CRANFIELD UNIVERSITY

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SCHOOL OF ENVIRONMENT ENERGY AND AGRIFOOD
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PhD
Academic Year: 2011 - 2015

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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

The Subsea blowout preventer (BOP) which is latched to a subsea wellhead is one of several barriers in the well to prevent kicks and blowouts and it is the most important and critical equipment, as it becomes the last line of protection against blowout. The BOP system used in Subsea drilling operations is considered a Safety – Critical System, with a high severity consequence following its failure. Following past offshore blowout incidents such as the most recent Macondo in the Gulf of Mexico, there have been investigations, research, and improvements sought for improved understanding of the BOP system and its operation. This informs the need for a systematic re-evaluation of the Subsea BOP system to understand its associated risk and reliability and identify critical areas/aspects/components.

Different risk analysis techniques were surveyed and the Failure modes effect and criticality analysis (FMECA) selected to be used to drive the study in this thesis. This is due to it being a simple proven cost effective process that can add value to the understanding of the behaviours and properties of a system, component, software, function or other. The output of the FMECA can be used to inform or support other key engineering tasks such as redesigning, enhanced qualification and testing activity or maintenance for greater inherent reliability and reduced risk potential. This thesis underscores the application of the FMECA technique to critique associated risk of the Subsea BOP system. System Functional diagrams was developed with boundaries defined, a FMECA were carried out and an initial select list of critical component failure modes identified. The limitations surrounding the confidence of the FMECA failure modes ranking outcome based on Risk priority number (RPN) is presented and potential variations in risk interpretation are discussed.

The main contribution in this thesis is an innovative framework utilising Multicriteria decision making (MCDA) analysis techniques with consideration of fuzzy interval data is applied to the Subsea BOP system critical failure modes from the FMECA analysis. It utilised nine criticality assessment criteria deduced from expert consultation to obtain a more reliable ranking of failure modes. The

MCDA techniques applied includes the technique for order of Preference for similarity to the Ideal Solution (TOPSIS), Fuzzy TOPSIS, TOPSIS with interval data, and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE). The outcome of the Multi-criteria analysis of the BOP system clearly shows failures of the Wellhead connector, LMRP hydraulic connector and Control system related failure as the Top 3 most critical failure with respect to a well control. The critical failure mode and components outcome from the analysis in this thesis is validated using failure data from industry database and a sensitivity analysis carried out. The importance of maintenance, testing and redundancy to the BOP system criticality was established by the sensitivity analysis. The potential for MCDA to be used for more specific analysis of criteria for a technology was demonstrated.

Improper maintenance, inspection, testing (functional and pressure) are critical to the BOP system performance and sustenance of a high reliability level. Material selection and performance of components (seals, flanges, packers, bolts, mechanical body housings) relative to use environment and operational conditions is fundamental to avoiding failure mechanisms occurrence. Also worthy of notice is the contribution of personnel and organisations (by way of procedures to robustness and verification structure to ensure standard expected practices/rules are followed) to failures as seen in the root cause discussion. OEMs, operators and drilling contractors to periodically review operation scenarios relative to BOP system product design through the use of a Failure reporting analysis and corrective action system. This can improve design of monitoring systems, informs requirement for re-qualification of technology and/or next generation designs. Operations personnel are to correctly log in failures in these systems, and responsible Authority to ensure root cause analysis is done to uncover underlying issue initiating and driving failures.

Keywords:

FMECA, Risk Analysis, Subsea BOP, Fuzzy-TOPSIS, PROMETHEE

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“Unto God be the glory, great things he hath done! For he has done great”

Days, months and years have come and gone, and this study has finally come to an end, a means to greater new beginnings, and it has been remarkable. To everyone that made the challenging journey worthwhile, this piece is to say a huge thank you for believing in me and sharing in the dream.

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Finally Romans 8:37 …

“Yet in all these things we are more than conquerors through Him who loved us”

... I want to thank God almighty for making this dream come through.

DEDICATION

I dedicate my thesis unto Him, the Author and Finisher of my faith, and

in loving memory of my Late Aunt Ada Dearson George, for speaking words when they had no life…

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LIST OF ABBREVIATIONS

ABS	American Bureau of Shipping
AC	Alternating Current
ADF	Automatic Disconnect Function
AHP	Analytical Hierarchy Process
AIAG	Automotive Industry Action Group
AIPMV	Accumulator Isolator Pilot Manipulator Valve
AMF	Automatic Mode Function
ANP/APR	Annular Pipe Ram
AP	Annular Preventer
API	American Petroleum Institute
API RP	American Petroleum Institute Recommended Practice
BHA	Bottom Hole Assembly
BHP	Bottom Hole Pressure
BP	British Petroleum
BOEMRE	The Bureau of Ocean Energy Management, Regulation and Enforcement
BOP	Blowout Preventer
BSEE	The Bureau of Safety and Environmental Enforcements
BSR	Blind Shear Ram
C	Criticality Number
CCU	Central Control Unit
CFMEA	Concept Failure Modes Effect Analysis
CSB	Chemical Safety Board
C&K	Choke and Kill
DEA	Data Envelopment Analysis
DC	Direct Current
DFMEA	Design Failure Modes Effect Analysis
DM	Decision Making
DMs	Decision Makers
DP	Dynamic positioned
EDS	Emergency Disconnect Sequence

EED	Energy, Exploration, and Development Insurance
EH	Electro Hydraulic
EIL	Environmental Integrity Level
ELECTRE	Elimination Et Choix Traduisant la Realit'e (elimination and choice expressing reality)
ENVID	Environmental Hazard Identification
ESD	Emergency Shutdown
FFMEA	Functional Failure Modes Effect Analysis
FM	Failure Mode
FMEA	Failure Modes Effect Analysis
FMECA	Failure Modes Effect and Criticality Analysis
FTC	Fails to Close
FTO	Fails to Open
GOM	Gulf of Mexico
GTL	Gas to Liquid
HAZID	Hazard Identification
HCM	Hydraulic Control Manifold
HCU	Hydraulic Control Unit
HIL	Hardware-in-the-Loop
HPHT	High Pressure High Temperature
HPR	Hydraulic Pressure Regulator
IEC	The International Electro-technical Commission
IFMEA	Interface Failure Modes Effect Analysis
I/O	Input/ Output
IMO	International Maritime Organisation
ISO	IMO International Standard Organisation
IT	Information Technology
IMCA	The International Marine Contractors Association
LPR	Lower Pipe Ram
LRMP	Lower Riser Marine Package
MADM	Multi Attribute Decision Making
MCDA	Multi Criteria Decision Making
MIL	Military (US Armed Forces)

MMS	Mineral Mining Service
MODM	Multi Objective Decision Making
MODU	Mobile Offshore Drilling Unit
MTTF	Mean Time to Fail
MUX	Multiplex Control System
NACE	National Association of Corrosion Engineers
NASA	National Aeronautics and Space Administration
NOPSA	The National Offshore Petroleum Safety Authority (Australian)
NORSOK	‘Norsk Sokkels Konkuranseposisjon (Norwegian Technology Centre)
OLF	The Norwegian Oil Industry Association
P	Pressure
PFD	Probability of Failure on Demand
PLC	Programmable Logic Controller
PMAIV	Pod-Mounted Accumulator Isolation Valve
PR	Pipe Ram
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PSV	Pod Selector Valve
RBD	Reliability Block Diagram
ROV	Remote Operated Vehicle
RP	Ram Preventer
RPN	Risk Priority Number
SHR	Subsea Hydraulic regulators
SAE	Society for Automotive Engineers
SAIV	Surface Accumulator Isolation Valve
SC	Spuriously Closes
SEM	Subsea Electronic Module
SHR	Subsea Hydraulic Regulator
SIL	Safety Integrity Level
SINTEF	Stiftelsen for industriell og teknisk forskning (Foundation for Scientific and Industrial Research)
SMAIV	Subsea Mounted Accumulator Isolation Valve
SO	Spurious Opens

SPF	Single Point Failures
SPM	Sub Plate Mounted
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
TRC	Technical Risk Categorisation
TRL	Technology Readiness Level
TQP	Technology Qualification Plan
UK	United Kingdom
UPR	Upper Pipe Ram
US	United States
VBR	Variable Bore ram
f	frictional
h	Hydrostatic
sg	Surge
sw	Swab
t	Operating time
α	Failure mode ratio
β	Probability of the failure effect
γ	Component failure rate

1 INTRODUCTION

The dwindling onshore oil and gas reserves and the ever increasing global demand for petroleum products is driving exploitation of reserves in remote offshore locations in order to cope with the insatiable appetite of an energy hungry world. The volatile oil price and the unprecedented hike in energy demand, prior to the current climate in which oil supply exceeds demand, had ushered the affinity for prospects in great water depths. This rapid shift towards great depth and ultra-deep waters offers complex environment, which is remote for operations and not typically explored part of the earth. Exploration and production within this harsh environment offers a number of technical challenges in the area of flow assurance, installation, intervention and monitoring especially for ultra-deepwater (DNV-GL, 2014; TTA 7, 2008). The pressures to the system and challenges associated with subsea-production are magnified by the highly saline wet environment (Fidler, 2009).

Considering the entire exploration and field development cycle, drilling operation is the most expensive element with a high need and requirement for safety. There are a number of problems that can occur during drilling operations, particularly for subsea wells. The occurrence of kick is an example of an issue that can be catastrophic. Kick is described as the unwanted influx of formation fluid into a wellbore during drilling operation as a result of pressure difference in the wellbore. This influx is undesired, because it can flow up to the surface and result in a blowout with potential consequence of a major spill, fatalities and loss of rig. A blowout is an uncontrolled flow of hydrocarbon or even salt water from a well to the surrounding environment, an ultimate consequence of a kick. To avoid an undesired influx and maintain well control, drilling systems have been designed with first-line and backup barriers. The blowout preventer (BOP) is one of several barriers in the well to prevent kicks and blowouts. It is the most important and critical equipment, as it becomes the last line of protection against blowout.

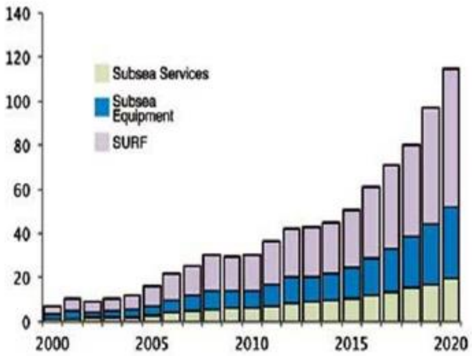
The BOP is a structure with a large set of valves and rams placed on the top of the well that can be closed when the drilling crew have uncontrolled flow of formation fluid in the wellbore. Naturally blowouts do not just happen, there are series of unscheduled events with indicators that require actions from the supervisors and when this is not properly managed, fatal accidents occur with an associated failure of the last line of defence (the BOP). Globally and in the history of the offshore industry there have been blowout cases which is not uncommon given 573 well releases/blowouts is recorded in the Stiftelsen for industriell og teknisk forskning -Foundation for Scientific and Industrial Research (SINTEF) database as at 2013. It is important to mention not all past blowout incidents have had potential to result in a major spill such as the most remarkably IXTOC 1 well blowout in 1979 which led to the greatest single spill in the Gulf of Mexico (GOM) before the Macondo incident in 2010 (Page, 2010). The six worst offshore blowout incidents by volume are listed in Table 1-1.

Table 1-1: Six worst offshore blowout incidents by volume (Adapted from King, 2010)

Blowout Incident	Location/Year	Amount of Oil Spill (bbl.)
Deepwater Horizon (Macondo)	Gulf of Mexico, USA/ 2010	4,900,000
Sedco 135F and the Ixtoc I	Bay of Campeche, Mexico/1979	3,552,000
Abkatun 91	Bay of Campeche, Mexico/ 1986	247,000
Ekofish Bravo Platform	North Sea, Norway/ 1977	202,381
Funiwa No. 5 Well	Forcardos, Nigeria/1980	200,000
Hasbah Platform Well 6	Persian Gulf, Saudi Arabia/1980	105,000

Nineteen blowouts cases had occurred in the GOM between 2007 and 2009 (Cheremisinoff and Davletshin, 2010). The published results of the Bureau of Safety and Environmental Enforcement (BSEE) on dangerous well occurrences such as blowout shows a decrease in the gulf between 2008 and 2012, and a reverse trend observed for the UK (Mannan et al., 2014). Although the actual number of blowout occurrence was higher in congruence with the level of drilling activity. It is evident from the above Table 1-1 that blowout incidents have been and will still remain a global concern especially with considering the number of wells that were under development and a potential over six thousand wells expected to be drilled (see Figure 1-1 showing statistics and forecast for Subsea market and operations).

Despite the awareness that would have sprung up given the lessons learned and the opportunities for improved training and research on the subject of well control and the BOP, these incidents still occur. Preventive and mitigation measures can be used to reduce the risk of a blowout as it cannot be eliminated.



(a)

	Operational	Under Development	Planned/Possible	Total
Floaters	280	41	340	661
Fixed Platforms	9,273	128	1,421	10,822
Subsea Wells	4,504	406	6,466	11,376

(b)

Figure 1-1: (a) Subsea market forecast 2014 to 2018, (Douglass Westwood 2014). (b) Statistic of Offshore production systems worldwide operational and 2014 onwards (Morgan 2014).

Priority is given to preventive safety measures to reduce the probability, as risk is the product of probability of occurrence and the consequence. Thus risk analysis has been seen to be of great importance with applicability in offshore drilling operations, challenged with safety issues arising from harsh and remote environments. It is pertinent to note, that besides the ultimate failure of the BOP which can be catastrophic, there are other failures of the BOP that may require its retrieval to surface and a suspension of drilling activity. Retrieving the Subsea BOP and the marine riser owing to a problem have been associated to be one of the most expensive downtime events. The maintenance of reliability and readiness of well control equipment for the safety of lives, equipment and environment, is thus of great importance and top priority.

The prevalence of subsea BOP system related failures amidst several studies on the system and its component(s) carried out questions its reliability. Thus there is a new call to understand BOP failures and malfunctions, and how risk studies can be translated to improved reliability. The foregoing corroborates with the Norway's Petroleum Safety Authority identification of people management, risk and barriers as the three main issues/ subjects requiring in-depth study for better management tools, reliable decision making and prioritisation process, and overcoming safety challenges within the petroleum industry.

1.1 Past Blowout Events

Blowouts incident constitutes one of the highest occurrences amongst other recorded accidents within the offshore industry's exploration and production of oil and gas (Ismail, et al. 2014). In the life of a well, the drilling operation phase has been associated with the greatest number of loss of well control/blowout incidents. In Ge et al (2015) survey of 134 blowout incidents from 1970 to 2013, 89% occurred during drilling operation. Table 1-2 shows a list of notable incidents in the last fifteen (15) years. This section attempts to discuss some notable past blowout incidents (major accident and some near misses) for context as part of the introduction and to support the rationale and importance for the research work.

Table 1-2: Notable past blowout incidents

Blowout Incident	Location/Year	Damage /Associated Loss	Water Depth
Ensco 51	Gulf of Mexico, USA/ 2001	Gas blowout and fire.	191ft (58.2m)
Arabdrill 19/ Khafji Field	Persian Gulf, Saudi Arabia/2002	Structural collapse, blowout, fire, and sinking (Gas &Oil)	94ft(28.6m)
Adriatic IV (Temsah Platform)	Mediterranean Sea, Egypt/2004	Well blowout and fire on platform (Gas)	263ft (80m)
Usumacinta (Kab 101 Platform)	Gulf of Mexico/2007	Well blowout on platform, 22 Killed	82 (25m)
West Atlas Rig (Montara Wellhead P	East Timor sea, Australia/2009	Well blowout and fire on rig and platform (Gas &Oil)	250 ft (76m)
Deepwater Horizon (Macondo)	Gulf of Mexico, USA/ 2010	Well blowout and fire on rig, 11 killed in explosion (Gas)	5000 ft (1500m)
Vermilion Block 380 Platform	Gulf of Mexico, USA/ 2010	Well blowout and fire, 1 injured	340ft (104m)
Funiwa 1A well (KS endeavour Rig)	Nigeria/2012	Well blowout and fire on rig, 2 killed in explosion (Gas)	40ft

On December 10, 1978 the IXTOC 1 well (water depth of 50m) drilling was commenced by Sedco 135F for Petroleos Mexicanos. Drilling mud loss started at a depth of 3615 m on the early of June 2, and circulation was lost at 3625 m.

As well appeared stable after several unsuccessful attempts to regain circulation, a decision was made to pull the drill string and insert a plug into well. Mud flowed up unrestricted to platform, given no mud hydrostatic column, and the extreme high pressure during well sealing attempts. The BOP was closed on the lower pipe but it could not shear the thicker drill collars, and thus could not prevent flow of oil and gas to surface. The well blowout occurred on the 3rd of June, 1979, thereafter rig collapse and sank on wellhead area on the seabed, spilling over 3.5 million barrels of oil to the GOM as well was not capped until 290 days later. To relieve the gushing well pressure, two relief wells were drilled and then IXTOC-1 well killed nine months later (Jernelov and Linden, 1981)

The 2002 Arabdrill 19 blowout in Saudi Arabia was the result of a structural failure. One of the legs of the jack-up rig, located over a production platform, buckled leading to the rig collapse on the platform and destroying the production tree. This resulted into a blowout and fire with both rig and platform sank. In August 2007 the Minerals Management Services (MMS) published a decrease in fatalities following blowout incidents between 1992 and 2006 within the GOM (Izon et al., 2007). Not long in October, 2007, there was the Usumacinta blowout incident which occurred during the drilling of Kab-103 well when the rig collided with the platform, ruptured the production tree on Kab-101 and subsequently led to a fire, death of 21 persons with one missing, and estimated spill of roughly 422 barrels/day rate. The main cause of the incident was a rig move off following a cold weather front that brought storm winds of 130km/h with waves of 6-8m in the GOM forcing oscillating movements of Usumacinta (Ismail et al., 2014).

The Seadrill owned West Atlas rig had been drilling H1 Well on the Montara Field development and progressively bedding smaller casings from January to April, 2009. The water depth was 77m, well depth below the rig being 3787m, and vertical depth of 2655m with 9 5/8” casing string in reservoir. The 9 5/8” casing shoe (primary barrier) which was defectively installed failed and despite noticeable indications, there was no pressure test conducted. Only one of two approved secondary well control barriers, pressure containing and anticorrosion cap (PCCCs) that were slated to be installed was actually fitted. There was no testing and verification in-situ of the PCCCs and H1 Well drilling activity was suspended (Rig departed) with believe that the casing fluid was over-balanced to the pore pressure. On the 21st August, 2009, Rig returned to discover the 13 3/8” PCCC was never installed on well and the 9 5/8” cap required removal following thread corrosion. Fifteen hours later a blowout occurred, as equipment was moved off to other wells. The unmanned rig caught fire and collapsed onto the platform below it. There was no loss of human life, hydrocarbon flowed for 75 days at an estimated rate of 400 to 1500 barrels of oil/day, and the environmental damage was relatively little (Galton, 2011).

Unfortunately, on the 20th April, 2010, uncontrolled high flowrate hydrocarbon from the Macondo well in the GOM found its way to surface of the Deepwater Horizon Rig resulting into an explosion (upon contact with an ignition source), and killed 11 persons. This incident was caused by the inability of the Deepwater Horizon BOP (10K Cameron 18 ¾” upper and lower annular preventers, 15K Cameron 18 ¾” Rams with ST locks except the Casing Shear Ram) to shut the well, which led to the sinking of the drilling rig following the explosion, and one of largest spill ever in recent times (speculated to be over 4million barrels) as the leak lasted for 87 days prior to well been plugged and killed.

The Macondo well had been drilled and to be abandoned temporarily for completion later with plan for required activities in place, negative leak-off tests was conducted and results which noticeably indicates seepage into well was misjudged by well-site personnel.. Thereafter an underbalance was observed allowing flow from reservoir during mud and seawater displacement. The weaknesses in the well barrier, testing, verification, maintenance and monitoring led to the Macondo incident with the root technical cause being poor annular cement and shoe track barriers which failed to isolate hydrocarbons in the formation (Christou & Konstantinidou, 2012). There was further warning signals missed especially in relation to mud monitoring before differential pressure noticed. The upper annular preventer (UA) was closed at 21:43 to seal the annulus around drill pipe and prevent fluid from rising above the BOP to riser, but this failed as indicated by well data. The rubber element of the UA is believed to have eroded, thereafter a pipe ram of similar rubber element and design was activated to close which sealed the flow. The middle and upper pipe rams were likely closed by rig crew as indicated by pressure data at 21:47, which resulted in pressure build-up within the drill pipe and fluid above BOP from through riser to rig without any fluid addition given closed pipe ram. First explosion occurred at 21:49 on the rig.

Emergency disconnect sequence (EDS) were activated at 21:56, and rig abandoned at 22:28. The emergency functions failed as the blind shear ram (BSR) should have been activated, rig and riser disconnected from BOP allowing for move away of the rig from the wellhead. The well was not sealed as the initial explosion probably satisfied conditions for the AMF/deadman backup system automatic activation severing hydraulic lines, power and communications to the BOP, hence BSR could not close as designed. The BSR was closed 33 hours after the explosions.

Further failure analysis by the Chemical safety Board suggested the segment of the drill pipe that was between the BSR blades was off-centre, as it had buckled due to increased internal pressure and resultant significant differential pressure between inside and outside the pipe, thus the BSR was partially closed and could not seal well (see Appendix A.3). The partial closure was because side of the drill pipe was trapped in the ram blocks and not within the perimeters of the shearing blade. The punctured drill pipe led to flow from the well re-established and also there were latent failures in the redundant control pods which aided AMF/deadman activation. Such latent failure includes and not limited to (CSB, 2014):

- drainage of 27 V battery, that powers solenoid valves during the AMF/deadman sequence, arising from miswired blue pod
- Failure of the AMF/deadman sequence activation through the yellow pod whose solenoid valve was also miswired and as such coils should have

generated magnetic fields opposed each other. However due to draining battery only one was energised unopposed to activate AMF.

- There is an assumption of a possible reduction in performance of batteries given the temperature of the environment.

In addition, another limitation was the inadequacy in the design and operation of the BOP System, as it had a single shear ram which was not able to cut tool joints.

Table 1-3: BP payments related to the Gulf Coast recovery (BP, 2015)

BP's payments related to Gulf Coast recovery	
Activity (as at 28th February, 2015)	***Funding***
Response and Clean-up	$ 14.3 billion
Claims, advances and settlements	$13.6 billion
Funding for the natural resources damage assessment process	$1.3 billion
Early restoration projects (approximate cost of approved projects)	$ 698 million*
State-led tourism campaigns	$179 million
State-led seafood marketing programme	$48.5 million
State-led seafood testing	$25.4 million

*$629 million has been provided to the trustees to date.

BP has spent over 28 billion dollars for the recovery of the Gulf coast as seen in Table 1-3 The cost of failure is huge and this cost could rise depending on the US Supreme Court judgment on claims, excluding the lives lost and production lost.

Following the Macondo incident was a well kick taken on Gullfaks C well on the 19th of May, 2010 that could have resulted in a sub-surface blowout and /or explosion, as gas was released on platform. The root cause was a hole in the casing leading to a drilling mud loss to formation during reservoir hole cleaning and subsequently an influx of exposed reservoir fluid into the well. (see PSA, 2013 & Vinnem, 2014). Thereafter was the Mariner Energy's vermilion Block 380 incident (platform blowout and fire, one injured and 13 survivors) in the same 2010. In 2012, a likely gas-kick issue that lead to an outburst of flame on Chevron's KS Endeavour drilling rig, approx. 6miles off coast Nigeria, with a blowout on rig which collapsed and two persons killed. The cause was linked to a failed BOP; hence drillers could not control the gas-pressure. There have also been a number of recorded cases of the BOP system component failures such as damage of both the blue and yellow multiplex (MUX) control lines of the BOP control system. This resulted in the Mobile offshore drilling unit crew disconnection of LMRP in Canada-Newfoundland and Labrador Offshore Area, March 2015, and abandonment of drilling perforation operations due to the malfunction of a BOP valve in April 2015 during drilling of the Isobel deep exploratory well in the Falklands/Malvinas islands.

A brief review of the notable past blowout incidents have been presented in this section and it shows there are a number of possible causes or factors such as the failure of the BOP system. Figure shows the several contributing factors of a blowout which informed Dervo and Blo-Jensen (2004) approach for calculating blowout frequency. Holand (1997) opines the causes are complex and that though simple direct causes can lead to blowout incidents, the associated indirect cause are complex. These includes poor decision, ineffective or inadequate maintenance and procedures, complex organisational structure, working environment, low manning, inadequate use and training of personnel. This is in agreement to Ge et al. (2015)'s survey which concluded that design and management defects were found to be two most important causes from a contribution rate to a blowout incident standpoint. It is evident that besides prevention measures, early warning signs, mitigation, preparedness and planning to manage accidents of this nature, the failure of the BOP System, the interest of this thesis, as a secondary barrier is crucial (Christou and Konstantinidou, 2012). Stakeholders need to assure the performance of the BOP system as an entity and its constituent components as a well barrier, given the consequences can be far-reaching as proven by the Macondo accident.

1.2 Statement of Research Drive

Original Equipment manufacturers (OEMs) of BOP system and components, drilling contractors, operators of Subsea wells, class societies and regulatory bodies desire to have a better understanding of the `Subsea BOP System given its safety critical nature. Regarding the BOP system, the following information is vital:

- Details of each component or subsystem such as failure modes and mechanisms, historical failure rates, functional and pressure testing intervals, related maintenance activities, spares change-out regime, operating equipment condition, and installation.
- Operation engaged when failure occurred or was identified, weather condition and other environmental characteristics associated with the region of drilling operation, rig type (e.g. semi-sub), and level of experience of operations personnel.
- Details of critical components in the system, complexity of the system (BOP type- number of rams) and redundancies, interdependencies, consequences given failure of a component/activated function, age of system, cost of repairs following downtimes, and a possible blowout with spills.

Improved understanding of the BOPs system relative to its functionality, operating condition and environment is important to avoiding and/or reducing blowout occurrence during drilling operations especially.

There is a considerable amount of works on the application of risk and reliability analysis techniques to assess or understand the risk and reliability level of the BOP system. This entailed the failure data analysis of BOP system components for different set of exploratory wells as documented in the different phases of SINTEF JIP reports, fault tree analysis to ascertain the availability of the BOP system, failure modes effect and criticality analysis of the BOP System, other system specific studies such as comparison of BOP control systems, and a combination of these (discussed in detail in Chapter 2).

It can be attested that in some of the previous works on BOP system, where data (e.g. MTTF) was accessible, quantitative reliability assessments have been done. It is no surprise that failures have occurred from the industry's experience which could be associated to how much insight relative to improving functionality or the preciseness such assessments provide. It is important to state that MTTFs do not explicitly define reliability without a statement of the principal statistical distribution of time to failure which informs why different reliabilities can be associated with an MTTF value. Also obtaining exact quantitative expressions, following reliability assessment, cannot be attained for complex systems- often characterised by multiple failure mechanisms with possible interacting stresses (mechanical and environmental).

While it can be admitted that data access can be challenging, manufacturer's equipment specifications and statistical failure rates are the easiest to access. However, the available information may not be in proper format with the necessary specific detail for different situation. It may be important to know which failure modes were considered, confidence limit relative to sample size and failure rate, specific equipment, application, and environment in deriving the reliability data. Also these may have been considered in a company's database, but their correctness and how they have been post-processed can be a concern if details of applicability of such data are not made available to users. Example of concerns could be if non-random failures and/or some level of criticality failures have been filtered out in the derivation of the failure rates. This informs the requirement for data to be cross-checked or validated against expert's judgement prior to being used in the assessment of a system. In essence identification of component failure modes contributions to the unavailability and/or unreliability of a complex system using statistical data can potentially be challenging.

In a system reliability study, the first step usually involves a Failure Mode Effect and criticality Analysis (FMECA) as a technique at a design stage of a project. It has been useful for reviewing safety critical systems to identify possible problems. The FMECA is that tool for identifying and understanding failure modes and mechanisms proactively and does provides a basis for continuous improvement actions. State of the art analysis of the BOP System using FMECA includes Januarilham, (2012) and American Bureau of Shipping (ABS), (2013). In both works, critical failure modes were realised using the risk priority number (RPN) scores derived from the product of ratings assigned to severity, occurrence and detectability. The rating for the three factors can take several scales e.g. a scale of 1 to 10 as in ABS (2013) with 10 corresponding to almost certainty to occur and 1 unlikely to occur or a scale of 1 to 5 as in Januarilham, (2012). The shuttle valve for the BSR, BSR piston, BOP stack Flange, BOP stack gasket, and the rubber housing annular preventer were identified as the first five critical items in Januarilham, (2012) while ABS identified the double-acting Sub-plate mounted valve, Shuttle valve, Choke and kill lines and valves, Annular and pipe ram. Januarilham, (2012) analysed both components and sub components and also considered some failure cause/mechanism as failure mode.

FMECA outcome heavily depends on experience of experts as to minimize failures at initial life especially is to foresee failure modes where there is no history of failures and this depends heavily on competency, experience and access to information to the designer. While FMECA has been beneficial to the understanding and ranking of identified failure modes, it is not without limitations. This includes how representative is the use of three criteria considered in deriving RPN, the relative importance of the criteria are not considered, and also different failure modes may have the similar RPN, from different set of scores assigned to the criteria, of which their individual risk implication (Pillay and Wang, 2003).

The foregoing weakness associated with the RPN approach and in addition to complex systems being associated with multiple, and often conflicting factors which needs to be optimised, presents a multi-criteria decision problem (Walker et al., 2006).. There is a need for work on assessment of the BOP system, given the possibility of incidents cannot be ignored. Thus, an approach that would guide the assessment of critical failure risks for informing and/or priorities reliability improvement effort is eminent. This research attempts to verify and validate known knowledge and potentially contribute to increasing the know-how of the BOP system, inform knowledge on improvements for equipment specification, and design and also general well control procedures (from the last line of protection/barrier perspectives) for a safer deepwater drilling. The design of the next generation BOPs and maintenance strategy development for the

BOP systems can also benefit from the results of this work. This research is timely as currently there is an increased number of deepwater explorations, and operations, with multiple planned wells to be drilled ahead, provided oil and gas price is fairly stable for viability.

1.3 Research Aim and Objectives

The aim of the research is to provide an enhanced understanding of the BOP functionality and associated failure modes with a focus on determining their criticality order of importance. Consequently, the objectives that would support this aim can be summarised as:

- An assessment of the BOP system using the traditional FMECA method which will entail :
  - System breakdown and component identification
  - Identify the critical failure modes and
  - Critical components identified from the Risk Priority Number (RPN) ranking inference.
- Analyse risk implications in the evaluation and identification of critical failure modes e.g. using the RPN or classical risk definition as the basis for criticality order.
- Develop a multi criteria analysis approach for a robust assessment of the BOP system reliability, by way of failure mode rankings, which considers more than 3 criteria.
- A comparison of different MCDA and FMEA methods ranking order outcomes and demonstrating the utility of MCDA in risk and reliability analysis. This is supported by a sensitivity analysis.

1.4 Methodology

This section sets out to describe the framework for the research which aims to understand the criticality importance of the components of the BOP system and how they can fail using a multi criteria assessment approach. Here the methodology following the research problem identified in section 1.2 is contextualised with respect to the system of interest, and decision outcome sought. The implementation approach described in 7 steps proposed to achieve the aim of this research.

The assessment of the BOP System entails a technical risk (failure modes) identification and evaluation with an incorporation of uncertainty. While some of the uncertainty such as lack of data or correct model to represent the system, (model and statistical uncertainty) there may be other sources. Uncertainty sources such as limited knowledge of decision maker influencing his preference, and unforeseen variations from system and/or environment (e.g. stress on systems due to greater drilling depth, for which information is limited) may result in imprecision in decision makers or expert's preference or assigned values. However, the MCDM method applied has capability to handle such limitations. A methodology is proposed based on the following Steps:

The first step is scoping for problem definition. This entails the review of state of the art in literature and field reports to understand the system and be able to identify the nature of the problem and decision sought. In the context of the research problem being a decision problem, its definition entails an identification of alternatives (failure modes), analysis criteria, constraints, and any other information available for the selection of an appropriate MCDA technique.

The second step entails the definition of the BOP system, boundaries, component functionalities, and operational requirements. This will serve as the basis for the application of FMECA analysis. Step 3 involves the application of Failure modes effect, and criticality analysis technique to the BOP system to identify failure modes and their associated mechanisms and their effect with respect to a loss of well control. An initial assessment based on RPN and risk as a product of consequence and likelihood of failure occurrence will be conducted to understand their criticality.

Critical failure modes based on Step 3 are identified and a select list of critical failure modes (risk) to be assessed as alternatives using enhanced techniques is deduced in Step 4. Step 5 is the development and application of MCDA technique using multiple criteria for evaluating identified failure modes alternatives. This involves the selection of an appropriate list of criteria to assess the technical failure risk criticality, Selection of decision makers and elicitation of their preferences and application of MCDA framework to BOP system failure modes. Step 6 is the generation of a list of critical failure modes ranks given the failure risk criteria used in the analysis. Finally Step 7 is the validation of analysis outcome. This involves a sensitivity analysis with a discussion of outcome in itself and against other results, and final presentation of a robust reliability case for assessing the reliability of a BOP System. The methodology is depicted in Figure1-1 and details of the actual elicitation process and MCDA framework is described in Chapter 3.

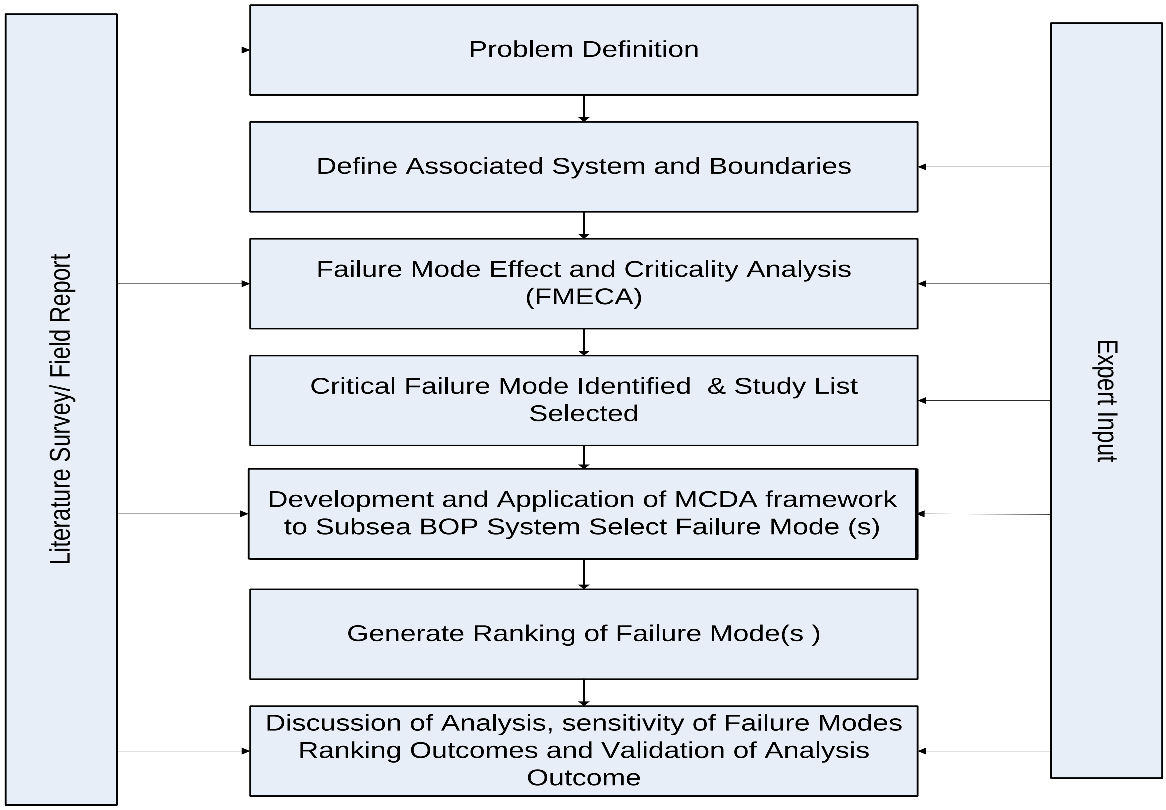


Figure 1-2: Flowchart of Research Methodology

1.5 Thesis Structure

This report is structured in Chapters ranging from 1 to 6. Chapter 1 presents the premise for the research from a broad angle and then specifies the research aim and objectives to drive contributions. Given the concerns from past accidents such as the notable recent Macondo incidence case discussed in the introduction, related and previous works, a definition of the analysis problem and implementation approach as part of the research methodology were presented. Chapter 2 introduces the background of subsea blowout risk and then a focused review on the BOP system design, components, functionality, and other concerns. Also reviewed are previous risk and reliability analysis works with application to the offshore/marine/subsea industry and more specifically the BOP System of interest. In the review of failure modes, effect and analysis technique, salient concerns to note when implementing the FMECA process as part of a project is discussed. Thereafter an introduction to MCDM application to risk analysis methods such as the FMECA to improve decision making which stems from the limitations with FMECA technique is presented. Chapter 3 presents the development of the multi criteria decision making techniques in more detail (The techniques of interest (TOPSIS, PROMETHEE, and Fuzzy sets) are also presented). This entails the data collection process and how it was achieved. Also presented is a description of the expert elicitation, the selection of assessment criteria and alternatives, definition of criteria and how the data was processed and interpreted for the assessment.

Chapter 4 is an assessment of the Subsea BOP system using the FMECA to identify critical failure modes and their varying effects ranging from no effect to a complete loss of well control is presented. It also presents how a failure mode can be more critical than another depending on the ranking approach considered. The application of the developed research framework to the BOP system and assessing the risk importance of selected component critical failure modes as a case study is presented. The different ranking outcome from the application of MCDM techniques to the BOP System is also presented. Chapter 5 presents a discussion of results and validation of outcome from MCDM analysis. Also, the challenges with the data collection process and general lessons learnt from implementing the framework are highlighted. Finally, the thesis is completed in Chapter 6 with a conclusion, statement of contribution, and recommendations.

2 LITERATURE REVIEW

2.1 Drilling and Well Control

There was an increase in exploratory and developmental drilling operations within the oil and gas industry in the last decade, before the recent drop in oil prices in 2015 slowed down these activities. Main operation of a typical drilling process commences with lowering and setting up of initial conductor casing with the aid of an installed wellhead assembly at the seabed, providing mechanical foundation for further drilling by cementing around the casing, thereafter lowering of a riser and BOP in preparation for setting up and cementing of further casing strings, and the production casing. Throughout most of the drilling process (running and pull out of hole of drill string/casing repeatedly with smaller diameters), the BOP is placed on the well (see Figure 2-1 for a typical offshore well design schematic). These operations are very risky and expensive as they require a lot of man-hour planning, execution, and support. One of the major challenges they face is the risk of a possible loss of well control. This chapter will explore well concepts: kick mechanism, detection and prevention. Well barriers are discussed for drilling operations with a special attention to the Blowout preventer (BOP). The BOP's components, functions, operation and testing, failures and failure modes with a synopsis on its design and reliability guidelines are also addressed.

