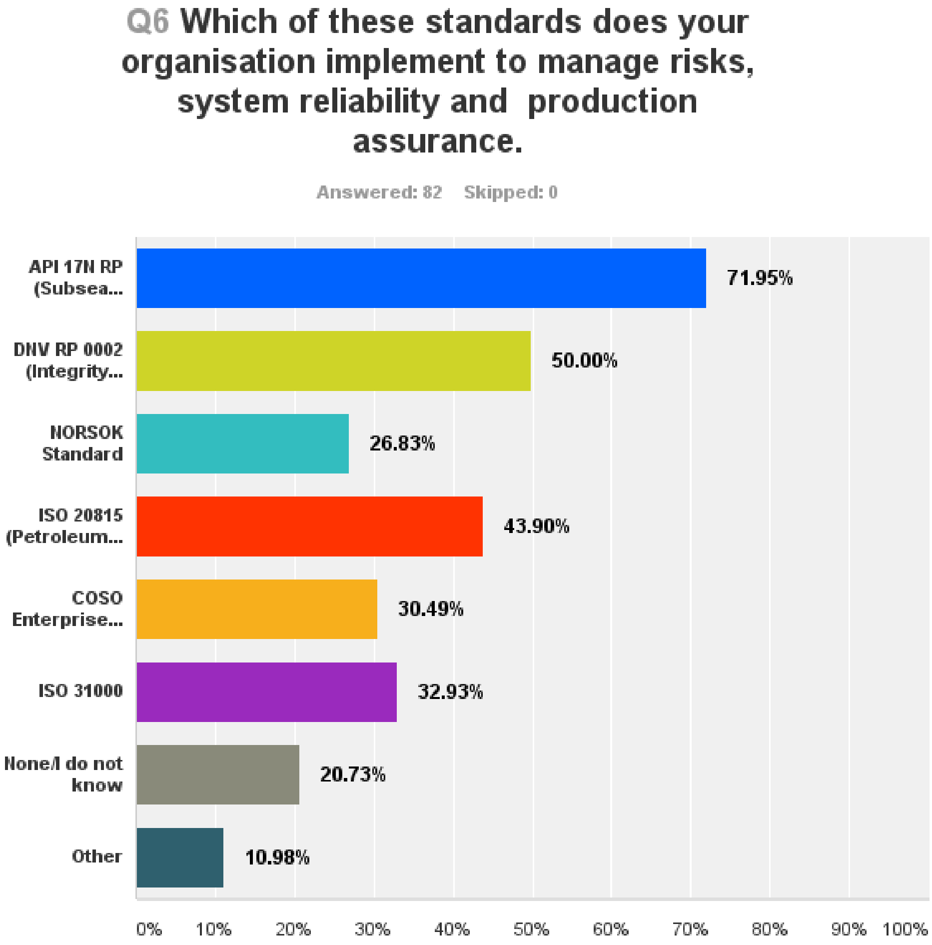


Figure 40: Implementation Level Chart

The result in Fig 40 shows that majority of the respondents use multiple frameworks for risk management with about 71.95% out of the 82 saying their organisations implement the API 17

N RP. The DNV RP 002 was being implemented by 50% of the population while about declared they use just one defined policy. About 20.73% do not know all or some of the standards being used at their organisation. This is of great concern; perhaps there is no proper awareness concerning the frameworks used within the company. This calls for proper employee involvement and motivation.

7.7 Respondent Opinion on Best-Fit Standard.

Q7. In your own opinion, which of the following standards do you think has the best approach to reliability, integrity, risk and production assurance management for the subsea oil and gas industry.

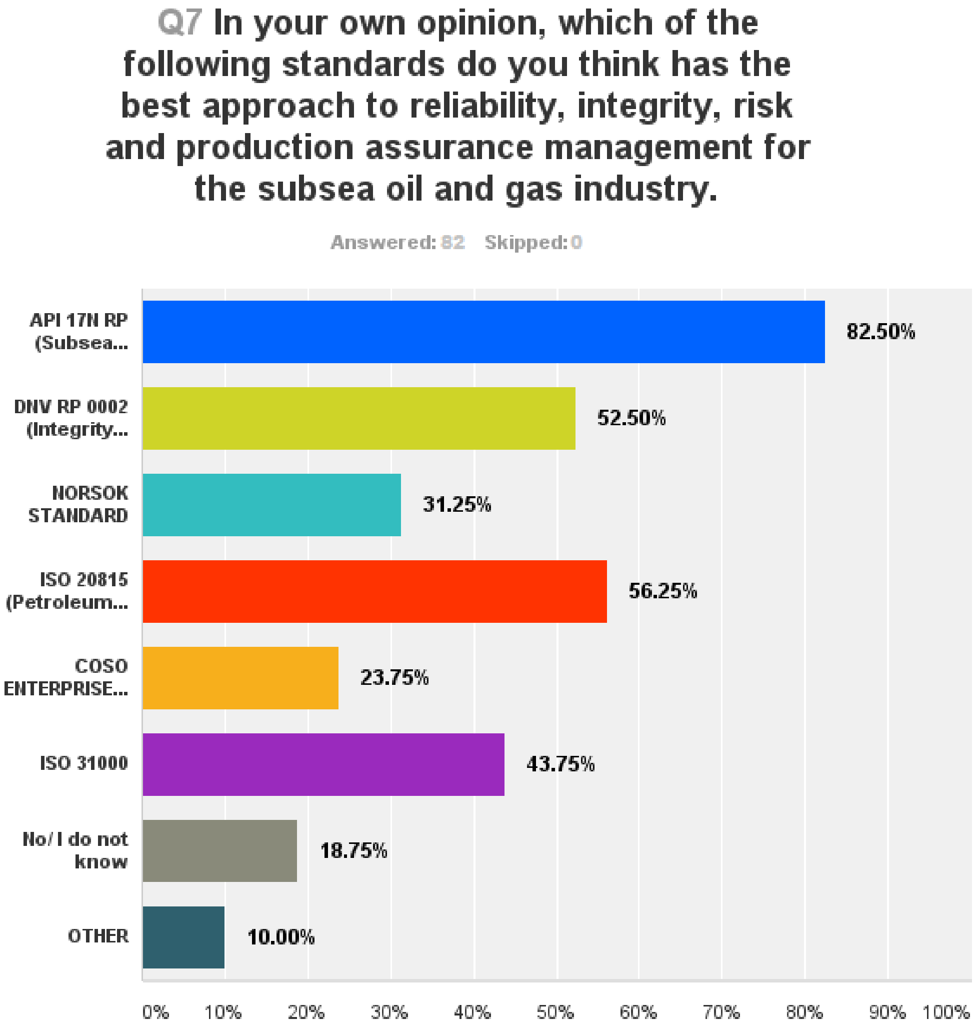


Figure 41: Standard with Best-Approach Nomination Chart

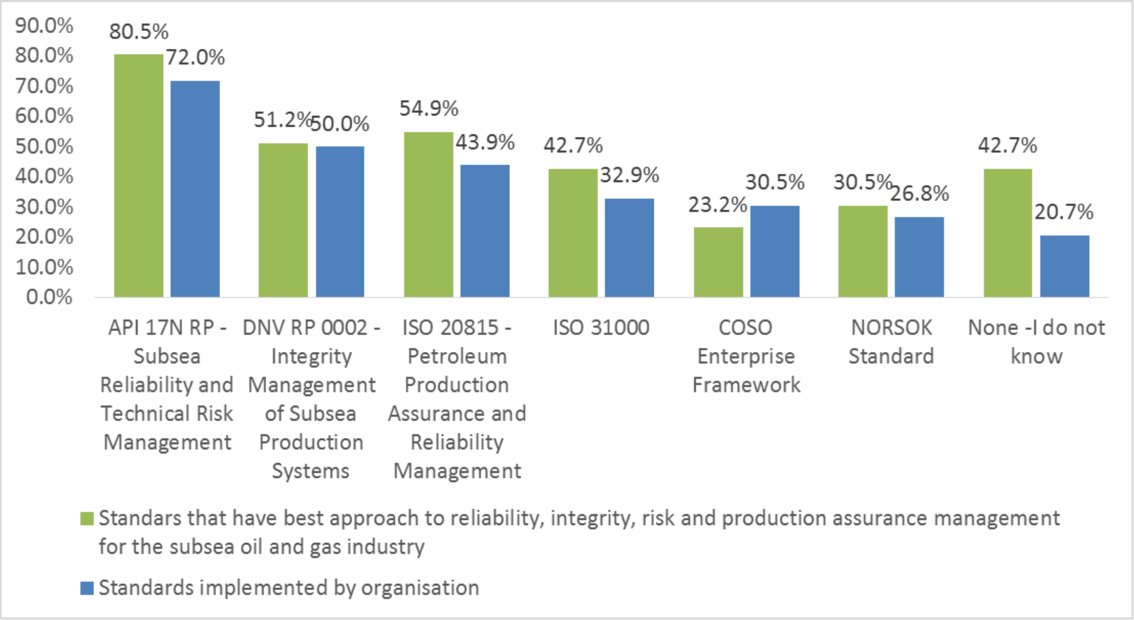


Figure 42: Correlation of Standards Implemented and Best Approach Nominations.

From Fig 42, it could be inferred that, Standards that are thought to have the best approach to reliability, integrity, risk and production assurance management for the subsea oil and gas industry are implemented within the organization with permissible deviations reflected in lower percentage which could simply be due to cost restrictions or a different approach taken by the administration.