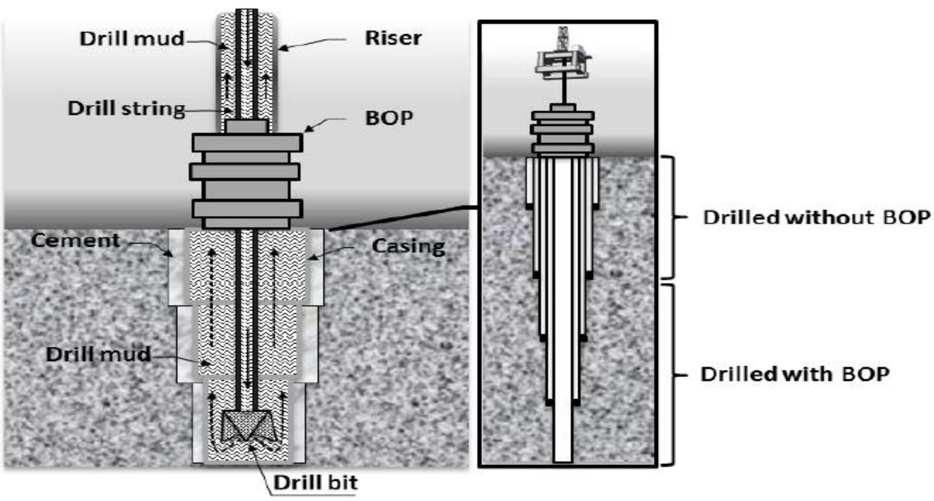


Figure 2-1: Typical offshore well design schematic

2.2 Well Control Concepts

All means of preventing the uncontrolled release of wellbore fluids to the external environment and uncontrolled underground flow is collectively known as well control. During normal drilling two pressures operate at the well bottom: the hydrostatic pressure from the weight of drilling mud and pressure from the reservoir. The former counterbalances the latter to prevent inflow into the wellbore. This is known as primary well control and should the balance be disrupted by well problems (e.g. improper mud control or poor casing installation), a potential loss of well control could arise.

High pressure combination in sections of the well and low formation strength in other parts, often combined with high temperatures, create the possibility of loss of well control during drilling. Hence a requirement that the operations must be carried out with a set of barriers. For every intended operation, a risk assessment usually needs to be carried out considering the possibility of a loss of well control or general well integrity failure. Typical well control systems consist of the BOP and its control system, diverter system, choke and kill system, riser system, and wellhead connectors.

2.2.1 Kick Mechanism

The influx of gas, oil or water into the well resulting in instability in the well is known as a kick. It is commonly defined as “an intrusion of unwanted formation fluid or gas into the wellbore such that the effective hydrostatic pressure of the wellbore fluid is exceeded by the formation pressure” (US CSB, 2014). The two conditions necessary for a kick to occur are: (a) exposure of the permeable and porous formation and (b) pore pressure is greater than the bottom-hole pressure (BHP). The kick is an initial event that can potentially escalate into a blowout.

There is a great deal of uncertainty before and when planning drilling operations. This is evident as the fracture pressure, pore pressure and BHP are not known prior to drilling. The well planning team decides on an anticipated BHP and this could vary during drilling, affected by factors such as irregularities in hole shape and temperature. These factors are special for different drilling sub-operations. Pressure contributors to the BHP for each of these phases are the hydrostatic pressure (P_h), frictional pressure (P_f), and those of swab (P_{sw}), and surge (P_{sg}) (see Eqn 2.1). Five different sub operations are identified in (Khakzad et al., 2013):

- Drilling ahead
- Tripping operations
- Static conditions
- Casing operation
- Cementing operation

$$BHP = P_h + P_f + P_{sw} - P_{sg} \qquad 2.1$$

The hydrostatic pressure is that arising from the drilling mud column and is a function of the mud density, and height. Gas-cut mud and annular losses can result in a decrease in the hydrostatic pressure as it reduces the height and density respectively. The pumping rate is associated with frictional pressure. During tripping operation (drill string been run into wellbore), the positive pressure gradient formed is known as surge pressure and on the other hand when the drill string is pulled out of the well, the negative pressure gradient is known as the swabbing pressure. The viscosity of the mud, wellbore diameter and speed of tripping determines the P_{sw} value.

(Holand and Awan, 2012) stated kicks do not just occur, hence anticipating situations that can result in kicks and taking preventive actions is the best way to avoid well control issues. Wellbore pressure control through pressure margin is a basic means of kick prevention. The difference between the maximum pore pressure and minimum fracturing pressure in an open-hole section is the pressure margin during drilling. It is important that a fracture or kick does not occur by ensuring, any increment in the BHP is smaller than the difference between the fracture pressure and the BHP, while a reduction in the BHP is smaller than the difference between the BHP and pore pressure (Assuming a constant pore pressure and fracture pressure). Maintaining the BHA within this margin will prevent a kick or fracturing from occurring.

Conventional overbalance drilling appears preferable from a kick prevention stand point but could also lead to annular losses and a kick likely, should the formation be fractured from a major over balance drilling. In the alternative, despite the advantage of higher penetration rate by near balanced drilling, which makes it seemingly preferred for deepwater drilling, it could result into a kick, following an event of certain conditions (e.g. loss of circulation or unexpected gas cut) leading it into an underbalanced condition (Nguyen, 1996). A better insight into the kick mechanism would aid the definition, evaluation and planning of well control procedures, safer and lower-cost well operations. Kick simulators can also be used to study kick scenarios to provide realistic kick tolerances margin. To avoid well control problems, it is not only about having practices/procedures that will prevent a kick, but identifying swift means of detection. While kick free drilling cannot be guaranteed by any technique, the detection of influx remains critically important. Influx detection is traditionally by observed mud-level increase in the mud pit, flow checking, or having to stop drilling and to check if the well is flowing. Early detection is necessary.

2.2.2 Blowout

A blowout arises as the result of well secondary barriers failure. This is the outcome of a kick escalation, following either a non-detection of the kick and thus not activating the barriers or failure of the secondary barrier. More insight can be gathered on the effect of the secondary barrier on the well control process, when the blowout path is known (given kicks can arise through the drill string, annulus and casing as well). A kick up in the drill pipe would consist as the greatest drilling risk (Flak, 1997). When well pressure control is lost, a blowout occurs. The cause of a blowout may be too low mud weight, technical equipment failure, stuck pipe (swabbing), procedural failure, gas cut mud, poor cementing, improper fill-up of hole, and more often a case of the combination of several factors (Hauge et al., 2011). During drilling, sudden lost circulation and blowout can result from a casing holed by pipe defects or drill pipe wear. Blowout is characterised as an abrupt, powerful and unrestrained release of gas, oil, water, and mud from the well.

Blowout potential varies from one well to another based on factors such as well design, formation characteristics and flowing fluid (see Appendix A.1 for different elements that can contribute to blowouts as in (Dervo and Blom-Jensen, 2004). The catastrophic nature of blowouts is depicted in Figures 2-2. The deepwater horizon is shown before and after the blowout to depict the explosive nature of a blowout occurrence. Some of the consequences of a blowout include a loss of human lives, loss of equipment, Loss of reserves, production stopped, environmental problems. There have been as much as 49 remarkable offshore well blowouts with oil spills since 1955, eight of which was between 2001 and 2012. It is recommended that every week a blowout prevention drill be carried out for such emergency readiness by the drilling team. There should be an audio-visual alarm/warning device close to the driller's console, for indicating pit level following an increase or decrease in the drilling mud volume.

(a) Rig before blowout **(b) Rig after a blowout.**

Figure 2-2: **Deepwater horizon rig (US CSB, 2014)**

There should be also an accurate measurement of the required mud volume and an assurance that when string is being pulled out, the well is filled with mud. There is a need to ensure that when a well kicks the mud pump is closed using a control device near the driller stand.

2.2.3 Well control Methods

There exists a number of well control techniques which can be classified based on the nature of bottom-hole pressure applied. If the control of influx into well is done using a constant BHP, there are three methods namely: Wait and weight method, driller's method and concurrent methods. When a constant BHP cannot be applied, applicable well control methods are: volumetric methods, bull heading, top kill, killing diverted blowout and low choke pressure methods. A procedure needs to be established for controlling the well using any of the above methods. This procedure will describe the well killing. A sample flow chart for kick control procedure when drilling, tripping or pulling out of hole (no pipe in BOP) is shown in Figure 2-3.

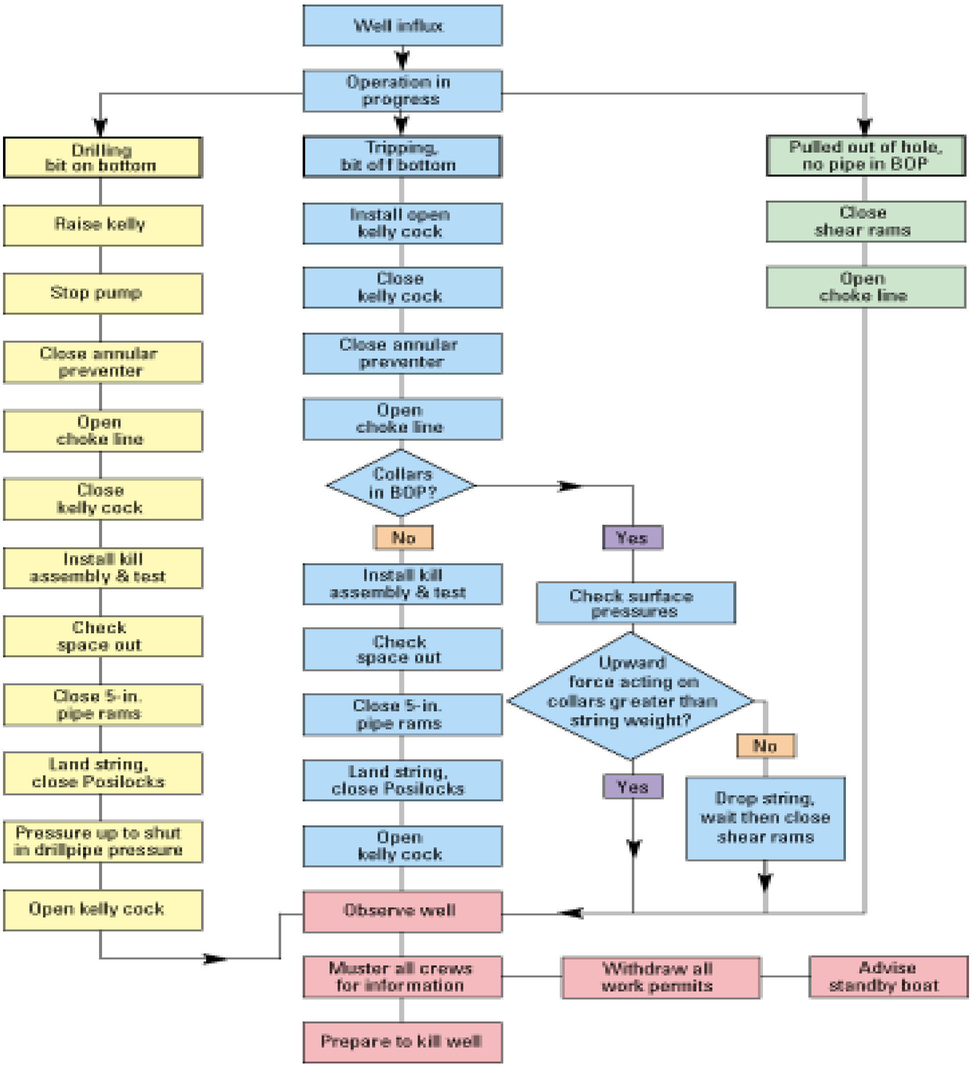


Figure 2-3: Sample Kick Control Procedure flowchart (Schlumberger, 2013)**.**

2.2.4 Well barriers

In ensuring well integrity for safe operations, barriers are used as a medium to prevent, control, or mitigate unwanted incidents or accidents. These barriers can be physical or non-physical; active or passive, technical or human operational systems. A means of containing wellbore fluid and pressure is using barriers. Thus barriers ensure unintended influx, cross-flow and outflow to the external environment is prevented. Ideally at least two barriers are required for most operations, in the event one fails, there exist a back-up. The first impediment to this unwanted flow (kick) is the primary well barrier and the back-up is the secondary well barrier that impedes any further undesired flow; this is known as the two-barrier principle. Although for operations in which the pressure differential does lead to uncontrolled cross flow in the wellbore between formation zones (but not to external or surface environment) one barrier can be used. In the (NORSOK Standard, 2012) for well integrity in drilling and well operations, 58 different barriers were listed with their acceptance criteria presented (entailing their constituents, function, design selection and construction, use, test and verification as well as common barrier elements possibility). If there exist common barrier elements (an element that is shared by the primary and secondary barriers thus two independent barriers envelops cannot be established), risk analysis should be carried out with risk reduction methods applied. The barriers required should be identified before the beginning of any operation or activity with a plan on how it is to be monitored and clearly defined acceptance criteria. Following the installation of the barriers, integrity and function verification of the barrier needs to be done through techniques such as function testing, pressure testing and other methods. In the event of a change in loads, conditions or even lifetime extensions, a re-verification has to be done.

In respect of well control during drilling there is a hydrostatic and mechanical control point associated with the barrier. The drilling stage entails the periods from when the well is spudded to preparation for completion or testing or side-tracking, suspension and abandonment of well. It is important to understand the level of risk associated with the drilling process and then ascertains if a minimum or higher standard of barrier is required. A Swiss cheese description of the different barriers that failed which led to the Macondo Deepwater Horizon accident in 2010 is shown in Figure 2-4. Some barriers are conditional, typically functional as a barrier in some operations and in others not as a barrier. The BOP system is seen as a last line of defence whose failure to seal well can lead to fire, and spill. Another important aspect is the understanding of the stability of barriers to outgassing and corrosion (relative to seal failures), high/low temperature, pressure spikes, tensile loads and corrosion component (relative to barrier degradation). There is thus a need for risk assessment to be carried out following well barrier degradation.

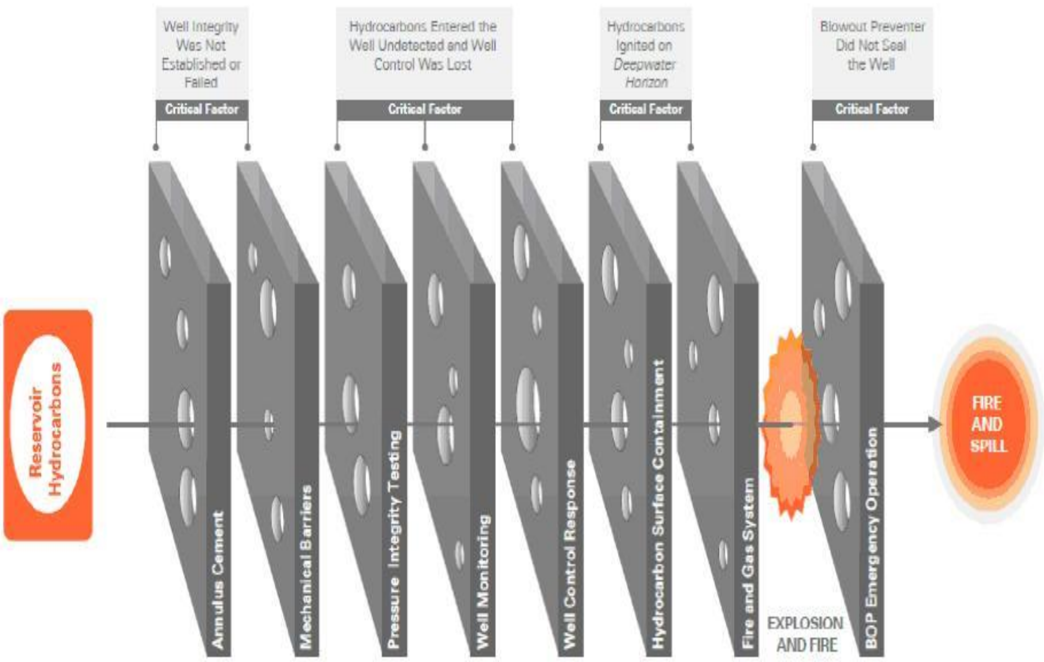


Figure 2-4: A Swiss cheese description of the barriers (Physical and operational) that failed at the Macondo Deepwater Horizon accident (BP, 2010)**.**

Another important aspect is the understanding of the stability of barriers to outgassing and corrosion (relative to seal failures), high/low temperature, pressure spikes, tensile loads and corrosion component (relative to barrier degradation). There is thus a need for risk assessment to be carried out following well barrier degradation. This is to ascertain its cause, potential for escalation, the reliability and availability of the primary and secondary barriers. There also has to be a plan to re-establish well barrier following a restoration.

The different well barrier elements that have to be established for the four drilling operation situations (running non-shearable drill string; drilling, coring and tripping with drill string; running non-shearable casing; and through tubing drilling and coring) is depicted in Figure 2-5, however the BOP systems is the focus of this thesis.

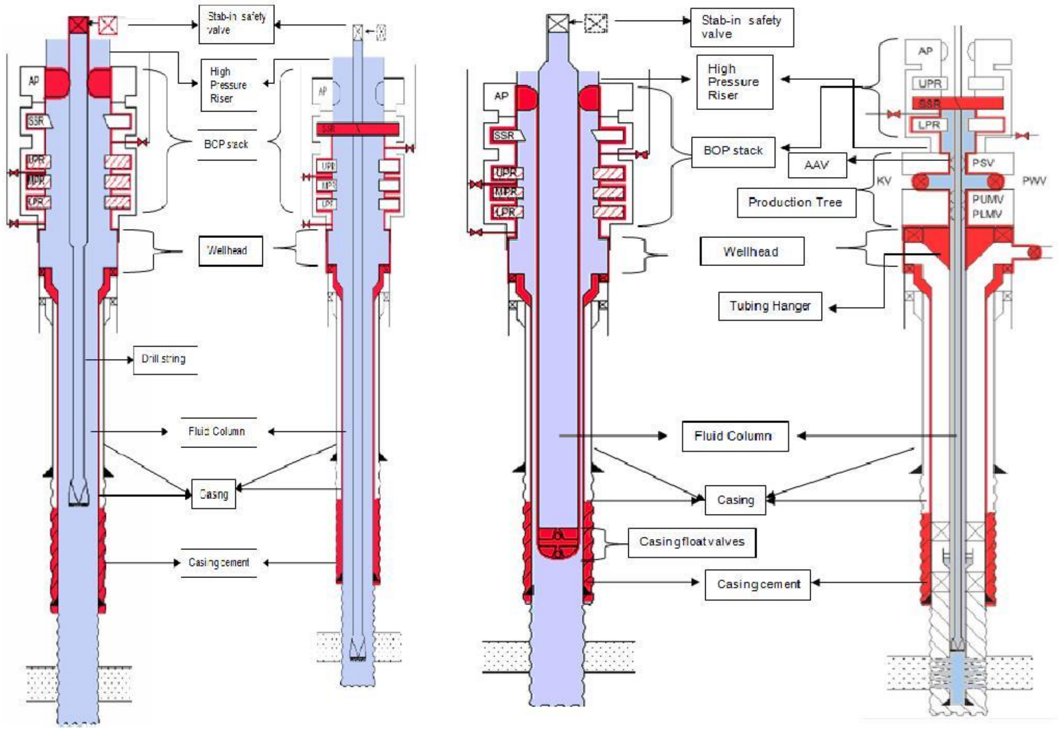


Figure 2-5: Well barrier schematic for different drilling situations (Left to Right) (a) running non-shearable drill string (b) drilling, coring and tripping with drill string; running non-shearable casing; and through tubing drilling and coring (NORSOK Standard, 2012)**.**

2.3 Blowout Preventer System

The BOP system is an integral part of the drilling system and is a safety critical system. It is located between the riser and the wellhead for subsea drilling system. The BOP system usage goes beyond the primary well control barrier function to include a range of routine operational tasks such as formation strength and casing pressure tests. The BOP system entails three major components: the lower marine riser package (LMRP) assembly, the BOP stack and the control system. The blowout preventer in itself comes in two major types: annular and ram preventers, however different BOP types are arranged in a certain configuration into what is known as a BOP stack. The blowout preventer (BOP) stack consists of an assembly of valves with unique functions such as closing around the drill string pipe, casing, or tubing and even severs the string and plugging the wellbore, in an emergency. In the instance of fluid influx into the wellbore to the surface, when other well barriers have failed, the BOP is used to hold flow and pressure of reservoir fluid. There are two basic types of BOPs namely the annular and ram preventers and they are characterised by different sizes, pressure ratings and styles. The BOP stack has at least one annular BOP on-top of several ram BOPs. A subsea BOP stack is expected to have at least four remote-controlled, hydraulically operated BOP consisting of an annular BOP, one BOP equipped with blind shear rams and two Pipe rams. The deepwater Horizon BOP stack and its components are shown in Figure 2-6. Also a detailed description of the LMRP assembly in Figure 2-7 with the parts described in side Table. The BOP is the secondary barrier or seemingly the last line of protective action against kicks and blowouts.

The BOP stack basic functions include:

- Restricting well fluid to the wellbore
- Serve as a medium to add fluid to wellbore, and
- Ensuring withdrawal of controlled volumes of fluid from the wellbore

Other functions, in addition to the above include (API STD 53, 2012):

- Shut-in well by sealing the annulus between the casing and the drill pipe.
- Wellbore pressure monitoring and regulation
- Averts any further influx into the wellbore from the reservoir
- Completely closing off the wellbore to seal the well, if no pipe is in the hole
- Severs the drill pipe or casing to seal well in emergencies (e.g. emergency disconnect)

- Centralizes and supports the weight (hang off) of the drill string in the wellbore

During drilling operations, the BOP is used in different scenarios namely well shut in, snubbing, stripping and BOP testing as seen in the functions listed earlier. Some well control approach may require the use of both the ram and annular preventer. Usually the choice preventer for well control is the annular preventers, when a kick is taken. However both have often been used to highlight the grave degree of safety measures taken to avoid the occurrence of a blowout. The BOP is attached to the wellhead using collect or flanged connectors and how it is installed is dependent on the location and nature of the drilling environment. For an onshore well, it is located below the drilling rig floor in the cellar, for offshore environment with a floating drilling unit, the BOP is attached to the wellhead on the seabed and just below the rig floor on the Texas deck, if it is offshore with a bottom supported drilling unit. BOP stack can be classified based on the number of components, into 6 classes namely Class V-VIII. Table 2-1 shows the class configurations of annular and ram preventers by Chevron, with greater redundancy found in the subsea types. This reflects the complexity with subsea environment and the need for improved system reliability. The arrangements of the BOP stack is usually based on rated working pressures in psi of 2K, 3K, 5K, 10K, 15K and 20K which determines the types of flanges and gaskets used in the design.

Table 2-1: BOP Classes and their Component Counts (Source: Satler J., 2013)

Installation	Class	Number of Components	
		Annular	Rams
Surface	IV	1	3
	V	1	4
Subsea	VI	2	4
	VII	1	6
	VII	2	5
	VIII	2	6

The conventional and modern typical BOP configurations are placed in parallel in Figure 2-6 for comparison. Refer to the Appendix A.2 for alternative description of the BOP System.

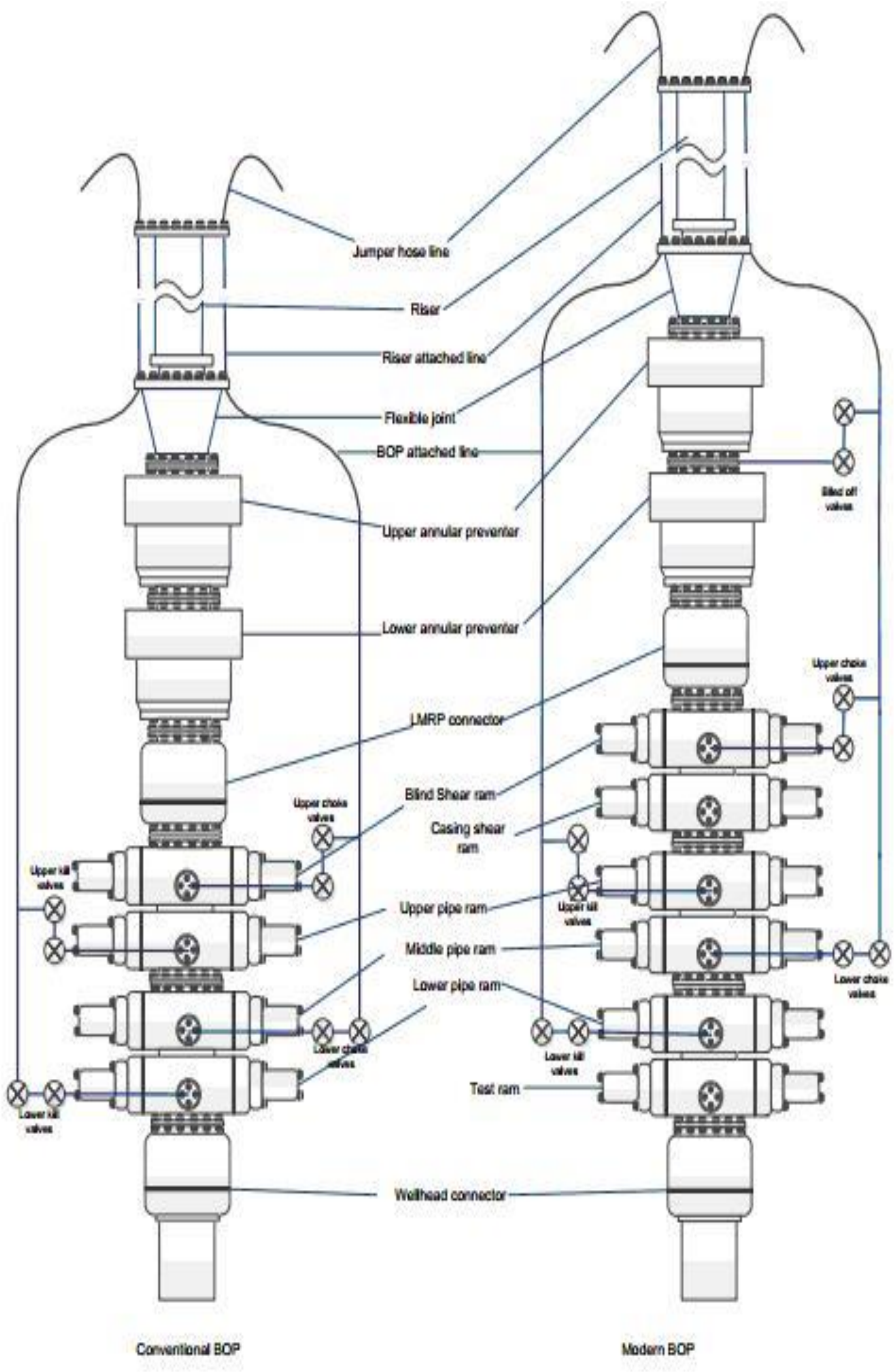
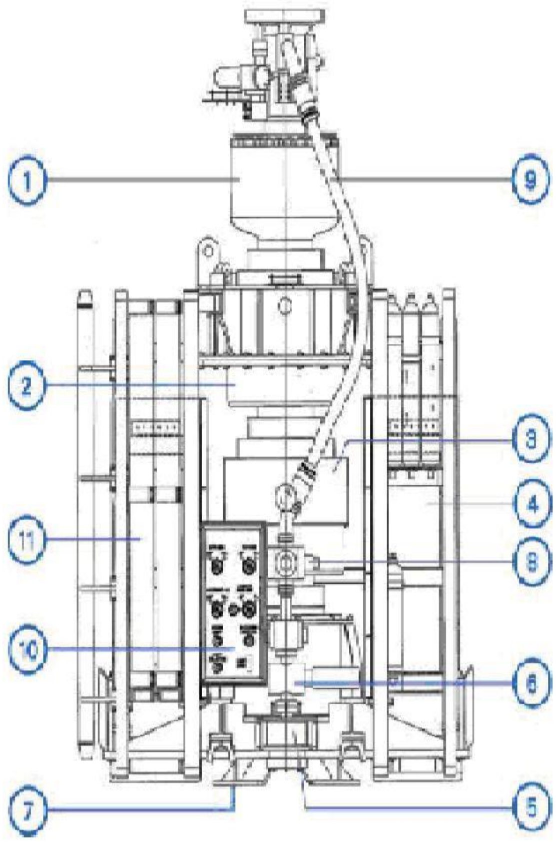


Figure 2-6: Typical BOP configuration comparing conventional and modern architectures (Holand and Awan, 2012).



LABEL	COMPONENT
1	Flex Joint Riser Adapter
2	Upper Annular Preventer
3	Lower Annular preventer
4	Control Pod
5	Choke and Kill connectors
6	Choke and Kill Isolation Valves
7	LMRP Connectors
8	Gas Bleed Valves
9	Choke and Kill Flexible Lines
10	ROV Interface Control Panel
11	LMRP Hydraulic Accumulators

Figure 2-7: Detailed view of the LMRP assembly (Source: Transocean, 2010)

From the figures in addition to the annular preventer on the LRMP and the rams in the BOP stack as earlier mentioned, there are other special additional components. The BOP components will be described in the following sections.

2.4 Annular blowout preventers

This blowout preventer is used to seal around pipes and casing or wire line. Annular preventer squeezes an elastomer packer across the annulus in an upward and inward movement to seal the well and prevent upward fluid movement within the wellbore. It allows slow rotation and vertical movement while sustaining sealing action, thus of great use for drilling operations like stripping and snubbing. There a number of companies that manufactures the annular preventers used in the oil and gas industry, with each having their unique product design features. Annular preventers such as Cameron DL, Hydril GL, Hydril GK, Hydril GX/GXS, Hydril Annu-Flex and Shaffer Spherical have been known to be used. The Cameron DL BOP is shown in Figure 2-8 and for its specific details and those of Hydril Appendix A.2 can be referred.

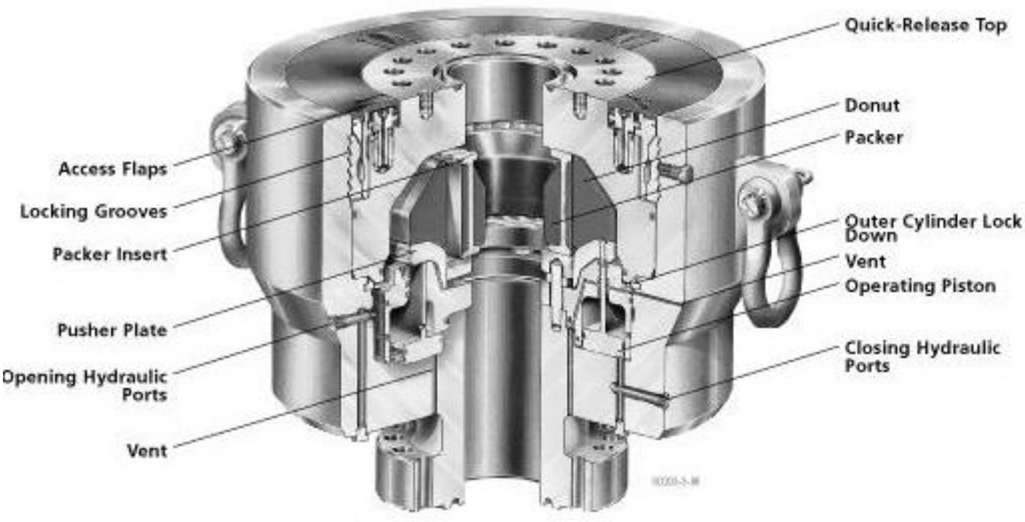


Figure 2-8: The Cameron DL BOP

2.5 Ram blowout preventers

The Ram BOP is a valve that consists of two opposing rods (a pair of opposing pistons and ram blocks) which are hydraulically operated for sealing function. The ram block extends through the BOP housing guide chambers and towards the centre of the BOP wellbore to stop flow or left retracted to allow flow. Elastomeric seals and packers for sealing against the ram blocks are fitted into the inner and top faces of the ram blocks, against each other, against the guide chambers, against the drill pipe running through the wellbore, and against the wellbore. Choke and kill valves and piping are connected through outlets on the body of the BOP. There are various sizes and design of the ram block for handling different specific drilling operations. Ram preventer type design determines the nature of the sealing such as complete closure by cutting drill pipe (Blind shear ram), sealing capabilities for one pipe size (pipe/casing ram) and for more than one pipe size (variable rams).

a) Pipe/Casing ram

Pipe or casing ram preventers can close the annular space around a drill pipe and casing respectively, when hydraulically activated. Their openings are semi-circular which matches the diameter of the pipe or casing (see Appendix A.2. for a plan view of the BOP Pipe ram before and upon demand).

b) Variable Bore Rams (VBR)

This type of pipe rams can close around a range of drill pipe diameters and tubing utilising flexible packers (Transocean, 2011). There is also a dual bore flex packer that can seal three different pipe sizes in two different bores. A typical bore ram, and a flex packer type shown in Appendix A.2.

c) Blind shear ram

A ram designed to close off annulus when no pipe is in the hole is known as a blind ram. This means should a demand be made on a blind ram when a drill string is in the hole, it would not shut the annulus. A blind shear ram (also known as sealing shear ram) is designed to seal the wellbore, regardless of the bore been occupied by a drill pipe. Usually this type of ram is activated when all other rams have failed in shutting the well. A typical blind shear ram operation is depicted by Figure 2-9.

d) Test rams

This is a VBR that is inverted for sealing pressure from above. It reduces required time for both BOP pressure testing preparation and drilling operations resumption afterwards. Once the test ram is closed, pressure testing can be carried out on other ram preventers above against the drill string and the annulus (Transocean, 2011). This inhibits the exposure of the wellbore below the BOP from test pressure. The quality of the wellhead connector test and successful closure of the BOP probability will be reduced by the test ram. It is believed potential leakage paths below the lower pipe ram preventer in the stack will be added (Holand and Awan, 2012).

The principle of the closing and opening functions of a ram preventer are the same, with direction of the hydraulic fluid relative to the intended piston and wedge lock movement (inward or outwards) as the difference. The ram preventer functions are driven the BOP control systems and basically hydraulically powered. Figure 2-10 shows the working of the ram as fluid from the control pod is routed through the inlet port to the shuttle valve. The operation sequences prior to this point described (i.e. hydraulic fluid moving from the accumulators (subsea or surface) through the regulator and SPM valve in the control pod to the shuttle valve) is explained in detail in the BOP control system section.

The fluid that passes through the shuttle valve is routed to push the piston inwards for a closing function and the wedge-lock moves behind the piston to prevent back movement. During this piston-inward movement that projects the packers or blades (for sealing or shearing depending the ram type), the hydraulic fluid behind the piston is circulated to the surface through another shuttle valve.

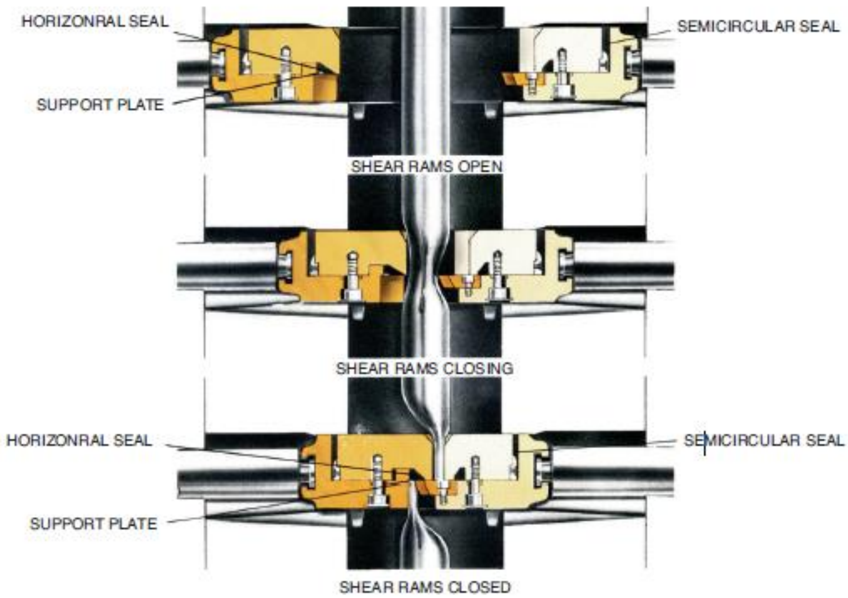


Figure 2-9: A schematic of three possible functional mode of the BSR.

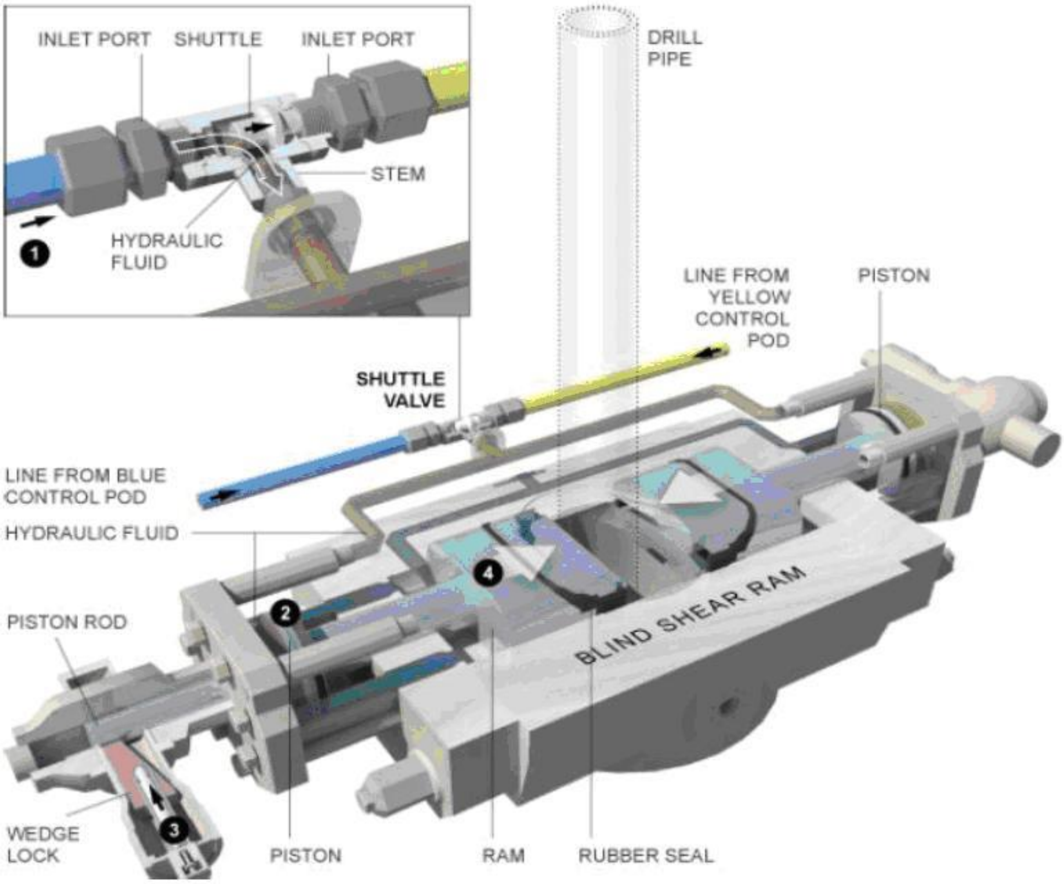


Figure 2-10: How a ram works with the shuttle valve zoomed in. (Lund, 2011)

2.6 Choke and kill system

The BOP system is equipped with two parallel high pressure rated pipes (choke and Kill lines) for providing flow connections between the surface and the BOP stack on the seabed. The choke and kill for surface BOP Stacks are attached to the drilling spool on the opposite sides, below one of the ram preventers while for subsea BOP stack, multiple staggered connections are used to control the route of flow (see Figure 2-15 [right]) (Chapman and Brown, 2009), (Hawker, 2001) . The subsea BOP stack choke and kill lines thus offers multiple flow paths routes with a difficulty to ascertain which will be choke line. The outlet on BOP stacks and rig pumps are connected via the Kill line (Schlumberger, 2011). When pumping through drill string is not possible (say when drill pipe is pulled out and the well is pressured), heavy mud can be pumped into the wellbore through the kill line. It can be located below blind ram. The functions of these lines are as their name implies and the primary role common to both the surface and subsea BOP system are (Chapman and Brown, 2009):

- Well control fluid routing from the annulus of the drill pipe or drill casing to the choke manifold using the “choke line”
- Route kill fluid, when needed, into the annulus using the “Kill line”

In addition to the above for subsea BOP Stack system, other functions include:

- In the event of a leak or plugged line, a back-up line is available
- To aid pressure testing by providing a path for such test.
- Providing a circulation route for sweeping the BOP to remove gas (one way down and the other up).
- Providing circulation medium for a well-sealed by the BSR and drill pipe hung off on a pipe ram (see Figure 2-11 [left]).

How the BOP stack is built up and the operator’s preference determines where the lines are attached to the stack. A typical choke and kill line configuration is shown in Appendix A along with additional functions.

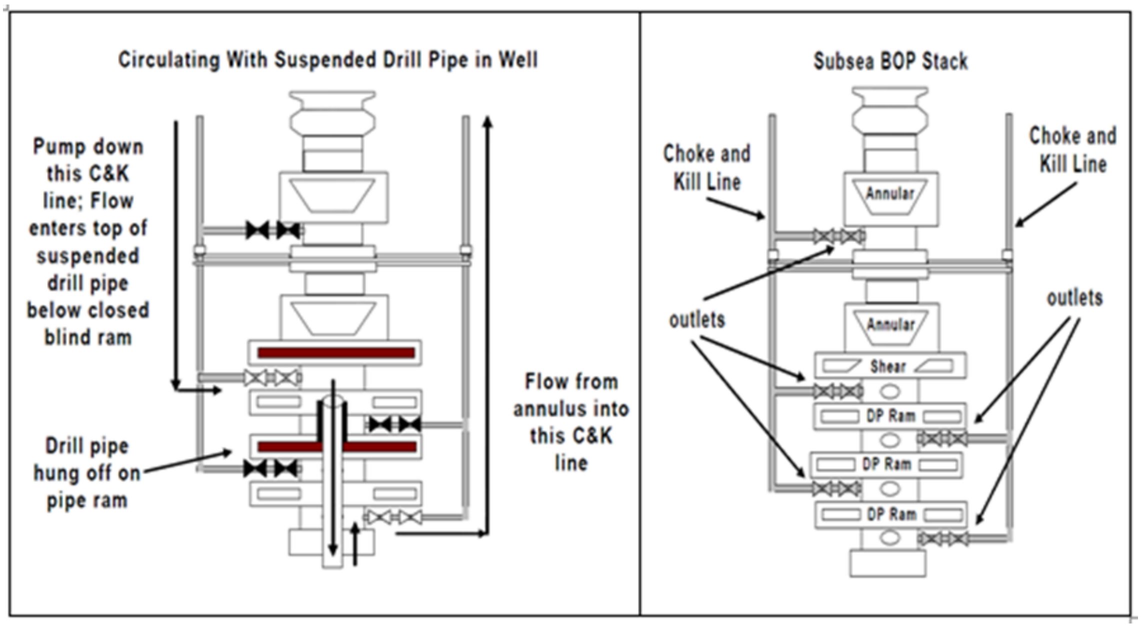


Figure 2-11: Subsea Stack with two choke and kill lines having five connections to the stack at dissimilar heights (left) and well circulation using two Choke and Kill lines to a suspended subsea well with drill pipe hung off on a pipe ram and BSR closed over it (right). (Chapman and Brown, 2009)

The choke/kill lines are closed or isolated using the choke/kill valves. As close to the outlets as possible, two valves are placed in series with the goal of increasing system reliability. These valves are hydraulically controlled by the BOP control system. A fail safe design is used for the choke/kill valves to ensure that an operator always has control of the valves. This implies hydraulic pressure is required to sustain opening function and if pressure is lost. They would be forced into close position by loaded springs. The choke and kill valves provide the means for controlling the BOP functions. They can be adjustable or fixed. An advantage of the adjustable valve is in its ability to allow more control of fluid parameters, but may be more susceptible to erosion than the fixed type under prolonged use.

2.7 The BOP control system

A critical component of the BOP stack is the BOP control system which is responsible for activating the functions of the rams and annular preventer using rig power or not. The components of the control system which can be found topsides and subsea are electrical /electronic and hydraulic components make up the subsea BOP control system. There are two main control system principles for the BOP in different drilling systems:

- Pilot Hydraulic control (Conventional and Pre-charged type)
- The electro-hydraulic system and/or Multiplex (MUX) control

The different control systems have similar operating philosophy for control of fluid. How the pilot signal is transmitted from the rig to the pilot valve in the subsea pod is what defines the difference between these control systems. While plain signal is used for activating the pilot valves in the pilot hydraulic control system (conventional), a pre-charge pressure is given to the pilot signal for the pre-charged control system to reduce the response time (period between activation and complete operation of an intended function) of the BOP function. Thus the conventional pilot hydraulic and the pre-charged pilot hydraulic are similar, with the possibility of the former been converted to the latter type (Transocean, 2010). Control system types vary from rig to rig, however there has been an increase in the use of multiplex control system, as seen in some rigs being changed from pilot hydraulic to multiplex one in the last decade, following maturity of the technology. This move has been seen for drilling in greater water depths (900 meters to greater than equal to 1600 metres) which requires quicker closing times for the BOP and overcoming umbilical handling problems. Thus the electrical cables which operate solenoid valves were used to replace the hydraulic lines that controlled the pilot valves.

The electro-hydraulic system like the MUX uses electric signals instead of hydraulic pilot signals (from the surface) to actuate the solenoid valve on the control pod that transmits a hydraulic pilot signal to the control valve that releases power fluid for chosen BOP function. However large amount of wires are required for solenoid valve activation to effect BOP functions (since a set of wires with a pod-mounted solenoid valve is required for a single BOP function). Hence the interface connections and control bundles are bulky (see Figure 2-12 for typical cables of the different controls system types).

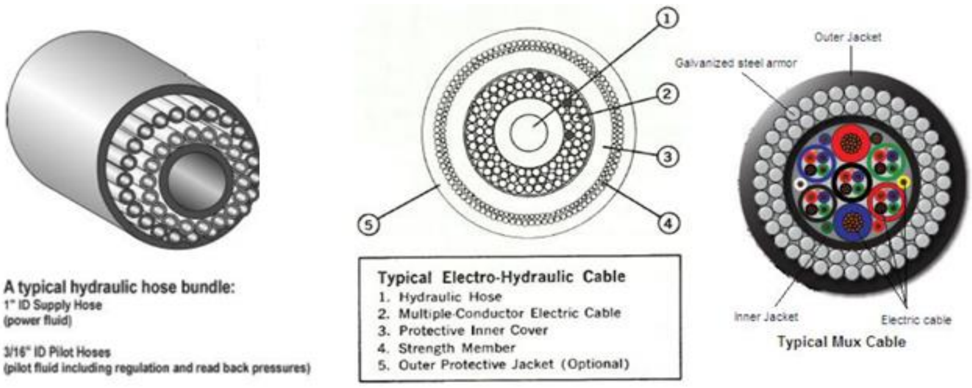


Figure 2-12: Typical hydraulic hose (left), electro hydraulic cable (middle), and MUX cable (right) (Goins, W., Sheffield, R., 1983) (Umbilicals, 2009) (Rig Train, 2001)

Simultaneous execution of commands through the time division multiplexing system provides a relatively compact electrical umbilical thus control umbilical having fewer lines. The SEM using programmable logical controller (PLC) receives a command which is decoded and translated to an electric signal to be sent to the right solenoid valve and then other sequences which is similar to those of electro-hydraulic control systems. The pre-charged pilot hydraulic system can also be used for deepwater of depths ranging from 900 metres to

1600 metres. It is worth mentioning, that the response time increases with depth for the pilot hydraulic system while it is independent of water depth for the MUX system. The response times is based on the valve or BOP closure and seal off. The API recommended practice specifies the maximum closing times for BOPs (for subsea installations) should not exceed 60 seconds for annular preventers and 45 seconds for rams. BOP controls system for subsea drilling operation consists of the following main components discussed thereafter and a functional diagram is depicted in Figure 2-13.

The control items topsides consist of the control panels and the hydraulic/ supply utilities central. There are at least 3 panels namely the central control unit (CCU), the driller's panel and the tool pusher's panel. The CCU is an integrated console with redundant stations for system monitoring, system diagnostics and back-up control which serves as the point of interface to both subsea and surface controls and the main electronic hub. The driller's panel is the one of the surface controls panel that is located on the driller's floor. It is micro-processor based and multiplexed with the CCU with colour coded labelling for component functions, alarm monitoring and general system status monitoring. The interdependency of the panels with the CCU is reduced by the micro-processor electronics.

There are accumulators (pressure vessels designed to store fluid power) located on the topsides and a collection of these is known as the accumulator bank. The topsides accumulator provides back-up should the HPU fails. As drilling operation progresses into deeper waters, the time requirement for executing a BOP function increased and informed the desire to have hydraulic fluid readily available subsea through mounting accumulators on the subsea stack. Subsea accumulators may reduce the Emergency Disconnect Sequence execution time, depending on the design (McCrae, 2003). The hydraulic power unit (HPU) delivers hydraulic fluid from topsides onwards into hydraulic jumper hose bundle, through the hose reel, subsea hydraulic hose bundle (umbilical), subsea accumulator and finally subsea control pod. The subsea controls on the BOP stack is housed in the subsea yellow and blue pods.

The subsea electronic modules (SEMs), hydraulic pressure regulators, subsea transducer modules (STMs), hydraulic accumulators and hydraulic valves, and solenoid pilot valves. In response to commands from the surface control with the exception of the Automatic Mode Function system, functions on the BOP stack are activated by the yellow and blue pods (Shanks et al., 2013). In each of the pods on the BOP stack, there are two SEMs, hence 4 SEMS in a BOP system (see Appendix A.2 for a picture of a typical SEM). The SEMs consist of AMF controllers, programmable logic controllers (PLC), fuse boards, power supply units, batteries, and communication boards. The activation of functions from the surface controls implies transmission of a signal to the SEMs to energize the respective solenoid valves, which directs the pressurized hydraulic fluid to a specific BOP function (US CSB, 2014). There are two operating coils in every solenoid valve with one coil connected to each SEM in a pod, permitting either or both SEMs to operate the valve. During normal subsea operation, both SEMs in each pod receive a surface control system signal for the activation of their respective coil in the solenoid simultaneously.

The pod selector valve position determines the direction of flow of hydraulic power fluid (3000 psi) from surface into subsea regulator valve within one of subsea control pods. Supply of power fluid from the subsea accumulator is routed to the regulator as a backup. The subsea pods (active and redundant) each have two subsea plate mounted (SPM) valves which are meant to regulate the valve for venting the power fluid on the opposite side of the ram and majorly direct power fluid to the ram. The active pod’s SPM valve is responsible for supply of hydraulic control fluid for opening or closure of the ram BOP. Pressurized hydraulic fluid is not supplied to the redundant pod’s SPM valve, though the valve is open, no flow goes through the valve. The regulated fluid (1500 psi) goes through to the shuttle valve and then enables flow to execute the intended function BOP function.

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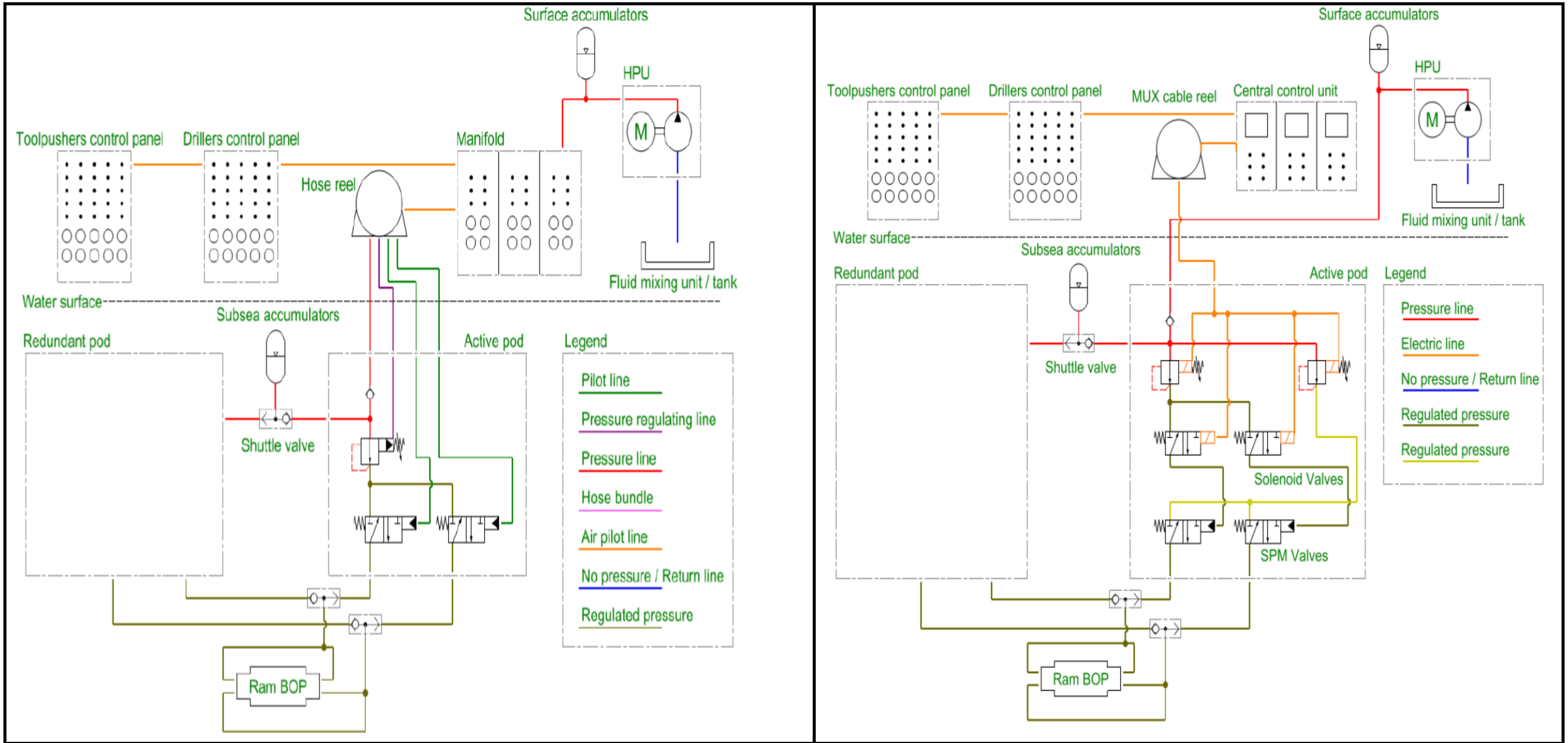


Simple Hydraulic Control System	Multiplex Control System schematic

Figure 2-13: BOP Control Systems Schematics (Kozel, 2015)

The BOP stack function can have different operating position such as the 2 position function (open or close function), 3 position function (open and close function), close assist function and the straight through function. The difference between the 2 positions and 3 position functions is that the former has only one pilot line, as it has only close or open positions. This control function (pilot lines which moves from the manipulator valve, connecting pressure switches and branches to the different pods) can be operated manually and remotely from the control panel.

The block position function is activated to detect leakage in the preventer and control system by flow in the pilot control valve. It enables the preventer to be closed and released off any control pressure through the SPM valves in both pods. It is similar to the close and open position function but the solenoid valves are half-way open to enable pilot control valve being centred with access for venting pilot fluid into SPM valves. Subsea hydraulic valves on the BOP side outlets use the two-position function, since they must be hydraulically pressurized to be in open position or closed under their own spring force by venting hydraulic fluid. This is known as the Fail-safe-close principle however, this type of operation for subsea choke and kill valves or terminology is not used in the industry today. This is owing to rumblings from incidents and court cases stating under certain conditions, the “Fail-safe-close” valves have proven to malfunction. This is also the case with the close assist function, which is similar to the BOP side outlets with two position control, but with a combination of a separate accumulator cylinder dedicated for supply of closing pressure. The straight through functions such as the supply of pressure to the ball joint, pod latches, and accumulator isolation valves which require small volume of fluid avoids the SPM mounted valves and uses the pilot pressure (orange line) directly for the functions.

In recent MUX systems, redundancy has been introduced with multiple PLCs driven by software (vendor supplied or custom). Redundancy can be seen in several paths in the design of the electronic systems to reduce any single-point failure potential. Sequential actions and logic can be exploited, an advantage the MUX system offers, via custom programming. Also compared to the hydraulic system, there is no control valve manifold present in the MUX, as electric signals would be used rather than pilot signals, as in hydraulic for control of subsea functions. MUX system remote control panels are completely electric with no interface with the hydraulic pump unit for control or read-back of subsea functions. Thus relinquishes the pump hydraulic unit’s ability of a direct manual control (Vujasinovic and McMahan, 1988).

The complexity introduced by the signal processing hardware, which raises some concerns on the reliability of the MUX control system, calls for well-trained personnel to operate, maintain and troubleshoot the system. Though they possess quicker response time than the all hydraulic and thus usable for deepwater but the difficulty to activate automatic or sequenced controls (a requirement for drilling from a dynamically positioned rig) and the reliability concerns informed the drift to the preference of the MUX a preferred control system choice (Childers et al., 2004). Experience has shown that the retrieval of the BOP and riser for repair has been associated with the hydraulic component rather than the electrical. There are some precautionary concerns or measures that are worthy to be mentioned relating to the BOP control system. These include

- The control of power should be within easy reach on driller’s floor and there should be an installation of a remote control panel for the BOP, within safe distance from the driller’s floor.
- Suitable markers to be used for identification of BOP controls.

2.8 Secondary Intervention Systems (Emergency Modes)

Shutting in a well using an automated system has become standards on all drilling rigs, following greater concerns for safety of personnel and the environment. The potential use of use of emergency backup systems could be required by three emergency situation systems namely: procedures initiated by operator, loss of main control mitigating emergency and major disasters (e.g. riser system damage). Any of these back-up systems depicted below can be used depending on the need in a particular situation. The two most important types the ROV and the Acoustic alongside the Automatic Disconnect functions are discussed. Figure 2-14 shows the different emergency control system types. Refer to Sattler, (2004), Holand, (2011), Kozel, (2015) and Appendix A.2 for more details.

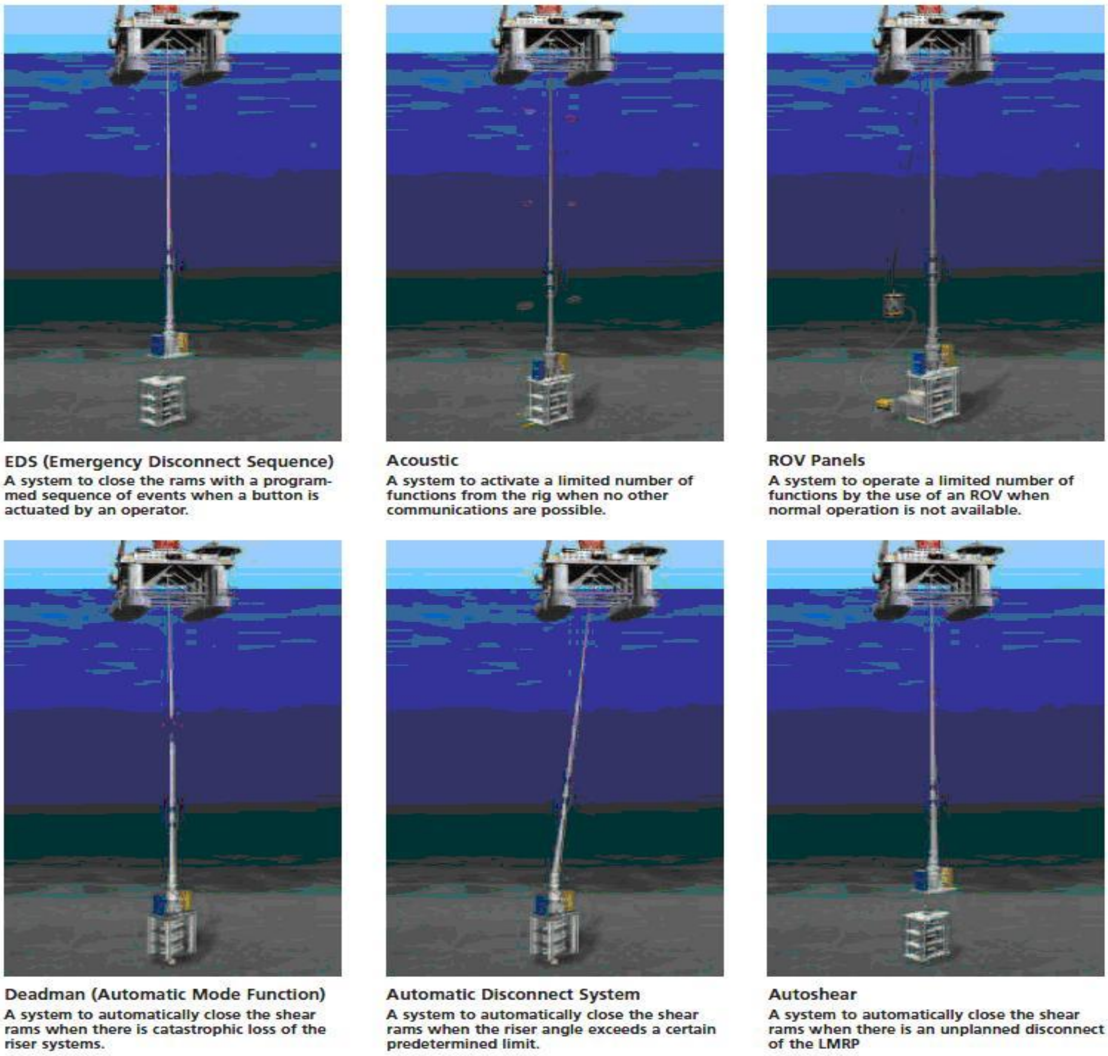


Figure 2-14: Different Emergency Control Systems (Cameron, 2006)

2.9 Previous Works on the BOP System

Most of the earlier documented work on the BOP system is confined within the industry and equipment manufacturers especially. However there have been a few in publications on salient concerns based on authors experience or company development programme to sell the sophistication of their product, while others are outcome of Joint Eras, with the third being after the Macondo

Incident at the Gulf of Mexico as Industry Projects (JIP) made available to the public. These works have been divided into 3 shown below:

2.9.1 Earlier works on Blowout Preventer Pre-1998 (Era 1):

SINTEF have presented the most in-depth work on the BOP system and its reliability for subsea operations. These studies have been funded by the Norwegian Petroleum Directorate and different oil companies for more than two decades now. Initial SINTEF Studies have been carried out in phases namely: Phase I (Rausand, 1983), Phase II (Rausand et al., 1985), Phase III (Holand and Molnes, 1986), Phase IV (Holand, 1987), Phase V (Holand, 1989) entailed failure data analysis for exploratory wells that were drilled submersible wells, evaluation of mechanical BOP components, testing and operations control, maintenance, availability and test intervals recommendations. (Holand and Rausand, 1987) presented a study on the performance of subsea BOP in the North Sea between 1978 and 1986. Daily drilling reports, final well reports, BOP test reports and equipment failure reports were reviewed and meantime to fail failure rate and downtime estimation conducted for different components of the BOP system. Regarding the blowouts and the BOP being a safety barrier, its components testing and testing intervals were examined. Variations were observed in the test interval and found to influence a components Mean fractional dead time. It was also reported that the reliability of the lower pipe ram and the wellhead connector were vital towards enhancing BOP availability.

The Emergence of greater depth exploration for oil and gas led to Deepwater (DW JIP studies). The Phase I DW study was carried out between on 140 wells drilled between 1992 and 1997 and also different control systems were compared in the Phase 1 DW using fault tree analysis to understand their performance relative to closing a well in the occurrence of a kick (Holand, 1997a; Holand, 1997b).

(Fowler, 1994) used the failure modes and effect analysis (FMEA) and the FTA in the safety system analysis of well control equipment. The ram BOP and the accompanying controls were found to be very reliable despite human errors.

2.9.2 Blowout preventer works between 1999-2009 (Era 2):

SINTEF Phase II DW analysed BOP failures for the MMS in relation to both safety and downtime. This study was analysed 83 deepwater wells ranging in depths of 400 to 2000 m, which were drilled between 1997 to 1998 (Holand, 1999b; Holand, 1999a; Holand and Skalle, 2001). These were updated in a subsequent report that examined different configurations, testing and kick data from a safety perspective for enhancing the availability of the BOP report (Holand and Skalle, 2001). Other publications from industry includes:(Chapman and Brown, 2009; Childers et al., 2004; Sattler, 2002; Shanks et al., 2003; Sattler, 2003; Sattler, 2004; Springett and Franklin, 2008; Sattler, 2009; Jorge et al., 2001).

Jorge, N. (2001) review on BOP system depicts an increasing failure rate and higher downtimes with the effect of depth- the result of greater hydrostatic pressures and stress. The understanding of the depth effect followed on with the investment of industrial research on controls systems and improvement of maintenance and testing intervals as seen in the 2001-2010 follow-on publications. (Shanks et al., 2003) had showcased a novel way of meeting planned requirements in the offshore Drilling industry by performance specification of equipment. It discusses the practical reliability issues associated with a deepwater (10,000 ft.) BOP control system from design consideration to estimation and planning tests for reliability requirements to assure evasion of unplanned maintenance by pulling system to surface.

The BOP controls systems and how associated reliability issues can be addressed through qualification testing for a defined period of use and between maintenance periods were presented in Shanks et.al (2003). It was observed functionality specification given to vendors rarely had performance requirements for the components, rather these were developed in the process. The importance of testing requirements for component level reliability demonstration was emphasised. It was reported that the shipyard time of a MODU was the best time to perform major maintenance, on a complex deepwater MUX BOP control systems, during its five-year interval inspection period. Childers et al.,

(2004) reviewed the BOP controls system technology and then presented a new cost effective, simple electro-hydraulic (EH) control system design that can serve as an alternative to existing MUX systems used in deepwater and ultra-deepwater drilling. “The new concept centres on running electrical lines to critical solenoid pod functions that are very time dependent and hydraulic pilot lines to all other non-critical time dependent functions”. Piloted all-hydraulic controls system components may be used with the new EH without a requirement for modifications to the existing BOP stack or LMRP.

Springett and Franklin, (2008) presented innovative design aspects of new generation BOPs which were informed by challenges associated with greater water depths and challenging reservoirs. These includes but not limited to:

- a reduction in stack-mounted accumulator bottles from 98 of as much as 126 bottles for shearing function to 7 depth compensated bottles,
- an increased available shearing force by an innovative split piston which can result in a reduction in rubber pressure and consequently shear ram blocks exposed to lower stresses.
- Improved monitoring with the use of MUX cable
- An enhanced fluid recovery system rather that can overcome possible closing of BOP functions inadvertently due to surface high back pressure, should hydraulic fluid be returned rather than been vented to sea.

Denney, (2009) presented a decision tree to assist drilling crew in deciding on a stack-pull decision or not. It presents two case studies and acknowledges that it is almost impossible for a comprehensive decision matrix to be developed however, recommends for minimum requirements for LMRP/BOP functions and a consensus on stack-pulling philosophy be specified prior to drilling program commencement. The need to invest resources in root cause finding and to analyse scenarios especially in relation to how the minimum requirements is impacted is emphasised (see Sattler, 2009 for full paper with 4 case studies).

2.9.3 Post Macondo period from 2010-2015 (Era 3):

This incident has come to be a game changer for the drilling and well control industry with direct impact on the blowout preventer technology, operation procedures, qualification procedures, regulations, and how it relates to the new drilling limits. Consequently, number of works with focus on different aspect of the technology arose as discussed below and in the following subsection. While majority of these relate to improvement in requirements, technology and regulatory aspects, there have been also technology assessment or appraisal works from Academia amongst the post-Macondo interest groups.

(Sattler and Gallaner, 2010) studied the reliability history of well control systems operating in the GOM (based on 99.58% of subsea wells drilled between 2004 and 2006 under the jurisdiction of the Mineral Mining Service (MMS)) considering both surface and subsea BOP systems. It was observed that failure rates were lower for subsea systems than surface and that the higher the redundancy, the lesser the MTTF hence the higher classes of BOP had smaller MTTF. Failure distributions for subsea components from four different studies (Post Latch-JIP data, Pre-Latch-WEST surveys, SINTEF Phase V and DW phase II) were compared with controls system having the most substantial number of failures compared to other equipment classes. It is believed the complexity associated with the system and the challenges with hydrostatic resulting from deeper water were the responsible for the significant number of failures. However, given that the chances of well control incident resulting from an equipment related problem is very remote, upon consideration of redundancy in system with reliability. Also the control related failures could easily be spotted during a function test. The study showed improvement in BOP reliability over prior studies as it showed components with higher MTTF days than those of SINTEF phase V and then Phase II DW. However, Phase II DW was not directly comparable as it included failures during testing (before first successful testing) which accounted for higher failure rates.

Holand and Awan (2012) divided BOP failures into two main groups namely the safety critical and non-safety critical failures in their study of 279 wells spudded between 2007- 2009 in the US GOM. The criticality is with respect to well control and observed failures were summarized relative to BOP location and operation/test. The non-safety critical failures, those that occur when the BOP is not acting as a well barrier, can be observed when the BOP is on the rig floor, being run and during installation testing. The safety critical ones, those that occur when the BOP is acting as a well barrier, can be observed when drilling starts following the acceptance of the installation test.

A failure of the BOP would not mean the complete safety barrier function of the BOP failed. It can imply a component failure or failure of the BOP control system. BOP failures based on where/when they were detected can be grouped into three as shown in Table 4-2. In Holand and Awan, (2012), most of the BOP failures (i.e. 71%) occurred when the BOP was on the wellhead. 35 of the 110 failures on the wellhead occurred during installation testing and the rest were during normal operations or regular BOP test. The testing after landing the BOP, the first time or during subsequent landings of the BOP or the LRMP is referred to as installation testing. In the study, 156 failures were identified in total of which 45% are attributed to control system.

Table 2-2: The classification of BOP failure based on observation (Holand and Awan, 2012)

Failures category	**Sub-activities**
BOP on the rig	• Test prior to running BOP • Other/unknown
While running or pulling the BOP	• Test while running BOP • Normal operation • Other/Unknown
When BOP on the wellhead	• Test after running BOP • Test after running casing or liner • Test schedules by time • Normal operation • Other/unknown

The failure modes associated with the BOP components are mainly similar and common modes includes failure of a component to open or close, leakages which could be internal or external, failure to lock/latch or unlock/unlatch, failure to shear or seal, etc. The annular preventer had the internal leakage and fail to fully open as the dominant failures with the former greater in occurrence (see

Table 2-6 for failure rates). Fail to close is a rare failure mode for the Annular BOPs based on Holand, (1999). The internal leakage has been observed also to be the most dominant failure mode amongst others (external, leakage, fail to close, fail to open and other unknown) and has accounted for about 70% of the ram BOP failures in Holand and Awan, (2012) study. The choke line has leakage as one of the major failure modes associated with it. The External leakage is the most severe failure mode in a choke and kill valve. A leakage in the BOP will ensue should such leakage occurs in the lower inner valve below the LPR when attempting to close in a well kick. In all-purpose, more external leakages have occurred in the link between the inner valve and the BOP body, than the link between the two valves in series. Commonly, within a common valve block would the two valves be located (Holand, 1999)

The internal leakage failure mode is not as serious as an external leakage. Choke and kill valves are always in series of two. However, in the event of the two valves fail another leakage would be needed before the well fluid can reach the surroundings. Failure of both valves in series has been mentioned in earlier studies.

There was no direct trend observed for MUX control system reliability (MTTF) with age (Holand and Awan, 2012), when it was desired to ascertain if the improvements in newer built equipment would translate to improved reliability. In a particular category of failures, 7 out of the 11 failures in the MUX happened during the running of the BOP to the wellhead and they were all failures on the blue pod. Considering the control systems generally five types of failure modes, which are associated with the control functions and the pods, are mentioned in Holand and Awan, (2012). These include:

- Loss of one function both pods
- Loss of all functions one pod
- Loss of all functions both pods
- Loss of one function one pod
- Loss of several functions one pod

Of the control system failure modes the loss of functions and both pods, a critical failure mode, is found only in the multiplex control system. This failure mode implies that the BOP cannot be operated. A spurious operation of the BOP function may occur with any of the control systems. The spurious operation failure mode had been considered in a previous SINTEF report (Holand, 1999).

State of the Art FMECAs are those of Januarilham, (2012) and American Bureau Society (ABS). Januarilham (2012) carried out an analysis of critical component in the BOP System relative to safety of personnel following a kick occurrence and initiation of well shut-in procedures. The reliability block diagram, FMECA & criticality matrix, and redundancy & effect analysis techniques are applied to the BOP system with hydraulic control. Shuttle valve for blind shear ram (e.g., for closing function), Blind shear ram, additional critical components inside shear ram: ram piston, flange and gasket (in the BOP stack) and annular preventer (rubber housing) were identified as the critical components of the BOP system. The shuttle valve was identified as a most critical component in all three analysis outcomes while the others were identified in two of the three analysis approaches. It was however emphasised that these critical component might not be critical should they fail after a shut-in has already been initiated (consequence will be a case of delay to operation) and during testing given several safety measures and procedures to manage expected problems. The redundancy table shows a several redundancies have been built into the BOP system such as an alternative hydraulic supply and control system, redundant flow path route, redundant similar or alternative component for required function.

The American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) FMECAs is more comprehensive given three (3) different analyses was conducted with different experts from OEMs, drilling contractors, and Operating companies and findings summarised in a fourth report (ABS, 2013b; ABS, 2013a; ABS, 2013c; ABS, 2013d). This level of depth in detail can only be achievable due to available resources, considering the cost of experts' time. The analysis of the BOP system, components and associated control systems data presented in these ABS studies are in relation to an operation in the GOM, operating depth of 5000ft and deeper and three BOP configurations (Classes VI, VII, and VIII BOP system). Eleven (11) major BOP functions (eight of which are specified in API RP 53 Standard, Section 7.1.3, and the extra functions identified by the analysis team) and 52 functional failures were identified, and agreed upon following the initial scoping for the functional FMECA and during the FMECA sessions. In addition to the 11 major functions, FMECA 3 considered two (2) more items (not functional failures- The acoustic and ROV secondary control systems), to be of importance to safe BOP system operations, however these were not assessed in the equipment-level FMECA. Both functional and equipment level FMECA approaches were considered in the studies with the major equipment failures which are responsible for and/or contributed to a functional failure identified through the former approach. Also in the equipment FMECA, potential generic failure modes for equipment were adjusted to better portray the major failure means as understood from the functional FMECA. General equipment failure modes identified were grouped into mechanical (e.g. corrosion, leaks, and plug) and electrical/electronic failures (e.g. erratic output, processing error, and loss of or degraded power).

Critical failure modes by way of risk ranking techniques and their effects were identified in order to evaluate the BOP maintenance, inspection and testing (MIT) current practices which were aligned with the related component/functional failures frequencies. Also potential major equipment failures (failure modes) including associated components were identified and evaluated to understand their impact on BOP performance, as well safe-guards for detecting and preventing failure modes. Functional failures were ranked using highest average RPN and the greatest occurrences due to equipment failures in all three FMECA. The severity rankings in the functional FMECA 3 were also subdivided into personnel, environment, and downtime. Majority of the functional failures assessed had high scores of 8 and above assigned to downtime severity (from the worst case ranking among the three groups). The control system was the most frequent equipment occurring failure in the BOP system in all three FMECAs and next three items were those of Pipe rams, Choke and Kill lines and valves and Blind shear rams failure respectively in two of the three FMECAs. In two of the 3 FMECAs, the connector and rigid conduit were the hardest to detect while the autoshear system was hardest to detect in all three FMECAs. The most important equipment failures are the Blind Shear Rams in all three FMECAs. The Blind Shear Rams is recorded as the most important item in all three FMECAs, and Casing shear rams, Connector, Blue and yellow Pod hydraulics, Choke and Kill lines, Pipe rams, Hydraulic Supply Lines and Subsea Accumulators in two of the three FMECAs. Function test, and pressure tests are the most frequent safeguard measures/MIT task in all three FMECAs and thereafter dimensional/ultrasonic testing and rebuilding/replacing equipment in two of the three FMECAs. The level of indenture in FMECA 3 is slightly different as it had more distinct components and more specific failures causes than in FMECA 1 and 2. The difference in these 3 FMECAs are minor with the outcomes similar with varying degree of details. The other significant difference as identified in the report is the variation in RPN rankings which can be due to differences in design and operations, and subjectivity associated with assigning score to the RPN factors, as they are dependent on the experience of the expert.

Drægebø, (2014) compared the reliability of an electro-hydraulic and that of an all-electric BOP system using Reliability Block diagram, FMECA, functional analysis and the fault tree techniques. It concluded that he all-electric BOP technology was more reliable and less susceptible to failures. The all-electric system was of lesser weight, have accumulators been replaced with batteries, no shuttle valves, with more redundancies in the controls items with superior monitoring, and more environmental friendly. However, it is still a new technology with potential challenges and several other important factors that needs to be considered to support the conclusion in (e.g. it has to be commercially and technically viable).

(Cai et al., 2012b) carried out an evaluation of the subsea BOP considering common cause failures which included a Markov model for reliability assessment. This was influenced by research findings that redundant systems (e.g. BOP systems) reliability analysis is best conducted in a flexible manner using the Markov model (Liu and Rausand, 2011; Yu et al., 2005). (Cai et al., 2012b) took account of the BOP system complexity and the difficulty of solving large Markov models, the BOP system split into seven independent (failures and repair) modules: control stations, ram preventer (RP), control pod, LMRP connector, TMR controller, annular preventer (ANP), and wellhead connectors and combined with the Kronecker product approach (see: (Rausand and Høyland, 2004)). BOP stack configurations and mounting types control pod (i.e. retrievable and non-retrievable pods) effects on three subsea BOP systems (1 ANP, 4 RP; 2 ANP, 5 RP; 1 ANP, 6 RP) was studied based on the Markov model. The finding showed lower performance for BOP systems with non-retrievable than for those with retrievable. Also over a period of time, Performance a BOP system can be reduced from with a one less annular preventer and cannot significantly improve with a one more ram preventer. The subsea control pods and the control stations were suggested to be the two most important components (compared to others) given a variation in their MTTF and failure rates produces greater effects on the system reliability and availability.

(Cai et al., 2012a) presented a reliability analysis of two subsea blowout preventer control systems configurations (Double dual modular redundancy and the triple modular redundancy) using Markov modelling. A comparison of the configurations was done using the multiple error shock approach (see: (Hokstad and Bodsberq, 1989) for common cause modelling. The system was split into independent modules and the Kronecker product of the modules state probabilities used to compute the Probability of failure on demand (PFD) and their safety integrity levels calculated to be SIL 3. The subsea BOP control system being a low-demand system, thus its reliability can ideally be measured using the PFD.

(Klakegg, 2012) discussed current conventional reliability assessment techniques applied to the BOP as an example of a safety critical systems and proposed improvements to the approaches. A possible improvement of the BOP reliability computed estimates presented using the fault trees and minimal-cut sets post processing with possibility of common cause failures being considered. Following the challenges with functional testing of BOP components, especially the shear ram, not all dangerous undetected failures are discovered. Thus approximations for the PFD as defined in (Rausand and Høyland, 2004) is rendered non-conservative, given an imperfect functional testing. The need to consider undetected failures by functional test was also proposed, thus considering criticality to safety, (Klakegg, 2012) suggested the inclusion of the probability of critical to safety unavailability or test independent failure (Hauge and Onshus, 2010) or a test coverage factor C (Hauge et al., 2010) to the computation for PFD for minimal-cut set. It is believed this approach would deduce more conservative and better reliability estimates than the conventional. The PFD value is increased by the inclusion of common cause failures which results in a reduction of reliability. The event tree analysis was identified to be very useful in presenting a better risk picture of different BOP operational conditions and an out of well control escalation event. In (Klakegg, 2012), the control system failure modes offer the greatest contributions to the BOP system unreliability. (Pinker, 2012) presented an integration of the event tree analysis with the fault tree analysis was applied to the BOP system for an enhanced assessment of the BOP system reliability. Sequence of events is considered and the event tree end states were evaluated using the fault tree. The approach of minimal-cut set post processing for estimating PFD towards a better conservative approximation was earlier presented in (Lundteigen and Rausand, 2009) and the rational is that computed BOP system PFD (relative to failure to close wellbore during a well kick) using fault tree analysis in previous reliability of BOP studies have been approximations.

Zhang, (2015) assessed the BOP system using Bayesian network modelling approach. It attempts (to show how a more detailed analysis than those of traditional Fault tree analysis can be achieved as multiple states and dependent failures can be handled. The availability and reliability of three different BOP configurations was compared. The modern BOP (2 AP, 2BSR, 3 PR) was more reliable than the DWH (2 AP, 1BSR, 2 PR, 1CSR) and the classical (2 AP, 1BSR, 3 PR), however overtime, there would be no difference in the reliability of the latter two configurations suggesting the absence of one pipe ram Is not fully masked by the inclusion of an additional CSR. The pipe rams contributed more to the total system failure than the BSR and the Annular. However, the results are dependent on the modelling assumptions and data used or the analysis. It was also concluded that critical to availability improvement is an effective repair strategy.