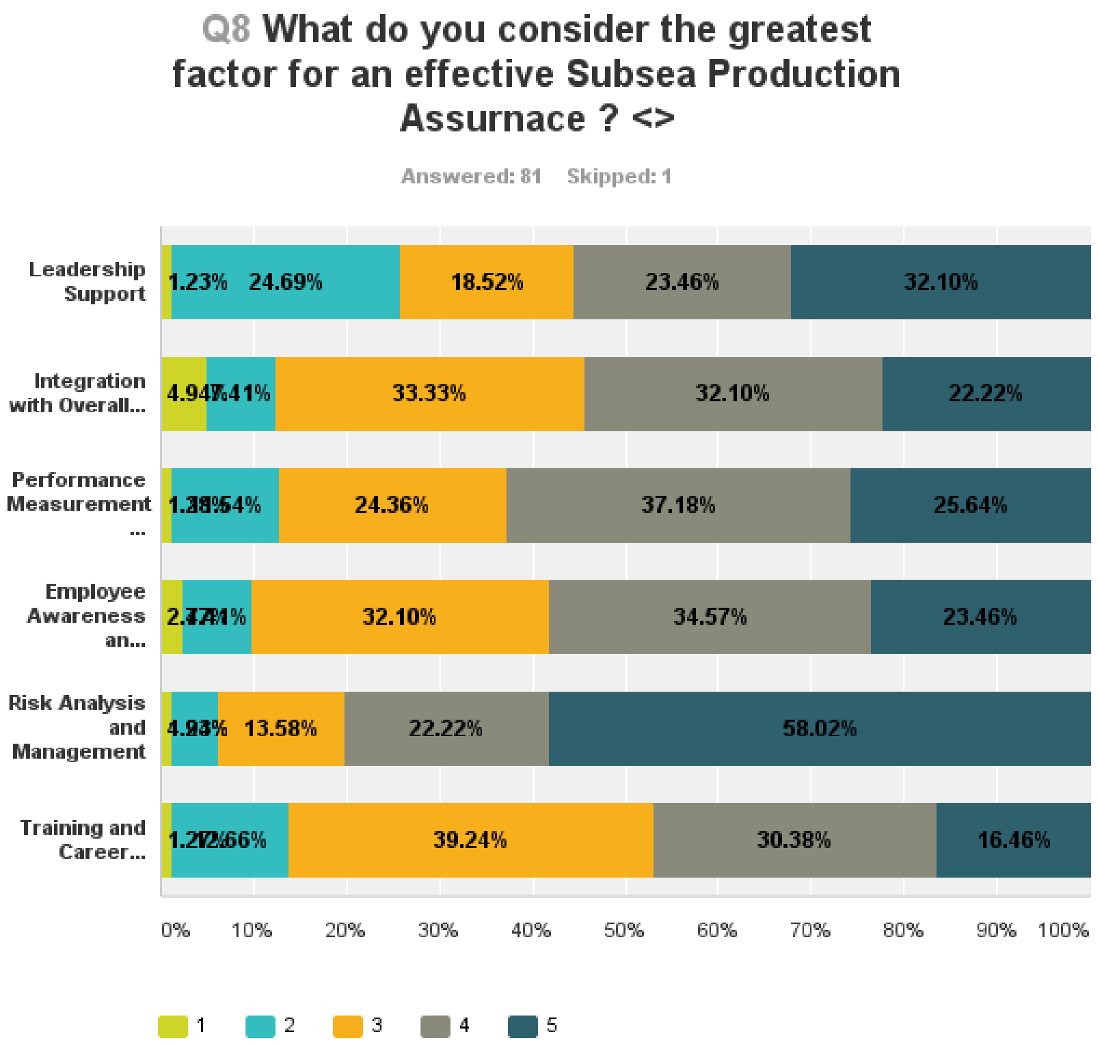
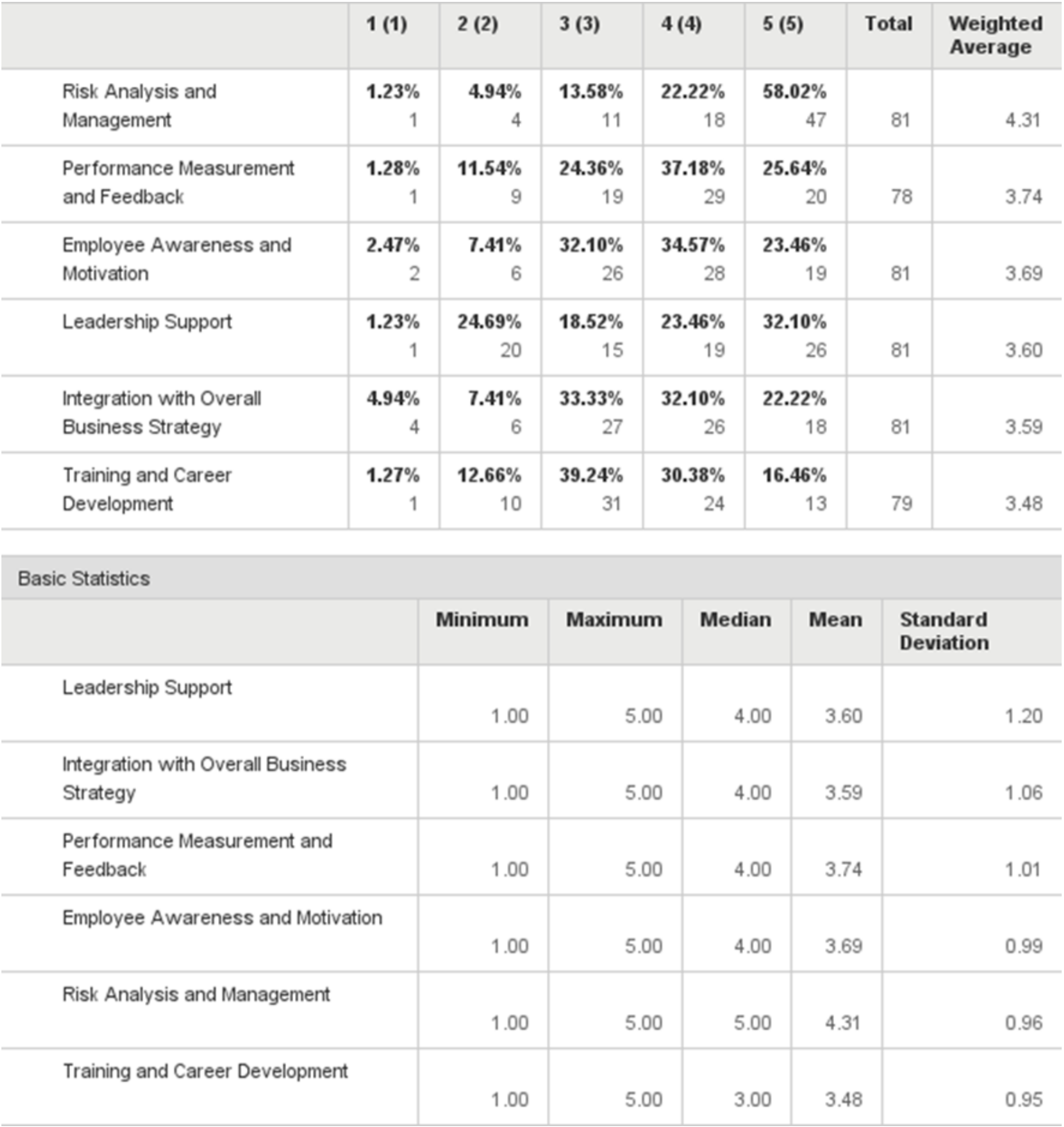


Figure 43: Factors for Effective Subsea Production Assurance

Table 28: Descriptive Statistics of respondents on Factors for Effective Subsea Production Assurance



	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	Total	Weighted Average
Risk Analysis and Management	**1.23%** 1	**4.94%** 4	**13.58%** 11	**22.22%** 18	**58.02%** 47	81	4.31
Performance Measurement and Feedback	**1.28%** 1	**11.54%** 9	**24.36%** 19	**37.18%** 29	**25.64%** 20	78	3.74
Employee Awareness and Motivation	**2.47%** 2	**7.41%** 6	**32.10%** 26	**34.57%** 28	**23.46%** 19	81	3.69
Leadership Support	**1.23%** 1	**24.69%** 20	**18.52%** 15	**23.46%** 19	**32.10%** 26	81	3.60
Integration with Overall Business Strategy	**4.94%** 4	**7.41%** 6	**33.33%** 27	**32.10%** 26	**22.22%** 18	81	3.59
Training and Career Development	**1.27%** 1	**12.66%** 10	**39.24%** 31	**30.38%** 24	**16.46%** 13	79	3.48

Basic Statistics

	Minimum	Maximum	Median	Mean	Standard Deviation
Leadership Support	1.00	5.00	4.00	3.60	1.20
Integration with Overall Business Strategy	1.00	5.00	4.00	3.59	1.06
Performance Measurement and Feedback	1.00	5.00	4.00	3.74	1.01
Employee Awareness and Motivation	1.00	5.00	4.00	3.69	0.99
Risk Analysis and Management	1.00	5.00	5.00	4.31	0.96
Training and Career Development	1.00	5.00	3.00	3.48	0.95

Table 28 indicates that proper risk analysis and management, routine performance measurement and feedback and employee awareness and motivation are keys to successful implementation of subsea production assurance. However, there could be hidden patterns within the data. Therefore, a quick hypothesis and test may need to be performed to reveal any trend in the data.

Hypothesis 1: Is there a specific notion that shapes views regarding specific standards as the best approach to reliability, integrity, risk and production assurance management for the subsea oil and gas industry?

Factor analysis can magnify and uncover this latent notion as shown in Table 29. So applying it to the chosen standards, there were two factors emerging explaining about 61% in the variations of standards that are seen as best approaches.

Table 29: Factor loadings to risk standards.

Standard	Component	
	Factor 1	Factor 2
API 17N RP (Subsea Reliability and Technical Risk Management)	-.201	.748
DNV RP 0002 (Integrity Management of Subsea Production Systems)	.084	.839
NORSOK Standard	.486	.619
ISO 20815 (Petroleum Production Assurance and Reliability Management)	.614	-.100
COSO Enterprise Framework	.766	.148
ISO 31000	.754	-.178
None/I do not know	.809	.167

The extraction method used in this analysis is the Principal Component Analysis and the Rotation Method was Oblimin and Kaiser Normalization [Ogasawara, 1999; Jolliffe, 2002]. The rotation converged in 6 iterations.

On applying factor analysis to standards that has the best approach to reliability, integrity, risk and production assurance management for the subsea oil and gas industry, there were two factors emerging explaining about 61% in the variations of best approaches.

- The first factor is related to *API 17N RP (Subsea Reliability and Technical Risk Management)* and *DNV RP 0002 (Integrity Management of Subsea Production Systems)* as the best approach and **not** regarding *ISO 31000*.
- The other factor is related to *COSO Enterprise Framework*, *ISO 31000* and *Production Assurance and Reliability Management)* and **not** regarding *API 17N RP (Subsea Reliability and Technical Risk Management).*

Hypothesis 2: How is evaluation factors for an effective Subsea Production Assurance related to each other?

Using Principal Component Analysis, it can be seen that the respondents can be divided into three segments by graphing the first principle component with product or service provided (positive values, large negative values and small negative values*)*.

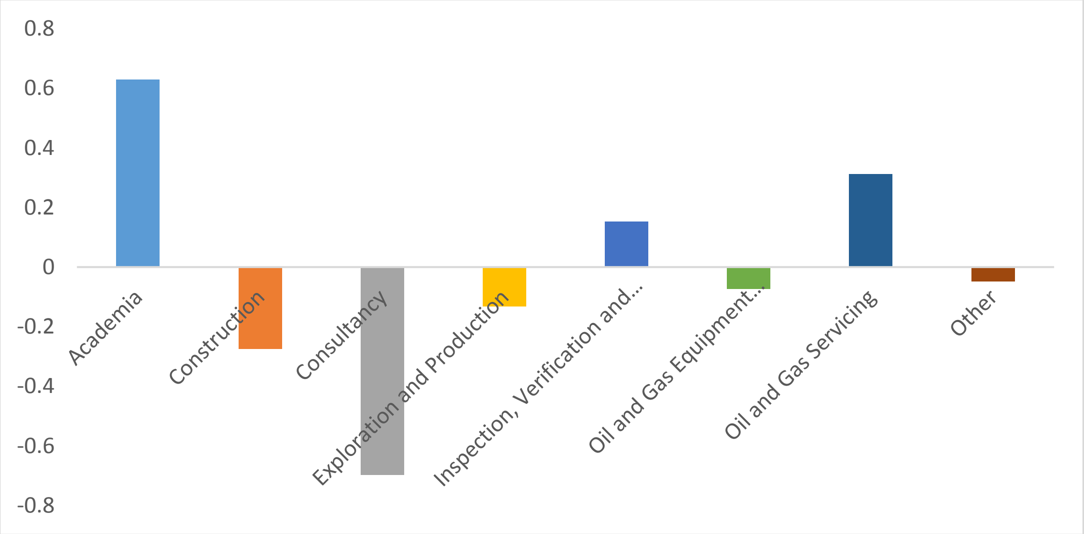


Figure 44: Average of the first principle component by kind of product or service

Applying cluster analysis to this dataset, we can derive the three following groups:

- *<u>First group</u> will tend to have **high** evaluation for Employee Awareness and Motivation and Risk Analysis and Management but **low** evaluation for Performance Measurement and Feedback.*
- *<u>Second group</u> will have **high** evaluation Leadership Support, Integration with Overall Business Strategy and Training and Career Development but **low** Risk Analysis and Management.*

- *Third group will have* ***high*** *evaluation for Risk Analysis and Management but* ***low*** *for Integration with Overall Business Strategy and for Employee Awareness and Motivation.*

Hypothesis 3: What affects evaluation of factors, for an effective Subsea Production Assurance?