2.9.4 Blowout and BOP System components failure database.

Several national and international databases with records of drilling operation related failures and accidents exist and these include (Godziuk, 2015):

- Hydrocarbon Release Database (HCR) – United Kingdom;
- Marine Accident Investigation Branch (MAIB) – United Kingdom;
- Danish Energy Agency (DEA) – Denmark;
- Petroleum Safety Authority (PSA) databases – Norway;
- Well Control Incident Database (WCID) - International Association of Oil and gas Producers (OGP);
- Worldwide Offshore Accident Databank (WOAD) – Det Norske Veritas - Germanischer Lloyd (DNV-GL).
- SINTEF Offshore Blowout Database – Norway;

The SINTEF database is the most comprehensive blowout and BOP component failure related database. The BSEE e-Well system- well activity reports (WAR) is the main source of information for the study in the unrestricted published version of ExproSoft report on Deepwater Subsea BOP Systems Reliability and Well kicks (Holand and Awan, 2012). WARs provide well and operational data, with an activity summary conducted on the well, which operators submit to BSEE. The study entailed data collected systematically from 259 wells spudded between 2007- 2009 (all drilled in water depths of greater than 610 m) in the US GOM Outer Continental Shelf (OCS). While there was data for when the BOP was on the rig, being deployed or pulled up, and when the BOP is on wellhead, only the last was considered as the first two were considered as non-safety critical failures. Failures considered in the study, for a total in service time of 15056 BOP-days, were 156 BOP related failures in total. Table 2-3 shows an overview of failures and associated data.

Table 2-3: Overview of failure and associated data (Holand and Awan, 2012)

BOP System Component	BOP-days* in Service	Item Service days	Number of Failures	Total Lost time (hrs)	MTTF (item in service)	MTTF (BOP-days*)	Average Downtime per failure (hrs)	Average Downtime per BOP-day* (hrs)
Annular Preventer	15056	28150	24	2344.5	1173	627	98	0.156
Hydraulic Connector	15056	31142	8	638	3893	1882	80	0.042
Flex/Ball Joint	15056	15056	1	288	15056	15056	288	0.019
Ram Preventer	15056	77264	23	1765.5	3359	3359	77	0.117
Kill and Choke Valves	15056	160310	4	136	40078	40078	34	0.009
Choke and Kill Lines, all	15056	15056	17	1992	886	886	117	0.132
Main Control System	15056	15056	72	4712	209	209	65	0.313
Dummy item	15056	-	7	1572	-		225	0.104
Total	15056	-	156	13448	-		86	0.893

*** BOP- days refers to number of days spanning from the first time when BOP was latched on the wellhead to when it was pulled from wellhead last time**.

In order to provide more context for validity of the above data to be used for validation, given the limited source of data and survey period (2007 -2009) for data in Table 2-3 , an additional data set (SINTEF Phase II DW data shown in Table 2-4) from an earlier study is further considered to follow good practice.

SINTEF Phase II DW data were collated from wells drilled in the US GOM OCS from 1997 and 1998 in water depths ranging from 400 m to 2000 m (Holand and Rausand, 1999). However, for this study daily drilling report (DDR) was the major source. A detailed description of a well's drilling activity is what makes up a drilling report (which was not accessible to the general public) and thus more detailed than WAR. Only DDRs from Operator AP were analysed. Besides the survey periods, the difference between the two survey data sets in this section is an increased BOP-days in service and an improvement in Mean Time to Fail (MTTF) compared to previous studies. Although the level of the average downtime per BOP-day for both studies were similar, (Holand and Awan, 2012) suggested that that WARs do not contain details of less critical failures which would normally result in less downtime.

While ExproSoft is still pursuing the WellMaster BOP product consisting of SINTEF database on offshore blowout and kicks, hopefully in the near future a better robust data handbook would be made available.

Table 2-4: Overview of failure and associated data (Holand and Rausand, 1999)

BOP System Component	BOP-days* in Service	Item Service days	Number of Failures	Total Lost time (hrs)	MTTF (item in service)	MTTF (BOP-days*)	Average Downtime per failure (hrs)	Average Downtime per BOP-day* (hrs)
Annular Preventer	4,009	7,449	12	336.50	621	334	28	0.08
Connector **	4,009	8,019	10	117.75	802	401	11.8	0.03
Flexible Joint ***	4,009	4,009	1	348.5	4,009	4,009	248.5	0.06
Ram Preventer	4,009	16,193	11	1,505.25	364	364	136.8	0.38
Kill and Choke Valves	4,009	31,410	13	255.5	308	308	19.7	0.06
Choke and Kill Lines, all	4,009	4,009	8	37	501	501	4.6	0.01
Main Control System	4,009	4,009	60	1,022	67	67	17	0.25
Dummy item ****	4,009	-	2	116	-	2,005	58	0.03
Total	4,009	-	117	3,738	-	34	31.1	0.91

***** **BOP- days refers to number of days spanning from the first time when BOP was latched on the wellhead to when it was pulled from wellhead last time.**

****** **For one LMRP connector failure the lost time was not available because the daily drilling reports were missing. Two to three days were lost.**

******* **For the flexible joint failure 250 hours more time was used to work on stuck pipe/fishing problems after the flex joint failure was repaired. This work was most likely a result of the flexible joint failure.**

******** **The Dummy item in Table x is used to include two BOP failures that were impossible to link to a specific BOP item. Both these failures occurred when preparing to run the BOP and were poorly described.**

In the absence of any other open accessible sources BOP WellMaster data source is considered the best case for validation as the widely used OREDA database does not contain BOP component failure data. However, for some control related items failure data for similar components would be considered from the OREDA volume 2, handbook.

Considering failure criticality, a further failure data set available for some specific failure modes is presented in Table 2-5 as the earlier tables data were overall component failure (which considered all modes for a particular component). Chief source is from the Holand report and a few from the OREDA handbook and one from Expert engineering judgement. Also it is important to state that only critical failure modes have been considered in terms of a loss of well control.

Table 2-5 : Critical failure data available for some specific component modes (Adapted).

BOP System Component	BOP-days* in Service	Item Service days	Number of Failures	Total Lost time (hrs)	Average Downtime per failure (hrs)	MTTF (days in service)			Data Source
						Lower Limit	Mean	Upper Limit	
Annular Preventer Fails to Close	15,056	28,150	1	268.00	0.018	5,934	28,150	548,805	Holand
Annular Preventer Fails to fully Open	15,056	28,150	8	84.00	0.006	1,950	3,519	7,071	Holand
Annular Preventer Internal Leakage (leakage through a closed annular)	15,056	28,150	4	712.00	0.047	3,075	7,038	20,603	Holand
Annular Preventer External Leakage			-						Holand
Wellhead Connector External Leakage	15,056	15,056	1	96	0.006	3,174	15,056	293,528	Holand
Wellhead Connector External Leakage	15,056	15,056	1	96	0.006	3,174	15,056	293,528	Holand
Connector Fails to Lock	15,056	15,056	1	168	0.011	3,174	15,056	293,528	Holand
Connector Fails to Spuriously Unlocks	15,056	15,056	1	24	0.002	3,174	15,056	293,528	Holand
Flexible Joint External Leakage	15,056	15,056	1	288	0.019	3,174	15,056	293,528	Holand
Ram Preventer Fails to Close	15,056	77,264	1	6.00	0.000	16,287	77,264	1,506,318	Holand
Ram Preventer Fails to fully Open	15,056	77,264	1	24.00	0.002	16,287	77,264	1,506,318	Holand
Ram Preventer Internal Leakage (leakage through a closed annular)	15,056	77,264	7	660.00	0.044	5,876	11,038	23,516	Holand
Choke and Kill Valves Internal Leakage	15,056	160,310	1	0	0.000	33,793	160,310	3,125,360	Holand
Choke and Kill Valves External Leakage			-	-					Holand
Choke and Kill Valves Fails to Open			-	-					Holand
Choke and Kill Valves Fails to Close			-	-					Holand
Choke and Kill Lines (Riser Attached Line) External Leakage	15,056	15,056	6	924	0.061	1,271	2,509	5,762	Holand
Choke and Kill Lines (Jumper Hose Line) External Leakage	15,056	15,056	0	0					Holand
Choke and Kill Lines (BOP Attached Line) External Leakage	15,056	15,056	0	0					Holand
Controls- Loss of one function one pod	10,942		6	144	0.013	934	1,824	4,188	Holand
Controls- loss of several functions one pod	10,942		1	0	0.000	2,307	10,942	213,322	Holand
Controls (All modes- Multiplex electrohydraulic)	10,942		28	10,942	0.230	285	391	550	Holand
Solenoid Valve Fails to close		8,403	34			27,778	86,508	4,166,667	OREDA Vol2 Pg.60
Shuttle Valve Failure			4				13,750		Expert Judement
Subsea Loss of Accumulation			1			50,813	277,778	∞	OREDA Vol2 Pg.60
Hydraulic Tubing Leakage						2,825	10,851	4,166,667	OREDA Vol2 Pg.60

* BOP- days refers to number of days spanning from the first time when BOP was latched on the wellhead to when it was pulled from wellhead last time.

The BOP control system components were attributed to be cause of 45% of failures in the dataset and also associated with the highest downtime of BOP subsystems. In addition, while data in (Holand and Awan, 2012) shows a lower frequency of failures, a coarse ranking of safety critical failures was presented in the study (though based on severity) as follows (in order of criticality importance):

1. One failure causing wellhead connector external leakage
2. One spurious opening of the LMRP connector (Unknown cause, no autoshear in BOP)
3. One control system failure that caused total loss of the BOP control
4. One shear ram leakage in closed position
5. Upper and lower variable bore ram leaked at the same time

6. Two incidents, pipe ram failed to close
7. Nine incidents, loss of all functions one pod
8. Two incidents, pipe rams leaked in closed position
9. One flexible joint external leak
10. One failed to close annular incident
11. Four incidents, annular preventer leak
12. Six choke and kill line leaks
13. Five incidents with loss of one function both pods.

2.10 BOP Testing and Maintenance

Given the use of state of art design approach (e.g. Design for excellence), industry standards (American Petroleum Institute, API specification 16A) high-class company standards by Equipment Manufacturers, the products are usually fit for purpose upon delivery. Thorough testing and maintenance is required as a used system may not perform as the old one –knowing equipment that has been in operation (in the field) is associated with most problems and not with new ones (Montgomery, 1995). A 7 to14 days window is recommended for a function test on the BOP and its controls, although every 7 days is recommended by (API STD 53, 2012) and Oil and Gas UK, as operations allow. The BOP needs to be pressure tested every 14 to 21 days after use or before the day crew is on board (MMS Consents up to 21 days, UK allows 14 days only). However, local regulations have to be followed with respect to test frequency and duration (HSE, 2015). This informs the need for proper procedures and specification to be available for equipment inspection and testing by third party maintenance personnel. Also technical information should/must be shared by manufacturers as a basic part of a quality management system. The quality control process should involve proper documenting of changes/modification through the use of inspection and testing procedures for consistency and criticality identification. This procedure should be living with constant updating and distribution. It should also specify acceptance criteria for activities and provide a list of sources for the specifications, so personnel can refer to them when required.

When not in service and in the process of moving from one well to another, inspection (visual and dimensional) of the BOP components and operating system can be carried out. Also ram blocks can be greased and protected, gaskets, ram packers and rubber seals can be removed. The gaskets and seals can be replaced annually. Damaged metal parts can be repaired or replaced. Upon completion of the aforementioned and reassembling, testing of the operating system and preventers can then be done.

Preservation is also a recommended practice when the equipment is temporarily stored or moved or shipped and in the case of the BOP being located onshore pending shipment to offshore location. This requires a corrosion protection assurance procedure such as cleaning and painting exterior, upon disassembly, application of anti-rust on cavities, use of preservative fluid to fill up hydraulic system and plug holes. Proper maintenance needs to be carried out as a way of assurance that rams at their rated pressures is fit- for- purpose. In between well maintenance, elastomers can be re-qualified using specific tests like the drift test for annular and sealing characteristic test for ram preventers (O&G UK, 2014). Mckay et al., (2012) presented a BOP dashboard development process by simplifying complex BOP diagnostics with the goal of having to improve operational decision process in assessing risk when critical functions are impaired. Huse and Alme, (2013) showed a real time BOP monitoring tool developed to understand the effect of a potential failure as it relates to if to halt drilling and pull a BOP for repairs or not. Risk Spectrum software was used to build a BOP risk model using integrated information from a fault-tree modelling and FMEA workshops with risk and subject matter experts. Qualitative risk levels can be monitored on-line and actual fault-finding and planning process is enabled.

2.11 Regulatory/Recommended Practice/ Standards requirements

The installation of the Blowout Preventer is a common insurance warranty and a normal regulatory requirement for well control related system activities. The importance of this mechanical equipment for sealing a well, as a means of well control, is seen in the Energy Exploration and development (EED 8/86) definition of “well out of control” for insurance purposes/coverage in United States.

“… a well shall be deemed to be out of control only when there is an unintended flow from the well(s) of the drilling fluid, oil, gas, and water above the surface of the ground or water bottom, 1. Which flow cannot be:

*Stopped by the **use of equipment onsite and/or the blowout preventer**, storm chokes or other equipment required…”*

The relevance of the BOP is also seen in the EED8/86 only drilling warranty statement:

“It is warranted that where the Assured is the operator or joint operator on any insured well being drilled, deepened, serviced, worked over, completed and/or reconditioned, a blowout preventer(s) of standard make will, when in accordance with all regulations, requirements and normal and customary practices in the industry, be set on surface casing or on the wellhead and installed and tested in accordance with usual practice”

Besides this warranty perspective above, generally in different regions, some statements or guidelines concerning the BOP system functionality are stated in national or regional standards or regulations. The API RP 53 is the recommended practices for blowout prevention equipment systems for drilling wells, with the last edition being the 3rd and following the Macondo accident, a number of amendments are being made a 4th edition. This however has some statements or rules which the US Bureau of Safety and Environmental Safety (BSEE) may disagree with in every/some context and as such may require some consultations before it is released. The Australian regulation (NOPSA) expects companies to follow recent industry best practice on the use of preventive barriers or alternate accepted standards like the API. Risk-based approach to regulation is adopted rather than a prescriptive one.

As was evident in the Macondo case, the BSR was not able to shear and seal the $5\,{}^{1}/_{2}{}^{"}$ drill strings in compression. This fuelled the obvious requirement for redundancy, given there is only one BSR, one shuttle valve and monitoring of the BOP systems using MUX cable not been independent. The need for back-up systems has heightened given the occurrence of BOP failure events and as such there is new interest concerning the extent of regulatory requirements for BOP control systems. The US Mineral Management Service (MMS) specifies three types of back-up control systems for subsea BOP in use in the Gulf of Mexico which includes acoustic, deadman and ROV operated. However in Norway, there is a regulatory requirement for the use of back-up control system for subsea BOP functions (NORSOK Standard, 2012). In the UK, there is no explicit regulatory requirement for the use of acoustic back-up control systems for subsea BOP, but the HSE does specify a requirement that suitable equipment and procedure be provided to handle drive-off situations for dynamically positioned rigs. While in other countries like Brazil and Italy, it is not compulsory to have back-up systems with acoustic signal transmissions. So far we have seen that despite the occurrence of certain accidents in the time past and the call for innovations or review of failures, the BOP design is not without limitations and this poses some reliability concerns. This guides the basis for regulatory requirements within a prescriptive environment. Some of these limitations as identified by Rees (2011) are:

- The pace of advancement in drilling technology is fast and as such the maximum BOP pressure rating is struggling to match up in pace.
- Frequent full emergency testing of all functions is not considered to be practicable.
- Component failures have come to be seen as random failures, which might still occur, while some go unseen/unknown, regardless of BOP manufacturers continued research and development.
- Inability of the BOP to cut through some tubular components e.g. (drill string connection)

The design of the control systems are usually in accordance to specifications of certain standards like the API 16D and API 16E. In addition to API RP 53 other recognised standards associated with well control systems and BOP System and these are all being reviewed incorporating the lessons learnt from the

Macondo and Montana incidents. Table 2-6 shows a summary of some changes in regulations, standards and policies following the Macondo incident.

Table 2-6: A summary of changes in policies, regulations and standards following Macondo blowout

<table>
<tr><th rowspan="2">Country</th><th colspan="4">Majors Changes</th></tr>
<tr><th>Changes registered</th><th>Discussed standards in this study, as revised after Macondo blowout</th><th>Earlier edition</th><th>New edition</th></tr>
<tr><td rowspan="7">USA</td><td rowspan="7">- New offshore drilling regulation including the Drilling Safety Rule, the Workplace Safety Rule, and the requirement of the performance – based regulations for all operators in the OCS
- BOEMRE split into 3 institutions: BOEM, BSEE and ONRR
- SEMS regulations that authorize unannounced rig inspections and third party audits</td><td>API Spec 16A
"Drill through equipment (BOPs)"</td><td>2004</td><td>Dec. 2012</td></tr>
<tr><td>API Spec 16C "Choke and kill systems"</td><td>1993</td><td>May, 2013</td></tr>
<tr><td>API Spec 16D
Control systems for drilling well control equipment and diverter systems</td><td>2004</td><td>Jan. 2013</td></tr>
<tr><td>API Std 53 "Recommended Practices for Blowout Prevention Equipment Systems for Drilling Wells"</td><td>1997</td><td>Jan.2012</td></tr>
<tr><td>API RP 65-part2 "Isolating potential flow zones during well construction"</td><td>2002</td><td>Dec. 2010</td></tr>
<tr><td>API RP 75 "Recommended Practices for a development of safety and environmental management for OCS operations and facilities"</td><td>2004</td><td>Apr. 2013</td></tr>
<tr><td>API RP 96 "Deepwater well design Considerations"</td><td>New</td><td>Ed.1, Mar. 2013</td></tr>
<tr><td rowspan="4">Norway</td><td rowspan="4">- PSA established a project team to follow the DwH accident
- Supervision and other measures which could improve health, safety and the environment (HSE) on the Norwegian continental shelf (NCS)
- Specification in Norsk D-001 that the mud gas separator (MGS) should no longer be connected directly to the diverter system.
- a "safety system" designed to divert any gas in the riser to the overboard lines and safely away from the rig
- improved procedures in Norsok D-010 for planning, mixing, pumping and qualification of cement as a primary barrier
- MOC procedure covering the well life cycle should be included in the operator's management system steering documentation
- Requirement in Norsok D-Z013 of a quantitative analysis to establish and/or tone required performance standards for all relevant barriers</td><td>Norsok D-001 "drilling facilities".</td><td>1998</td><td>Ed 3, Dec. 2012</td></tr>
<tr><td>Norsok D-002 "well intervention"</td><td>2000</td><td>Applicable for all wells after Jan 1st, 2014</td></tr>
<tr><td>Norsok D-010 "well integrity in drilling and well operations"</td><td>2004</td><td>Rev4, 2013</td></tr>
<tr><td>Norsok Z-013 "Risk and emergency preparedness assessment"</td><td>2010</td><td>Ed. 3, Oct. 2010</td></tr>
<tr><td>UK</td><td>- The creation of the DHIRG, OSPRAG and WLCPF
- peer review reinforcement of well design assessments and rigorous auditing for MODUs
- adoption of minimum, prescriptive safety standards for fail-safe devices such as the blowout preventer</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>ISO</td><td>- Several ISO standards are being updated, and mostly are
- To adopt the outcome of the API work and Norsok standards.</td><td>ISO/TC 67 "Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries"</td><td>The latest update 2009</td><td></td></tr>
</table>

Surprisingly for some BOP system components, there exists no industry standard. The shearing capability of the ram is not guided by any form of standard which is currently being addressed by amendments in new regulations and standards. See the recent BSEE final ruling on well control for updates (Reference). It is worth mentioning that besides the use of regulatory requirements or specification for design and operation of critical components like the BOP, if available, that of company or equipment manufacturers based on best engineering judgement is used.

2.12 Current Reliability concerns and Improvement Strategies

According to (Huse and Alme, 2013; Sattler, 2013) some of the concerns of interest associated with the BOP are:

- Identification of the non-critical and critical components, their failures, effects and mitigation factors
- Reliability of the BOP system and function
- Components and systems Redundancy capabilities and stack configuration
- Management of change
- Hydraulic control systems leak
- Advance maintenance systems and philosophies
- Integrity of the system as a whole
- Regulatory/ Industry minimum requirements

Recommendations made in (Holand, 2011) concerning the BOP control systems and the independency of the pods includes:

- Each pod should have a separate hydraulic line
- The pods should have as little as possible communication and for instances where a communication is required, it should be ensured that possibilities for isolation be available
- A case of the control of both pods being ruined by a single subsea failure should be avoided

In McCarthy (2012), considerations regarding design requirements for new BOP were presented for assurance in their use. This includes:

- The need for operators understanding on the use of BOP- this entailed how, when and their ability to execute such task when under pressure. This requires unambiguous procedure.
- Drilling operation be put to a stop following a faulted BOP.
- The need for expert system decision aids and instrumentation for timely warning of a loss of well control to enable quick and effective action prior to rig's safety system.

There are some BOP system components or aspects that there exists no industry standard for example, the shearing capability of the ram is not guided by any form of standard which is currently being addressed by amendments in new regulations and standards.

Another interesting dimension is the concern of challenge offered by new drilling limits and technology capabilities. Currently there are a number of technologies developed to address associated drilling industry difficulties such as deepwater/greater water depths, hurricane/typhoon, remote Areas (e.g. Artic Cycle <-40 to -60 deg. C), managed pressure, geothermal conditions, underbalanced drilling challenges (Lobo, F., 2010). This presents reliability concerns such as the maximum working pressure of the BOP's is normally 1500psi with a 10000 ft. limit water depth. However, a new generation BOP with a 20,000 psi working pressure has been unveiled with main components designed, built and qualified by testing (see (Shanks et al., 2012)). Figure 2-15 depicts the operating conditions for BOP components and Limitations offered by HPHT Environments while global HPHT fields have been categorized to show the current BOP limits and future challenge in Appendix A.2.8

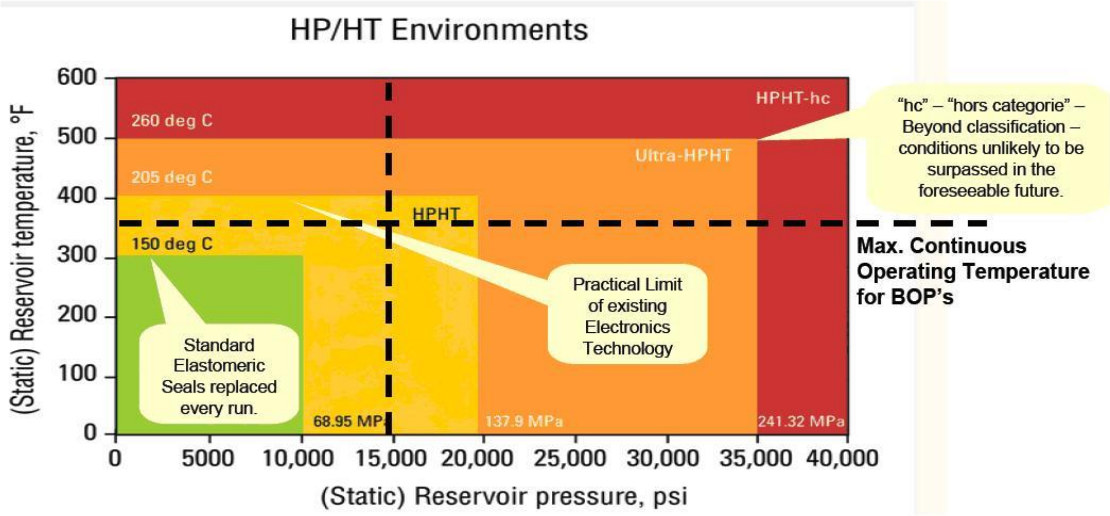


Figure 2-15: Operating conditions for BOP components and Limitations offered by HPHT Environments (Lobo, 2010)

2.13 Risk and Reliability Analysis- Recap of its Application to the BOP system

In all systems and products developed, an acceptable well-known inevitable phenomenon is failure, hence the need to understand why, how, and when they seize to meet required functions. (ISO 20815, 2010) defined failure "as the termination of an item's ability to perform a required function". It further emphasis that failure is an event, differentiating it from fault which is a state of item after failure. (Del Frate et al., 2011) defined failure as the inability of an engineered system, product or service to meet design team's goal for which it has been developed. There are several variations in the definition of failure (event or goal-oriented, state or condition) for greater detail see (Del Frate, 2014). These potential failures could introduce hazards to system, individuals and the environment or constitute a loss and, whatever the perception is, they may constitute undesired events and thus seen as a risk. When hazards are categorised according to their potential impact, given their inherent operational nature, and associated loss form and what they impact, it can benefit risk analysis (Tweeddale, 2003). The range of hazards associated with offshore industry are categorised as follows (API 14J, 2007) :

- Blowouts
- Process leaks
- Riser/pipeline leaks
- Non-process fires
- Non-process spills
- Structural collisions
- Diving Accidents
- Marine collisions
- Marine events
- Transport Accident
- Construction accidents
- Personal (or occupational) accidents
- Attendant Vessel Accidents

These possible failures are potential hazards sources which could impact the facilities, personnel and affect marine environment. Hence an understanding of their nature (e.g. inherent risk) is important (MacCollum, 2007). In the decades of existence of the offshore industry, several major accidents have been witnessed, some of which were with catastrophic consequence. Records of these incidents in general have been recorded (see (Cheremisinoff and Davletshin, 2010; Christou and Konstantinidou, 2012) and well control/BOP related incidents presented in chapter 1. Also, there is a rapid expansion in the offshore industry in terms of developments with the recent paradigm shift towards deep and ultra-deep waters, introducing more complexity and new challenges. These challenges present risks and also technology improvement efforts to close their gaps could also present new risk (as there is no experience with them). To enhance the overall understanding of the process conditions and design of critical technologies, operating modes and failures of equipment, structural condition and deterioration mechanisms, procedures and critical components/regions, risk analysis techniques are utilised. This in turn can inform a justification and plan for targeted risk reduction and even reliability improvement for specific new technologies and critical aspects of existing technologies.

Risk associated with equipment has a direct influence on equipment operational reliability and uptime. Considering risk as a combination of two factors the frequency of an event occurring and its consequence (e.g. cost), if it occurs gives an insight. This suggests two possible risk reduction perspectives by way of consequence reduction (focuses on defect fixing, ease of executing maintenance, accepts failure and reacts to them) and reducing frequency of occurrence or reducing the probability or chance, thus number of failures (preventive and proactive). Reliability is defined as "*the ability of an item to perform a required function without failure under stated conditions for a stated period of time*" and as such the opposite of chance of failure -risk (Rausand and Høyland, 2004). Accordingly, addressing equipment risk informs/prioritises required reliability improvements hence most risk analysis techniques are also considered or used for reliability studies.

Risk analysis is a process that involves the identification, assessment, risk management with monitoring and reviewing, and communication of the risk picture (Figure 2-1 shows a schematic of the process). However the context or basis of the assessment and the system description with specified boundaries has to be pre-defined or agreed before the initiation of the process. The risk management stage entails control by the reduction of risk to an acceptable level, or risk avoidance or prevention (depending on chosen alternative), the documentation, implementation and administering, and financing of the process and chosen alternatives. It can be seen that risk assessment is only an integral part of risk analysis which is a lifecycle activity. Hence some of the output documents of risk analysis are living documents that are constantly updated following the progress in the development stage and when modifications in designs and/or to the operation mode are made.

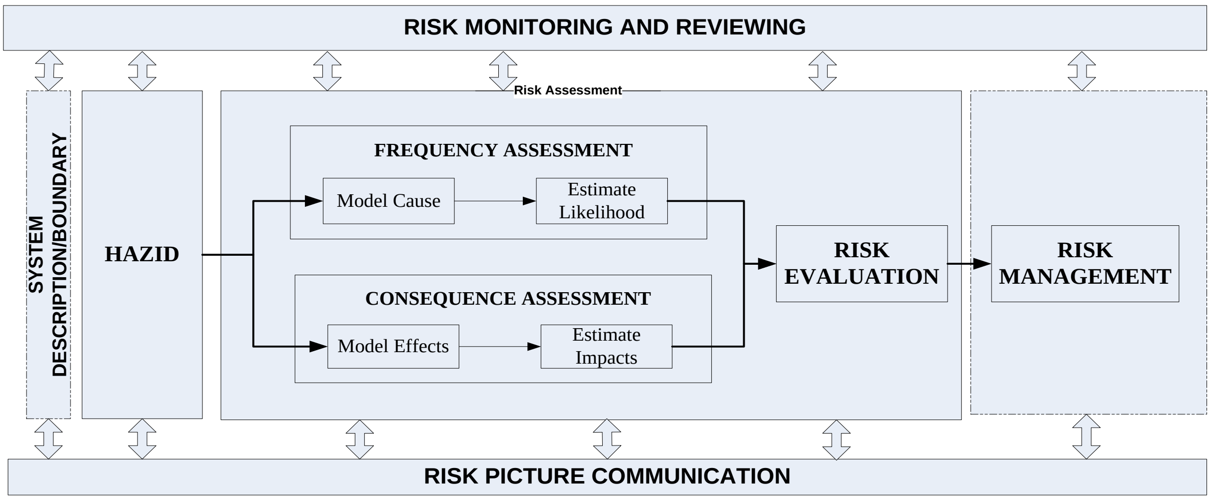


Figure 2-16 Risk Analysis Process Framework (Adapted from ABS, 2000)

There are a number of techniques being used in risk analysis to assess systems/products and events under certain conditions and following a failure, such as the failure modes effect and criticality analysis (FMEA/FMECA), and Hazard and operability studies (HAZOP). The wide use and gains of risk assessment cannot be over emphasised. While some developed techniques and approaches have been established, with new conceptual frameworks or variations considered the suitability to some bespoke need/event, it is still with some challenges which stems from its foundation as a science (Aven and Zio, 2012).

Risk assessment has seen many applications in the offshore industry and has come to stay as a veritable element for the cost effective and efficient way of assuring safety in the selection, design, use of different concept and systems as well interaction(s) amongst them. Scenarios of various stages in projects, equipment or system design and associated operational programs/applications have been reviewed (see Appendix E) with a view of inherent or introduced hazards/failures that poses risks in meeting defined objectives. Techniques used to assesses these risks and their benefits and limitation have also been highlighted. We have also seen the role played by experts and also the case of incomplete/ unavailable data or knowledge in the course of these assessments. The general knowledge of components or systems can be improved with knowledge of their failure phenomena (while some of these failure modes are known, others are not.), scenarios and improved standardisation of products and methods. Application of FMEA has been established in the offshore, marine, subsea industry as well. This is not surprising as the FMEA/FMECA technique has shown to be very useful as it is repeatable and applicable to concepts, detailed options and solution to validate requirements at higher level. While FMEA is a risk assessment techniques, it is also a reliability assessment technique, given the relationship between risk from failure and reliability.

2.14 Failure Modes Effect and Criticality Analysis (FMECA)

The rapid development of technologies with increasing complexity following tight constraints from the stakeholders’ requirements and usage of the environment has received extensive interest in the assessment of failure occurrence likelihood in engineered equipment. The effects of these failures are diverse and can be associated with catastrophic consequences, necessitating for a tool to allow understanding of the cause and consequences and prioritizing critical aspects requiring more attention or resources. The development of FMEA technique stemmed from the need for a reassurance that a systematic review of system failures have been carried out to understand their causes, effects and associated risk (Mohr, 2002). The Failure Mode Effect Analysis (FMEA) is that tool for identifying failure modes proactively and provides a basis for continuous improvement actions. In a system reliability study, the first step involves an FMEA as a qualitative analysis technique at a design stage of a project. It has been useful for reviewing safety critical systems to identify possible problems. This FMEA technique which is now relevant to most reliability engineers in many high consequence industries, i.e. food services (Sperber and Stier, 2009; Bertolini et al., 2004) and the medical industry (Shebl et al., 2012; Franklin et al., 2012; Vélez-Díaz-Pallarés et al., 2013; Thornton et al., 2011) attempts to addresses concepts that can impact on reliability improvement or realising set reliability goals and requirements. The current drive of exploiting reserves in greater water depths and in the artic regions presents new challenges and risks. Thus risk contributing factors need be understood by oil and gas activities-chain equipment/system manufacturers, in the course of product development to operations and monitoring. These factors can be addressed by an effective technique like the FMEA (Tiku et al., 2005); (Robert and Laing, 2002). To understand this technique, certain basic concepts are defined as follows (Carlson, 2012):

a. *Function and Failure*: A function is the basic intended function of a component or process, typically to a given standard or requirement. An item could have several functions and a verbal-noun format is used to describe these functions. Failure is a state of not functioning or working. It could also be complete or partial seizure of functioning state.

b. *Failure modes*: These are defects or errors in a component, process or design that affect the customers. This is also defined as the manner in which a component or operation fails in meeting or delivering intended functions or associated requirements. This may be presented in different forms namely: complete failure, inadequate delivery of function or poor performance, intermittent performance, spurious and or performing an undesired function.

c. *Mechanism and Cause*: Mechanism is the process through which stresses (chemical, mechanical, electrical or physical) individually or in combination induce failure. The causes are the original stress types that initiates the failure which could be design, process or quality defect and even human related. Potential failure causes such as high temperature, relative humidity, thermal cycling, and sudden vibration can result to failure mechanism (e.g. corrosion, wear, fatigue, etc.) at component level.

d. *Effect and Severity*: The failure's consequence on the environment, end-user, or system is known as the effect. There can be one or more levels of the effects in terms of description (e.g. local or global effect) or in terms of stage/phase based on the type of FMEA (e.g. assembly or manufacture level). Severity is a measure of the effect for a given failure mode. This relative ranking within FMEA scope is ascribed without regard to the probability of occurrence of how considered failure mode can be detected.

e. *Controls*: This is a technique use to remove or reduce the risk of a potential cause of failure. These controls can be either preventive or corrective based on planned or recent actions. They are intended to reduce the probability of occurrence and increase the probability of these failures being detected respectively.

Once the failure modes and their effects have been identified, a criticality ranking can be carried out. When a criticality ranking is involved, the analysis is known as a failure modes and effects criticality analysis (FMECA), thus FMEA and FMECA should not be used interchangeably. The criticality ranking can be qualitative or quantitative, depending on the requirement of the client and/or data available. The qualitative criticality analysis utilises descriptive groupings for the severity and failure likelihoods (refer to US Military 1998). Risk associated with identified potential failure modes or problems during the analysis can be evaluated using the Risk Priority Numbers or criticality analysis methods (Riplova, 2007).

- *Risk Priority Number:* This entails the assigning of a value or rating (based on a defined scale of e.g. 1- 10) to the severity of each failure effect, likelihood of occurrence and likelihood of prior detection of each failure cause. Then the product of the three values gives the RPN as shown in Equation 2.2

$$\text{RPN} = \text{Severity x Occurrence x Detection} \qquad 2.2$$

The RPN can thus be used for ranking or comparing the failure modes to inform maintenance actions. Thus the RPN reflects the weightiness of the potential risks or failure mode critical to systems safety, reliability and robustness of the process.

- *Criticality Number:* This implies computing criticality number (C), used to depict the risk levels of failure modes, described in MIL-STD-1629A- “Procedures for performing a failure mode, effects and criticality analysis”. Equation 2.3 shows how the criticality number for a specific failure mode (i) is obtained.

$$C_i = \alpha_i \,.\, \beta_i . \lambda_c . t \qquad 2.3$$

Where β is the probability of the failure effect, α failure mode ratio, at an operating time, t and component failure rate λ .

2.14.1 Advantages and Drawback of the FMEA/FMECA

Inherently, the design of the FMEA/FMECA methodology is structured to provide a documentation of identified failure modes, failure mechanisms, and their associated risk designed into a product or process. This risk can then be prioritized and followed up. In the light of these outcomes there are a number of benefits. The FMEA process can reveal weaknesses in the system design (revealed by designers) that were not obvious. This structured process can provide a rough picture of classes of system effects following failures. Thus informs requirements and criteria for planning and carrying-out testing, planning maintenance, reliability growth and other associated actions. Development of procedures and controls for monitoring, fault –detection, trouble-shooting could also benefit from the output of FMECA. Risk and resource minimisation and over designing efforts as a way of mitigation actions can be spotted and addressed collectively. Most important of all benefits is that the FMEA/FMECA process serves as more rigorous design review process, with less bias if well-facilitated and output actions taken. The benefits are varied for the lifecycle of the product or process, e.g. at the early stage of product development, as cost of resolving improvements following an advance failure mode recognition, low cost savings could be achieved (Dunkle, 2005). Other benefits as identified in Mohr (2002) are its use to complement Preliminary hazard Analysis given corresponding hazards, ensuing from failures identified during the FMEA, can be updated to the Preliminary hazard List or Analysis, if they have not been previously registered.

Despite the pros of FMEAs mentioned above orienting about its ability to evaluate and inform product integrity improvements, it is not without limitations. The most obvious drawback is the implementation of the FMEA process can be cumbersome and onerous, as conclusions for each failure mode has to be reached. Also system dependencies are usually not accounted for in FMEA analysis (Franceschini and Galetto, 2001; Lipol and Haq, 2011). Another disadvantage of the FMEA is handling the occurrence of a double jeopardy (multiple failures) or a case of the occurrence of a complex failure modes resulting from multiple failures, FMEA Is not able to uncover it directly. An important issue of concern is why the beneficiary needs such analysis (scope of the analysis) and how the analysis outcome would be utilised. It is important to understand the rationale, as FMEA/FMECA requires enormous effort and resources, if it is safety need driven or altruistic (Mohr, 2002). Also given that system vulnerability to single point failures (SPFs) are identified by this technique an obsessive fear for SPFs can be created by a facility holder and thus directs attention to critical failure mode/component lists and implementation of redundancy. This misdirected fear could shift focus on other possible threats to systems' demand/functionality. FMEA/FMECA requires a multidisciplinary team to provide better coverage, which could be challenging to assemble subject experts at a spot, especially in dealing with complex equipment. The exposure and experience of the committee members involved in the FMEA workshop determines the quality of the output. The complexity of the problem (system and failures) is a determinant for difficulty or rigorousness of the approach (from an implementation perspective) and thus the number of experts in the FMEA team can vary (Scipioni et al., 2002).

Different group of personnel can carry out an FMECA on the components of a particular system and identify failure modes with a small degree of similarity. Only three factors are considered by the RPN and they are essentially safety related. While it avoids relative importance of the three factors, given they are assigned same importance, which is not always the case practically; there are concerns of subjectivity with the FMECA technique in representing associated risk from identified failure modes. The computed RPNs for the overlapping failure modes might be causing a different failure mode prioritization, suggesting the need for further analysis and verification. Similarly rank reversals may occur, and failure modes differently ranked.

Also different failure modes identified in an FMECA study may have the same RPN, from different set of scores assigned to severity, occurrence and detection, of which their individual risk implication may also be different (Pillay and Wang, 2003). This means failure modes with similar RPN values, could have different impact on the system. Also a failure mode that would in reality be considered more critical (e.g. from a severity perspective) than another could have a lesser RPN and consequently a lower rank. This is as a result of ordinal scale numbers used for the ranking that only interprets one failure mode to be worse or better than the other, and does not say to what extent. Thus as a standing rule, regardless of the demarcation for criticality of failure modes, failure modes with high severity would always be addressed or looked-up for corrective actions (Gouyet et al., 2011) & (Carlson, 2012). In addition to the already mentioned shortcomings, (Liu et al., 2013) also observed that while the precise evaluation of the three risk factors is difficult (Liu et al., (2011); Liu et al., 2012; Yang, J., Huang, H.-Z., He, L.-P., Zhu, S.-P., Wen, D., (2011)) the RPN mathematical representation is questionable (Kutlu and Ekmekçioğlu, 2012; Gargama, H., Chaturvedi, S.K., (2011)) and sensitive to risk factor computations variations (Chin et al., 2009).

2.15 Application of MCDA to Risk Analysis/FMECA

The benefits of the integration of Multi-criteria decision-making analysis (MCDA) technique to risk analysis can be extended to address the gaps or weakness identified with the FMECA process and outcome. Several studies have highlighted the gains of integrating multi-criteria decision making techniques to/for risk analysis for/towards an improved decision making (Georgekutty et al., 2012; Heller, 2005). One of such gains is the presentation of an evaluation with preferences for combined risk and benefit as against traditional balance of risk. (Catrinu, 2010) states that the integration of these two approaches is promising as it provides a good understanding of the problem and the contributions of judgements made by decision makers. While this integrated approach is not a replacement for the traditional techniques, it suggests opportunities for an improved analysis and even more conservative approach in the analysis (Georgekutty et al., 2012). The five categories were popular MCDM (e.g. AHP, TOPSIS), artificial intelligence (e.g. Rule based and Fuzzy rule based), mathematical programming (e.g. DEA), integrated (e.g. TOPSIS Grey theory, Fuzzy AHP-fuzzy TOPSIS) and other approaches (e.g. Cost based model, Quality function deployment, minimal cut sets theory).

To obtain an informed and realistic ranking of system associated risks (a criticality order for identified risks-failure modes), MCDA applications can entail using multiple criteria (rather than 3 in conventional FMECA) and a particular MCDA analysis, or strictly prioritising failure modes identified from an FMECA. This creates room for other factors with varied level of importance to be considered, and also a targeted use of expert elicitation to rank the risks. More specific analysis based on a hierarchy of criteria (failure driving factors or/and cause) can be applied to a select failure mode of interest. Another dimension to this is the use of fuzzy set representation of expert information or available data set type for weights of criteria (for conventional 3 criteria FMECA or more than three criteria) for each failure mode.

2.16 Summary

The role of the drilling activity is pivotal to the success of the offshore oil and gas industry and characterised with lots of risk, which includes blowout, and uncertainty compounded by harsh environment and increasing water depth. The subsea blowout preventer identified to be the last line of defence for preventing blowouts has been associated with failures, incidents, uncertainties associated with its functionality. This informs the need to assess the failure risk using a structured framework to better understand its criticality. Academic interests have attempted to use Bayesian and Markov chain techniques for reliability analysis with very obvious outcomes. There has also been an attempt to improve the estimation of probability of failure on demand as seen in (Klakegg, 2012) with a couple of works on the fault tree analysis model of the BOP system and functions. The control system failure modes have been identified to offer the greatest contributions to the BOP system unreliability. Critical components and failure modes have also been identified from these works with concerns identified and improvement options suggested aftermath of the Macondo incident such as shift in attention to the shearing ram (specification and performance) and need for redundant ram to improve redundancy.

The aforesaid shows that there is a dire need for a robust and accurate approach for estimating reliability of the BOP system as much as understanding the system failures and their criticality; given some dangerous failures may go undetected during functional testing.

The main previous works on BOP system entailed operational failure data analysis, fault tree analysis and the FMEA/FMECA. It is established that while there are several risk and reliability techniques which complement the attainment of goals (e.g. reliability target or risk acceptance goals), the FMECA has been seen to be very central in the activities cycle and its outcome feeds into design improvement, supports other analysis techniques (e.g. FTA), planning for mitigations and other general management decisions. This informs the aim of this work to apply another dimension in understanding BOP system failures criticality and their criticality importance to inform reliability level improvement decisions. This new approach would be stemmed on understanding the BOP system criticality, based on a fundamental FMECA outcome and then applying multi-criteria analysis techniques to assess the different failure modes against a set of defined criteria.

3 Multi Criteria Decision Analysis Methodology

A multi criteria decision analysis is a decision support technique for assessing risks and their consequences with respect to different factors. This approach does its evaluation of consequence or failure risk or alternatives using the different attributes features independently rather than transforming all into comparable units (e.g. monetary units as in a cost benefit analysis).

There are different associated criteria and/or dimensions of decision support problems which includes number of goal (single or multiple), decision maker type, problem structure (well-structured or ill-structured), problem character (threat, or opportunity, design or choice) and degree of difficulty (simple or complex), and ease of consequence prediction (Grunig and Kuhn, 2013). The two major classes of decision making problems in decision science are namely the multi-objective decision making (MODM) and multi criteria decision making (MCDM). The existence of a predetermined alternative is what constitutes the major difference, which is absent in the former as it constitutes mostly optimization problems with several objective functions to satisfy (Yoon and Hwang, 1995). The MCDM is also known as Multi attribute decision making (MADM) or multi-criteria decision analysis (MCDA). While there have been attempts to distinguish between MCDA and MCDM, the former being developed by Americans and later by European schools, in this thesis, they are used interchangeably. Managers and decision makers are faced with a number of challenges ranging from effective use of resources in projects, from concept defining phase to managing assets phase, to making concrete decision on tasks such as assessment, prioritization or even selection amidst constraints (Dashti et al., 2010).

These challenges often entail making preference decisions relative to multiple criteria/information which often are conflicting and subject to varying forms of uncertainty and risk. Expert opinions and best engineering judgements are integrated in these decision problems, thus requiring a systematic framework for representation of all information (Bolar, et al., 2013; Huang et al., 2011). A chance is thus given to the decision maker by the MCDM techniques to better structure the decision making process such that all information that are relevant and available are utilised and integrated in obtaining the preference order of the alternatives (Koele, 1997). MCDM have been used in solving many real world problems such as risk and safety analysis of systems and products (e.g. Offshore structures, Airport Sea port, Nuclear Plant, Container ship, and Roll-on Roll-off ferry problems) (Kabir et al., 2014; Alias et al., 2008).

A model for MCDM execution as shown in Figure 3-1 is described before the different techniques are discussed. The MCDM process typically arises with a decision issue of concern, necessitating a thorough investigation and change with an obvious need for a preference. The next stage is about structuring the problem: defining the problem, choose the attributes/criteria to measure the objectives, and alternatives are specified.

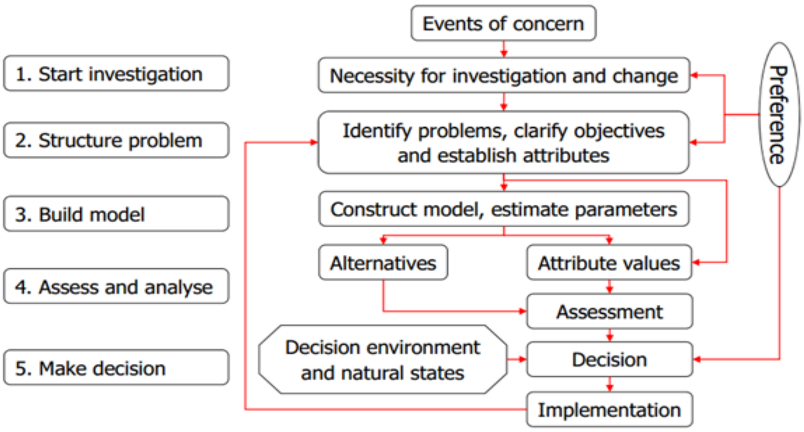


Figure 3-1: Multi Criteria decision Analysis Model (Yang, 2008)**.**

A model is built for estimating the parameters and scales defined for measuring the criterion scales in comparable units. Weights are assigned to the attribute/criteria to reproduce their relative importance. A mathematical algorithm for ranking alternatives is selected and applied, and then an alternative is chosen. However, in the presence of some sort of superior detail, external preference can be applied at the investigative and problem structuring stage or even in the final decision level. There are different situations in which the goal of making a decision is required, thus “different kind of decisions”. The objective of the decision could be a case of ranking or risk prioritization and make a comparison of alternatives decision, a selection of a single alternative decision, or even to assess extent of contributing factor to the objective based on certain defined criteria. A reflection of performance in meeting the set objective must be seen in the chosen criteria (Saaty and Vargas, 2006).

For a set of feasible alternative, the best alternative can be obtained using the MCDM procedure. A matrix format for representing the MCDM problem is shown as follows, for a case of m alternatives $(A_1, A_2, A_3, \dots, A_m)$ and n criteria $C_1, C_2, C_3, \dots, C_n)$ (Zeleny, 1982):

$$M = \begin{bmatrix} A_1 \\ A_2 \\ \dots \\ A_n \end{bmatrix} \begin{array}{c} \begin{array}{cccc} w_1 & w_2 & \dots & w_n \\ C_1 & C_2 & \dots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{1n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \end{array} \tag{3.1}$$

Where the performance rating of an alternative, A_i under criterion C_j is denoted as x_{ij} and the weight of criterion C_j is w_j.

While often decision making is seen as an outcome, (Zeleny, 2008) postulates that it is the selection and determination of criteria and alternatives, through information collection, evaluation and processing to result in a measurable action. These intermediate steps that are interrelated are repeated until the results is actionable, i.e. a decision is reached.

Once the criteria are chosen, they must be assessed using a set of qualities (Dodgson et al., 2009):

- Completeness: this entails all possible criteria would have been considered and that capture vital aspects of the objectives sought through MCDM
- Redundancy: this entails ensuring that no redundant or similar criteria have been chosen
- Operability: the criteria should be explicit enough and applicable to the alternatives relative to the objective. Also clearly the weight or scale of measurement should be commonly shared amongst the criteria.

- Mutual Independence: the chosen criteria should be independent, meaning a decision maker should be able to allocate a score or weight to a criterion without consideration for the score for other criteria.

However some MCDM techniques do have unique features that can assess related criteria as long as definitions can be provided for weights to be provided independently. From earlier discussion it can be deduced that elicited preference information or weights can be obtained by direct assignment, Eigenvector approach. Other approach includes the entropy method, Kano's model, distance-target model, and Simple Multi Attribute Rating Technique (SMART).

3.1 Decision makers Scores and Normalisation techniques in MCDA

The essence of the normalisation is to transform the different dimensional attributes to non-dimensional attributes to permit comparison across criteria. There are different approaches, which are presented below (Yoon and Hwang, 1995):

3.1.1 Vector normalisation

(a) Weights are transformed to comparable scales using Equation 3.2.

$$r_{ij} = \frac{x_{ij}}{\sum_i^m x_{ij}^2}, \quad i = 1, \dots, m; \quad j = 1, \dots, n \tag{3.2}$$

(b) When considering attributes as either benefit (positive) or cost (negative), a similar form of normalisation to be used is shown below:

$$r_{ij} = \begin{cases} \dfrac{x_{ij}}{\sum_i^m x_{ij}^2}, & when\ \ x_{ij}, is\ a\ value\ for\ benefit\ attribute \\ \dfrac{1/x_{ij}}{1/\sqrt{\left(\sum_{i=1}^m \left(1/x_{ij}\right)^2\right)}}, & when\ \ x_{ij},\ \ is\ a\ value\ for\ cost\ attribute \end{cases} \tag{3.3}$$

3.1.2 Linear normalisation

There are different types of linear normalisation which can be in the representations in Equation 3.4 to Equation 3.6 as follows:

$$r_{ij} = \frac{x_{ij}}{\sum_{i}^{m} x_{ij}}, i = 1, \dots, m \; ; j = 1, \dots, m \qquad 3.4$$

$$r_{ij} = \begin{cases} \frac{x_{ij}}{x_j^{\wedge}}, i = 1, \dots, m \; ; j = 1, \dots, m \; ; x_j^{\wedge} = \max_i x_{ij}, \; when \; x_{ij}, is\ a\ value\ for\ benefit\ attribute \\ \frac{x_j^{\sim}}{x_{ij}}, i = 1, \dots, m \; ; j = 1, \dots, m \; ; x_j^{\sim} = \min_i x_{ij}, \; when \; x_{ij}, \; is\ a\ value\ for\ cost\ attribute \end{cases} \qquad 3.5$$

$$r_{ij} = \begin{cases} \frac{x_{ij} - x_j^{\sim}}{x_j^{\wedge} - x_j^{\sim}}, for\ benefit\ attributes \\ \frac{x_j^{\wedge} - x_{ij}}{x_j^{\wedge} - x_j^{\sim}}, \; for\ cost\ attributes \end{cases} \qquad 3.6$$

Regarding decision makers score of importance on criteria an indirect means of obtaining such weights is presented in the next section.

3.1.3 Entropy Method (Pomerol, J. 2000)

The weights, w_j , of the criteria j, to be used for a multi criteria analysis can be obtained indirectly, as opposed to the traditional notion of asking decision makers for weights of importance ascribed to the criteria. This method is founded on the belief that a criterion's importance is a direct function of the information it conveys relative to the set of alternatives (failure modes). The entropy method takes out the decision maker's subjectivity in weights determination and can address a scenario of conflicting evaluations of criteria weight. Also in the event the outcomes are unreal, then a decision maker can be consulted to improve the weights by a factor. The entropy method is described as follows:

- An estimate value e_{ij} is obtained by normalising the decision matrix for each alternative

$$e_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \qquad 3.7$$

Where $i \in \{1, \dots, m\}$, $j \in \{1, \dots, n\}$, and x_{ij} represents valuation of an alternative i, relative to criterion j.

- The Entropy of each criterion is evaluated using the equation below, with $k = 1/\ln(m)$

$$En_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}) \tag{3.8}$$

- Measure of Dispersion MD_j of the intrinsic information for each criterion can be obtained from Equation 3.9. It entails the inherent contrast intensity of a criterion, and a higher value will mean the criterion is of more importance to the problem.

$$MD_j = 1 - En_j \tag{3.9}$$

- The objective weight, w_j , of each attribute can be obtained using the Equation 3.10 below:

$$w_j = \frac{MD_j}{\sum_{i=1}^{n} MD_j} \tag{3.10}$$

In the following sub-section different MCDM approaches of interest will be discussed briefly with some elaboration where needed.

3.2 Brief Review of Different MCDA techniques

There are several techniques proposed to solve the MCDM problems, which have been applied in a variety of fields. These MCDM methods have been classified in diverse ways by different researchers based on theory, method, approaches etc. and no consistency has been identified in the grouping, given some are extended forms of others. Based on the type of the alternatives being evaluated, the MCDM methods were categorised into continuous (i.e. identified optimal value can vary infinitely- Linear Programming, goal programming and aspiration based models) and discrete (those with a finite number of alternatives, given a set of objectives and criteria) (Janssen, 1992; Ananda and Herath, 2009). (Nijkamp et al., 1990) further classified the discrete methods into weighting and ranking methods.

These methods could be qualitative (uses ordinal scales), quantitative (cardinal or ratio scales) and mixed methods (Ananda and Herath, 2009). The application of the last class is dependent on accessible data type. (Wang et al., 2009) identified the different multi criteria decision making methods into elementary methods (e.g. weighted sum and weighed product methods), Unique synthesizing criteria methods (e.g. Analytical hierarchy process-AHP, Technique for order of preference by similarity to ideal solution- TOPSIS, Grey relation methods and integrated approaches such as MCDA combined with fuzzy method) and outranking methods e.g. (Elimination et choice translating reality- ELECTRE and Preference ranking organization method for enrichment evaluation-PROMETHEE). MCDA have been classified into compensatory (AHP, TOPSIS, PROMETHEE, Multi Attribute Utility Theory, Expected Utility Theory, Simple and multiplicative weighting methods) and Non compensatory methods such as Dominance, Elimination by expert, Conjunctive and Disjunctive, Maximin, Maximax and ELECTRE methods. Non-compensatory methods are considered simple and do not allow trade-off amongst criteria and the contrary is the case of compensatory method. These techniques have been approached from either a probabilistic or deterministic or fuzzy approach. While it is not intended to review all of the different MCDMs, a general description of the techniques of interest and where necessary greater detail is presented. Also, given the main focus in this work is on the application of selected techniques for ranking alternatives, of which in this work- it is for the improvement of rankings of failure modes provided by the FMEA, thus a concise review will be presented later on the application of these techniques to improve FMECA RPN ranking outcome.

While MCDA is useful, its limitations besides availability of data and competent decision makers, includes conflicting rankings of the alternatives can be generated by the various MCDA models for a common set of decision matrix even under states of certainty, difficulty faced by analyst in selecting appropriate technique and also interpreting the results appropriately (Coman and Ronen, 2009; Kujawski, 2003). Decision makers may consider the process to be clumsy and time-consuming or drawn to focus more on the process than how justified the outcome is (Zeleny, 2008). However the decision maker's ability to facilitate the application of the approach effectively without turning into specialists in the techniques is what constitutes a success in the use of MCDM technique.

3.2.1 The technique for order of Preference for similarity to the Ideal Solution (TOPSIS)

TOPSIS was developed by Huang and Yoon (1981) and has become a widely used MCDA technique to select the best alternative given a finite number of criteria. Its original structure is drawn on the shortest distance of a compromise solution from a displaced ideal solution. The best alternative is known to have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution.

Problems with multiple alternatives and multiple criteria have been analysed and solved using TOPSIS, via alternatives comparisons and rankings. The alternative rankings are cardinal and attribute preferences do not need to be independent (Yoon and Hwang, 1995). Its applicability is based on values of attributes with commensurable units and that are monotonically decreasing or increasing. Euclidean distance metric is used for obtaining the separation fro the ideal solution. The logic in TOPSIS is sound as it denotes basis for human choice. Also its practicality with computer support by way of easy computation process makes it a preferable technique for handling problems MCDA (Behzadian, M. et al., 2012; Kim G. et al, 2009.).

The variations in the TOPSIS extension or proposed modified models have been effected in varying the defining rationale or/and computation for the distance from the ideal positive and negative solutions, the input data representation and handling, weights generation techniques, and also of interest is in relation to the calculation of the relative closeness coefficient. The successful application of the TOPSIS method for solving diverse nature of real world problems multi criteria problems, given the advantages mentioned has been demonstrated by a State of the Art review by Behzadian, M. et al., (2012). The traditional approach of this technique can be administered in eight simple steps (described in Equation 3-11 to Equation 3-19). While the extensions comprise variants of some of the steps or additional steps added to the stages for identifying the preferred option or in the case of the system of interest the most critical failure mode.

The following assumptions are made relative to the equations in the traditional TOPSIS technique steps described in Figure 3-2:

- Let us assume an MCDA problem with *n*-attributes/criteria and *m* failure modes and that a score can be obtained for each failure mode with respect to each criterion.
- Let x_{ij} be the priority score of failure mode i with respect to criterion j
- Let $\boldsymbol{P}$ and $\boldsymbol{N}$ be the set of positive (i.e. benefit) and negative (i.e. cost) criteria. Benefit criteria is that which an improvement in its potential or it be of higher weight will result in achieving the decision problem goal, while the contrary is known as the negative criteria, which is desirable to be reduced. These conventions depend on the nature of the MCDM goal.

Step 1: A matrix of priority scores ascribed to each failure mode relative to a particular criterion represented as $X = (x_{ij})_{n\,\mathrm{x}\,m}$ is constructed.

Step 2: Obtain a set of weights $w_{j,}$, of importance for each criterion such that:

$$\sum_{j=1}^{m} w_j = 1\,, \quad j = 1, \dots, m \qquad 3.11$$

Step 3: Obtain the normalised decision matrix (r_{ij}) using an ideal equation as described in Equation 3.3.

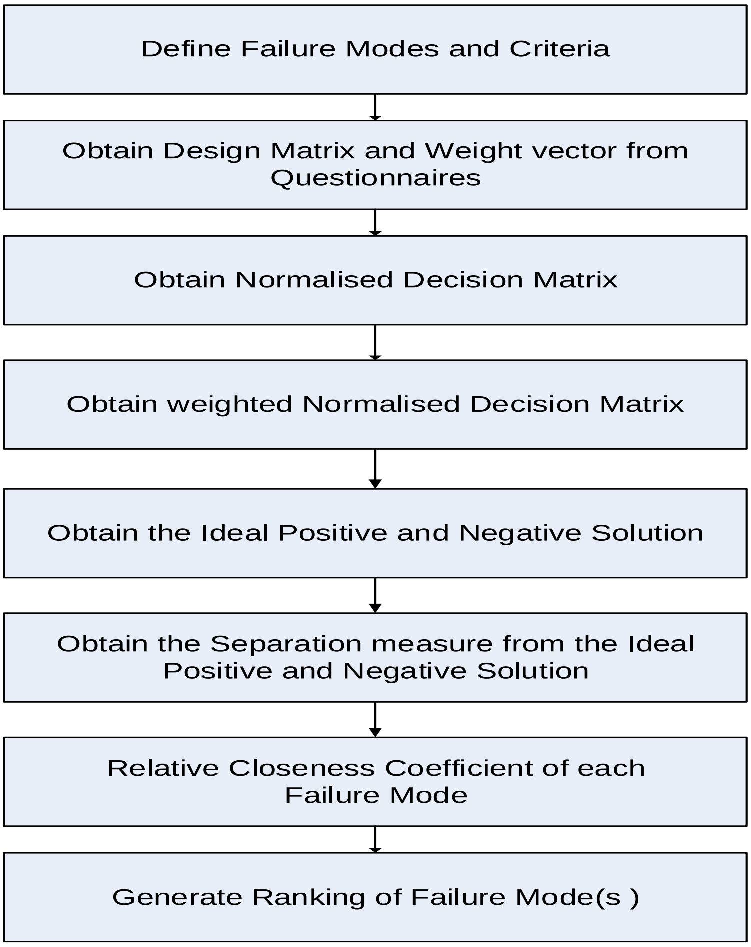


Figure 3-2: Flowchart of the TOPSIS methodology

Step 4: Normalised weighted decision matrix (V_{ij}) is obtained by multiplying each column of the normalised decision matrix (r_{ij}) by the associated weight, w_j of each criterion:

$$\boldsymbol{V_{ij} = w_j r_{ij}} \qquad 3.12$$

Step 5: The Positive ideal solution (PIS) and negative Ideal solutions (NIS) are determined

$$\boldsymbol{A^{+} = (v_1^{+}, v_2^{+}, \ldots, v_n^{+}) = \left\{\left(\max_i\{v_{ij}\} \middle| j \in P\right), \left(\min_i\{v_{ij}\} \middle| j \in N\right)\right\}} \qquad 3.13a$$

$$\boldsymbol{A^{-} = (v_1^{-}, v_2^{-}, \ldots, v_n^{-}) = \left\{\left(\min_i\{v_{ij}\} \middle| j \in P\right), \left(\max_i\{v_{ij}\} \middle| j \in N\right)\right\}} \qquad 3.13b$$

Step 6: Separation measures for each alternative failure mode $\boldsymbol{i}$, is determined. The separation from the positive ideal solution (PIS) $\boldsymbol{S_i^+}$, and negative ideal solution (NIS) $\boldsymbol{S_i^-}$, is obtained in the traditional TOPSIS by the Euclidean distance:

$$\boldsymbol{S_i^+} = \sqrt{\left\{\sum_{j=1}^{m}\left(\boldsymbol{v_{ij}} - \boldsymbol{v_j^+}\right)^2\right\}}, \boldsymbol{i = 1, \ldots, m}\ ;\ \boldsymbol{j = 1, \ldots, n} \quad 3.14a$$

$$\boldsymbol{S_i^-} = \sqrt{\sum_{j=1}^{m}\left(\boldsymbol{v_{ij}} - \boldsymbol{v_j^-}\right)^2}, \qquad \boldsymbol{i = 1, \ldots, m}\ ;\boldsymbol{j = 1, \ldots, n} \quad 3.14b$$

The greater the degree of influence by way of closeness of the ideal solution translates to the failure mode for which an improvement action should be more priority.

Step 7: For each particular failure mode, the degree of closeness RC_i, to the ideal solution is calculated in this step using Equation 3.15.

$$\boldsymbol{RC_i} = \frac{\boldsymbol{S^-}}{\boldsymbol{S^+} + \boldsymbol{S^-}}\ ;\quad \boldsymbol{i = 1, \ldots, m} \quad 3.15$$

Step 8: Rank the failure modes in descending order based on comparison of the RC_i values, with the most critical one being with the highest value.

There are a number of extensions for the TOPSIS method with variations in the approach used to adapt some of the steps in the traditional method described above. These extensions have presented claims for better rank outcomes or suitability for available data, problem type and context surrounding the administration of the process (e.g. Interval data, fuzzy data/method, separation distance-Euclidean/Minkowski/Manhattan, extension by combination with other methods). See (Izadikhah, 2009; Tu et al., 2011; Song et al., 2013; Martin et al., 2013; Zamri and Abdulla, 2014) and some of the published works on improving TOPSIS using fuzzy numbers are discussed in section 3.4.

3.2.2 PROMETHEE

J. P. Brans developed the Preference Ranking Organisation method for Enrichment Evaluations (PROMETHEE) approach which was first presented at a conference in the Université of Laval, Québec, Canada (Brans and Vincke, 1985). Following several successful application of this methodology, over the years Brans and Mareschal further developed a number of variations namely PROMETHEE II, PROMETHEE III (ranking based on intervals), PROMETHEE IV (continues case), PROMETHEE V (MCDA including segmentation constrains) PROMETHEE VI (human brain representation). A visual PROMETHEE GAIA (interactive model) was developed in 1988 by Brans and Mareschal which it utilises the PROMETHEE approach to create the graphical representation. In the most recent Visual PROMETHEE version there are roughly 16 display formats. Several successful application of the method to solving different problems have been published (Behzadian et al., 2010; Cinelli et al., 2014; Veza et al., 2015; Veza et al., 2015). Amongst the several extensions, the most commonly used is the PROMETHEE I and II.

PROMETHEE as a MCDA method make use of information between criteria and within each criterion. The weights or the relevant importance of the criteria sums to 1. Considering information within criteria, a preference function for each criterion which expresses the difference in performance of one alternative over another is required. It is worth noting that PROMETHEE preference structure is based on pairwise comparison.

One of the goals of PROMETHEE approach is to allow more transparency in the decision process by putting a structure to it, and to deal with criteria and decision maker preferences which can be different and vague respectively. In order to obtain a compromised solution decision maker can use weights and other preference data to guide the process. Though assigning weights or preference value for criteria can be difficult when there exists more than two or three criteria in a decision problem. Inputs for the PROMETHEE methodology consists a matrix of selective actions (alternatives, or failure modes in this work).

Given A is a set of n possible alternatives $(\mathrm{a}_1,\ \mathrm{a}_2, \dots, \mathrm{a}_\mathrm{i}, \dots, \mathrm{a}_\mathrm{n})$, and a criteria evaluation set $(\mathrm{g}_1(*), \mathrm{g}_2(*), \dots, \mathrm{g}_\mathrm{j}(*), \dots, \mathrm{g}_\mathrm{k}(*))$, an MCDA problem, $\max\left\{\{\mathrm{g}_1(\mathrm{a}), \mathrm{g}_2(\mathrm{a}), \dots, \mathrm{g}_\mathrm{j}(\mathrm{a}), \dots, \mathrm{g}_\mathrm{k}(\mathrm{a}) \middle| \mathrm{a} \in \mathrm{A}\}\right\}$ can be defined depicting the decision makers goal of identifying an alternative while optimising the criteria set (i.e. minimising some criteria and maximising others is not objected). The steps to follow using the PROMETHEE technique are described in Figure 3-3 and thereafter.

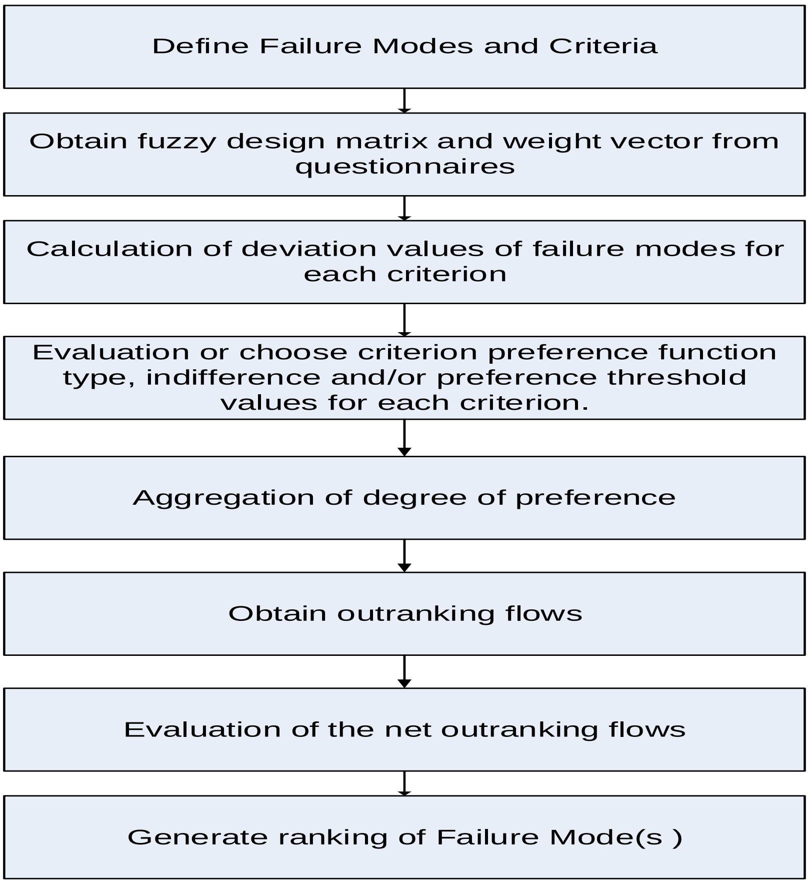


Figure 3-3: Flowchart of PROMETHEE-2 methodology

3.2.2.1 Calculation of deviation

For a pair of evaluation of a criterion j for alternatives a and b, $\mathrm{g_j(a)}$, and $\mathrm{g_j(b)}$, their difference or deviation between them is expressed as:

$$d_j(a,b) = g_j(a) - g_j(b) \qquad 3.21$$

3.2.2.2 Preference function Evaluation

$\mathrm{P_j(a,b)}$ is considered the preference degree of a criterion j for two alternatives a and b. Preferences can be considered as real numbers ranging from 0 to 1, hence the definition of preference functions used to estimate the degrees of preference:

$$P_J(a,b) = F\left(d_j(a,b) \right) ; \quad \forall\, x \in [-\infty, \infty],\ 0 \leq F(x) \leq 1 ; \qquad 3.22$$

Three possible dominance relations are a case of one alternative is preferred over the other, they are indifferent or incomparable. Thus, if an alternative is preferred over the other on a criterion and the contrary on another criterion, it constitutes a concern. In choosing the compromised solution, additional information is required to define or represent these preferences. Such information includes trade-offs between criteria, weights for relative importance of the criteria, an evaluation function that aggregates all the single preference function into one to obtain a solution that is optimal. Six different types of preference functions (see Table 3-1) have been identified which can be ascribed to each criterion (Brans and Mareschal, 2005).

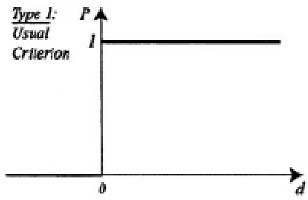
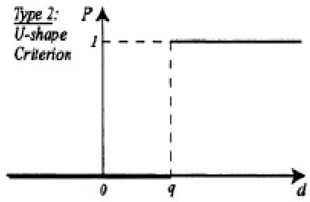
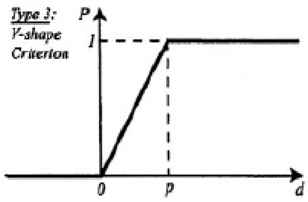
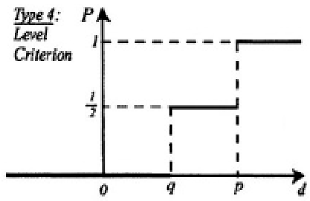
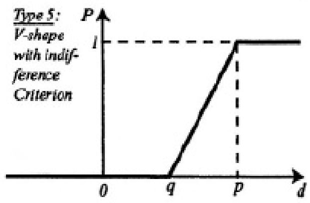
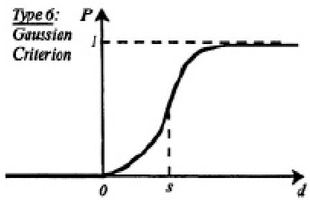
3.2.2.3 Aggregation of degree of Preference

A global preferential index, π can be generated for each pair of alternative by aggregating the preference degrees of all criteria for each pair of alternatives.

$$\begin{cases} \pi(a\,,b) = \sum_{j=1}^{k} w_j \times P_j(a,b) \\ \pi(b\,,a) = \sum_{j=1}^{k} w_j \times P_j(b,a) \end{cases} \qquad 3.23$$

The outranking graph is shown in Figure 3-4 to depict the global preference index calculated for a pair of alternatives with the arcs depicting the outranking and outranked character.

Table 3-1: PROMETHEE generalised Preference function of Criteria (Brans & Mareschal, 2005)

Generalised criterion	Definition	Parameters to fix
	$P(d) = \begin{cases} 0 & d \leq 0 \\ 1 & d > 0 \end{cases}$	–
	$P(d) = \begin{cases} 0 & d \leq q \\ 1 & d > q \end{cases}$	q
	$P(d) = \begin{cases} 0 & d \leq 0 \\ \frac{d}{p} & 0 \leq d \leq p \\ 1 & d > p \end{cases}$	p
	$P(d) = \begin{cases} 0 & d \leq q \\ \frac{1}{2} & q < d \leq p \\ 1 & d > p \end{cases}$	p, q
	$P(d) = \begin{cases} 0 & d \leq q \\ \frac{d-q}{p-q} & q < d \leq p \\ 1 & d > p \end{cases}$	p, q
	$P(d) = \begin{cases} 0 & d \leq 0 \\ 1 - e^{-\frac{d^2}{2s^2}} & d > 0 \end{cases}$	s

Parameter to fix as expressed in the Table 3-1 above refers to the thresholds.

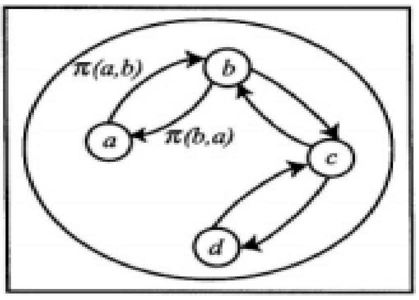


Figure 3-4: Valued out ranking graph (Brans & Mareschal, 2005**)**

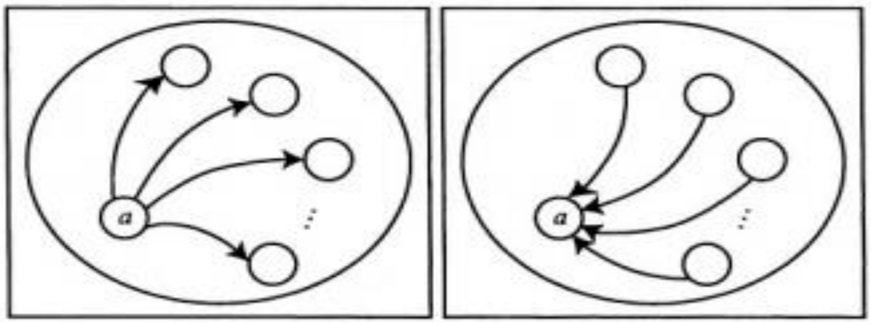
3.2.2.4 Out ranking flows

The outranking flows can be obtained from equations (X) and (X), where $\phi^+\ (a)$ is the positive outranking flows and $\phi^-\ (a)$ is the negative outranking flows of failure modes (alternatives). In some literature they are represented as $Phi^+\ (a)$ and $Phi^-\ (a)$ respectively.

$$\phi^+\ (a) = \frac{1}{n-1}\sum_{x\epsilon A}\pi(a,x) \qquad 3.24a$$

$$\phi^-\ (a) = \frac{1}{n-1}\sum_{x\epsilon A}\pi(x,a) \qquad 3.24b$$

Figure 3-5 depicts the outranking flows diagramatically. The left box (i.e the positive outranking flow) depicts an alternative, a is outranking others and the right box depicts an alternative a outranked by others. The greater the value ϕ^+ , the more preferred the alternative is and likewise for the contrary.



(a) (b)

Figure 3-5 : PROMETHEE outranking flows: $\boldsymbol{\phi^+\ (a)}$ on the left and $\boldsymbol{\phi^-\ (a)}$ on the right (Brans & Mareschal, 2005)

The positive outranking flow is also known as leaving flow and the negative as the entering flow. These are partial pre-order for alternatives which is the goal of PROMETHEE I, while ranks from total pre-order for alternatives (net outranking flow) consists the PROMETHEE II technique (Brans et al., 1984).

3.2.2.5 Evaluation of the net outranking flows

This measure depicts which alternative (failure mode) is better (more critical), is the balance between the positive and negative outranking flows. The greater the net outranking flow value, the more preferred will the alternative be compared to others.

$$\phi(a) = \phi^+(a) - \phi^-(a) \qquad 3.25$$

In the context of this thesis, a preferred alternative i.e. failure mode would be more critical than others would as it maximises the net outranking flows. This analysis can be performed for several scenarios depending on the decision problem being analysed (Veza et al., 2015). Scenarios could consist of different set of criteria weight or different analyst viewpoint for criteria weights and relative weight of criteria considering alternatives.

3.2.3 Fuzzy Theorem and Fuzzy MCDA

Given MCDA analysis utilises input from experts, which are often vague and expressed in linguistic terms, the concept of fuzzy set was introduced. Hence the fuzzification of MCDA approaches as seen in literature. Considering expert's imprecise judgement or scales, fuzzy set theory enables analysts to describe and represent expert's preference in a more flexible manner. In this section, the fuzzy set theory is introduced briefly and then fuzzy MCDA approaches discussed.

3.2.3.1 Fuzzy Set Theory

A fuzzy number expresses the relationship between a quantity, x that is uncertain, and a membership function, μ ranging from 0 to 1. A fuzzy set is an extension of traditional set theory such that x is a member of set A possessing a membership degree μ. Fuzzy sets can be represented in several ways such as triangular, trapezoidal or Gaussian. In this thesis, the triangular fuzzy set representation is used given their ease of computation and convenience in fuzzy representation and information processing (Balli and Korukoglu, 2009). Triangular Membership Function:

A fuzzy number with Triangular membership function $\bar{A}$ is characterised by (a_1, b_1, c_1), $a_1 < b_1 < c_1$ as shown in Figure 3-6. Its membership function features are presented in Table 3.2.

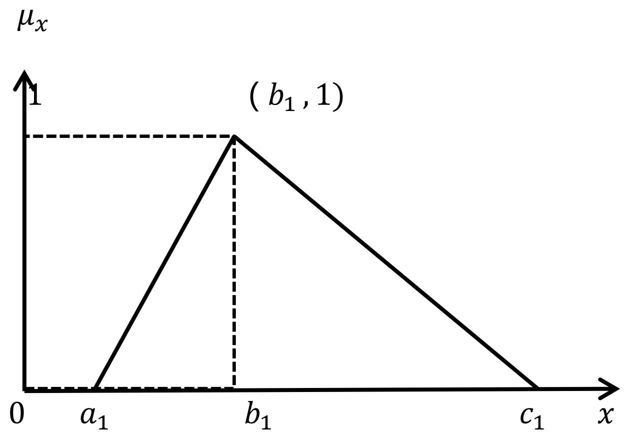


Figure 3-6: Fuzzy number $\bar{A}$ with triangular membership function.

Table 3-2: Triangular membership function features

	Membership function	Ranges
	0	$x < a_1$
	$\frac{(x - a_1)}{(b_1 - a_1)}$	$a_1 \leq x \leq b_1$
$\mu_{\bar{A}}(x) =$	$\frac{(c_1 - x)}{(c_1 - b_1)}$	$b_1 \leq x \leq c_1$
	0	$x > c_1$

Fuzzy numbers with triangular membership function can be subjected to a number of related arithmetic operations, some of which are listed below. If

$\tilde{A} = (a_1, b_1, c_1)$ and $\tilde{B} = (a_2, b_2, c_2)$ are representations of Triangular fuzzy numbers (TFN), then:

Addition: $\tilde{A} + \tilde{B} = (a_1, b_1, c_1) + (a_2, b_2, c_2) = (a_1 + a_2, b_1 + b_2, c_1 + c_2)$ 3.26

Multiplication: $\tilde{A}.\tilde{B} = (a_1, b_1, c_1).(a_2, b_2, c_2) = (a_1 a_2, b_1 b_2, c_1 c_2)$ 3.27

3.2.3.2 Defuzzification

This process transforms a fuzzy number into a crisp number. There are a number of defuzzification methods for transform Triangular fuzzy numbers into crisp numbers. Three of which includes (Ganesh, 2006):

$$\frac{a_m + b_m + c_m}{3} \tag{3.28}$$

$$\frac{a_m + b_m + c_m}{4} \tag{3.29}$$

$$\frac{a_m + b_m + c_m}{6} \tag{3.30}$$

Another unique operation is the product of a fuzzy number and a crisp number. If w_j is a weight of criteria and $\tilde{A} = (a_1, b_1, c_1)$ is a TFN, the weighted fuzzy number, which is their product, can be expressed as $\widetilde{A} = (w_j\, a_1, w_j\, b_1, w_j\, c_1)$ and also considered as a TFN.