The extent to which an organization adheres to a defined standard for preventing downtimes from technical and operational risks is highly correlated with the evaluation of factors according to what type of product or service presented by the company, role in current job and size of organization. Table 30 presents the correlation of respondents' groups and their company's profile with evaluation of every separate factor.

Table 30: Correlation of factors and evaluation of adherence to a defined standard according to respondents' characteristics.

Greatest factor for an Effective Subsea Production Assurance							
	Factor	**Leadership Support**	**Integration with Overall Business Strategy**	**Performance Measurement and Feedback**	**Employee Awareness and Motivation**	**Risk Analysis and Management**	**Training and Career Development**
Kind of product / service the company offer	Oil and Gas Servicing						
	Oil and Gas Equipment Manufacturer	-0.54					
	Exploration and Production	-0.66				0.77	
	Construction				-0.51		
	Consultancy	-0.7					
	Inspection, Verification and Certification		-0.91		0.71		
	Academia						
Role in the your current job	Engineering						
	Operations	-0.55				0.64	
	Human Resources	-0.98	-0.87	-0.87		0.5	-0.5
	Finance	-0.66		0.65	0.6		-0.56
	Senior Management	-0.51					
	Research and Development	-0.58	-0.76	-0.55	-0.6		
Size of your organization	0-9 Employees			0.74			
	10-49 Employees		-0.51				
	50-249 Employees		-0.55				
	Above 250 Employees						

** Negative correlations indicate a higher evaluation with less adherence to a defined standard for preventing downtimes from technical and operational risks, while positive correlations indicate higher evaluation with more adherence.

The highest correlations are reflected as following:

- Evaluation of Leadership support is highly correlated depending on; the kind of product or service presented especially to consultancy companies (0.7) and respondent's role at current job with a very high correlation for human resources (0.98).

- Evaluation of Integration with Overall Business Strategy is only highly correlated with Inspection, 'Verification and Certification' type of companies, job roles as human resources (0.87) and Research and Development (0.76) and more correlated for medium sized companies formed of 10-49 or 50-249 employees.
- Evaluation Risk Analysis and Management is the most correlated factor depending on Exploration and Production company type (0.77) and for an 'Operations' job role (0.64).

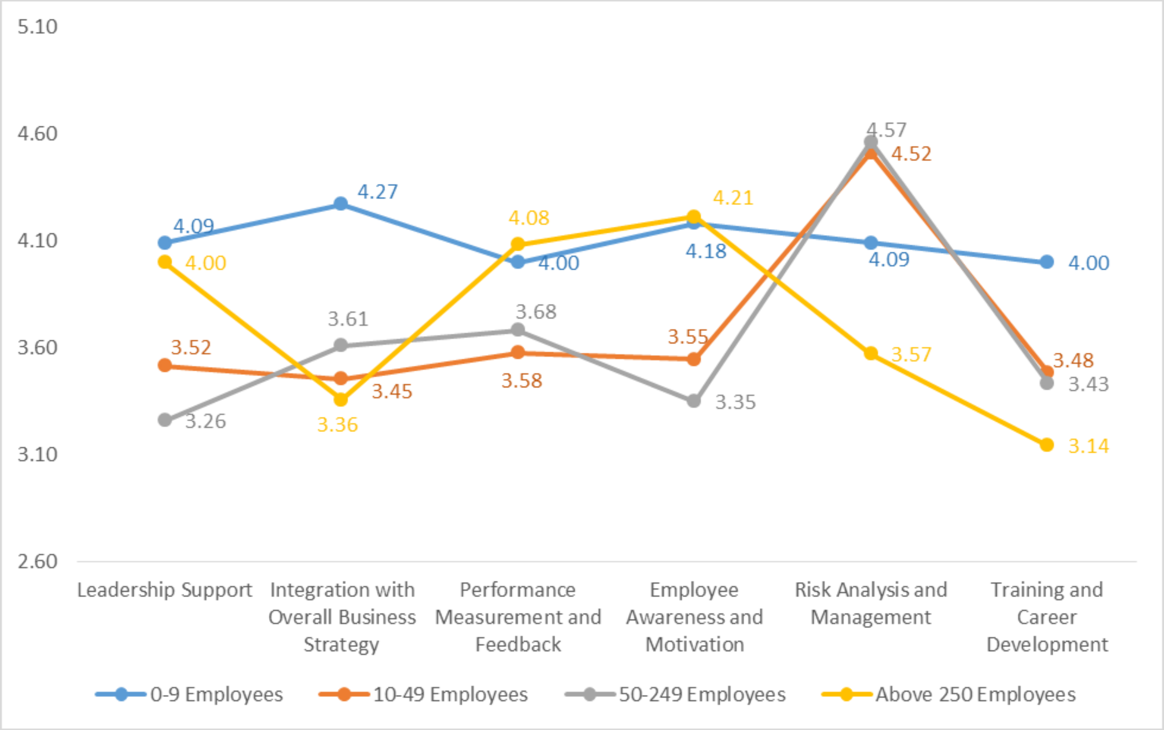
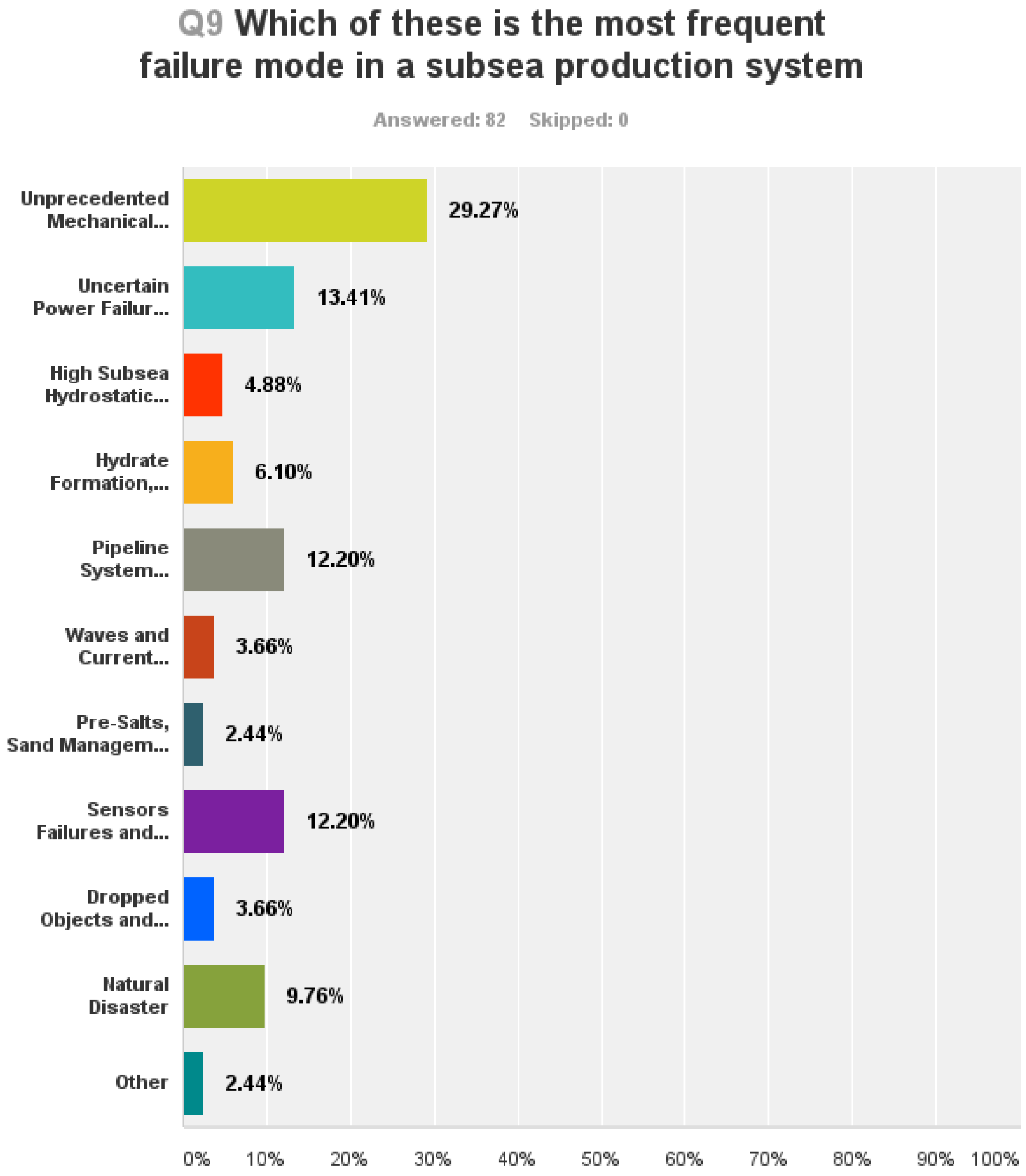


Figure 45: Average evaluation for factors according to company size.

Fig 45 describes the relationship between the important success factors for subsea production assurance and size of the companies as obtained from the survey. Recall that 0-9 employees mean small companies. 10-49 employees indicate medium size companies while 50-249 employees indicate big companies and above 250 employees indicate mega-companies.

For medium and large companies, risk analysis and management was identified as the most important factor vital for subsea production assurance and reliability. This could be attributed to their size and decentralised structure which makes it easier to enforce policies and controls. Mega companies on the contrary, indicated that employee motivation and awareness are the most important challenge vital for subsea production assurance. It can be deduced that as the companies get bigger, the focus shifts from awareness to implementation basis of the sheer size of the companies. The smaller subsea companies possibly face less risks due to their scale of operations and as such were not as keen on the risk management factor, but were more concerned about aligning production with their overall business strategy.

7.8 Which of these is the most frequent failure mode in a subsea production system.



The most frequent failure mode in a subsea production system is unprecedented mechanical failures as indicated by 29% of respondents. Power failures, sensors and pipeline fracture are also major problems while pre-salt oil processing problems is one of the least problems. The challenge reliability assurance requires that subsea oil and gas firms need to focus and invest more on the mechanical integrity of subsea hardware using robust qualification and verification programs at the design stages of the modules. The accelerated life testing model recommended in this thesis should be used to model, analyze and forestall unprecedented and catastrophic failure of subsea hardware components and pipeline. Adequate redundancy for sensors and data relay systems are crucial for condition monitoring using a mix of lasers, sensors and fiber optics since they are often semi-conductors with varying life span. It would prevent data loss, power loss or cut in transmission since most of them are non-repairable. This demands that robust verification programs as recommended by DNV 306 RP are routinely implemented to ensure that only well-tested components with high tolerances and adequate redundancy make it to the sea.

CHAPTER 8

Practical Implications of this Work

This chapter describes the integrated model developed with specific focus on the lessons drawn from the survey and how the previously proposed numerical models fit into a whole-system lifecycle framework for optimal performance of subsea assets. The results and discussions in this chapter will give clear recommendation for controlling the risks in subsea production operations in alignment with the objectives stated at the beginning of this thesis.

8.1 Implication of the Quantitative Data Analysis in the Research

•What problem is the study trying to solve, and is it important?

The research is trying to solve the problem of unplanned failure of oil and gas equipment during operation in subsea environments because OREDA data only considers individual failure time of each component and not how the interaction among the components and with how external forces lead to failure. This is important because unplanned failure of a subsea oil and gas production system could result in economic loss, safety risk, fatality or even sanctions.

•To what extent does the paper solve the problem it describes?

It solves the problem by considering and modelling the key factors that could stress the equipment and make it fail using a probabilistic distribution in the form of Weibull model. This was applied to the much rougher and deeper West African Offshore environment since OREDA data mainly comes from equipment usage in the Norwegian and North Sea Oil fields which are much shallower. This means that OREDA data is used as baseline data prior to application of an external stress on the Weibull probability distribution for a realistic reliability index.

•What is the "intellectual nugget"?

The key 'intellectual nugget' of the research is the development and proposition of a new a model for stressing a low-stress failure data such as OREDA MTTF in order to predict a realistic failure curve and optimize an asset which has little or no documented field records but is bound to face exponential covariate operational stresses afield. In essence, the reliable operating window of a subsea equipment can be predicted and optimized based on the Accelerated Failure Testing method described in this paper to prevent unplanned downtimes, costs and safety issues.

•What is the main contribution or conclusion? Is it important?

Yes it is very important. The contributions of [Barabadi, 2014] and few others authors enlisted in the reference list support the fact that the research made some valid positive contribution to existing knowledge because it not only did consider the impact of temperature [as in Barabadi 2014 for instance] on a piece of marine hardware but additionally considered pH and pressure (Co2 fugacity) in addition to temperature which were all primarily sourced, measured and embedded in the Norsok' corrosion profile equation based on physical data conditions from West Africa Offshore region. System failure results from a combination of failure events or failed components and this assumes a continuous probability. Therefore, the covariate external stress was further incorporated into a generated Weibull reliability model to develop a new reliability model which was validated in the case study.

The applied concept is quite new, justified and makes sense. More so because this is a much detailed method - never used in this form anywhere, applied to a new subsea system (the first compact SCS was installed at Asgard in 2015 wherein only very little is known about its field performance yet), applied to a location that has not been analysed previously – Offshore West Africa.

Furthermore, human factor reliability was also addressed using an improved Barrier and Operational Analysis method. The major improvement was the modification factor calculation and the expression of the revised risk probability as a percentage not as an abstract number. In so doing, it becomes easier to add and analyse technical reliability indices which is normally expressed in percentages according to the method prescribed in the work as a risk influencing factor.

The analysis reveals that a high component MTTF does not directly translate to high reliability, instead the cumulative MTTFs together with frequency and times of failure gives better prediction of system reliability

8.2 SWOT Analysis of Major Findings from Survey.

Considering the findings from the survey, Table 31 presents a snapshot using a SWOT diagram which contains the findings from the survey.

Table 31: SWOT Table of Findings

Strengths	**Weaknesses**
• The survey opinions have high validity because it came from a sample size of 82 whom are subsea experts 55% of them were from production activities. Engineers and operations personnel made up majority of respondents. • Subsea reliability and risk awareness cut across all subsea company sizes as about 92% of the companies adhere to a form of technical and/or operational risk standard. Respondents believe that reliability and risk management adds measurable economic value to the firm • Two third of the population have a key personnel who co-ordinates risk and reliability management activities. • Most of the organisations surveyed only have a fairly well-defined reliability and risk management policy especially the API 17N RP and DNV 002 RP accounting for 70% and 50% respectively.	• Up to 17% are not aware that risk management adds measurable economic value to firms' operations. • 20 % do not know if any standards are being used in their organisations. • Notwithstanding the fact that most of the companies have ORM systems, a sizable fraction of the respondents do not know the requirement of the policy and its implementation plans since there is huge lack of communication, risk culture and a big hindrance caused by the silo-approach which is obtainable in many of the organisations.

Opportunities	**Threats**
• The belief that recognized Standards adds economic value is not independent, it changes with respect to; product or service company offer, Role in current job. • Majority believe that risk management is a key tool that could deliver competitive advantage and help to minimise losses due to operational failures in firms. . • A good number of the respondents (65%) think that ISO 31000 has a more comprehensive risk management approach. This is so because it is easy to understand. • Respondents indicated that the most important factors for a successful implementation of reliability and risk are leadership support, risk communication Employee participation and motivation.	• Size of company does affect the perception of risk areas as bigger companies tend to focus more risk analysis while small companies focus on overall integration of programs for production assurance. • Majority of the firms affirmed that the key threat to reliability and production assurance are mechanical failures, power failures, data management/sensory relays, and pipeline failures. • Lack of awareness and leadership commitment in some of the firms especially the small businesses is also considered a threat.

Considering the issues pointed out by the survey, a SWOT analysis was performed in order to summarise several pertinent issues which could be seen in quadrants above. This following discussion focuses on enhancing the strengths identified, remedying the weaknesses, exploiting the opportunities and suggesting solutions for the threats. Reliability and Risk Management is a strategy which requires both technical and business input as it heavily relies on people, processes, management approaches and a whole lot of commitment from each team. In order to achieve efficiency in subsea production firms, key advice which centred on integrating Subsea Asset Reliability and Risk with Organisational Structure, People, Process and Human factors, are discussed in alignment with the research questions that informed the survey.

Discussion and Recommendation on Subsea Asset Risk Awareness Level

One of the rationale for the survey was to test the awareness level of subsea production firms. Based on the survey finding, the level of risk and reliability management awareness was found to be high for technical-inclined business organisation, however, its implementation and control is highly influenced by the size of a company and the number of employees in the value chain who actually get involved in the process. Large subsea firms take risk assessment seriously while the small firms were not as keen. Interestingly, the pattern may indicate that the bigger the subsea production capacity, the bigger the risks seemingly.

It is commendable to discover that various risk and reliability management policies either purely technical, operational or both are being adopted by majority of the companies. Notwithstanding, subsea companies irrespective of size need more enterprise-wide awareness campaign highlighting the economic merits and importance of Operational Risk Management and Asset Reliability. This will enable the employees to familiarize with the intricate first principles of the standards and policies particularly their role towards raising alarm on any perceived human factor or operational risk. Although, a reliability or risk engineers job is to keep track of the reliability register, the task cannot be effectively done in isolation or by just a single person but rather collectively thorough open communication channels and risk reporting across all teams. Risk awareness, alertness and control has to be enmeshed in every functional department within the firm and their roles within the subsea production system so that risk control can start at the very heart of machine-human-process. Subsea operators that wish to carry out risk or reliability assessment may need to engage a risk/reliability expert whose first immediate task would be to assess each operational sector/activity against required deliverables to prevalent failure and then advise the operators/employees on the how to habitually generate activity-based risk reports so that appropriate measures are taken to prevent the fatality of losses or huge economic losses. The key strategy here is creating a risk culture based on a bottom-to-top approach and not the usually unperforming silo-type strategy which is obtainable at some subsea firms. A bottom-to-top approach focuses better on the tiny details of a system and not just the broad perspective as per top-to-bottom. These could be done using the checklists and relevant standards, depending on operations and business needs. A top-to-bottom approach is then routinely applied as an appropriate audit for aligning risk and reliability activities with overall company aims.

Discussion of Key Challenges

Majority of firms affirmed that key threats to production are mechanical failures, power failures, data management/sensory relays, and pipeline failures while natural disasters, salt management, and hydrostatic pressure were rated low challenges. A careful examination of the pattern of responses show that the key problem is hardware failure – a reliability issue.

The integrated model presented in this chapter will provide details of how to ensure that asset reliability and risk severity of each event for production assurance at all times. It could be supported by the established standards such as API 17N RP, DNV 002, ISO 20815 and many more robust frameworks. Meanwhile the SAIRR checklist incorporated the best aspects of all these standards discussed.

Regarding production assurance problems, these can be managed by adopting any of the following factors (Kusiatan, 2005),

(a) Simulation of processes using software packages or small prototypes prior to full deployment so that operation dynamics would be reasonably comprehended. For instance, this was done using the Pipesim software for analysis flow output conditions in order to derive the parameters for evaluating pipe-pump efficiency options as containedin Chapter 5. The RBD analysis and optimization using the ALD reliability software is another example of how operation dynamics of a system can be visualized first to identify the failure modes so that an adequate optimization is effected.

(b) Alternative solutions may include creation of redundant links for failures, creating robust tolerance and continuous improvement through business decisions.

On a serious note, production assurance risks are very dynamic and eruptive. Therefore, they require more proactive measures by making smart reliability and risk analysis using the high stress model recommened in this work. The choice of risk management policy has to be supported by the organisations top echelon for it to be taken seriously across the firm. Risk awareness audits starts form the top management down to the lowest ranks and coupled with adequate communication between functional multi-disciplinary groups and alignment of risk control strategies with overall organisational goals thereby integrating People, Process, Assets and the Petroleum Product or Subsea Service. Implementation is a collective task which starts from the roots which could be the shop floor, rig men at platform at sea or controls personnel at remote station and up through the organisational ranks.

As observed in the survey, leadership support, performance measurement and employee motivation were the requirements indicated by the expert respondents for full implementation of a risk-reliability policy.

Discussion and Recommendation Emphasis on the Human Factor.

Subsea Asset Reliability and risk management is widely seen by the respondents as an assured tool for risk management for safety and economic advantage. The major challenge with it is the capability of understanding the various RIFs in subsea environment and integration and implementation of the chosen framework. This may require special training, especially technical reliability analysis for the mechanical failures. The integrated model proposed a methodology for calibrating sorting these into human reliability analysis for commercially oriented staff and technical reliability for technically inclined analysts. The other problem is the silo approach which exist in many companies who either do not share information across departments or simply just appoint a chief risk personnel to take care of all the organisation-wide risk management with slight negligence towards the human factor risk originators themselves, the employees who ought to partake in the process of risk enculturation. These problems constitute threats and weaknesses to realising the full potentials of ORM.

Increased demands of safety and operational uncertainties in the oil and gas sector require that a robust team of employees who are well-informed are allowed to run the business. Since majority of the respondents expressed enthusiasm towards the adoption and practice of risk management, it would be worthwhile to exploit the enthusiasm expressed by inculcating a risk culture within teams. The enhanced BORA framework proposed in Chapter 4 is a good way to account for human factor risks because it identifies the various Risk Influencing Factors, ranks and compares them against industry average and generates an index score of its probability of occurrence. Most importantly, staff must be encouraged to communicate any hazard observed no matter how little so that it may be controlled before it grows into an accident or disaster. This communication could be encouraged through rewards for memo submissions to the risk /reliability chief or each risk control designed or suggested.

Discussion and Recommendation Emphasis on Subsea Production Assurance

Subsea production assurance matters is certainly a topic that has a direct clear impact on stakeholders such as customers, clients, partners, employees, government, suppliers, distributors thus it is imperative to establish a production management strategy which incorporates reliability of assets and risk control of the subsea production business. The idea is to have a wider perception of risk and not localize it just on the technical rotating parts of a subsea facility.

From the survey, production assurance and reliability appears as a serious concern but since risk and reliability has become more and more a predictive concept it could be extrapolated to ensure improve performance in production capacity design and assessment. The nature of subsea environment makes subsea personnel more vulnerable to occupational risks which could hinder production, therefore routine safety assessment should be carried out on the subsea facility and equipment to ensure compliance with regulations and to detect any potential hazards.