α –cuts of a fuzzy number can be characterised as $A^{\alpha} = \{x|\mu_A(x) \geq \alpha\}, \alpha \in [0, 1]$, where A^{α} can be represented denoted by $[A_l^{\alpha},\ A_u^{\alpha}]$ as a non empty limited closed interval with A_u^{α} as the upper limit and A_l^{α} , lower limit. The α –cuts of a triangular fuzzy number $A = (a, b, c)$ is expressed as:

$$A^{\alpha} = [A_l^{\alpha},\ A_u^{\alpha}] = [(b - a)\alpha + a\, , (c - d)\alpha + c] \tag{3.31}$$

For a value of $\alpha = 0$, the left and right spreads of the triangular fuzzy number are identified, and for $\alpha = 1$, the central value is identified.

The fuzzy theorem described establishes its utility for handling complex real world problems often characterised by conflicting interest/variables, vagueness in decision makers viewpoint and representation, and imprecision. Given this standpoint for a long period, an increasing attention has been placed on the application of fuzzy set theory in MCDA (Figueira et al., 2005; Lai and Hwang, 1996) Several publications have been seen on the application of fuzzy theorem to different MCDA techniques. To limit this review to a few, in this work application to TOPSIS technique would be used, hence in the next subsection a brief review and description of Fuzzy TOPSIS and a Fuzzy TOPSIS using interval data is presented.

3.2.4 Fuzzy TOPSIS

This is an extension of the TOPSIS method with adaptation to adequately represent real world scenarios using fuzzy data set rather than crisp data as in conventional TOPSIS. Initial works processed the fuzzy problem information and then converted it crisp (non-fuzzy detail) by way of defuzzification and solve the problem to reach a solution. These includes the works of (Chen, 2000) converting TFN from group decision and obtaining crisp distance (Euclidean) between two TFNs, and also (Chu and Lin, 2003; Chen and Bi, 2010)). In a group decision environment also intuitionist fuzzy set was combined with TOPSIS by (Boran et al., 2009). (Ye, 2010) presented a fuzzy TOPSIS approach (Atanassov's interval-valued intuitionistic fuzzy numbers) for group decision making selection problem given incomplete and uncertain information environment . (Jahanshahloo et al., 2006) and (Wang and Elhag, 2006) proposed fuzzy TOPSIS approach applying the alpha-cut set concept in their fuzzy number representation.

Currently there are viewpoints suggesting to retain the fuzy interval property throughout most of eight TOPSIS method steps, rather than an initial conversion of fuzzy detail to crisp before or early in the analysis. Also of interest is the combination of fuzzy TOPSIS in hybrid with other MCDA technique such as fuzzy AHP (Kutlu and Ekmekçioğlu, 2012). (Secme et al., 2009) presented an integrated fuzzyAHP and TOPSIS to solve an MCDA problem.

An interval valued fuzzy set was introduced by Zadeh as a fuzzy set generalisation (Zadeh, 1975b; Zadeh, 1976; Zadeh, 1975a). The relevance of this concept was made more meaningful from the contributions of (Biswas, 1994; Deschrijver and Kerre, 2003) interval-valued fuzzy relations and implication (Gorzalczany, 1987) approximate reasoning of interval-valued fuzzy set. The degree of certainty of fuzzy data can be expressed as an interval $[0, 1]$. This representation can be used to complement the limitation of expert's ability to quantify their evaluations or opinion as a number or exact value. This informed the need to emphasise the interval property of decision variables which was termed interval valued fuzzy sets. (Turksen, 1996) and (Cornelis et al., 2006) did express strong views of ordinary fuzzy set form representation was not enough, rather the interval property should be emphasised in the linguistic variable.

Recent works with applications of interval data concept to represent fuzzy information with application to MCDA includes (Zamri and Abdulla, 2014; Jahanshahloo et al., 2006; Jahanshahloo et al., 2009). A fuzzy TOPSIS methodology is described in Figure 3-7 which retains the fuzzy property of the alternatives evaluation.

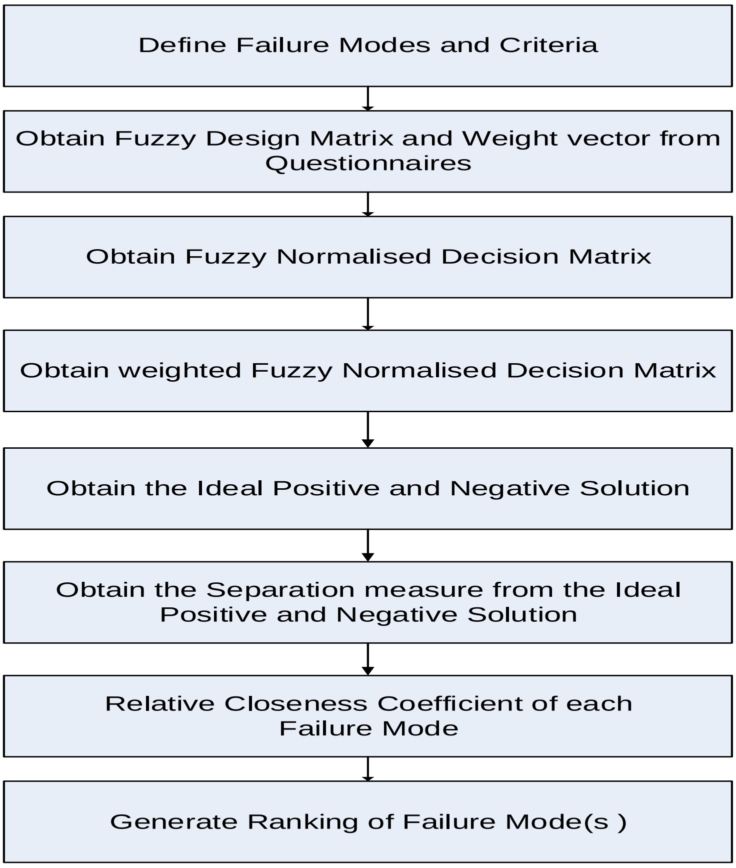


Figure 3-7: Flowchart of the Fuzzy TOPSIS methodology

For a set of m alternatives $A_1, A_2, \dots, A_m$ for which experts would have to select or prioritise using a set of criteria $C_1, C_2, \dots, C_n$, suppose X_{ij} is an evaluation of alternative A_i with respect to criterion C_j, an MCDA problem can be formulated with interval data converting the triangular fuzzy number representation to a set of alpha cuts $X_{ij} = [X_{ij}{}_l^\alpha,\ X_{ij}{}_u^\alpha]$.

Table 3-3: Interval data Multi criteria Decision Making matrix format

	Criterion 1	Criterion 2	...	Criterion n
Alternative 1	$[X_{11}{}_l^\alpha,\ X_{11}{}_u^\alpha]$	$[X_{12}{}_l^\alpha,\ X_{12}{}_u^\alpha]$	...	$[X_{1n}{}_l^\alpha,\ X_{1n}{}_u^\alpha]$
Alternative 2	$[X_{21}{}_l^\alpha,\ X_{21}{}_u^\alpha]$	$[X_{22}{}_l^\alpha,\ X_{22}{}_u^\alpha]$	...	$[X_{2n}{}_l^\alpha,\ X_{2n}{}_u^\alpha]$
⋮			...	
Alternative m	$[X_{m1}{}_l^\alpha,\ X_{m1}{}_u^\alpha]$	$[X_{m2}{}_l^\alpha,\ X_{m2}{}_u^\alpha]$	...	$[X_{mn}{}_l^\alpha,\ X_{mn}{}_u^\alpha]$

Also let $W = [w_1, w_2, \dots, w_m]$ be the weights of the criteria, with w_j as the weight of criterion C_j.

The normalised fuzzy decision matrix is genreated with the normalised values calculated as follows:

$$n_{ij_l}^{\alpha} = {X_{ij_l}^{\alpha}} \Big/ {\sum_{i=1}^{m}\left[\left(X_{ij_l}^{\alpha}\right)^2 + \left(X_{ij_u}^{\alpha}\right)^2\right]} \quad ; j = 1, 2, \ldots, n \qquad 3.32a$$

$$n_{ij_u}^{\alpha} = {X_{ij_l}^{\alpha}} \Big/ {\sum_{i=1}^{m}\left[\left(X_{ij_l}^{\alpha}\right)^2 + \left(X_{ij_u}^{\alpha}\right)^2\right]} \quad ; j = 1, 2, \ldots, n \qquad 3.32b$$

Thus $\left[n_{ij_l}^{\alpha},\ n_{ij_u}^{\alpha}\right]$ is the normalised form of the interval $[X_{ij_l}^{\alpha},\ X_{ij_u}^{\alpha}]$.

The weighted normalised fuzzy decision matrix , with consideration of the importance of each individual criterion, is generated as follows:

$$\bar{v}_{ij,l} = w_j\, n_{ij_l}^{\alpha} \quad ; i = 1, 2, \ldots, m, \ \ j = 1, 2, \ldots, n \qquad 3.33a$$

$$\bar{v}_{ij,u} = w_j\, n_{ij_u}^{\alpha} \quad ; i = 1, 2, \ldots, m, \ \ j = 1, 2, \ldots, n \qquad 3.33b$$

The fuzzy positive ideal solution and negative ideal solution is defined as follows:

$$\overline{A^{+}} = \{\bar{v}_1^{+}, \bar{v}_2^{+}, \ldots, \bar{v}_m^{+}\} = \left\{\left(\max_i \bar{v}_{ij,u} / j \in I\right), \left(\min_i \bar{v}_{ij,l} / j \in J\right)\right\} \qquad 3.34a$$

$$\overline{A^{-}} = \{\bar{v}_1^{-}, \bar{v}_2^{-}, \ldots, \bar{v}_m^{-}\} = \left\{\left(\min_i \bar{v}_{ij,l} / j \in I\right), \left(\max_i \bar{v}_{ij,u} / j \in J\right)\right\} \qquad 3.34b$$

Where $\bar{v}_i^{+} = (1, 1, 1)$ and $\bar{v}_i^{-}$ = (0,0,0), $i = 1, 2, \ldots, n$ the for each benefit or cost criteria.

The distance of separation of each of the alternative from the calculated fuzzy positive ideal solution and negative ideal solution is obtained as follows:

$$d_i^{-} = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_i^{+}) \ \ i = 1, 2, \ldots, m \qquad 3.35a$$

$$d_i^- = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_i^+) \quad i = 1, 2, \dots, m \qquad 3.35b$$

The relative closeness coefficient for obtaining the ranking order of all alternatives is calculated (using the distance of seperations from the previous) as follow:

$$RC = {d_i^-}\Big/{d_i^+ + d_i^-} \qquad ; i = 1, 2, \dots, m \qquad 3.36$$

The set of theoretical foundations required for the development of an MCDA framework given the choice of the FMECA as an assessment technique, and discussion of the applications of MCDM to risk analysis (Chapter 2) has been presented.

3.2.5 Elicited Weights Definitions

Based on the definitions below, experts are able to provide a scaling factor/weight for the importance of each criterion in assessing the BOP System design (failure modes) and also a relative scale for the impact of a criterion on a selected failure mode of the BOP System. There are two types of weights to be elicited from experts for the analysis. The Weights of importance or relevance of the criteria list (w_j) is a scaling weight of the relevance of the criterion with respect to the BOP System delivering its required functions as specified towards assuring well control or preventing a loss of well control. Weights of the relative importance of a failure mode i relative to each of the criterion j, ($x_{i,j}$) is a measure of the criticality or preference intensity for a failure mode to be more critical over others with regards to the contribution or relationship with a criterion. The criticality measure is with respect to a potential loss of well control due to BOP failure (ranging from a loss of partial function to a complete loss of well control following a component failure mode occurrence).

In this thesis, relative weights are assigned to individual evaluation criterion to describe the experts' preference information. The weights are based on the experts' preferences and experiences and it was initially proposed to use a subjective scale of 0 to 10 recommended by Yoon and Hwang, (1995), with calibration that 10 stands for very important while 0 represent for very unimportant. However experts preferred to use linguistic scale for assigning weights. The weighting of the importance was done by linguistic variable measure, and the representative triangular fuzzy numbers (TrFN) are shown in the Table 3-4. The choice of the different weight variables was majorly informed by Expert 10 wealth of experience and Expert 6 who had some background knowledge about MCDA.

Table 3-4: Linguistic variables for importance of failure modes with respect to a criterion

Linguistic Variable	Abbreviation	TrFN
Absolutely High	AH	(0, 0.1, 0.2)
Very High	VH	(0.1, 0.2, 0.3)
Fairly High	FH	(0.2, 0.3, 0.4)
Slightly High	SH	(0.3, 0.4, 0.5)
Medium High	MH	(0.4, 0.5, 0.6)
Medium	M	(0.5, 0.6, 0.7)
Medium Low	ML	(0.6, 0.7, 0.8)
Low	L	(0.7, 0.8, 0.9)
Very Low	VL	(0.8, 0.9, 1)

A sample expert decision datasheet for the failure modes against the risk criteria used for the assessment is shown in Table 4-7. It depicts the use the Linguistic variables described in Table 3-4.

3.3 Development of MCDA Risk assessment framework

The set of functions for which the BOP System is expected to deliver is in preventing a potential loss of well control. Hence all components have their functions that are critical to achieving the overall system goal. It is intended to understand the criticality of a complex system in delivering a set of required function. Hence the need to rank a select set of j representative failure modes (alternatives) of the system using a set of i criteria (which can be used to describe or assess the inherent design of the system, e.g. design assurance, testing, etc.).

A Multi criteria decision making analysis framework for the assessment of the Subsea BOP system, using selected critical failure modes identified from the FMECA analysis (Chapter 4), is presented in Figure 3-3. This framework describes how the elicitation process was carried out, generation of decision matrix, data post processing and application to selected MCDA techniques for obtaining the criticality of the selected failure modes (by way of ranking). These are further explained in the associated subsections. Experts were contacted and elicited to support the framework development and the provision of weights for the actual assessment of the BOP System. The elicitation process helped defined and refined the selection of the criteria to be used for the assessment, the suitability/representativeness of the select critical failure modes, and how and the form/nature of the elicited weights (fuzzy linguistic). The methods considered for the MCDM analysis in this thesis are influenced by the nature of the data collected and guided by the findings on suitability of methods identified earlier in this chapter.

The questionnaire was developed and then administered with n decision matrix obtained. These are then processed and aggregated for input to the MCDM analysis. The expert decision matrix can take the form of a fuzzy or crisp or interval-data, form depending on the respective MCDA technique applied. In this thesis, fuzzy approach combined with TOPSIS (using normal, de-fuzzified, and interval fuzzy data inputs) and PROMETHEE are used to analyse the select list of critical failure modes based on the defined criteria.

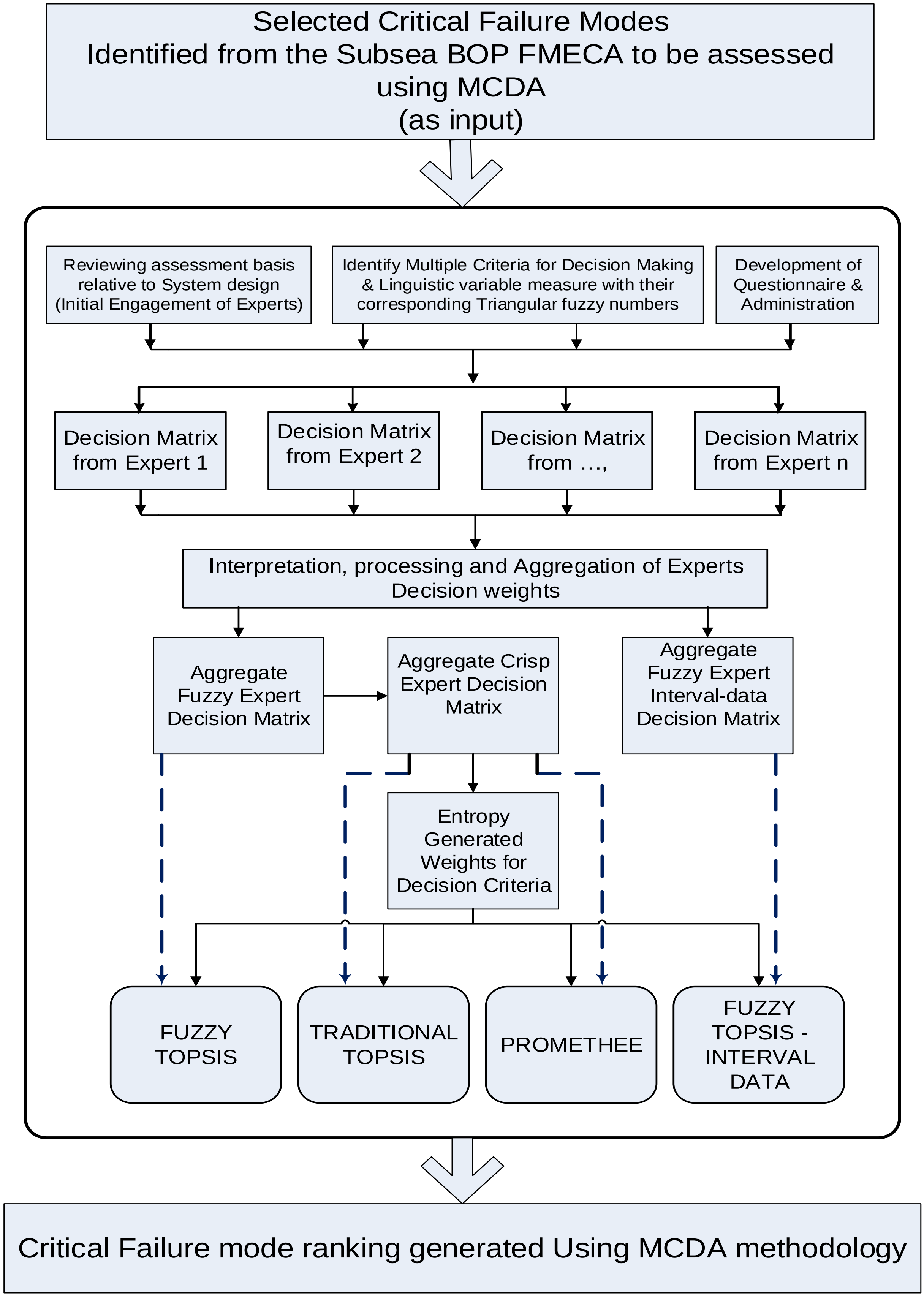


Figure 3-8: MCDM Risk Assessment Framework

3.3.1 Expert Elicitation

Experts are elicited to ascertain weights for criteria and failure modes relative to a criterion. This could be as a group or individually, depending on availability. An expert is considered as one with requisite drilling knowledge and competency in subsea well control. A competence yardstick would be years of experience with well controls-BOP and possession of an International Well Control (IWCF) certification as a requirement. This certification is the industry benchmark for supervisors of well control operations, and establishes understanding of the BOPS System functionality and associated attributes such as the criteria to be used for the MCDA analysis.

The process began in March, 2013 with identification of potential experts through LinkedIn and by searching for experts on google using buzz words “Subsea BOP Supervisor”, “Drilling Engineer+ Subsea BOP “, “Senior Subsea Engineer”, and “Subsea Drilling Engineer”. Over 40 experts were contacted, out of which 10 returned with response “Not an expert enough to contribute to assessment” and 30 responded with request for questionnaires and the remainder failed to respond. Amongst the interested experts, 12 of them requested for further clarification and definitions of terminologies upon introduction of the thesis aim. These questions initiated a dialogue process which helped the refinement of the criteria definition, criteria selection, data form (crisp or linguistic), and completeness/ appropriateness of the failure modes to be assessed.

In the process 3 of the12 declined to contribute to the assessment on the basis that it was time consuming and one expert requested not to be contacted again. Consequently, 26 experts were administered the final questionnaire to obtain decision matrix and only 10 experts responded completely.

3.3.2 Elicited Experts

A summary of experts (all IWCF Certified) elicited for this research is presented below:

Expert 1: Deepwater Drilling Engineer with an Operator for over 7 years experience working in the offshore industry. Experience spans involvement in different drilling and completion campaigns in various fields in the North Sea, West Africa, and GOM.

Expert 2: A Subsea Engineer with 12 years' experience entailing the planning supervising and executing various well control equipment maintenance in Brazil, Nigeria, Ghana, Congo, Angola, and Equatorial Guinea. He has grown through the ranks from a well control technician to Supervisor with a wealth of experience diagnosing faults, investigating malfunctions and breakdowns, disassembling and repairing various BOP systems on different drilling rigs. This expert has experience developing preventive maintenance strategies and responsible for decision tree for BOP and its control system.

Expert 3: Subsea Engineer with 5 years' experience with an OEM as a package engineer for drilling control systems. Prior to being Package engineer, he was an assistant driller for 3 years with an Operator.

Expert 4: Subsea Engineer with just over 10 years of experience in maintaining the BOP and associated equipment in relation to Preventive Maintenance System. This expert had spent three years in total as a mechanic and technician, before taking the Accelerated Rig Training (ART) course. Expert 4 had passed all the Subsea modules and became an Engineer, spending the last 4 years as a Subsea well control supervisor with a drilling contractor.

Expert 5: Subsea Drilling engineer with a Danish operator spanning over four years' experience on various campaigns in the North Sea (UK/Norway). He has had extensive training and supervision in the area of well control.

Expert 6: A Wells and intervention Engineer with an Operator in Nigeria. This expert has been involved in various Subsea drilling operations. This expert has completed most of the requisite subsea equipment trainings and is a chartered engineer.

Expert 7: Senior Subsea Engineer with over ten (10) years experience working in the subsea industry. This expert has a good understanding of subsea BOP mechanical systems as well as developing and implementing maintenance requirements/ programs .This expert has spent the last five years as a specialist in subsea electro-hydraulics BOP control systems in GOM.

Expert 8: Subsea Supervisor/ MUX BOP Surveyor with eight years' experience working on offshore deep water drilling rigs. This expert has solid experience in maintaining and operating BOP stack and controls as well as associated equipments. Expert 8 also has a working knowledge with sixth and seventh Generation Deepwater Drill-ships in West Africa and Brazil.

Expert 9: Well control instructor in a training school with prior working experience, as a Subsea Engineer, with a drilling contractor spanning 8 years in total. Most of which were on 5^{th} and 6^{th} Generation Drill-ships. He has been an instructor for the last 5years.

Expert 10: Well control equipment superintendent (subsea engineer) with over twenty years' experience. This expert has been responsible for various new build BOP systems on various jack-up, semi-sub rigs, and drill ships in water depth ranging from 450 to 10,000 feet. In the last five years this expert has been a trainer and involved in inspection, surveying, and commissioning of well control equipment, on various engineering projects globally.

The elicitation process was implemented in three stages:

- Introduction of the thesis aim and objectives to the Experts – this was to provide them both a high-level viewpoint of the research, to emphasise the importance the work, and how it can also systematically improve their understanding of the BOP system (which they have been working with for years). The introduction raised a number of questions and concerns which informed how best information will be collated and conditions for weights to be assigned. Some of these includes:

- An assumption on the BOP system type and Boundary.
- Agreement on the criteria which saw the splitting of improper maintenance criterion into two types as seen in the list of criteria.
- Their preference for linguistic representation for weights
- Lastly screening of failure modes credibility.

This process with the different experts also shaped the final version of the questionnaire (see Appendix) and rationale for chosen criteria used.

- Distribution and successive engagement of Experts with the assessment – distant experts were emailed the questionnaires and followed up with an initial average of 30 minutes Phone call each. Follow-up conversations to address questions and concerns (earlier mentioned) were done with Skype calls and questionnaire was administered to one expert in person over a period of 3 days in Denmark.
- Collation of all 10 experts' data into a single sheet and the combination of respective weights considering each criterion against corresponding failure modes (see Appendix for raw data).

3.3.3 Risk Criteria selection rationale and definition

The identification of criteria was initially informed by a derivation of sub-criteria, following the review of the BOP system technology, which could drive the three criteria that FMECA considers (occurrence, severity and detectability) individually. This is to account for the potential of experts to see each of them from different perspective, influenced by their experience and knowledge. A set of 14 general criteria /factors were initially identified(See Appendix D), However there was need to ascertain that no causality exists amongst them (see Appendix for a hierarchy diagram of initial sub-criteria). However, upon careful inspection of the initial criteria against the set of qualities specified by Dodgson et al., (2009) required for a criteria to be used in an MCDM assessment, there was some disagreement on the independence of some criterion (e.g. personnel competence could impact maintainability, Age could be correlated with failure mechanism, spare parts can be correlated with maintainability)

The set of criteria also needed refinement to reduce them to a sizeable number for easy questionnaire administering and lesser computational cost which is dependent on the amount of information obtainable however, and they have to be relevant. The selected set of criteria used for the MCDA analysis in this thesis was informed by experts, upon refinement of the initial set through series of discussions. The selection was an iterative process to capture the opinion of the ten different experts and that they align to the overarching goal of the analysis. The criteria agreed to be used for the analysis are as follows:

Improper maintenance 1 (C1): This measures the chances for an inability to restore the system to a functional state (i.e. the failure mode condition effected) with contribution from a lack of supervision (Maintenance includes spares and consumables replacement).

Improper maintenance 2 (C2): The chances for an inability to restore the system to a functional state but with contributions from a lack of competence by management (Maintenance includes spares and consumables replacement). Management captures all the personnel related profiling such as trainings received, job/shift factors etc.)

Occurrence due to Inspection/testing ineffectiveness (C3): This refers to the ability for the system to be tested or inspected effectively and assure perform its function as intended (this includes the testing interval contribution to effectiveness). This criterion is a positive variable, thus a lower score or weight would be assigned should a testing effectiveness most likely prevent failure mode occurrence and the contrary, would be a higher weight.

System or Component Complexity (C4): This measures the level of complication in the system due to increased interaction from more components, or combination of components from different manufacturers and its effect on the proper functioning of the equipment. E.g. more hydraulic supply routes, more tubing or complex stacking of hydraulic pipes from a multi shuttle valve assembly- which can create more leak paths.

Detectability (C5): This implies the ease of detecting a failure without it being hidden, i.e. the likelihood of a component or system functional state (working or not faulty) being noticed by a detection mechanism following an identified failure mode occurring. It is a negative variable.

Safeguards from Redundancy (C6): This is a measure of the system ability to recover from the occurrence of a fault or have alternative means or medium to ensure a fired function towards achieving well control is executed, i.e. a likelihood of a component or system function being safeguarded by redundancy following an identified failure mode occurring. This is a negative variable.

Loss of a function (ANOTHER) (C7): The potential for this failure mode to lead to loss of another function.

Loss of Multiple functions (C8): The potential for this failure mode to lead to loss of more than one function.

Loss of all functions (C9): The potential for this failure mode to lead to a complete loss of well control system function.

All of these criteria are positive parameters (higher weights are required to establish criticality) except C5 and C6 which are negative parameters (higher weight establishes lesser criticality and conversely).

3.4 The Subsea BOP System Failure modes under Assessment

The failure modes selected for the assessment are generated from an all-inclusive evaluation of the Subsea BOP system failure modes identified through the FMECA in chapter 4. The select list is presented in Section 4.5.

3.4.1 Input data interpretation for assessment

The collated decision matrix with linguistic inputs from different experts was converted into triangular fuzzy numbers, and aggregated in triangular fuzzy number form as shown in Table 4-8, and de-fuzzified into crisp values in Table

4-9. The crisp weights were then normalised as shown in Table 4-10. Considering the fact that most of the experts stated all criteria were important and declined to provide weights for the criteria importance, entropy method was introduced to derive the weights of importance for each criteria. These processed data was then used as input into the different MCDA techniques depending on the data forms required.

3.4.2 BOP System Failure mode ranking Using Conventional TOPSIS

The normal TOPSIS technique was applied using the crisp weights (de-fuzzified expert decision matrix), and criteria weights from entropy method. Outcomes from the different process stages, which include normalised decision matrix, weighted normalised decision matrix, the distance measures and failure modes rankings was obtained.

3.4.3 BOP System Failure mode ranking Using Fuzzy TOPSIS

The fuzzy TOPSIS technique was applied to analyse the BOP System using the fuzzy data with criteria importance weight. The fuzzy expert decision matrix is normalised while retaining its fuzzy form and then further weighted using the weight of the criteria. The fuzzy information was used to calculate the distance of separation and consequently the failure modes ranking.

3.4.4 BOP System Failure mode ranking Using Fuzzy TOPSIS - Interval method

This approach is similar to the previously applied technique but it considers the data in interval form showing the lower and upper values. In this instance the lower value of the lowest linguistic weight from the expert decision set, for a particular failure mode with respect to a criteria, is used and the upper value of the highest linguistic weight is used. The interval decision matrix and the weighted expert interval decision matrix were obtained using criteria weights. Then distance measures and ranking outcomes, from the relative closeness coefficient, for the different failure modes are obtained.

3.4.5 BOP System Failure mode ranking Using PROMETHEE

Crisp aggregate matrix data was used as inputted to Palisade Visual PROMETHEE software to generate ranks. Result were generated and exported out to an excel file. Visual depiction of results was not suitable as the number of actions (failure modes) analysed is high, as evident in the matrix. The weights of the criteria used are those generated from the entropy analysis.

3.5 Summary

The framework developed in this chapter would be implemented in chapter 4 using critical failure modes from FMECA analysis.

4 Failure Mode Identification and Prioritisation of a Subsea BOP System

This chapter presents the stem of the research in this thesis as it underscores the application of the FMECA technique to reveal weaknesses (as well as unique features) in the Subsea BOP system. System Functional and hierarchical tree diagrams were presented with boundaries defined. In this Chapter the FMECA analysis is presented with critical failure modes and deducible critical components identified. Thereafter a select critical list from the FMECA failure modes is then assessed using MCDA techniques (as presented in the developed framework in Chapter 3) with the failure mode criticality ranking outcome presented.

4.1 BOP System Model and Boundaries

The Subsea BOP system control functional diagram is depicted in Figure 4-1 and a high level system model of the subsea BOP system with representations of general function components and associated interfaces required to meet the overall goal of isolating a well to assure well control is depicted in Figure 4-2. The figure consist a representation of the system of interest with a demarcation line, the top section to mean Topsides or surface and the lower section referring to functions or items subsea. Also around the system (confined in a dashed external line) are the interfaces to the BOP System which includes emergency systems which unique functions are shown on the upper right and connection interfaces with the BOP system are shown on the lower left. The MCDA analysis in this thesis is focused on the items Subsea and the related components to the lower left-interfaces (blue demarcation in Figure 4-2). The transmission of signals and supply of power and hydraulics to fire a function is depicted in Figure 4-3. Figure 4-2 is illustrative to show different BOP function to be effected, however subsea BOP types and other main items can take different forms depending on the component whose function can be to open or close on an open hole or shear/seal on around a drill pipe. The presence of these various function was what is intended to be shown in Figure 4-3.

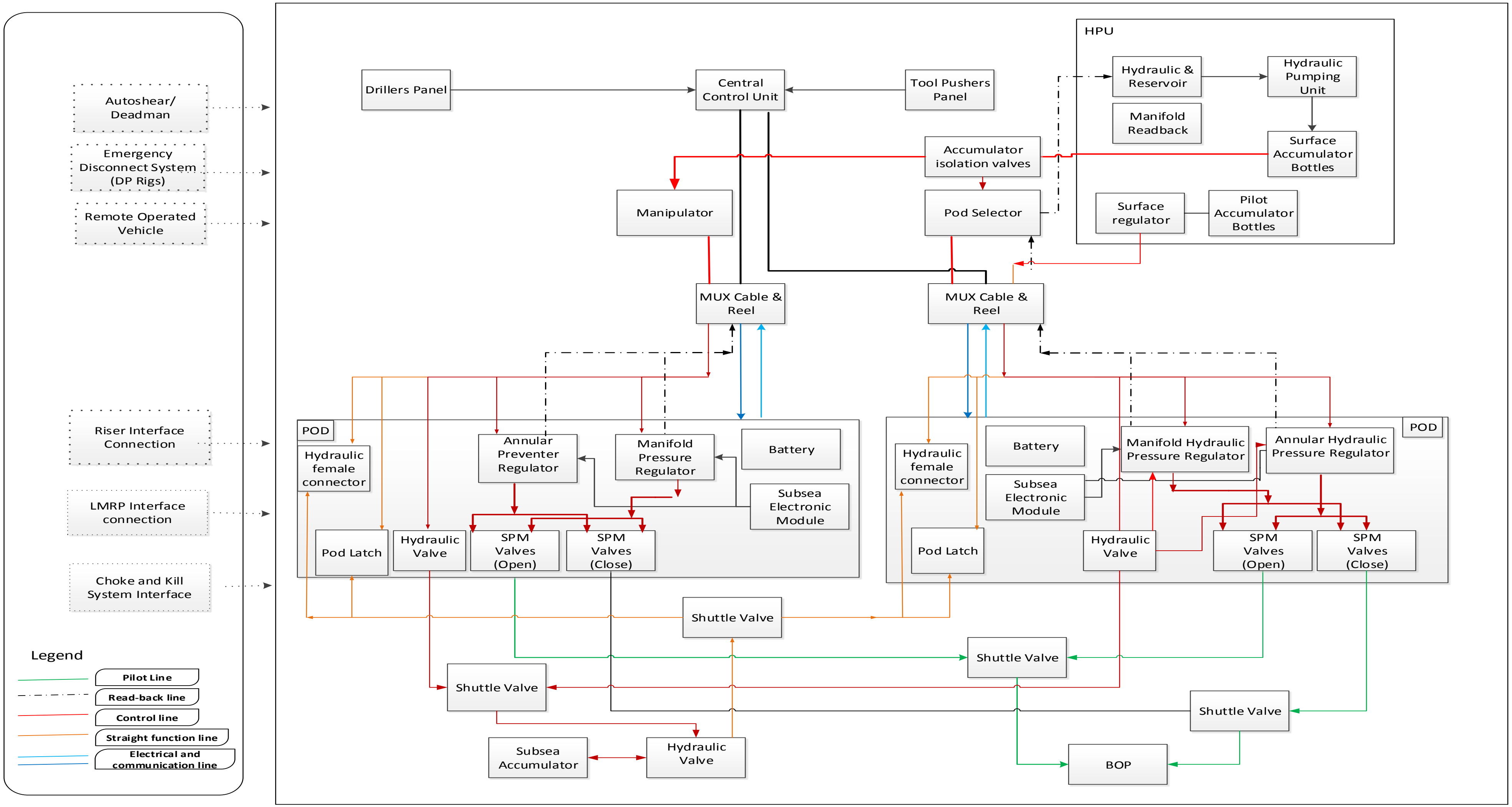


Figure 4-1: Functional Diagram of a Subsea Controls System

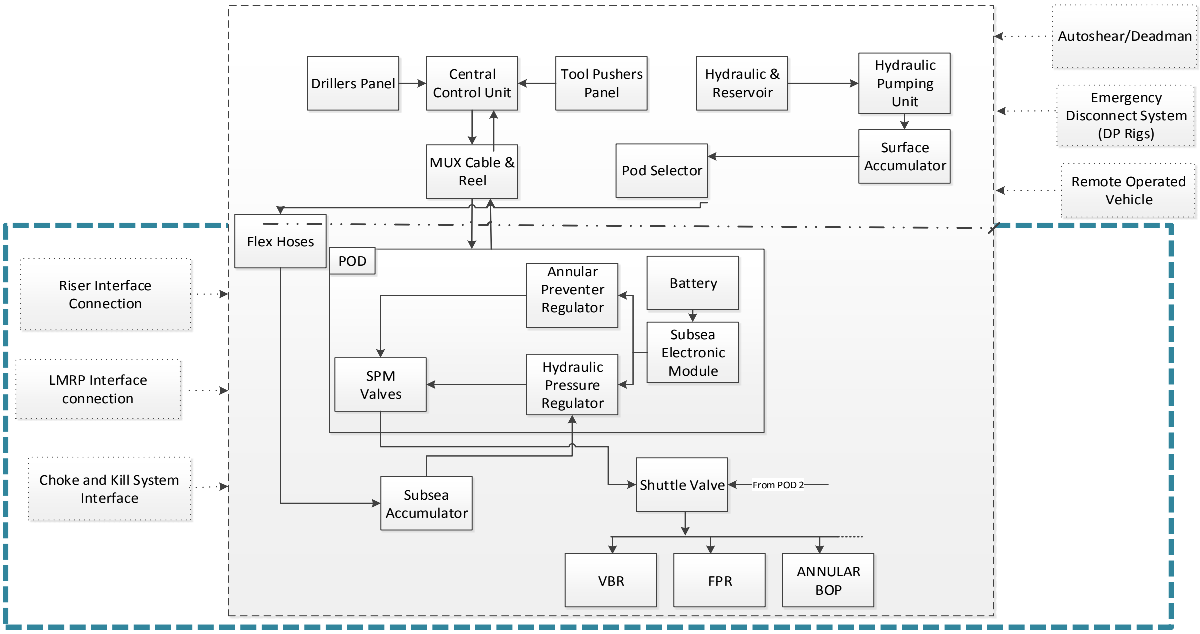


Figure 4-2: A high-level subsea BOP system model with interfaces and boundary

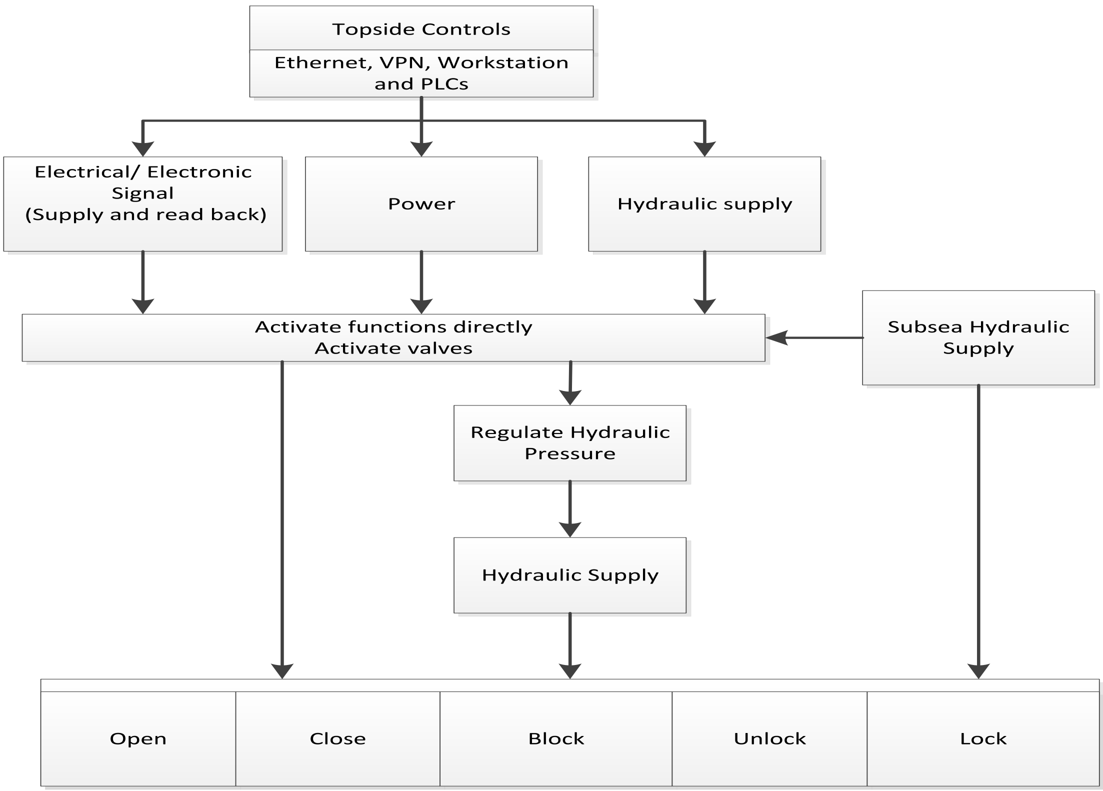


Figure 4-3: A functional flow to activate valves and component functions.