The enhanced Hubbert method which was developed in this work for production forecasting and planning could be merged with more modern and information technology systems such as SAP's (Systems, Applications and Products) Material Resource Planning (MRP) systems or the Material Production Schedule (MPS) applications. These tools, though beyond the focus of this research, could be incorporated into the results from process flow software such as *Pipesim* and *Olga* to visualize the subsea production system bottle-necks in real time and plan ahead for repair lead times and adequate artificial lift installation. Production normally targets the best efficiency possible in terms of cost, material usage and output delivery times. The key metrics to consider for efficient low cost production have been established and emphasised in Chapter 5 and these include power consumption, pipe diameter, fluid pressure and cost of pipe and velocity of flow.

8.3 Features of the Integrated Asset Reliability and Risk Analysis Model

One of the key objectives of this thesis is to develop an enhanced model of managing subsea assets and operational risks through a new robust system model. To accomplish this, lessons were drawn from the gaps and challenges highlighted in the literature review, numerical developments in case studies at the preceding chapters, the survey responses and the weaknesses in existing standards and methodologies. The newly proposed model is essentially an extraction of the best practises from existing standards, particularly, DNV OSS 306, API 15 RP N and ISO 31000 which were particularly based on the statistics from the surveyed subsea engineers and risk practitioners.

The strategic model consolidates crucial factors responsible for effective reliability, risk and subsea production assurance. The new model comes with a newly crafted checklist. The checklist is intended to guide both small, medium and large subsea oil and gas operators since the literature review and survey analysis results showed that the size of a firm is not necessarily an obstruction against the full implementation of subsea risk, reliability and production assurance. The model essentially focuses on:

- Transparency of risks across the key subsea production components of man, machine and process.
- Specifics on the numerical evaluations to be made in accounting Risk Influencing Factors.
- Leadership involvement and communication across functional groups.
- Awareness and training of employees in order to manage operational risks.
- Design considerations.

8.4 The Proposed Integrated Model

The integrated structural model presented in Fig 46 is the suggested guideline for the management of subsea asset integrity, reliability and risks. On a foundational level, the model design was fundamentally inspired by the good old Deming's PDCA ideology- a fundamentalist view of modern risk management. The new integrated model is clearly different in numerous ways due to the incorporation of specifics in terms of the type of Quantitative Risk Analysis (QRA) for the subsea production, analysis to carry out, for each of the risk areas in –man-machine-process dynamics. Human factor risks such as risk in communication, alignment with overall organisational vision, training and development, leadership support and risk awareness campaigns which were either completely absent or not clearly emphasised in existing risk management methodologies/frameworks,were clearly incorporated in the new model and checklist.

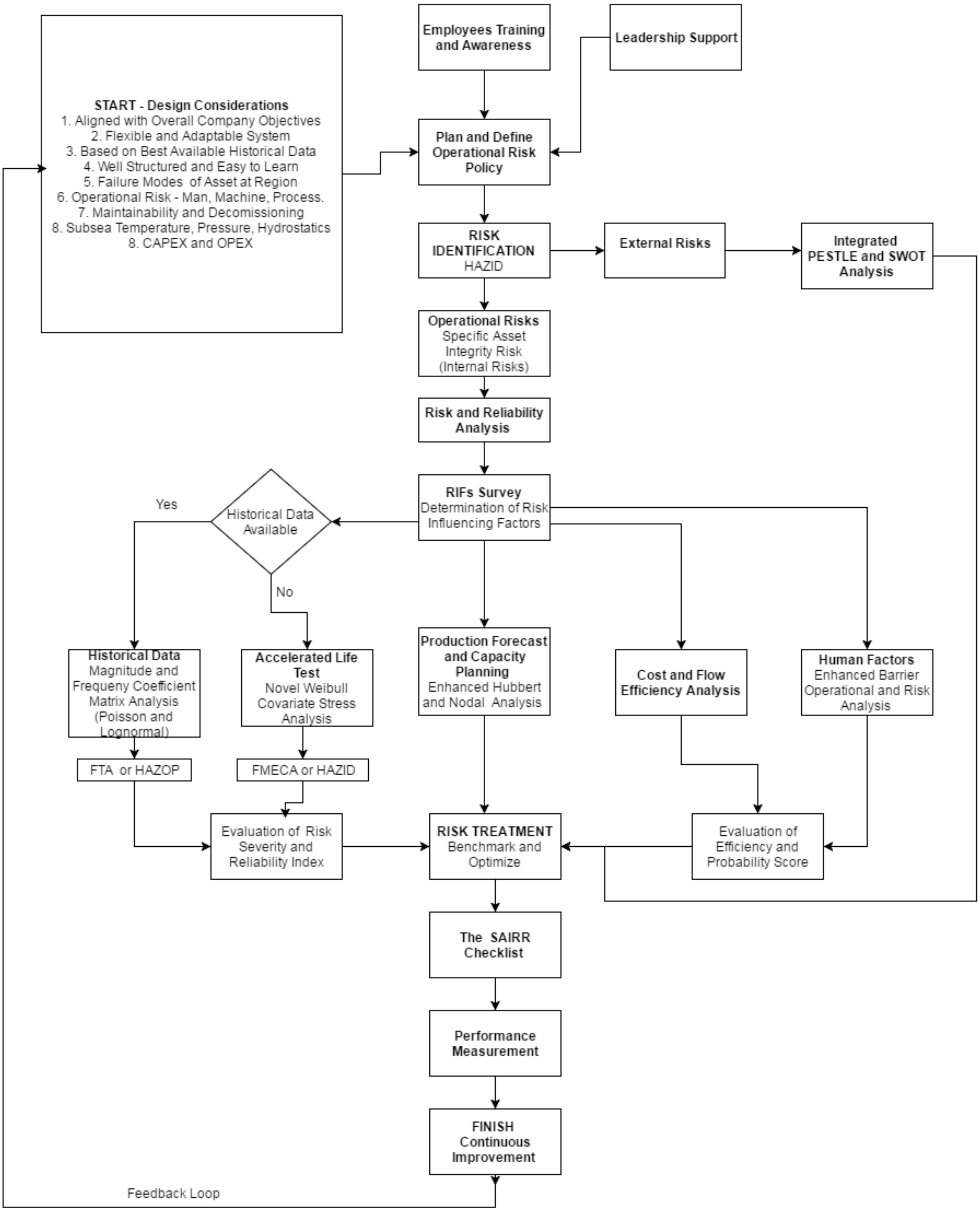


Figure 46: The Proposed Integrated Model

Another striking feature in the new model is that users can make a choice to use either the reliability Weibull covariate model for futuristic asset reliability estimations or the matrix severity model which depends on historical information as discussed in detail in Chapter 8. The Risk Influencing Factors (RIFs) are calibrated based on the key human reliability risks facing an asset or region and these are discovered through a combination of Hazard Identification (HAZID) study using a Delphi-style data collection method.

Other highlights of the model include the consideration of design variables at the start of the risk management process and also the consideration of external risks using PESTLE AND SWOT framework. This was done in order to further mitigate any interplaying risks from external sources which may be the root cause of the internal or operational ones.

Perhaps the most significant part of the model, was the inclusion of a Subsea Asset Integrity, Risk and Reliability Management (SAIRR) Integrated Checklist. This is an extensive but not exhaustive list of key requirements and considerations to make during risk and reliability as

The communication across functional teams in order to implement identify, analyse and evaluate the risks. This is clearly demonstrated by the feedback loops enmeshed into the new system model. Thereafter, the dangers/risks identified are analysed and prioritised before choosing and applying treatment. The cycle continues with performance review on those key design considerations at *START* as the cycle starts all over again from the take-off point for continuous improvement. The model could still be adapted to any subsea asset anywhere in the world as deemed fit according to the needs of the intending user but care must be taken in order not to distort logic, sequence and intentions of the models.

Other risk identification tools such as SWOT and PESTLE or FTA FMECA could be used at any stage to identify the potential operational risks as discussed in Chapter 2.

8.4.1 Sequence for Implementation of the Proposed Model

The implementation of the new model is a crucial part of this work because without a clear implementation plan.

8.4.2 Determination of Design Considerations

The first step towards implementation of the model is to establish the asset design specifications based on its intended working environment. The aim is to have a clear overall goal for the subsea system availability and efficiency. This could be done at the beginning of a fresh project or mid-life of an existing asset. The crucial activity here is to align risk and reliability exercise with the wider company objectives. Thereafter, the physical conditions of the sea which may include temperature, pressure, pH are established. Historical failure data or risks from man, machine or process are collected and the target operational costs are established. Based on this information, a reliability index is set. An efficiency index is also set and risk tolerance margin is established before proper system analysis starts in earnest.

8.4.3 Support from Leadership

Firstly, leadership support has to be sought. This will inspire the rest of both technical and operational employees to engage in the process within the company. The cost-benefit analysis of the process should be explained to the top management in a language they can understand which is economics, safety, reliability and risk metrics. Once this is done, it will be easier to win over the subordinates due to support and encouragement from the top leaders. The meeting with the top management may be done informally or formally.

8.4.4 Training and Awareness

Based on the support and mandate gotten from the company leadership and management, a sensitisation program shall be planned and delivered in-house to the rest of the employees. This can be accomplished within total contact session of about 7 hours; spread over a month depending on organisational operations. During these contact times, the risks in various systems are identified based on historical incidents and as mentioned earlier in the brainstorming session; parameters such as company objectives, current challenges, competitors are evaluated in order to develop a risk management strategy. The training shall consist of alerting the employees on the dangers, the risks within their respective working environment, the benefits of managing those risks and the essence of communication within interfacing teams for the prevention of mishaps. This is the rubrics for Risk and Reliability Assurance in an organisation.

8.4.5 Plan and Define Risk Policy

The setting of objectives involves defining the targets to be met by the risk management approach, how the targets will be achieved, and the participants of the programme. Specifics about the tolerance levels about a firm’s corporate objectives is depicted at this stage. This could be delivered by means of in-house workshops over a period of time depending on business engagement of the various and then supported massively by motivation from the organisations’ leadership and top management. Thereafter, the details of any supporting subsea standards, policy or framework with respect the requirements from each employee is adequately defined so that each employee is aware of his/her role. This aligns with the findings of the survey where respondents stated that employees’ participation is a major strategy which will booster the efficacy of Risk and Reliability Analysis.

8.4.6 Risk Identification

This crucial stage involves risk identification of both asset specific technical risks otherwise referred to as internal risks and the external risks. The technical risk assessment is evaluated using HAZID while the general external risks is analysed using a combination of SWOT and PESTLE. At this stage, the reliability Engineer runs a SWOT analysis of the operational activities of the firm. This will expose all the loop holes, challenges, opportunities and strong areas to be further fortified. A review of historical data from records or verbal interviews is conducted across the entire operational areas. These may include failure rates, waves severity, currents, corrosion profiles.

These data is obtained from the various operational departments within the firm which could be drilling, wells, production, mechanical, supply chain, management, human resources. The risks from trends and competition such as price of petroleum, new entrants and trends. The results of the SWOT analysis are then reviewed alongside the firms' corporate objectives in order to set an appropriate target. This would also provide the decision making team with the whole picture of the issues at stake and help in to deciding the best approach to manage the discovered risks. The model recommended in this work could be used since it has been tailored to suit the oil and gas subsea production industry.

8.4.7 Risk Analysis and Control

The step towards the actual risk analysis starts by calibration of risks inherent in a system. These could be technical and consist of cost parameters, temperature, pressure drop, efficiency. Others may include Human factors which is further split into task factors, administrative elements, personal factors, operational philosophy ratings using the enhanced BORA model presented in Chapter 4.

Whilst, there are several tools for risk identification, the approach recommended as depicted in the SAIRR checklist. This would not only help to identify as many risks as possible but also help to trace their root cause. It incorporates the PESTLE framework which is a proven and valuable tool for whole-system risk identification.

Historical data is used if available otherwise accelerated failure testing is carried out using the Weibull covariate reliability modelling and optimization principle proposed in Chapter 4. The latter gives a reliability index while the former gives a severity index based on four key factors, the risks themselves, the risk influencing factors, the magnitude and frequency of occurrence of the identified risks as shown in Chapter 6. For historical data, the matrix iteration method of Chapter 6 is used to calculate the severity of the risks so that a benchmark is decided for production assurance.

Process feasibility has become an integral part of risk analysis, therefore a clear methodology has been mapped out in Chapter 5 for predicting flow using Nodal analysis and pipe-pump flow efficiency calculation. This allows for selection of an optimum configuration of flow system from a range of physical parameters such as pressure drop, pipe diameter, power requirements and cost which are used to determine efficiency. These risks are quantified across all subsea production operations with the help of a risk matrix which may show the relationship between the severity, cost impact and urgency of a risk challenge using the formulae: *Risk Probability x Impact.*

Risk control in a subsea environment requires a preventive measure with an aim to have more automated/fail safe subsea systems and preventive identification strategy rather than manual processes and detective controls. The accelerated life testing method recommended in this thesis is a good preventive strategy which could provide information for the design of automatic redundant systems or sensor retrofits. From a commercial perspective, certain risks could either be treated, transferred by insurance or sharing with other operators, tolerated or terminated depending on circumstances. Whilst machine failures may not be completely terminated, they certainly could be treated and transferred or tolerated depending on impact on safety and project economics.

8.4.8 The SAIRR Checklist

The Subsea Asset Integrity, Risk and Reliability (SAIRR) checklist in Table 32 was developed based on the results of the survey and integrated model standards. It focuses on actions to be carried out by firms based on their size, scales and kind of operations. It addresses the specific key risk component areas to be investigated when making risk control decisions. It is aimed at helping subsea operators towards a thorough evaluation of risk areas in subsea operations. A pass or fail is ticked for each activity in such a way that a pass ends the query for the activity. However, a fail suggests a need for further action which could be any/or a combination of treatment, transfer or toleration or termination of a risk process.

Table 32: Subsea Asset Integrity, Risk and Reliability Checklist (SAIRR)

ID	Activity	Pass	Fail	Treat	Transfer	Tolerate	Terminate
1.1	Has the expected production been evaluated?						
1.2	Have the subsea production assets been selected based on expected output performance? For example, recovery rate						
1.3	Was the selection based on efficient least-cost options?						
1.4	Has the power requirement been identified and assured?						
1.5	Is there a historical data for the asset failure mechanisms if not has the failure modes been predicted?						
1.6	Has the reliability index of the system been evaluated?						
1.7	Are the reliability indices stressed enough with peculiar prevailing conditions of the subsea domain?						
1.8	Have the critical failure components been identified and optimized?						
1.9	Are there enough redundancies and fail-safe systems for the critical components?						
1.10	Has human reliability been considered?						
2.1	Is there a risk management policy or standard in place?						
2.2	Do all the relevant team members know the details of the standard and what their roles are?						
2.3	Is risk management decentralized across the teams?						
2.4	Are the managers highly supportive towards of the risk culture program?						
2.5	Is there continuous and adequate training for staff?						
2.6	Is there an adequate performance measurement for risk reporting and optimization?						
2.7	Are the lessons-learnt properly indexed and communicated?						

CHAPTER 9

CONCLUSION

The operational requirements of a subsea processing system can be understood and improved using a combination of physical, computational and stochastic projections. This study provides a significant piece of new knowledge which is obtained by intelligently crafting-out and building a selection of robust numerical models into an integrated whole-system model for realistically evaluating the production capacity, reliability, risk and cost-efficiency of emerging subsea oil production systems.

9.1 Research Findings and Conclusions.

- High MTTF of individual components is not directly proportional to high overall reliability of a system, rather the total cumulative of stressed MTTFs along with frequency and times of failure gives a better prediction of a system's reliability.

- It is more efficient and time-saving to (a) identify any infant mortality (b) identify over-designed components by applying Weibull failure model and Fusell-Vesely theory to their minimal cut sets for optimizing overall reliability index based on criticality and reliability importance of components. The initial basic reliability of the system was optimized by a margin of 52% from 0.45 to 0.95 based on the confidence interval of the whole reliability analysis. The failure rate of the components of a system can be stressed statistically for optimal smoothening of over-designed components and under-designed ones.

- The research revealed that there is no significant relationship linking the number of component cut- sets and expected failure, reliability, unreliability and failure frequency, but there seems to be a relationship between the number of cut-sets and severity index. Thus, the lower the cut sets, the higher the severity risk. However, the biggest contributor to the severity index is total downtime.

- Low subsea temperatures, high CO2 fugacity and pH variation has a significant impact on asset degradation rate, failure modes and frequency over a time series. Personnel factors such as competence of the operators, works stress, fatigue, stress, and ergonomics constitute the highest probability of risk influencing factors that could cause failure in a subsea gas compression system.

- The volumetric efficiency output of Electric Submersible Pumps in deep water subsea wells outperforms the PCP artificial lifts under the same subsea and oil-well conditions. While PCP technology seems to have good cost efficiency and low operating costs, the continuous rise in offshore oil production could trigger a proportionate increase in ESP field application far more than even rod pumps or PCPs which from this study have shown inefficiency towards lifting high fluid volumes in offshore situations. The study showed that production target was over the 12 years of production with an excess of 530 STB with 88% efficiency obtained.

- Based on the industry data received and analysis performed, latent sensor failure in drill bits is the top level failure with the most impact during offshore drilling. They are of high reliability importance because they help to control torque, annular pressure, load, vibration, temperature and pressure of drilling bit.

- Risk management is being implemented across all scales of the subsea industry. This survey result has confirmed that the size of subsea operation does not hinder implementation because it is a cultural concept and not a mere regulatory standard. Notwithstanding, bigger subsea companies expressed more awareness and know-how than the smaller and medium ones. This could be attributed to decentralisation of risk management in bigger firms rather than the silo-based approach in smaller firms.

9.2 Contributions of the Thesis: Highlights

This research is original and significant in a number of ways:

- This research produced a new Weibull-corrosion covariate reliability model for stressing baseline OREDA data of subsea components in order to obtain more realistic failure times and enhance their reliability designs or make adequate plans for tolerances and redundancies.

- A new methodology was developed for selecting optimal pump and pipe configurations for subsea oil and gas production based on flow output, power requirement and least capital cost.

- A new method was developed for calculating the severity of complex risk scenarios based on frequency and magnitude of perceived the risks.

- A survey was conducted on subsea oil and gas operators to understand how reliability and risk in being managed. The qualitative aspects of the integrated model.

- A new integrated model was developed for estimating present risks and predicting expected risks in the operation of a subsea oil and gas asset.

9.2 Recommendations:

- The accelerated life testing model based on Weibull-Corrosion covariate reliability is recommended for predicting a realistic failure rate compared to the basic reliability models which does not consider credible external influences. Reliability optimisation using the enhanced block diagrams recommended in chapter 4 and enhanced Fusell-Vesely analysis approach can be used to identify components' failure mode, critical reliability importance and optimize them thereby preventing costs associated with unplanned failures.

- The selection of an efficient subsea pump and/or pipe system requires a holistic consideration of the key physical and economic parameters that affect production performance.

- Subsea production firms should adopt a preventative approach for asset reliability and risk management by employing the proposed risk management model in Fig 7 rather than relying on crisis management or total neglect of operational risks.

- It is necessary that risk severity is evaluated from both a human reliability perspective as well as within a process/equipment scope for a broad picture and adequate control.

- All sizes of subsea production industry can apply risk and subsea reliability management to its subsea production system provided that the details of the policy are well-defined and the participants (no matter the size) are clearly furnished with their respective roles.

- There is need to create adequate redundancy for sensors used in offshore drilling bits.

  The efficiency of PCP could be enhanced by improving on corrosion resistant designs, large cavities and reliable components for underwater performance. Perhaps a robust design configured with wear-resistant underwater gears could increase rod's compression action and consequently, high volumetric output.

- The structural framework, guideline and the SAIRR checklist has for effective subsea production assurance incorporated the models developed in the study, the lessons learnt from literature and the discovery from the survey.

9.3 Strengths of the Research

The major strengths are enumerated below.

- In combining the statistical confidence bounds of a two parameter Weibull model and a corrosion-based covariate model to develop a new reliability model technical failure assessment, this study demonstrates that the lifecycle operational requirements of a subsea system can be understood and improved by analysing the effect of a corrosion stress on a Weibull failure data in addition to fuzzy scaling of human and operational barriers A case study of a subsea compression system was used to demonstrate the applicability of the model. The poor reliability index of the system can be optimized by breaking down component parts using Reliability-Block-Diagrams (RBD) and prioritizing the components based on reliability importance.

- The unique feature of the method is its focus on the integration of the supporting systems of a subsea asset. From the perspective of a subsea engineer, it implies a more holistic view of the system design including both the technically dependent main process and organisationally dependent supporting processes.

- The approach supports the step by step reduction of system complexity, from process to individual activities, and thus gives operators and technical staff the opportunity to recognise their role in the supporting processes. It thereby provides realistic inputs in terms of activity scope, time and required variables and resources. This approach has been found to result in a high acceptance of the model by the staff involved in the project.

- One important and unique feature of the subsea reliability and risk model proposed in this work is the inclusion of a measure of implementation and performance improvement and how this is expected to be looped back into system design for continuous improvement.

- It provided a structured analytical process which incorporates proven standards for the identification and optimization of main risk variables in a subsea system.

9.4 Future Research

The author acknowledges the benefits of this research, the relevant issues treated and the limitations therein. Further study on the topic could focus on the following issues:

- Results from a three-parameter Weibull covariate model could be compared against a two-parameter model using a larger failure data set.

- Validation of models with a real case study.

- Analysis may be performed on failure modes of subsea assets operating in cold Arctic waters beyond a 4000m depth especially those facing the stress of iceberg gouging.

- The reliability models could be applied to many other subsea processing equipment incorporating key influencing factors.

- Nodal analysis and production risk analysis on longer tiebacks from well to platforms or to shore.

- Determination of the relationship between reliability drivers and survivability variables.

- A more detailed questionnaire may be repeated over a larger sample size in order to actually measure the performance levels and concerns across each scale of subsea production. For instance, across small, medium and large scale companies.

- Future research may compare reliability management practices at contemporary subsea hotspots such as Brazil, West Africa and the Arctic to come up with a more robust risk management framework. This will help to bring out the best practices in each of the various cultures and further help to verify Hofstede's (1984) findings about uncertainty in work culture.

Finally, the information presented in this thesis is reliable at the time it was written and is meant to be beneficial to researchers, operation managers and risk practitioners who work in the subsea oil and gas sector. The work contains original specific advice as regards the common challenges to be expected, a proposed model for its management and recommendations on how to implement the model effectively in alignment with the overall business strategy so as to mitigate losses, enhance productivity and improve safety records.