4.2 Subsea BOP System FMECA

The FMECA of the Subsea BOP system was carried to understand the BOP system and provide a yardstick for measuring criticality of the failure modes of its components. The elicitation process, underlying assumptions and limitations are discussed below.

4.2.1 FMECA Expert Elicitation Process

The FMECA analysis is heavily dependent on expert knowledge to assess the validity of a system design and then understand design weakness through the structured process of the FMECA. This FMECA utilised the knowledge of Subsea Engineering experts with a bias for drilling, well controls and controls in general. A quality benchmark which defined who an expert was is the possession of an International Well Controls Forum (IWCF) certificate and years of experience with working on drilling rigs. These experts have been identified in the previous chapter. The experts contributed to the development of the analysis worksheet and also informed the selection of a critical list to further investigate. The FMECA process started with a scoping of system analysis and desktop review using general assembly drawings, piping and instrument diagrams, and existing literature. This pre-filled worksheet was then used to consult with experts by way of interviews. The data sheet was thereafter aggregated and cleaned up while outstanding items were followed-up over time.

4.2.2 Assumptions/Limitations

Assumptions made for the study and also limitations that may have some influence on the analysis are stated below:

- Redundancy is taken into consideration, meaning in case of a component failure, an alternative component would provide that function
- The Fixed Pipe Ram was considered equivalent to Variable Bore Ram for this analysis (This is based on similarity of purpose except of variable bore capability to handle different pipe size)

- Single point failure modes are considered only.
- Only criticality with respect to a loss from well control (from a kick) during drilling and disconnecting is considered.
- Emergency systems are not considered are not considered within the scope of this thesis.
- Financial severity is not considered, as the cost of a BOP failure leading a loss of well control is established already and directly related to the technical function which is considered only for this analysis.
- Software aspects of the BOP System are considered in this analysis.

4.2.3 Analysis Approach

A system level approach was considered for the analysis and the safety-critical nature of the BOP system suggests most components have to be functional all times. Identified failure modes were evaluated using weights based on three factors (severity, occurrence and detectability) on a scale of 1-10. Corresponding Risk priority numbers (RPN), which is a product of the weights of the three factors, and risk value based on the classical risk definition (product of the severity and likelihood), were also calculated. The following columns are included in the FMECA worksheets shown in Table 4-4.

- Sub-System
- Component
- Main function of component
- Failure mode identification number
- Failure mode –Lists relevant failure modes for the component
- Failure mechanism and causes- List relevant failure causes
- Local effects - Local effects of failure modes

- Detection method- What could detect the failure modes (e.g. alarms, testing, procedures)

- Criticality ranking- these are risk scores for severity, occurrence and ease of detection with a calculation for RPN risk scoring for each failure mode.

- Barrier/Safeguards – What can prevent or lower the frequency or severity of a failure mode.

The sequence of steps for collecting failure information on components to be evaluated is as shown in the column headings (listed above from subsystem to barriers consecutively). This is repeated for each component until the defined system is analysed. The three FMECA criteria and their corresponding rating scales or classes used in this analysis are shown in the Table 4-1 to Table 4-3.

Table 4-1: Occurrence of the failure mode (Adapted from Wisconsin, 2013)

Occurrence Ranking	Description of Occurrence
1	Nearly impossible occurrence
2	Very low occurrence
3	Low occurrence
4	Relatively Low occurrence
5	Moderate occurrence
6	Moderately high
7	Fairly high/ frequent occurrence
8	High occurrence
9	Very high occurrence
10	Extremely high occurrence

Table 4-2: Severity ranking

Severity Class	Description
1	No impact on BOP functionality and no associated downtime with drilling operations.
2	No impact on BOP functionality and no associated downtime, however required maintenance can be done when BOP is pulled to rig floor.
3	Partial loss on BOP functionality and very minor associated downtime of less than a day.
4	Partial loss on BOP functionality and minor associated downtime in the order of say 1 to 7 days.
5	Partial loss on BOP functionality and minor associated downtime in the order of say 8 to 14 days.
6	Partial loss on BOP functionality with potential for additional issues and considerable associated downtime in the order of 2 to 4 weeks.
7	Loss of BOP function resulting in suspending drilling operation, pulling of LMRP/stack, or with potential to lead to loss of well control and significant leak or pulling LMRP.
8	Loss of BOP function resulting in suspending drilling operation, pulling of LMRP/stack, or with potential to lead to loss of well control and major leak.
9	Loss of well control resulting in a drilling operation halted with associated downtime impacting greatly on drilling campaign for months.
10	Loss of well control resulting in a drilling operation halted with associated catastrophic consequences such as loss of asset, loss of lives, and extreme oil spill to the environment.

Table 4-3: Likelihood of detection ranking (Adapted from Carlson, 2012)

Severity Class	Likelihood of Detection	Description
1	Almost certain	Failure will almost certainly be detected with a probability of greater than 95% through specific monitoring/ detection or self-diagnostic / annunciation systems (e.g. alarms).
2	Very High	Failure will almost certainly be detected with a probability of 70% to 95% through specific monitoring/ detection or self-diagnostic / annunciation systems.
3	High	There is a good chance to detect failure with a probability of greater than 50% through specific monitoring/ detection or self-diagnostic / annunciation systems.
4	Moderately High	Failure can be detected through weekly testing or inspection.
5	Moderately	Failure may be detected through weekly testing or inspection.
6	Low	Failure detection only possible when BOP is pulled from the well.
7	Very Low	There is a poor chance to detect failure when BOP is pulled from the well.
8	Remote	Failure can probably detect during a general preventive maintenance.
9	Very Remote	Failure would only be detected during a major overhaul.
10	Absolutely Uncertain	Absolute certainty of non-detection.

4.3 FMECA Analysis Result

A system FMECA has been performed for the subsea BOP system and a total of ninety-five failure modes entries are recorded in the FMECA study. These are summarized in Table 4-4

Table 4-4: Subsea BOP FMECA Worksheet

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS														
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/ CAUSES	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
						LOCAL EFFECTS	GLOBAL EFFECTS		S	O	D	RPN		
BOP STACK	Fixed Pipe/Test Ram	Seal well around a drill pipe of fixed diameter	F1	Fails to open	Hydraulic failure (shuttle valve leaks) or Mechanical failures Human error	Affected ram not able to function.	No global effect. Loss time in drilling operation.	BOP visual indicator, pressure gauges/ testing, hydraulic system feedback, flow meter	3	4	2	24	Maintenance, testing and inspections, use of well trained and competent personnel, BOP function testing every week	
BOP STACK	Fixed Pipe RAM	Seal well around a drill pipe of fixed diameter	F2	Fails to close	Hydraulic failure (shuttle valve leaks) Insufficient closing pressure Mechanical failures (Damaged rubber seal) Plug formation between the drill string and BOP	Inability to test or fire a closing function or full closure restricted from hydrate plug.	loss of containment and potential well control loss if redundancy fails.	Function and Pressure testing of the BOP	9	5	2	90	Maintenance, testing and inspections, use of well trained and competent personnel, BOP function testing every week	
BOP STACK	Fixed Pipe RAM	Seal well around a drill pipe of fixed diameter	F3	Fails to fully open	Mechanical or hydraulic failure (shuttle valve leaks) The presence of hydrate plug formed in the ram cavity (e.g from water-based muds used to test or flush)	Slow activation of opening function.	Downtime - delay to operations	Indications through obstruction in th e bore passage during operations after running pipe.	3	4	2	24	Maintenance, testing and inspectionuse of well trained and competent personnel, BOP function testing every week	
BOP STACK	Fixed Pipe RAM	Seal well around a drill pipe of fixed diameter	F4	External leakage	Hydraulic failure or Mechanical failures (Damaged ram body bonnet seals, and ram packing rubber, gaskets and springs, damaged piston seat.)	Control or wellbore fluid leak inability to maintain wellbore or around pipe sealing.	Loss of containment and potential well control loss if redundancy fails	Active mud pit tank volume checks for missing fluid	10	6	3	180	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead. Use of well trained and competent personnel, BOP function testing every week Redundant preventers being available. Pump rate reduction (to cool fluids before reaching surface) when temperatures	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS														
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
													reach a specified maximum for elastomers to be in-form	
BOP STACK	Fixed Pipe RAM	Seal well around a drill pipe of fixed diameter	F5	Internal Leakage	Damaged bonnet seals, ram packing runners and top seats	control or wellbore fluid leak inability to maintain wellbore or around pipe sealing.	No immediate effect potential to worsen well control operation	During pressure testing- installation, on the rig testing (opportunistic testing during repairs and scheduled testing) Shut in Pressure variation; potentially an increase in trip tank volume	7	3	2	42	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead. Use of well trained and competent personnel, BOP function testing every week Redundant preventers being available. Pump rate reduction (to cool fluids before reaching surface) when temperatures reach a specified maximum for elastomers to be in-form	
BOP STACK	Variable Bore RAM	Seal well around pipe for a range of diameter (small)	F6	Fails to Open	Hydraulic failure (shuttle valve leaks) or Mechanical failures Human error	Affected ram not able to function.	No global effect. downtime - delay to operations	BOP visual indicator, pressure gauges/ testing , hydraulic system feedback , flow meter	3	4	2	24	Routine maintenance and inspection Ensure operators are well trained to understand and ensure compliance.	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS													
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
BOP STACK	Variable Bore RAM	Seal well around pipe for a range of diameter (small)	F7	Fail to Close	Hydraulic failure (shuttle valve leaks) Insufficient closing pressure Mechanical failures (Damaged rubber seal) Plug formation between the drill string and BOP	Affected ram not able to function. (not holding pressure)	Erosion of pipe in the well Potential continuous flow of fluid to surface Well control operation delayed	During pressure testing- installation, on the rig testing (opportunistic testing during repairs and scheduled testing)- Shut in Pressure(shut-in drill pipe pressure/stand-pipe or shut in casing pressure variation; During Well control scenario potentially an increase in trip tank volume or pit gain/	9	5	2	90	Maintenance, testing and inspections, use of well trained and competent personnel, BOP function testing every week
BOP STACK	Variable Bore RAM	Seal well around pipe for a range of diameter (small)	F8	Fails to fully Open	Mechanical or hydraulic failure (shuttle valve leaks)	When running a pipe, the pipe can potentially damage the ram body	downtime - delay to operations During well control operation ram is damaged and leakage will ensue.	Flow meter (flowrate of fluid through flowline to shale shaker before mud pit.	3	4	2	24	Maintenance, testing and inspections, use of well trained and competent personnel, BOP function testing every week
BOP STACK	Variable Bore RAM	Seal well around pipe for a range of diameter (small)	F9	Internal leakage	Damaged bonnet seals, ram packing runners and top seats	Inability to seal off the well resulting in leakages	Worst case: fluid influx gets to surface. However, quantity depends on the time span taken to close the VBR till th enext preventer is closed.	Shut in Pressure variation; potentially an increase in trip tank volume	10	6	3	180	Maintenance, testing and inspections, use of well trained and competent personnel, BOP function testing every week

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
BOP STACK	Variable Bore RAM	Seal well around pipe for a range of diameter (small)	F10	External leakage	Hydraulic failure or Mechanical failures (Damaged ram body bonnet seals, and ram packing rubber, slack ram housing flange, Damaged gaskets and springs, damaged piston seat.)	Leakage to the environment	Further deterioration of seals and bolts with potential of causing excessive spill to environment.	Reduction in hydraulic pressure	7	3	2	42	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead. Use of well trained and competent personnel, BOP function testing every week Redundant preventers being available. Pump rate reduction (to cool fluids before reaching surface) when temperatures reach a specified maximum for elastomers to be in-form	
BOP STACK	Blind Shear Ram	Cuts through specified drill pipe (but not tool joint) and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe.	F11	Fails to Shear and close	Mechanical (shear blade failure, bonnet door failure) or hydraulic failure (shuttle valve leaks or insufficient pressure) Different material class of Drill string- Ram not qualified to shear that dimension or size of drill string. Drillstring not centred in position	Function activates but not complete Leak of fluid from wellbore to topside and environment	Potentially result in a blowout in the event of a Kick loss of life, asset and	Detectable only upon activation based on indicators.	10	3	2	60	None Proper qualification to be carried out for attaining required functions (e.g. shearability) under condition of use as stated in the spec, scope of work or as prescribed in guidelines.	
BOP STACK	Blind Shear Ram	Cuts through specified drill pipe (but not tool joint) and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe.	F12	Fails to close (seal open-hole)	Mechanical (shear blade failure, bonnet door failure) or hydraulic failure (shuttle valve leaks or insufficient pressure)Plug formation between the drillstring and BOP	Inability to seal well in the event of Kick	Escalation of a well control event that could be a risk the asset and personnel	Easily detected during Function testingDuring operation, easily detectable as pipe to be sheared does not shear.	10	3	4	120	Routine maintenance,Comple te Pressure testing - at surface, during installation, periodical while on wellhead.	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS													
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
BOP STACK	Blind Shear Ram	Cuts through specified drill pipe (but not tool joint) and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe.	F13	Fails to Open	Mechanical or hydraulic failure (shuttle valve leaks) The presence of hydrate plug formed in the ram cavity (e.g from water-based muds used to test or flush)	Affected ram not able to function and presents delay to maintenance or operations program	No Global effect	BOP visual indicator, pressure guages/ testing , hydraulic system feedback , flow meter	3	4	2	24	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead.
BOP STACK	Blind Shear Ram	Cuts through specified drill pipe (but not tool joint) and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe.	F14	Fails to fully open	Mechanical or hydraulic failure (shuttle valve leaks) The presence of hydrate plug formed in the ram cavity (e.g. from water-based muds used to test or flush)	Affected ram not able to function and presents delay to maintenance or operations program	No Global effect	BOP visual indicator, pressure guages/ testing , hydraulic system feedback , flow meter	3	4	2	24	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead.
BOP STACK	Blind Shear Ram	Cuts through specified drill pipe (but not tool joint) and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe.	F15	Internal Leakage (via a closed ram)	Mechanical related failures- Damaged bonnet seals, ram packing runners and top seats. improper maintenance- missing seals over pressure during testing	Depending on the size of the leak, it can potentially expose the rig floor to maximum anticipated surface pressure (MASP) of the well. Inability to pass pressure testing during testing	Delay in Operation (If this is implies loss of a secondary barrier) Worse case: potential loss of well control	During a PT/FT it would not hold pressure SICP dropping or wellhead fluid dropping out of surface.	8	4	3	96	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead. Note: It is expected that during testing the sealing performance must pass the low pressure test and high pressure test. This is less likely to occur, however recorded for completion.
BOP STACK	Blind Shear Ram	Cuts through specified drill pipe (but not tool joint) and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe.	F16	External leakage	worn sealing elements, human factor, mechanical failures damaged gasket connections, or damaged body bonnet, misalignment	leakage to environment of control and/or wellbore fluid	Failure of ram to seal wellbore with pipe in hole or close open hole. Loss of containment	Pressure guages, hydraulic system feedback, flowmeter, Visual	9	5	2	90	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
BOP STACK	Casing Shear Ram	Cuts through casing and extends to seal wellbore. Also capable of sealing an open wellbore without a drill-pipe. (in this thesis it is assumed all shear rams should be able to shear and seal)	F17	Fails to close (seal open-hole)	Mechanical or hydraulic failure (shuttle valve leaks) Human error (e.g. ram closed on a tool joint)		The formation will be exposed to excessive pressure during testing ram- if the testing pressure is above the fracture pressure (from leak-off test) This constitutes bigger issue of losing mud to the well-formation fluid flows to the well and loose hydrostatic and thus fracture needs to be healed		9	3	2	54	Routine maintenance, Complete Pressure testing - at surface, during installation, periodical while on wellhead.
CHOKE AND KILL SYSTEM	CHOKE AND KILL LINES (flex, vertical-flex loop, horizontal flex loop)- BOP attached line	To circulate Kicks To inject fluid into the BOP	F18	External Leakage	mechanical deformation/damage (at coflex hose and jumper hose line) External Shock (e.g. bad weather) Over pressure Damaged or bad packing	Leakage of fluid	Down time in drilling process	ROV detection function and installation testing During maintenance on rig	6	6	4	144	Redundant lines
CHOKE AND KILL SYSTEM	CHOKE AND KILL LINES (flex, vertical-flex loop, horizontal flex loop)- BOP attached line	To circulate Kicks To inject fluid into the BOP	F19	Plugged line	hydrate blockage or	Inability to carry out choke and kill valve testing Inability to circulate fluid during a Kick	Down time in drilling process- if observed during a test e.g. when running the BOP delay in well control procedure-given the presence of a redundant line Potential tendency to worsen control effort	Function and installation testing Pressure gauges	7	3	4	84	Cooling or adding chemical inhibitors to circulation fluids , and/or increasing mud weight for stabilization

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
CHOKE AND KILL SYSTEM	CHOKE AND KILL LINES (flex, vertical-flex loop, horizontal flex loop)- BOP attached line	To circulate Kicks To inject fluid into the BOP	F20	Burst Line	Over pressure, Improper material qualification External destructive force/shock	Leakage of fluid to environment Potential delay in well control procedure	Loss of redundancy given second line available	ROV detection Pressure and installation testing	7	3	4	84	Redundant lines	
CHOKE AND KILL SYSTEM	Choke and Kill Line Jumper hose-line	To circulate Kicks To inject fluid into the BOP	F21	External leakage	Damaged or bad acting seals over pressure External shock induced damage	Inability to test choke and kill line	Loss of redundancy given second line available	ROV detection Pressure testing Visible inspection	6	6	4	144		
CHOKE AND KILL SYSTEM	Choke and Kill Line Riser Attached line	To circulate Kicks To inject fluid into the BOP	F22	External leakage	Mechanical deformation/damage (at coflex hose and jumper hose line) Damaged or bad packing seals, ring gaskets, line seals at riser joints Damaged hub on the kill line over pressure External Shock (bad weather)	Leakage of circulation fluid to the environment Inability to hold pressure and even test choke and kill valves delay in operations and potentially drilling programme No effect on well control	Potential for additional problems in circulating kick out of well- should a kick occurs	During testing (installation, while running BOP pressure gauges ROV detection	6	6	4	144		
CHOKE AND KILL ISOLATION VALVES	CHOKE AND KILL VALVES (Upper and lower- inner and outer choke/kill valve)	Regulates the flow of fluid between the choke & Kill lines and the BOP	F23	Fails to Open	Debris on seats,	During drilling fail safe valves are closed and riser is used to communicate between the surface and well control… riser disconnected (no communication to riser when BOP closed and) and the C&K should be able to flow all the way downInability to Kill well	Gas migration can occur overtime can occur and high pressure builds up at surface and formation (MAASP exceeded, fracture the shoe) if surface pressure greater than the MASSP)Not sure of actual volume of fluid required to pump	Pressure Gauges	8	3	3	72	more than one choke line	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS													
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
CHOKE AND KILL ISOLATION VALVES	CHOKE AND KILL VALVES (Upper and lower- inner and outer choke/kill valve)	Regulates the flow of fluid between the choke & Kill lines and the BOP	F24	Fails to close		Inability to shut-in the well		Pressure Gauges	8	3	2	48	
CHOKE AND KILL ISOLATION VALVES	CHOKE AND KILL VALVES (Upper and lower- inner and outer choke/kill valve)	Regulates the flow of fluid between the choke & Kill lines and the BOP	F25	Internal leakage (through a closed valve)	Mechanical failures- worn-out ring gasket	Valve would not hold low pressure Inability to test or have a good test	No global effect- operation can continue and problem fixed when BOP pulled	Pressure Gauges Test during installation and running of the BOP	8	6	4	192	Presence of redundancy in lines each having two valves in series Flushing and greasing of valve
CHOKE AND KILL ISOLATION VALVES	CHOKE AND KILL VALVES (Upper and lower- inner and outer choke/kill valve)	Regulates the flow of fluid between the choke & Kill lines and the BOP	F26	External leakage	worn-out ring gasket	leakage at the flange, connections or ring gasket between the valve and BOP body	External leakage to environment, if below LPR- the BOP will leak should during a well lick, a closure of the BOP is attempted		9	4	3	108	Presence of redundancy in lines each having two valves in series
LMRP	Annular Preventers	Seals the annulus around a drill pipe (different diameters) or tool going through the BOP	F27	Fails to close/ Seal	Closing pressure not maintained, Worn parts (sealing elements)	The	This can lead to extended leakage during a loss of well control with fluid	Pressure gauges, hydraulic system feedback, flowmeter, Pressure and function testing on-board rig	8	3	2	48	Presence of redundancy Routine Functional and Pressure Testing Good choice of sealing element Maintenance by way of repair or replacement Flushing through kill line, increasing the closing pressure to attempt closing
LMRP	Annular Preventers	Seals the annulus around a drill pipe (different diameters) or tool going through the BOP	F28	Internal Leakage (Hydraulic-control fluid section)	mechanical failures Worn-out sealing elements, Human factor	Leak at weep hole, unable to close chamber pressure	Potential increase in loss time Not critical to blowout hazard	Pressure and function testing on-board rig	5	1	2	10	Presence of redundancy Routine Functional and Pressure Testing Good choice of sealing element Maintenance by way of repair or replacement

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
LMRP	Annular Preventers	Seals the annulus around a drill pipe (different diameters) or tool going through the BOP	F29	Internal Leakage (via a closed annular)	mechanical failures Worn-out sealing elements (of piston, body), annular pack Pitting corrosion Human factor	Annular preventer unable to pass test on-board rig and during installation Inability to execute annular sealing function during normal operation	Potential increase in loss time Not critical to blowout hazard	Pressure gauges, hydraulic system feedback, flowmeter, Pressure and function testing on-board rig	8	4	5	160	Presence of redundancy Routine Functional and Pressure Testing Good choice of sealing element Maintenance by way of repair or replacement	
LMRP	Annular Preventers	Seals the annulus around a drill pipe (different diameters) or tool going through the BOP	F30	Fail to Open	mechanical failures Worn-out sealing elements (of piston, body), annular pack Pitting corrosion Human factor	Potential increase in rig downtime If during real well control situation and well has been killed and the annular is being opened to move the string and pipe will be stucked. This is a more catastrophic event from a financial point of well as the well will be lost, given the well will be side-tracked.	Not critical to blowout hazard	Pressure gauges, hydraulic system feedback, flowmeter, Observation of restriction in running a tool (usually large diameter tools) through annular-signals retracted sealing elements Pressure and function testing on-board rig	5	1	1	5	Presence of redundancy Routine Functional and Pressure Testing Good choice of sealing element Maintenance by way of repair or replacement	
LMRP	Annular Preventers	Seals the annulus around a drill pipe (different diameters) or tool going through the BOP	F31	Fail to fully open	Slow relaxation of the annular rubber Rig not perfectly positioned above the well	Inability to execute some operations (due to restriction) e.g. changing drill bit, running test assembly	Potential increase in rig downtime Not critical to blowout hazard	Pressure gauges, hydraulic system feedback, flowmeter, Observation of restriction in running a tool through it Pressure and function testing on-board rig	5	1	1	5	Presence of redundancy Routine Functional and Pressure Testing Good choice of sealing element Maintenance by way of repair or replacement	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
LMRP	Annular Preventers	Seals the annulus around a drill pipe (different diameters) or tool going through the BOP	F32	External leakage	worn sealing elements, human factor, mechanical failures damaged gasket connections, or damaged body bonnet, misalignment.	Leakage to environment of control and wellbore fluid	Loss of use of annular rams.	Pressure guages, hydraulic system feedback, flowmeter, Visual	9	3	2	54	
LMRP	Joint (Flexible)	To enable relative movement between BOP & Riser	F33	External leakage	Bad heat treatment resulting in a welding error	loss of fluid in the riser to the sea environment. loss of hydrostatic control and then influx of kick	worst case scenario: kick not well managed could result in a Blowout with potential for fatalities and loss of asset.	inspection	7	5	2	70	Routine maintenance and inspection Ensure operators are well trained to understand and ensure compliance.
LMRP	Hydraulic Connectors	Enables connection and disconnection of the LMRP, BOP an wellhead	F34	Fails to latch	Misalignment in the locking mechanism mechanical damage at the connection affecting lock mechanism e.g. damaged locking mechanism	LMRP or BOP stack fails to latch	No global effect	No hydraulic response Testing of BOP	5	2	1		
LMRP	Hydraulic Connectors	Enables connection and disconnection of the LMRP, BOP an wellhead	F35	Fails to unlatch	Failed Hydraulic system (e.g. solenoid valve failure) stuck connector	Disconnect at connection point extended damage to connector after a drive off	Leakage to the environment When drifting off, either due to bad weather or the occurrence of a black-out, when drilling from a DP vessel. Damage to riser considerable rig downtime, which is costly	No hydraulic response Testing of BOP sealing elements Only detectable in-use	7	3	2	42	Good maintenance practice is recommended Duly qualified materials and components be used.

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS														
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
LMRP	Hydraulic Connectors	Enables connection and disconnection of the LMRP, BOP an wellhead	F36	Spurious unlatching	Failed Hydraulic systems stuck connectorA combination of factors- POCV in the locking circuit of the LMRP leaks and damaged wire linked with the lock mechanism of the connector.	Disconnect at connection point extended damage to connector after a drive off	Leakage to the environmentWhen drifting off, either due to bad weather or the occurrence of a black-out, when drilling from a DP vessel. Damage to riser considerable rig downtime, which is costlyThis could result in a blowout potentially if it occurred during drilling-without a riser margin	No hydraulic responseTesting of BOPFunction activation indicator	10	4	2	80		
LMRP	Hydraulic Connectors	Enables connection and disconnection of the LMRP, BOP an wellhead	F37	External leakage	washed ring gasket seals	Leakage through the connector to the environment	Delay in drilling operation requiring a retrieval of BOP Stack or LMRP Potential loss of well control due to inability to control kick occurrence-if BOP on wellhead	Pressure testing No hydraulic response ROV inspection	7	3	2	42	correct rating of the connector during qualification and manufacture	
TOPSIDES	Pod Selector Valve (Manipulator valve)	Selects a subsea pod to be flowed at a point in time. Given only one of the two subsea pods is required to be flowed with hydraulic fluid for BOP function.	F38	Fail to move (Inability to change position i.e. stuck open /closed)	Solenoid valve failure, mechanical failure, corrosion, stuck (too high friction), obstruction, fatigue	No hydraulic fluid transfer	Hydraulic fluid cannot be transmitted into another subsea pod, should one of the pods fail. This would prevent the BOP from functioning with a potential for blowout as an outcome.	Visual monitoring of pressure transmitter and flowmeter. Valve position indicator lights.	2	4	2	16	Inspection, testing and maintenance be planned regularly and manual intervention.	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS													
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
TOPSIDES	Accumulator isolator valve (inside HPU)	Isolates hydraulic fluid from accumulator	F39	Fails to close	Mechanical failures, Corrosion, Wear	No significant effect as flow can still be stopped with isolator pilot valve.	No global effect	Monitoring of flow meter and pressure transmitter.	2	6	2	24	Routine maintenance and testing Valve redundancy
TOPSIDES	Accumulator isolator valve (inside HPU)	Isolates hydraulic fluid from accumulator	F40	Fails to open	Mechanical failures, Corrosion, Wear	No hydraulic fluid transferred through valve	No consequence owing to redundancy	Monitoring of flow meter and pressure transmitter.	2	6	2	24	Routine maintenance and testing Valve redundancy
TOPSIDES	Accumulator isolator valve (inside control manifold)	Isolates hydraulic fluid from accumulator	F41	Fails to open/close	Mechanical failures, Corrosion, Wear Stuck and no pilot supply	No hydraulic fluid transferred through valve	No consequence owing to redundancy	Monitoring of flow meter and pressure transmitter.	2	6	2	24	Routine maintenance and testing Valve redundancy
TOPSIDES	Hydraulic Power Unit (HPU)	Provide and control pilot and power hydraulic fluid	F42	External leakage of hydraulic fluid	External damage, Material failure, component failure	Leakage of control fluid to the environment	Loss of redundancy No immediate consequence (besides these can be fixed as on the deck)	Visual detection, Alarm and monitoring in the topsides CCU.	2	6	2	24	Redundancy exists as a safeguard
TOPSIDES	Hydraulic Power Unit (HPU)	Provide and control pilot and power hydraulic fluid	F43	Blockage of hydraulic	Dirts, debris,	Inability to supply hydraulic	Loss of redundancy No immediate consequence (besides these can be fixed as on the deck)	Visual detection, Alarm and monitoring in the topsides CCU.	2	6	2	24	Redundancy exists as a safeguard
TOPSIDES	Hydraulic Power Unit (HPU)	Communication of control and monitoring function between HPU and	F44	Loss of communicati on Loss of power supply	External damage, Material failure, component failure	Loss of one communication line Loss of redundant power supply	Loss of redundancy No immediate consequence (besides these can be fixed as on the deck)	Visual detection, Alarm and monitoring in the topsides CCU.	2	6	2	24	Redundancy exists as a safeguard

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS													
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
TOPSIDES	Hydraulic Jumper (HPU to reel) and couplings (inlet and outlet)	To transport and distribute hydraulic fluid through reel /subsea junction box to subsea	F45	Fluid leakage to sea	Coupling seal or tubing leak	Net loss of hydraulic fluid	No impact on operation Loss of redundancy	Fluid spill: HPU reservoir make-up rate Net loss of fluid in the system Increased pump cycle	2	6	2	24	
TOPSIDES	Hydraulic Jumper (HPU to reel) and couplings (inlet and outlet)	To transport and distribute hydraulic fluid through reel /subsea junction box to subsea	F46	Blockage	Dirts, manufacturing error	Reduced or no flow of fluids to end users	Hydraulic pressure build up & loss of supply to reach End Users. Impact on Operation	Comparison of Subsea & supply system pressures; Reduced or No flow No or slow end user operation	3	4	2	24	
TOPSIDES	Electrical Power and Signal Jumper (from topsides to reel) receptacle /plug connectors P/S	To maintain the separation of the Power and signal cable and to channel these from and to their appropriate connection points.	F47	Power/Signal channel supply failure	Corrosion, Short circuit, open circuit	Loss of power/ signal supply train to subsea end users	No effect on well control operations as the system will continue in a degrade mode Loss of redundancy	Power/Signal Monitoring system	3	4	2	24	Redundant path available
TOPSIDES	Electrical Power and Signal Jumper Power/signal line (P/S A)	To maintain the separation of the Power and signal cable and to channel these from and to their appropriate connection points.	F48	Power/Signal channel supply failure	Corrosion, Short circuit, open circuit	Loss of power/ signal supply train to subsea end users	No effect on well control operations as the system will continue in a degrade mode Loss of redundancy	Power/Signal Monitoring system	3	4	2	24	Redundant path available
TOPSIDES	Control Panels (Drillers and Tool Pushers)	To monitor operations (pressure, BOP functions) and with push buttons to command a function.	F49	Panel not working	Electrical fault. Manufacturing fault or otherwise.	Loss of power/ signal supply train to subsea end users	No effect on well control operations as the system will continue in a degrade modeLoss of redundancy	Power/Signal Monitoring system	3	4	1	12	Redundant path available
SUBSEA CONTROLS	Shuttle valve	To supply hydraulic from whichever source to the valve has a higher pressure to activate associated equipment function (e.g. ram opening)	F50	Fails to isolate/Stuck	Wear on slide, causing jam, Seized	Delay in fluid transfer No hydraulic fluid supply.	Loss of pressure & flow if usable supply line fails to supply resulting in loss of function (e.g Shearing, Shearing and sealing function not possible-	Pressure Indicator functions for shuttle valve and Preventer functions Hydraulic flow measurements	10	2	4	80	Accumulator Bank (Fails as is and fail safe close)

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
							loss of well barrier Potential loss of well control							
SUBSEA CONTROLS	Shuttle valve	To supply hydraulic from whichever source to the valve has a higher pressure to activate associated equipment function (e.g ram opening)	F51	External Leakage	mechanical damage	No Hydraulic fluid transfer	Shearing and sealing function not possible-loss of barrier Potential loss of well control	Indicator functions for shuttle valve and Preventer functions	9	4	2	72		
SUBSEA CONTROLS	Hydraulic Distribution Shuttle valve (Coupling + Tubing)	To contain and transport LP hydraulic fluid from the Shuttle Valve to a function	F52	Fluid leakage to sea	Coupling Seal or tube leak Mechanical failures-thermal fatigue, failures in gaskets, fittings, etc., vibration effects, inadequate support or external force not sufficient.	Fluid spill into sea (Poss. Environmental issues) Loss of LP supply to a function.	Impact on Drilling Operation Loss of BOP activation function	Hyd. Flow measurement	9	5	3	135	None; Accumulator Bank (Fail As Is and Fail Safe Close) in the first few hours before total system failure.	
SUBSEA CONTROLS	Hydraulic Distribution Shuttle valve (Coupling + Tubing)	To contain and transport LP hydraulic fluid from the Shuttle Valve to a function	F53	Blockage	Dirt, manufacturing error	Loss of LP supply for Activating a function	Hydraulic pressure build up & loss of supply to reach End Users. Impact on Operation	Comparison of Subsea & supply system pressures; Reduced or No flow No or slow end user operation	7	5	3	105	None; Accumulator Bank (Fail As Is and Fail Safe Close) in the first few hours before total system failure.	
SUBSEA CONTROLS	Manifold Hydraulic Pressure Regulator	Regulates control fluid pressure which is supplied to all ram functions, BOP side outlets hydraulic Valves, hydraulic connectors, and also systems with locking mechanism e.g. Cameron's wedge	F54	Unstable output pressures	Normal wear and tear on known low reliability component	Out of spec output pressure (Low Pressure)	No possibility of ultimate firing of specified ram and other associated function & activating valves and Potential loss of well control.	Pressure gauges Pressure Transmitters	10	6	2	120		

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS														
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
		lock												
SUBSEA CONTROLS	Annular Hydraulic Pressure Regulator	Regulates control fluid pressure which is supplied to the annular preventers only	F55	Unstable output pressures	Normal wear and tear on known low reliability component	Out of spec output pressure (Low Pressure)	Inability to activate annular function & function valves Worst case: Well control operation hindered.	Pressure gauges Pressure Transmitters	9	5	2	90		
SUBSEA CONTROLS	Pod/Stack Mounted Accumulator Isolation valve	Isolates hydraulic fluid in the Pod/Accumulator	F56	Fails to close/open	Mechanical failures, Corrosion, Wear	No hydraulic fluid transferred through valve	No consequence owing to redundancy	Monitoring of flow meter and pressure transmitter.	2	6	2	24	Routine maintenance and testing Valve redundancy	
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (Pressure Vessel)	To exclude water from electronics (nitrogen charge in pressure casing)	F57	Electrical short to circuit or earth	Leak along cable access	Loss of function of SEM. Potential loss of control of system pressure monitoring and flow parameters	Loss of redundancy. No effect on BOP operation Potential for unintended operation such as closing or opening or sealing against an open hole or drill pipe.	Alarm	2	1	1	2	Initial fluid contamination should be by dielectric fluid from enclosure with no effect	
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (Pressure Vessel)	To exclude water from electronics (nitrogen charge in pressure casing)	F58	Electrical short to circuit or earth	Leak along cable access	Loss of function of SEM. Potential loss of control of system pressure monitoring and flow parameters	Potential for unintended operation such as closing or opening or sealing against an open hole or drill pipe.	Alarm	9	2	1	18	Initial fluid contamination should be by dielectric fluid from enclosure with no effect	
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B)	To convert and regulate incoming supplies to 250V AC for input to the Rectifier and EMC	F59	No output	Transformer failure open circuit, earth fault	Loss of one channel power to Rectifier and EMC Filter.	Loss of redundancy. No effect on BOP operation	Loss of channel output	2	1	1	2	Other Channel available	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
	(Transformer)	Filter											
SUBSEA CONTROLS	Subsea Electronics Module A/B (Safety SEM A/B) (Transformer)	To convert and regulate incoming supplies to 250V AC for input to the Rectifier and EMC Filter	F60	Incorrect voltage at output; Erratic voltage	Transformer failure short circuit	Overvoltage could cause damage to rectifier.	No effect on BOP operations as the system will continue to run in a degraded mode for a period Loss of redundancy.	Probable loss of channel output	1	1	1	1	Other Channel available
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (Rectifier for EMC Filter unit))	To rectify the supply 250V AC to a DC Output to the EMC Filter	F61	Loss of output	Electronic fault; short circuit, open circuit	Loss of one channel power of DC Voltage to EMC Filter.	Loss of redundancy. No effect on operation	None	2	1	1	2	Other Transformer path and Rectifier will provide supply to the EMC Filter
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (DC EMC Filter)	To smooth the rectified DC input supply to the Power Supply Board.	F62	Fail to output	Electronic fault; short circuit, open circuit	Loss of supply to Power Supply Unit causing loss of DC - DC Converters	Total loss of power supplies to Instrumentation SEM end users. Loss of redundancy No effect on operation	No output to the Power Supply Board	3	1	1	2	Other channel
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (DC/DC Converter 5V)	To convert incoming DC Voltage to 5V DC and distribute for use in Mode, Serial and Analogue cards, and the Stack	F63	Loss of output	Short Circuit; open circuit	Loss of end user functions Loss of Instrumentation SEM	Loss of redundancy. No effect on operation	Modem failure alarm System dynamic indications	2	1	1	2	Other channel
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (DC/DC Converter 24V)	To convert incoming DC Voltage to 24V DC (Main) and distribute for use in Modem, Serial and Analogue cards.	F64	Loss of output	Short Circuit; open circuit	Loss of end user functions Loss of Instrumentation SEM	Loss of redundancy. No effect on operation	Modem failure alarm System dynamic indications	2	1	1	2	Other channel

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
SUBSEA CONTROLS	Subsea Electronics Module A/B (Instru. SEM A/B) (DC/DC Converter 24V Aux)	To convert incoming DC Voltage to 24V DC (Aux) and distribute for use in Serial cards.	F65	Loss of output	Short Circuit; open circuit	Loss of limited functionality of Serial card end users	Loss of redundancy. No effect on operation	System dynamic indications	2	1	1	2	Other channel	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Ethernet Modem)	To provide communication link with surface acting as a slave device to the surface controller	F66	Loss of function	Data corrupt, electrical fault	Fail to transmit command signal to PC104 stack. Command action failure.	Loss of Instrumentation SEM Comms Channel. Loss of Comms redundancy. No effect on operation.	Intermittent Comms. alarms, or alarm on Comms. line changeover	2	1	1	2	Alternate Ethernet modem available.	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Ethernet Modem spec voltage DC-DC Converter)	Provides spec voltage to the Ethernet Switch	F67	Loss of Function	Internal Failure	Loss of power to the Ethernet Switch	Loss of the ability to send and receive data to the SEM. Loss of redundancy. No effect on operation.	Intermittent Comms alarms, or alarm on Comms line changeover	2	1	1	2	Alternate Ethernet modem available.	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Ethernet Switch)	Connect all Ethernet enabled devices together to allow communications between them	F68	Loss of Function	Internal Failure	Loss of the ability to communicate to devices connected to the Ethernet Switch	Loss of the ability to send and receive data to the SEM. Loss of redundancy. No effect on operation.	Intermittent Comms alarms, or alarm on Comms line changeover	2	1	1	2	Alternate Ethernet modem available.	
SUBSEA CONTROLS	Instrumentation Subsea Electronics Module (Instru. SEM A/B) (PC Stack)	To receive and monitor incoming parameter signals and forward to MCP.	F69	Loss of function	Electronic failure; software error; software architecture error, incorrect address	Failure of Instrumentation SEM Comms, control and monitoring	No effect on operation. Loss of redundancy.	Loss of Communication	2	1	1	2	Alternate PC104 Stack available.	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (PC Profibus)	To transmit signals between PC Stack and Serial & Analogue cards	F70	Loss of function	Failure to convert the surface to subsea protocol	Fail to transmit command signal between the modem and the I/O devices.	No effect on operation. Loss of redundancy.	Communication error	2	1	1	2	Alternate PC104 Profibus available.	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Microcontroller)	To receive and acknowledge incoming commands and direct power to appropriate devices.	F71	Loss of function	Electronic failure; software error; software architecture error, incorrect address.	Failure of Instrumentation SEM Communication, control and monitoring.	Loss of redundancy. No effect on operation	Loss of Communication	2	1	1	2	None Other Channel
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Serial Board 1 & 2)	To distribute appropriate power supply and monitor measured parameters for forwarding to the Modem	F72	Fail to validate command; Fail to forward power to designated sensor	Electronic failure; software error; software architecture error	Loss of end user functions	Loss of redundancy. No effect on operation	Loss of Communications.	2	1	1	2	None Other Channel
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Serial Boards)	To distribute appropriate power supply and monitor measured parameters for forwarding to the Modem	F73	Spurious validation of command; Provision of inappropriate power supply to designated sensor	Electronic failure; software error; software architecture error	Inaccurate parameter reading	Loss of redundancy. No effect on operation	Communication error	2	1	1	2	Redundant Instrumentation SEM, Other Channel available
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Analogue Boards)	To power, monitor and convert sensor output data for transmission to a remote station via the Modem.	F74	Failure of all Analogue Board functions	Failure of ADC, Micro Com. or Profibus	Loss of Analogue Board output to the PC	Loss of all analogue derived indicators. Would potentially result in pod retrieval for repair No loss of operation (could continue through the mobilisation period)	Alarm at the MCP Total loss of analogue derived indicators		2	1	2	Redundant Instrumentation SEM, Other Channel available
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Analogue Boards)	To power, monitor and convert sensor output data for transmission to a remote station via the Modem.	F75	Fail to indicate individual channel parameter data value	Electronic failure; software error; software architecture error	Loss of parameter indication	No effect on operation Loss of redundancy.	Logical manual comparison with other instruments	2	2	1	4	Redundant Instrumentation SEM, Other Channel available

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS														
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Analogue Boards)	To power, monitor and convert sensor output data for transmission to a remote station via the Modem.	F76	Erroneous indication of individual channel parameter data value	Electronic failure; software error; software architecture error	Confusing indication supplied which takes operator time to confirm authenticity	No effect on operation Loss of redundancy.	Alarm 'instrument signal difference', not confirmed by manual comparison	2	2	1	4	Redundant Instrumentation SEM, Other Channel available	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (Analogue Boards)	To power, monitor and convert sensor output data for transmission to a remote station via the Modem.	F77	Fail to provide voltage & signal conditioning to P&T sensors	Electronic failure; software error; software architecture error	No power supply to third party instruments Loss of control data information	No effect on operation Loss of redundancy.	No power output signal	2	2	1	4	Redundant Instrumentation SEM, Other Channel available	
SUBSEA CONTROLS	Subsea Electronics Module (Instru. SEM A/B) (CANBus 1)	To provide communications network that interconnects component, designed to allow microcontrollers and devices to communicate with each other.	F78	Fail to validate command; Fail to communicate with microcontroll er	Electronic failure; software error; software architecture error	Loss of end user functions	Loss of redundancy. No effect on operation	Loss of Communication	2	2	1	4	None Other Channel	
SUBSEA CONTROLS	Safety Subsea Electronics Module (Safety SEM A/B) (Time Critical Modem)	To provide communication link with surface acting as a slave device to the surface controller	F79	Loss of function	Data corrupt, electrical fault	Fail to transmit command signal to solenoids valve via the Ethernet Switch. Command action failure.	Loss of Safety SEM Comms Channel. Loss of Comms redundancy. No effect on operation.	Intermittent Communication alarms, or alarm on Communication line changeover	2	2	1	4	Alternate Time Critical Modem available.	
SUBSEA CONTROLS	Safety Subsea Electronics Module (Safety SEM A/B) (Time Critical Modem spec voltage DC-DC Converter)	Provides spec voltage to the Ethernet Switch	F80	Loss of Function	Internal Failure	Loss of 3.3V power to the Ethernet Switch	Loss of the ability to send and receive data to the Safety SEM. Loss of redundancy. No effect on operation.	Intermittent Communication alarms, or alarm on Communication line changeover	2	2	1	4	Alternate Time Critical Modem available.	
SUBSEA CONTROLS	Safety Subsea Electronics Module (Safety SEM A/B) (Ethernet Switch)	Connect all Ethernet enabled devices together to allow communications between them	F81	Loss of Function	Internal Failure	Loss of the ability to communicate to devices (solenoids) connected to the Ethernet Switch.	Loss of the ability to send and receive data to the Safety SEM. Loss of redundancy. No effect on	Intermittent Communication alarms, or alarm on Communication line changeover	2	2	1	4	Alternate Ethernet Switch available.	