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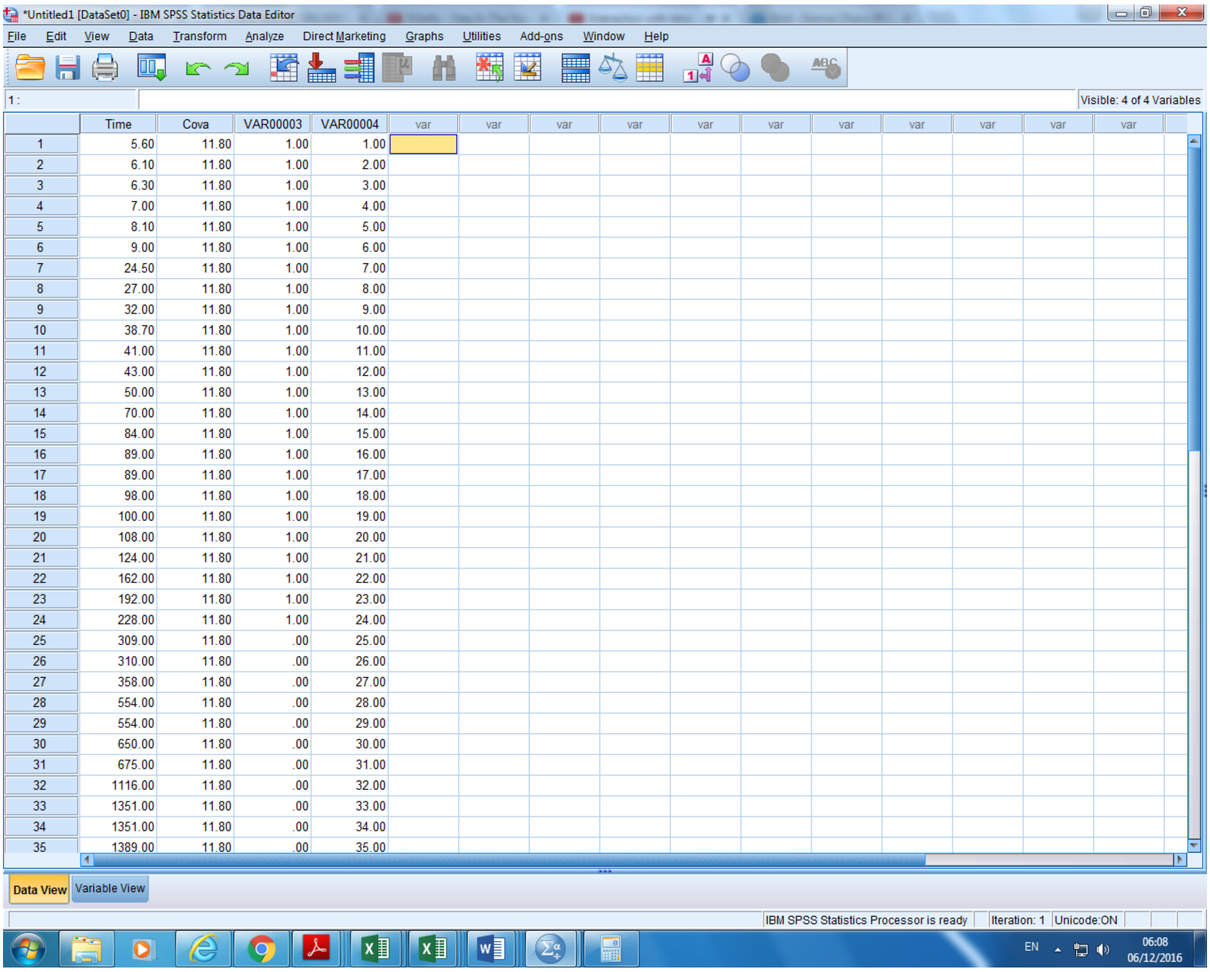
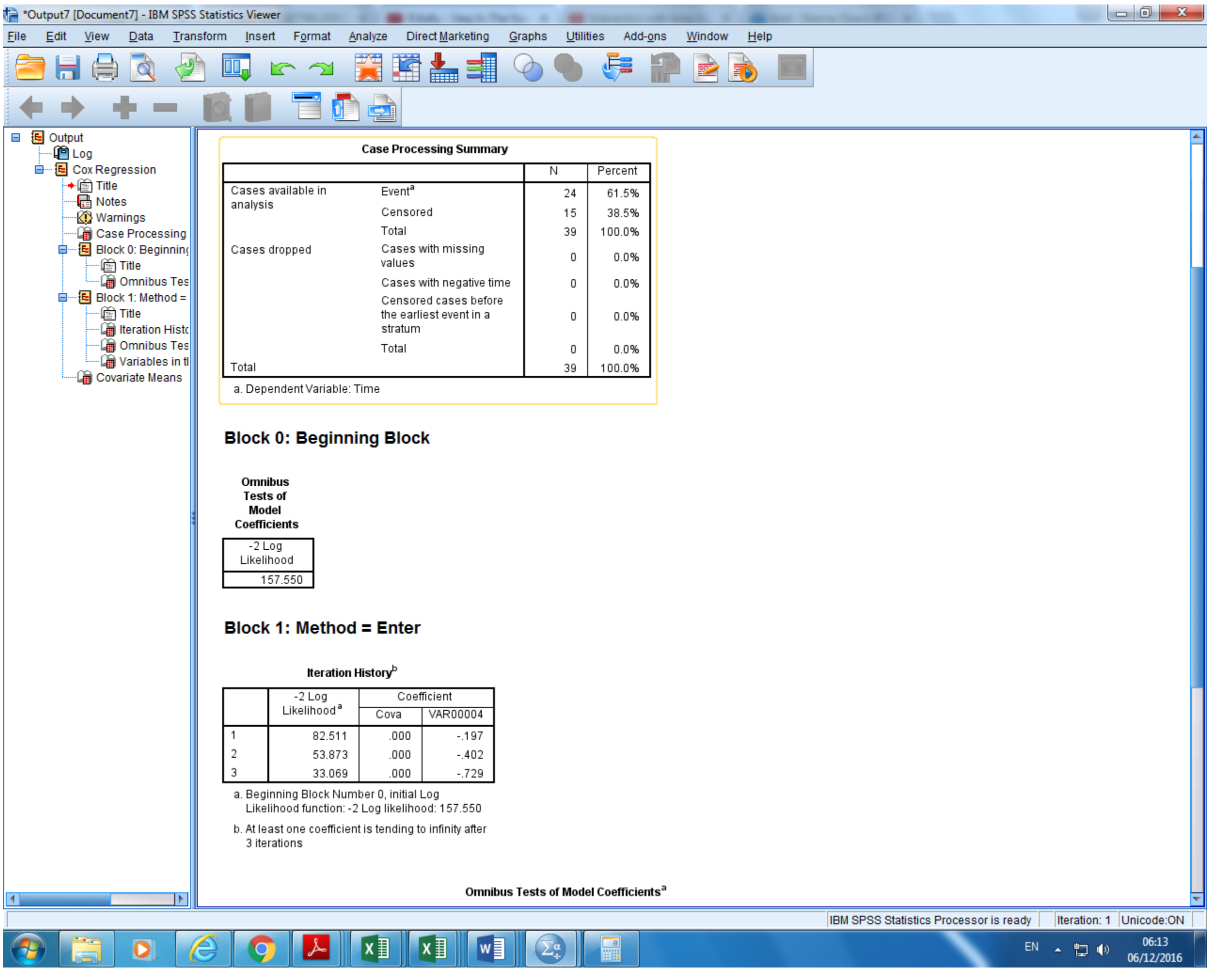


	Time	Cova	VAR00003	VAR00004
1	5.60	11.80	1.00	1.00
2	6.10	11.80	1.00	2.00
3	6.30	11.80	1.00	3.00
4	7.00	11.80	1.00	4.00
5	8.10	11.80	1.00	5.00
6	9.00	11.80	1.00	6.00
7	24.50	11.80	1.00	7.00
8	27.00	11.80	1.00	8.00
9	32.00	11.80	1.00	9.00
10	38.70	11.80	1.00	10.00
11	41.00	11.80	1.00	11.00
12	43.00	11.80	1.00	12.00
13	50.00	11.80	1.00	13.00
14	70.00	11.80	1.00	14.00
15	84.00	11.80	1.00	15.00
16	89.00	11.80	1.00	16.00
17	89.00	11.80	1.00	17.00
18	98.00	11.80	1.00	18.00
19	100.00	11.80	1.00	19.00
20	108.00	11.80	1.00	20.00
21	124.00	11.80	1.00	21.00
22	162.00	11.80	1.00	22.00
23	192.00	11.80	1.00	23.00
24	228.00	11.80	1.00	24.00
25	309.00	11.80	.00	25.00
26	310.00	11.80	.00	26.00
27	358.00	11.80	.00	27.00
28	554.00	11.80	.00	28.00
29	554.00	11.80	.00	29.00
30	650.00	11.80	.00	30.00
31	675.00	11.80	.00	31.00
32	1116.00	11.80	.00	32.00
33	1351.00	11.80	.00	33.00
34	1351.00	11.80	.00	34.00
35	1389.00	11.80	.00	35.00



Case Processing Summary

		N	Percent
Cases available in analysis	Event[a]	24	61.5%
	Censored	15	38.5%
	Total	39	100.0%
Cases dropped	Cases with missing values	0	0.0%
	Cases with negative time	0	0.0%
	Censored cases before the earliest event in a stratum	0	0.0%
	Total	0	0.0%
Total		39	100.0%

a. Dependent Variable: Time

Block 0: Beginning Block

Omnibus Tests of Model Coefficients

-2 Log Likelihood
157.550

Block 1: Method = Enter

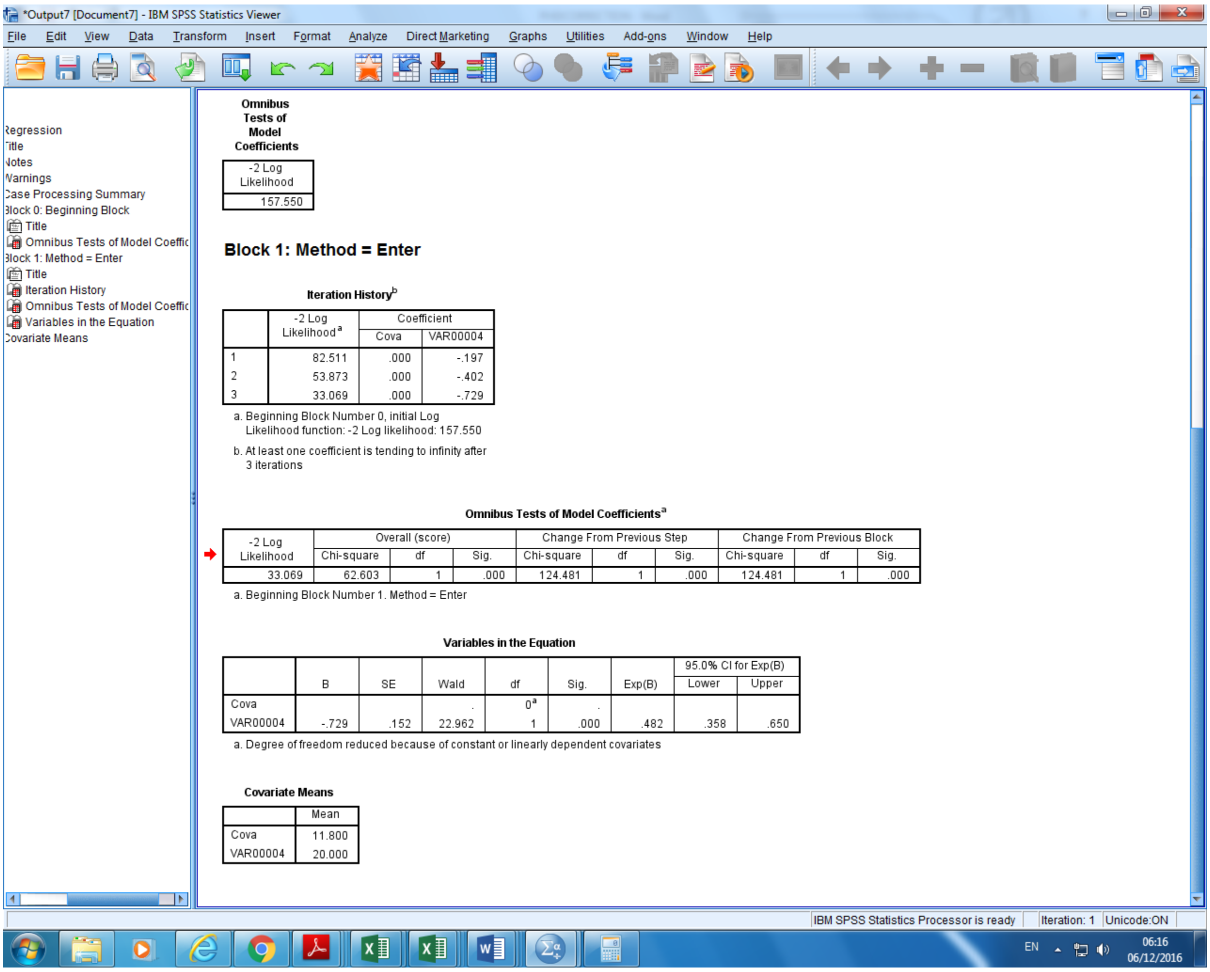
Iteration History[b]

	-2 Log Likelihood[a]	Coefficient	
		Cova	VAR00004
1	82.511	.000	-.197
2	53.873	.000	-.402
3	33.069	.000	-.729

a. Beginning Block Number 0, initial Log Likelihood function: -2 Log likelihood: 157.550

b. At least one coefficient is tending to infinity after 3 iterations

Omnibus Tests of Model Coefficients[a]



Omnibus Tests of Model Coefficients

-2 Log Likelihood
157.550

Block 1: Method = Enter

Iteration History[b]

	-2 Log Likelihood[a]	Coefficient	
		Cova	VAR00004
1	82.511	.000	-.197
2	53.873	.000	-.402
3	33.069	.000	-.729

a. Beginning Block Number 0, initial Log Likelihood function: -2 Log likelihood: 157.550

b. At least one coefficient is tending to infinity after 3 iterations

Omnibus Tests of Model Coefficients[a]

-2 Log Likelihood	Overall (score)			Change From Previous Step			Change From Previous Block		
	Chi-square	df	Sig.	Chi-square	df	Sig.	Chi-square	df	Sig.
33.069	62.603	1	.000	124.481	1	.000	124.481	1	.000

a. Beginning Block Number 1. Method = Enter

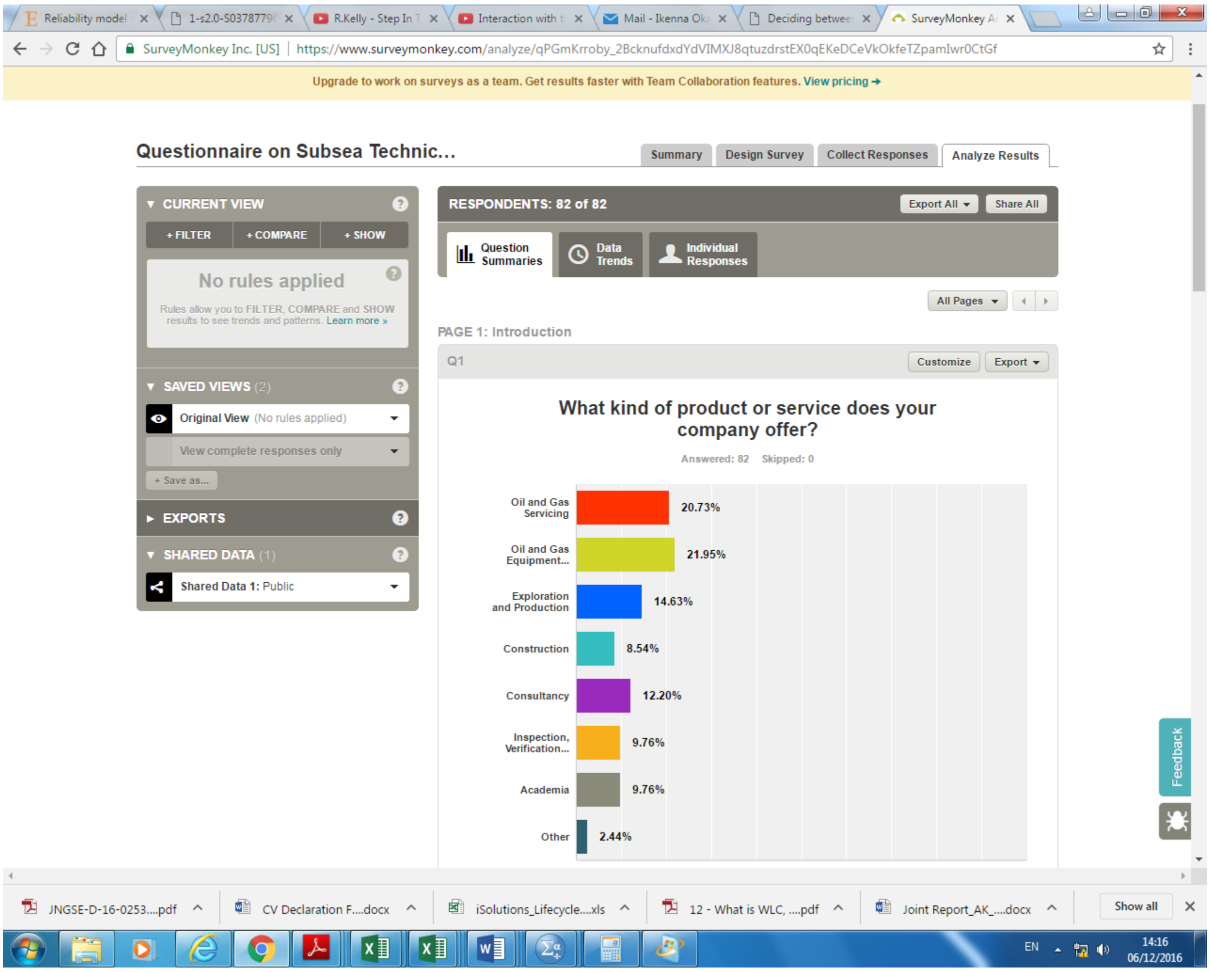
Variables in the Equation

	B	SE	Wald	df	Sig.	Exp(B)	95.0% CI for Exp(B)	
							Lower	Upper
Cova			.	0[a]	.			
VAR00004	-.729	.152	22.962	1	.000	.482	.358	.650

a. Degree of freedom reduced because of constant or linearly dependent covariates

Covariate Means

	Mean
Cova	11.800
VAR00004	20.000



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Questionnaire on Subsea Technic...

No rules applied

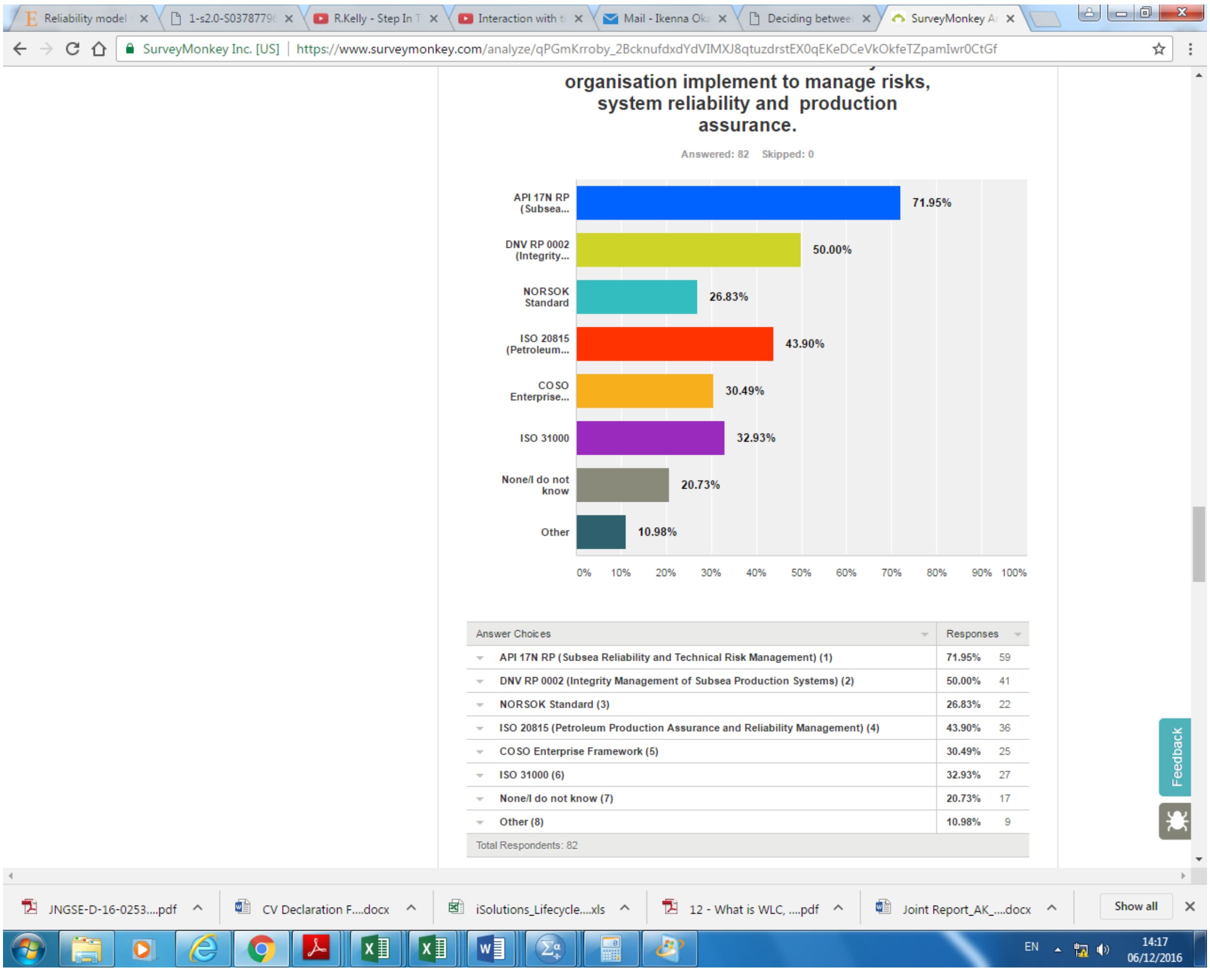
Rules allow you to FILTER, COMPARE and SHOW results to see trends and patterns. Learn more »

PAGE 1: Introduction

Q1

What kind of product or service does your company offer?

Answered: 82 Skipped: 0



organisation implement to manage risks, system reliability and production assurance.

Answered: 82 Skipped: 0

Answer Choices	Responses	
API 17N RP (Subsea Reliability and Technical Risk Management) (1)	71.95%	59
DNV RP 0002 (Integrity Management of Subsea Production Systems) (2)	50.00%	41
NORSOK Standard (3)	26.83%	22
ISO 20815 (Petroleum Production Assurance and Reliability Management) (4)	43.90%	36
COSO Enterprise Framework (5)	30.49%	25
ISO 31000 (6)	32.93%	27
None/I do not know (7)	20.73%	17
Other (8)	10.98%	9
Total Respondents: 82		