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
							operation.							
SUBSEA CONTROLS	Safety Subsea Electronics Module (Safety SEM A/B) (Solenoid Control Boards)	To provide the facility to control solenoids on demand via an electrical interface	F82	Fail to drive solenoid on demand	Short Circuit; Open circuit	Individual Solenoid coil fail to respond. Desired outcome not achieved	No effect on BOP operations as the system will continue to run in a degraded mode for a period Loss of redundancy.	Valve fails to respond	2	2	1	4	None Other Channel	
SUBSEA CONTROLS	Safety Subsea Electronics Module (Safety SEM A/B)(Solenoid Control Boards)	To provide the facility to control solenoids on demand via an electrical interface	F83	Selection of wrong solenoid	Electronic failure; software error; incorrect address	Operation set-up does not change as required.	Potential loss of well controlIf verification fails to detect error then incorrect valves could be operated resulting in abnormal operations	Verification mechanism	2	2	1	4	Robust Communication protocol	
SUBSEA CONTROLS	Subsea Pod battery	Provides signal and electric power to the subsea solenoid valve for BOP functions activation during emergency. When there is no communication (hydraulic and electric)from surface, the batteries will function with the aid of the PLC.	F84	Inability to supply required voltage	Thermal variation, corrosion, obsolete battery	Inability to function control valve (i.e. solenoid) with battery.	The Blind shear ram function would not be activated by the AMF in the event of an emergency well shut in. This presents a high probability of a blowout. Redundancy capability is thus reduced.	Following an emergency well shut in situation, and there is no sign of influx contained by BOP sealing. Thus this signals no communication from the surface.	2	5	2	20	Frequent scheduled testing, maintenance and inspection . Introducing blind shear ram function initiation redundancy by having a n acoustic intervention system for the BOP. Redundancy architecture of possible usage of batteries from other pods. (The system effect from the complexity of this structure needs investigation).	
SUBSEA CONTROLS	Small bore hydraulic tubing	Conduit system for pressurised hydraulic fluid for subsea control	F85	Leakage to ambient	Environment-corrosion, External damage, Material failure	loss of hydraulic supply leakage of fluid to environment	Potential loss of redundancy to relevant service Potential loss of function(s)	Pressure Testing /Function Testing	7	5	3	105		

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS														
BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
							Potential loss of well control							
SUBSEA CONTROLS	Subsea Accumulators	Maintain stored volume of pressurised hydraulic fluid for valve controls, rams, and other functions	F86	Loss of gas pre-charge or hydraulic leakage)	Leakage through the endcaps, and fittings Galvanic corrosion Seal damage	Gradual loss of stored energy (gas leak case) Inability to supply hydraulic in the event	Fired function (e.g. sealing, latching or locking) not activated. Inability to control well operation Potential instability during well control operations via affected function to be supplied hydraulic	Pre-charge Panel pressure indicator Possible noticeable HPU HP Pump short cycling.	8	3	5	150	Piston Accumulators have been selected, plus ability to connect in a back-up accumulator has been provided.	
SUBSEA CONTROLS	Subsea Accumulators	Maintain stored volume of pressurised hydraulic fluid for valve controls, rams, and other functions	F87	Loss of accumulation (Escape of hydraulic fluid	Damage to Piston, or bladder Connection or Accumulator leak	Loss of hydraulic fluid to sea. If undetected, eventual loss of pressure	Loss of BOP operation/functi on Loss of subsea fluid replenishment	HPU Reservoir fluid make-up rate (but failure could be hidden unless a loss of topsides LP supply occurs).	8	3	7	126		
SUBSEA CONTROLS	Solenoid valve	Receives electrical signal and supply hydraulic fluid to SPM Valves	F88	Fail to operate	Failure of coils (broken or burnt) Wire break or loss of air, Mechanical failure-low cycle fatigue	Transmission of pilot hydraulic fluid would not be effected.	Regulated fluid from regulator would not be transmitted through the SPM valve Delay in well control operations Potential loss of control with hydrocarbon release. Downtime to drilling programme	Valve position indicator (light) on the remote panels Alarm from PLC usage for solenoid monitoring. Monitoring of flowmeter and pressure transmitter	10	5	3	150		

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS
SUBSEA CONTROLS	Solenoid valve	Receives electrical signal and supply hydraulic fluid to SPM Valves	F89	Fail to operate	Low voltage	Plunger does not move Transmission of pilot hydraulic fluid would not be effected.	Inability of SPM to supply regulated fluid for firing function such as: Closing or opening ram/annular on open hole Sealing around drill pipe	Alarms Functional test	10	5	2	100	Redundant SPM and control fluid supply options
SUBSEA CONTROLS	Double Acting SPM Valve	Supplies Hydraulic control power fluid to to function ram	F90	Internal leakage	Rupture of part Mechanical failure	Slow transmission of hydraulic power fluid. Failure to maintain adequate sealing pressure on preventer/ram	BOP function (Sealing, shearing, connect or disconnect) not attained Potential Loss of well control.	Low Pressure Alarms Flow meters readings Pressure Test/Function Test	10	4	6	240	Redundant Pod Supply Function Test (Weekly) ROV intervention if required
SUBSEA CONTROLS	Double Acting SPM Valve	Supplies Hydraulic control power fluid to to function ram	F91	External leakage	General Mechanical failure (Spring failure, electrical failure, faulty solenoid, corrosion, solenoid valve failure	Transmission of hydraulic power fluid would not be effected. Failure to maintain adequate sealing pressure on preventer/ram	BOP function (Sealing, shearing, connect or disconnect) not attained Potential Loss of well control.	Pressure Transmitter Flow meters readings Pressure and Function Test	10	4	6	240	Redundant Pod Supply Function Test (Weekly) ROV intervention if required
SUBSEA CONTROLS	Single Acting SPM Valve	Supplies Hydraulic control power fluid to to function ram	F92	Internal leakage	Rupture of part or General Mechanical failure	Slow transmission of hydraulic power fluid. Failure to maintain adequate sealing pressure on preventer/ram	BOP function (Sealing, shearing, connect or disconnect) not attained Potential Loss of well control.	Low Pressure Alarms Flow meters readings Pressure Test/Function Test	9	6	2	108	Redundant Pod Supply Function Test (Weekly) ROV intervention if required
SUBSEA CONTROLS	Single Acting SPM Valve	Supplies Hydraulic control power fluid to to function ram	F93	External leakage	loss of pressure, electrical failure, faulty solenoid, corrosion, solenoid valve failure	Transmission of hydraulic power fluid would not be effected. Failure to maintain	BOP function (Sealing, shearing, connect or disconnect) not attained Potential Loss	Pressure Transmitter Flow meters readings Pressure Test/Function Test	9	6	2	108	Redundant Pod Supply Function Test (Weekly) ROV intervention if required

BOP SYSTEM FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS

BOP SUBSYSTEM	COMPONENT	FUNCTION	FM I.D	FAILURE MODE	FAILURE MECHANISM/	CONSEQUENCES		DETECTION METHOD	CRITICALITY RANKING				BARRIERS /SAFE GUARDS	
						adequate sealing pressure on preventer/ram	of well control.							
SUBSEA CONTROLS	Check Valve	conduit through which pilot pressure from the accumulator is supplied to the regulators	F94	Internal leakage	Worn or damaged valve internals.		No immediate effect on operation Potential for valves to result in BOP function fail to operate on demand.	Hidden failure	8	3	2	48		
SUBSEA CONTROLS	Check Valve	conduit through which pilot pressure from the accumulator is supplied to the regulators	F95	Plugged	Dirty seat; Debris, Contamination, Stiction	Check valve does not open on demand ; No hydraulic flow through to the pressure regulators	Possible Supply blockage results in no flow to Solenoid Valves. Well control operation hindered.	Pressure gauges and Transmitters	8	3	2	48		

4.3.1 Failure Mode Identification

The different potential failure modes of the BOP system identified in Table 4-4 are analysed in this section. Why it is important to identify component failures and the modes in which they can occur becomes obvious due to the criticality of the component and working towards an optimized drilling operation. Identification of failure can be achieved during testing prior to deployment or during operation via detection means, however during a design process failure identification can be attained from assessing a loss of function or dependency. The failure modes identified entailed component-related loss of a function, physical or chemical quantity, inability or failure to activate a function. The failure modes associated with the BOP components which are mainly similar and common modes include failure of a component to open or close, internal or external leakages, failure to lock/latch or unlock/unlatch failure to shear or seal, etc.

The output from the analysis also shows the prevalent failure mechanisms identified were corrosion and mechanical failures (wear, misalignment, brittle, deformation and fracture). The corrosion effect from the presence of hydrocarbons and seawater could affect the system in various ways e.g. leakage. The transition of the Subsea BOP operation from deepwater to dry dock could result in thermal expansions of the seals if the dry dock condition is hot. The hydraulic line can also experience thermal related failures. The poppet spring assembly of an accumulator can be fatigued from an excessive pre-charge which can result in bladder been pushed towards the poppet. Other mechanical related mechanisms include too high friction, severed part, galling, and vibration. Process related cause includes over pressure, plugged line, loss of supply (e.g. air), contamination, and leakage. Manufacturing and installation related causes like insufficient heat treatment, faulty connections, poor materials, wrong dimensions specified. Others include external causes such as shocks and human factors**.** An understanding of these mechanism constitutes the fundamental aspect of developing a risk and reliability model for improvement in designs (e.g. for mechanical systems, fault-tolerant, fail-safe or damage-tolerant designs approach can be employed), assessment of the system performance (e.g. availability) or identification of safe guards.

The effect of each failure mode following its occurrence was assessed with respect to the component itself (local), which majorly constitutes the direct effect of the function loss and the entire BOP system (global). Global failure modes effects range from no system effect to complete system failure resulting in kick not well managed could result in a blowout with potential for fatalities and loss of asset. Other global effects include delay in well control operation, potential damage to risers, when drilling from a DP vessel, downtime in drilling process, ram shearing and sealing function impossible; inability to supply hydraulic fluid, inability to maintain pressure, loss of hydraulic, flow cannot be isolated, minor or major leakage to the environment and also venting to sea. Some local effects could potentially affect the system over a time span e.g. loss of hydraulic pressure. Considering the similar nature of some components material composition and the environment, being subsea, it is not surprising a specific failure mode/cause can be associated with different components. However, such failure modes will result in likely different local effects unique to the component function and different failure modes could result in similar system effect.

Collectively, the inputs of experts in a failure assessment workshop could be affected by the breadth and depth of their experience, considering factors such as application system type, operating region and conditions, together with lessons learnt from documented reports which could have been potentially plagued with failure reporting limitations.

4.3.2 Evaluation of Failure modes through FMECA

Critical failure mode ranking from the analysis based on RPN is shown in Table 4-6. In addition to rankings based on RPN values, on the side was also presented rankings based on risk values (as a product of severity and occurrence). Critical failure modes were selected as a set with RPN values greater than 72 (Top 40%, highest RPNs) observed. The Pareto rule also known as the 80/20 rule (20% of causes generate 80% of the most benefit) has been established as a good preliminary approach to prioritisation (Lipol and Haq, 2011). In terms of failure criticality, the top 20% failures (Top 20% RPN-scores failure modes) should be a good reference point for prioritisation. However, considering the Pareto sample was small and the weakness of the FMECA-RPNs rankings, failure modes with severity values of 7 and above was included to the list. The list consists of the select 34 most critical failure modes in decreasing order upon processing the values from the FMECA worksheet. A list of fifteen (15) critical components was further derived from the select failure mode list and presented in decreasing order of criticality for each ranking metric in Table 4-5**.**

The failure mode of the Manifold Hydraulic Pressure Regulator giving unstable output pressure (F54) was the most critical based on the Risk value however, it was on the 10th rank for the RPN ranking as it had lower weight assigned for its detectability, meaning it could easily be detected. While the Double Acting SPM valve external leakage failure mode (F91) which was the most critical based on the RPN ranking was in the 6th rank for the risk based value, with a little higher weight assigned as it can be detected from a routine function testing or inspection while the BOP is being pulled (at worst case).

Considering both ranking schemes failure modes which standout to be very critical include the Fixed Pipe ram external leakage (F4), Choke and Kill Valve internal leakage (F25), Solenoid Valve Fails to Close (F88), Shuttle valve coupling and tubing external leakage (F52), Leakages associated with the Double acting SPM Valve (F90 & F91) and external leakages associated with Choke and Kill lines (F21 & F22). Also the predominant failure mode type in Table 4-6 is associated with leakage and a minority mechanical (inability to latch or function- close/open) and blockage related failure modes. The root cause/mechanisms of leakage are associated with material quality for tubing, body parts, or coils/wires, poor welds, if any, or improper alignment of connections, improper installation or fault arising from maintenance actions, especially with consumables like seals, gaskets and/with retainers. Others causes could be external such as impact from subsea equipment/tool and possible environmental induced stressors like temperature cycle, vibration for pipes, and most frequently corrosion for metallic items. These mechanisms inform the areas of focus when carrying out maintenance and also in future designs via of qualification or for existing design areas to be managed properly by way of inspection, testing and maintenance (see further discussed in Chapter 5).

It is also interesting to note that with respect to the potential of a risk of a loss of well control, critical component failure modes to bear in mind include the Blind shear ram fails to shear and seal wellbore (F11), Blind shear ram fails to close on open hole (F12), External Leakage of the Riser Flexible Joint (F33), Spurious unlatching of the hydraulic connectors for LMRP and wellhead (F36), the failure to isolate (F50) and the external leakage of the shuttle Valve (F51). A lot of the failure modes could cause a delay in well control operation with potential to lead to a loss of well control, if other redundant functions or hydraulic supply for example are also not available. If the Choke and Kill line is below the lower pipe ram, and there is a defect on that line or associated fail safe valve, the BOP will leak to the environment, should during a well kick, a closure of the BOP be attempted. If the valves fail to close then the surface would be exposed to wellbore pressure. During drilling fail safe valves are closed and the riser is used to communicate between the surface and well. If the riser is disconnected (no communication to riser when BOP closed) the Choke and Kill valves should be able to allow flow all the way down and if these valves fail to open, it presents an inability to shut-in well.

It is worth mentioning that the casing shear ram was not listed in the FMECA worksheet, this was because the experts assumed it to have similar failure modes with the blind shear ram. While there exist a difference in the type of tubulars they shear, experts agreed that for this assessment, any shear ram must be able to shear and seal. The failure of a Casing shear ram to close on an open hole could cause the formation to be exposed to excessive pressure during testing of ram. If the testing pressure is above the fracture pressure (from leak-off test), this will result in a loss of mud to the well formation fluid flows to the well, a loss of hydrostatic and thus fracture will need to be healed.

Table 4-5: Critical Components based on RPN and Risk Values (Main Analysis)

Rank	**Critical Components Identified**	
	Based on Risk Value (Product of S and O)	***Based on RPN (product of S, O, and D)***
1	Manifold Hydraulic Pressure Regulator	Double Acting SPM
2	Fixed Pipe Ram	Choke and Kill Valve
3	Single Acting SPM Valve	Fixed Pipe Ram
4	Solenoid Valve	Annular Preventer
5	Choke and Kill Valve	Subsea Accumulator
6	Blind Shear Ram	Solenoid Valve
7	Annular Hydraulic Pressure Regulator	Choke and Kill Line
8	Shuttle Valve coupling and Tubing	Shuttle Valve Coupling and Tubing
9	Hydraulic Connectors	Blind Shear Ram
10	Double Acting SPM	Manifold Hydraulic Pressure Regulator
11	Choke and Kill Line	Single Acting SPM Valve
12	Shuttle Valve	Small Bore Hydraulic Tubing
13	Riser BOP flexible Joint	Annular Hydraulic Pressure Regulator
14	Small Bore Hydraulic Tubing	Shuttle Valve
15	Subsea Accumulator	Riser BOP flexible Joint

Table 4-6: Critical Failure Mode list and their ranks based on RPN and Risk Values (Main Analysis)

Failure Mode Ranking from FMECA -Main Result			
Based on Risk Value (product of S and O)		*Based on RPN (product of S, O, and D)*	
Failure Modes	Rank	Failure Modes	Rank
Manifold Hydraulic Pressure Regulator Unstable output pressure	1	Double Acting SPM Valve External Leakage	1
Fixed Pipe Ram External Leakage	1	Double Acting SPM Valve Internal Leakage	1
Single Acting SPM Valve Leakage	2	Check Valve Internal Leakage	2
Single Acting SPM Valve Leakage	2	Choke and Kill Valve internal Leakage	3
Solenoid Valve Fail to Close	3	Fixed Pipe Ram External Leakage	4
Solenoid Valve fail to Operate-low voltage	3	Annular Preventer Internal Leakage	5
Choke and Kill Valve internal Leakage	4	Subsea Accumulators Loss of Pre-charge gas	5
Blind Shear Ram External Leakage	5	Solenoid Valve Fail to Close	6
Annular Hydraulic Pressure Regulator Unstable output pressure	5	Choke and Kill Line (Jumper hoseline External leakage	7
Fixed Pipe Ram Fail to Close	5	Choke and Kill Line (Riser Attached Line External leakage	7
Shuttle Valve coupling and Tubing External leakage	5	Choke and Kill Line (BOP Attached Line External leakage	7
Hydraulic Connectors Spuriously Unlatches	6	Shuttle Valve coupling and Tubing External leakage	8
Double Acting SPM Valve Leakage	6	Subsea Accumulators Loss of Accumulation	9
Double Acting SPM Valve Leakage	6	Blind Shear Ram Fails to Close (seal open-hole)	10
Choke and Kill Line (Jumper hoseline) External Leakage	7	Manifold Hydraulic Pressure Regulator unstable output pressure	10
Choke and Kill Line (Riser Attached Line) External Leakage	7	Single Acting SPM Valve Internal Leakage	11
Choke and Kill Line (BOP Attached Line) External Leakage	7	Single Acting SPM Valve External Leakage	11
Choke and Kill Valves External Leakage	7	Choke and Kill Valves External Leakage	11
Shuttle Valve External Leakage	7	Small Bore Hydraulic tubing Leakage	12
Shuttle Valve Coupling and Tubing Blockage	8	Shuttle Valve coupling and Tubing Blockage	12
Riser BOP Flexible Joint External Leakage	8	Solenoid Valve Fail to Operate-low voltage	13
Small Bore Hydraulic tubing Leakage	8	Blind Shear Ram Internal Leakage	14
Annular Preventer Internal Leakage	9	Blind Shear Ram External Leakage	15
Subsea Accumulators Loss of Pre-charge gas	9	Annular Hydraulic Pressure Regulator Unstable output pressure	15
Blind Shear Ram Internal leakage	9	Fixed Pipe Ram Fail to Close	15
Blind Shear Ram Fails to Close (seal open-hole)	10	Choke and Kill External Leak	16
Blind Shear Ram Failts to Shear and Close well	10	Choke and Kill Plug	16
Annular Preventer External Leakage	11	Hydraulic Connector Spuriously Unlatches	17
Check Valve Internal Leakage	12	Shuttle Valve Fails to Isolate	17
Annular Preventer Fails to Close/seal	12	Shuttle Valve External Leakage	18
Choke and Kill Valves Fails to Close	12	Choke and Kill Line Valve Fails to Open	18
Choke and Kill Valves Fails to Open	12	Riser BOP flexible Joint External Leakage	19
Check Valve Stuck Closed	12	Blind Shear Ram Failts to Shear and Close well	20
Fixed Pipe Ram Internal leakage	13	Annular Preventer External Leakage	21

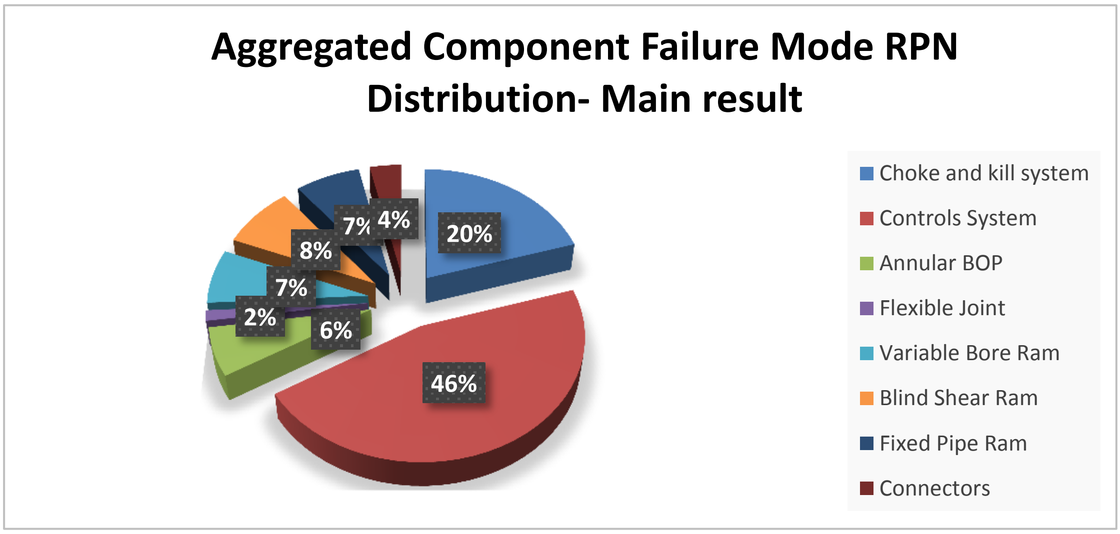


Figure 4-4: Aggregated Failure Modes RPN distribution of BOP System- Main Analysis

Common to the failure modes of the Annular preventer is that they could result in a potential increase in loss time. Also an Inability to execute some operations (due to restriction) e.g. changing drill bit, running test assembly can arise from a failure of the annular preventer to fully open and not directly critical to a blowout hazard. The electronics or electrical related failure modes mostly tend to a loss of redundancy and their functional roles are effected via another channel. Worthwhile to note that there exist unique features that prompts the thought to consider the Subsea electronic module as robust in ensuring system reliability and availability. This is supported by the elimination electronic-related single point failures in the architectural design via component selection and redundancy. Such features include interchangeability in modularity to aid replacement during maintenance, redundancy in power supplies and source to sink channels, a heat management system for the SEM that is passive, such that an alternative method for cooling is not required and it can function during testing at surface.

Categorising the total failure modes RPN of key BOP system component shows the control system has the greater contribution (46%), as seen in Figure 4-4, hence the main subsystem with potential BOP System failure source. This is not surprising as the annular BOPs and Rams depends on the controls to function. The highest single contributing components are the SPM Valves, Solenoid Valve, Accumulators and Manifold Pressure Regulator Valve. However, considering the safety critical nature of the BOP system, most of the components are important as mentioned earlier. The ranking outcome comparison showed some interesting observations, on the direction and importance of this study in understanding the BOP system to understand what component-based failure risk is worth looking at in a separate study or in-depth, improve the technical capability of the component and system ultimately towards protecting investment and environment. This explains why analysts have to be clear from the outset about what is expected from the failure modes and effect analysis and the need to be cautious in interpreting these ranking outcomes. Reliability practitioners and design engineers alike should understand what the output of the FMECA would feed into, and where necessary adjust or enhance their goals and/or requirements, so they can harness the full benefit of the analysis and resources spent.

4.3.3 Effect of Detectability Scores on RPN rankings

Detection of each of the identified component failure modes interestingly depicts that the majority of the failures would be easily detectible (as such had low weights), while the accumulators and double acting SPM valves related failure modes had moderately high values. The check valve internal leakage (F94) has the highest score for detectability as it can be hidden. The Blind shear ram fails to shear and close (F11) has a detectability score of 2 as it is detectible upon activation, however from a classical risk view, it would be a high risk. Similarly this observation applies to Riser joint external leakage (F33) and spurious unlatching of hydraulic connector (F36).

4.4 FMECA Summary

BOP system failure risk identification has been carried out in this section using the FMECA analysis technique and critical failure modes have been identified based on the RPN criticality ranking. Also for better context in understanding system weakness, critical failure modes based on the classical risk definition ranks have been provided as well for completeness and demonstrate the need for a more robust risk assessment framework. Again focusing on the critical list may deviate attention from other relevant components (e.g. subsea pod battery, pod selector valve and choke and kill lines) which may need reviewing to understand various possible sources of failure that could arise from bad practices or negligence from the designers, manufacturers and during the operations (on and off site).

A combination of interesting scenarios can be seen if detectability is improved or the likelihood is reduced. While it is not intended to directly compare the two ranking basis, it is desired to explore another perspective of failure mode importance, since the RPN rankings do not consider the relative importance of the three factors used to compute it. The variance in failure mode importance from both ranking basis is the result of the third factor detectability (a measure of failure mode not being detected). The three factors can be extended to include more factors to replicate system complexity or other distinct criteria can be introduced to assess the BOP system. Factors such as frequency of testing and inspection, personnel profile requirement, environment-depth, ease of restoration, nature of the field, failure mechanism rate or inspection effectiveness can be used to evaluate the failure modes associated with the BOP system. Hence a different approach to assess the subsea BOP system will be to apply a multi criteria decision making analysis technique.

4.5 Multi Criteria Risk Assessment of a Subsea BOP

The MCDA analysis presented in this section is a decision problem to rank failure modes (alternatives) using nine (9) criteria defined in the chapter 3. The selected failure modes under assessment are thirty-six (36) in number, generated from an all-inclusive evaluation of the Subsea BOP system failure modes identified in the FMECA earlier in the chapter. The basis of selection was initially to have a critical select failure mode list, which informed the rational to use the conventional Pareto sample (20%), based on the RPN scores. However, to provide a more representative picture of the system to be analysed in the MCDM analysis in consideration of the fact that a good proportion of the failure modes RPN scores were relatively low, 2 times the Pareto analysis was considered and in addition specific failure modes with higher scores for each of the three criteria (S, O, and D.).

The failure modes were also reviewed by experts as well for completeness or correctness as highlighted in Chapter 3. The failure modes assessed in this thesis are as follows:

- Manifold Hydraulic Pressure Regulator Unstable output pressure (F_1)
- Fixed Pipe Ram External Leakage (F_2)
- Single Acting SPM Valve External Leakage (F_3)
- Single Acting SPM Valve Internal Leakage (F_4)
- Solenoid Valve Fail to Close (F_5)
- Solenoid Valve fail to Operate-low voltage (F_6)
- Choke and Kill Valve Internal Leakage (F_7)
- Blind Shear Ram External Leakage (F_8)
- Annular Hydraulic Pressure Regulator Unstable output pressure (F_9)
- Fixed Pipe Ram Fail to Close (F_{10})
- Shuttle Valve coupling and Tubing External leakage (F_{11})
- Shuttle Valve coupling and Tubing- Post SV to BOP External leakage (F_{12})
- Wellhead Hydraulic Connectors Spuriously Unlatches (F_{13})
- Hydraulic Connectors Spuriously Unlatches (F_{14})
- Double Acting SPM Valve External Leakage (F_{15})
- Double Acting SPM Valve Internal Leakage (F_{16})
- Choke and Kill Line (Jumper hose line) External Leakage (F_{17})
- Choke and Kill Line (Riser Attached Line) External Leakage (F_{18})
- Choke and Kill Line (BOP Attached Line) External Leakage (F_{19})
- Choke and Kill Valves External Leakage (F_{20})
- Shuttle Valve External Leakage (F_{21})
- Shuttle Valve Coupling and Tubing Blockage (F_{22})
- Riser BOP Flexible Joint External Leakage (F_{23})
- Small Bore Hydraulic tubing Leakage (F_{24})
- Annular Preventer Internal Leakage (F_{25})
- Subsea Accumulators Loss of Pre-charge gas (F_{26})
- Blind Shear Ram Internal leakage (F_{27})
- Blind Shear Ram Fails to Close (seal open-hole) (F_{28})

- Blind Shear Ram Fails to Shear and Close well (F_{29})
- Annular Preventer External Leakage (F_{30})
- Check Valve Internal Leakage (F_{31})
- Annular Preventer Fails to Close/seal (F_{32})
- Choke and Kill Valves Fails to Close (F_{33})
- Choke and Kill Valves Fails to Open (F_{34})
- Check Valve Stuck Closed (F_{35})
- Fixed Pipe Ram Internal leakage (F_{36})

A sample expert decision data sheet with linguistic inputs from an expert is shown in Table 4-7 and the aggregated expert decision matrix in triangular fuzzy numbers are shown in Table 4-8. The de-fuzzified crisp aggregate expert decision matrix is shown as Table 4-9 and the normalised crisp aggregated weights obtained are shown in Table 4-10. Table 4-11 presents the criteria weights derived from the decision matrix using the entropy method. These processed data was then used as input into the different MCDA techniques depending on the data forms required.

Table 4-7: Sample Expert Decision Data sheet

	CRITERIA								
Failure Modes	Improper maintenance-LOCS	Occurrence Inspection/ testing ineffectivenes	Improper maintenance-LOCM	System or Component Complexity	Safeguards from Detectibility	Safeguards from Redundancy	Loss of a function (ANOTHER)	Loss of Multiple functions	Loss of all functions
Manifold Hydraulic Pressure Regulator Unstable output pressure	ML	ML	L	L	VH	FH	AH	FH	VL
Fixed Pipe Ram External Leakage	FH	AH	MH	ML	FH	MH	FH	ML	VL
Single Acting SPM Valve External Leakage	ML	ML	M	ML	VH	L	VH	L	VL
Single Acting SPM Valve Internal Leakage	M	ML	M	ML	VH	L	VH	L	VL
Solenoid Valve Fail to Close	M	MH	M	L	AH	AH	M	VL	VL
Solenoid Valve fail to Operate-low voltage	MH	M	M	L	FH	AH	M	VL	VL
Choke and Kill Valve Internal Leakage	SH	FH	L	ML	SH	VH	VL	VL	VL
Blind Shear Ram External Leakage	ML	L	VL	L	ML	VL	FH	ML	VL
Annular Hydraulic Pressure Regulator Unstable output pressure	VL	MH	L	L	VH	FH	AH	FH	VL
Fixed Pipe Ram Fail to Close	FH	FH	L	L	ML	MH	VL	VL	VL
Shuttle Valve coupling and Tubing External leakage	FH	M	ML	VL	SH	SH	VH	MH	VL
Shuttle Valve coupling and Tubing - Post SV to BOP External leak	FH	M	ML	VL	SH	VL	AH	VH	VL
Welhead Hydraulic Connectors Spuriously Unlatches	AH	FH	SH	MH	AH	VL	AH	VH	AH
Hydraulic Connectors Spuriously Unlatches	AH	FH	SH	MH	AH	VL	AH	SH	MH
Double Acting SPM Valve External Leakage	M	M	FH	SH	ML	MH	VH	M	VL
Double Acting SPM Valve Internal Leakage	SH	FH	MH	SH	MH	MH	VH	M	VL
Choke and Kill Line (Jumper hoseline) External Leakage	ML	M	L	L	AH	M	M	L	VL
Choke and Kill Line (Riser Attached Line) External Leakage	ML	M	L	L	AH	M	M	L	VL
Choke and Kill Line (BOP Attached Line) External Leakage	M	M	L	L	AH	M	M	L	VL
Choke and Kill Valves External Leakage	M	ML	VL	M	VH	MH	M	L	VL
Shuttle Valve External Leakage	MH	SH	VL	M	M	VL	AH	L	VL
Shuttle Valve Coupling and Tubing Blockage	ML	ML	ML	VL	FH	VL	VH	L	VL
Riser BOP Flexible Joint External Leakage	L	ML	ML	M	VH	VL	L	VL	VL
Small Bore Hydraulic tubing Leakage	FH	L	M	SH	SH	L	M	M	VL
Annular Preventer Internal Leakage	MH	MH	L	MH	FH	AH	L	L	VL
Subsea Accumulators Loss of accumulation	VL	ML	M	M	VH	VH	AH	VH	MH
Blind Shear Ram Internal leakage	MH	M	L	MH	VH	L	L	L	VL
Blind Shear Ram Fails to Close (seal open-hole)	ML	ML	L	MH	VH	L	L	L	VL
Blind Shear Ram Failts to Shear and Close well	ML	L	L	MH	VH	L	L	L	VL
Annular Preventer External Leakage	ML	ML	L	MH	VH	AH	L	L	VL
Check Valve Internal Leakage	L	ML	M	L	M	FH	MH	L	VL
Annular Preventer Fails to Close/seal	FH	FH	L	MH	VH	L	L	L	VL
Choke and Kill Valves Fails to Close	ML	M	VL	M	VH	MH	M	L	VL
Choke and Kill Valves Fails to Open	ML	M	VL	M	VH	MH	MH	M	VL
Check Valve Stuck Closed	VL	ML	M	L	M	VH	VL	L	VL
Fixed Pipe Ram Internal leakage	M	ML	MH	ML	FH	MH	FH	ML	VL

Table 4-8: Aggregate Fuzzy Expert Decision Matrix

Failure Modes	Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	(0.1, 0.31, 0.5)	(0.2, 0.53, 1)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0, 0.1, 0.2)
Fixed Pipe Ram External Leakage	F_2	(0.4, 0.66, 0.8)	(0.6, 0.85, 1)	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0.6, 0.7, 0.8)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)
Single Acting SPM Valve External Leakage	F_3	(0.2, 0.33, 0.5)	(0.2, 0.56, 1)	(0.3, 0.4, 0.5)	(0.2, 0.3, 0.4)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Single Acting SPM Valve Internal Leakage	F_4	(0.2, 0.4, 0.6)	(0.2, 0.34, 0.8)	(0.3, 0.4, 0.5)	(0.2, 0.3, 0.4)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Solenoid Valve Fail to Close	F_5	(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
Solenoid Valve fail to Operate-low voltage	F_6	(0.4, 0.51, 0.7)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
Choke and Kill Valve Internal Leakage	F_7	(0.5, 0.6, 0.7)	(0.6, 0.7, 0.8)	(0.1, 0.2, 0.3)	(0.2, 0.3, 0.4)	(0.5, 0.6, 0.7)	(0.7, 0.8, 0.9)	(0, 0.1, 0.2)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
Blind Shear Ram External Leakage	F_8	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)	(0.1, 0.2, 0.3)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)	(0.6, 0.7, 0.8)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	(0, 0.1, 0.2)	(0.4, 0.5, 0.6)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0, 0.1, 0.2)
Fixed Pipe Ram Fail to Close	F_{10}	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.2, 0.3, 0.4)	(0.4, 0.5, 0.6)	(0, 0.1, 0.2)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
Shuttle Valve coupling and Tubing External leakage	F_{11}	(0.6, 0.7, 0.8)	(0.3, 0.42, 0.6)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)	(0.5, 0.6, 0.7)	(0.5, 0.6, 0.7)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0, 0.1, 0.2)
Shuttle Valve coupling and Tubing - Post SV to BOP External leakage	F_{12}	(0.6, 0.7, 0.8)	(0.3, 0.4, 0.5)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)	(0.5, 0.6, 0.7)	(0, 0.1, 0.2)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0, 0.1, 0.2)
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)	(0, 0.1, 0.2)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)
Hydraulic Connectors Spuriously Unlatches	F_{14}	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)	(0, 0.1, 0.2)	(0.8, 0.9, 1)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)
Double Acting SPM Valve External Leakage	F_{15}	(0.1, 0.35, 0.5)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.2, 0.3, 0.4)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)
Double Acting SPM Valve Internal Leakage	F_{16}	(0.1, 0.56, 0.8)	(0.6, 0.7, 0.8)	(0.4, 0.5, 0.6)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	(0.2, 0.31, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	(0.2, 0.3, 0.4)	(0.1, 0.36, 0.5)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	(0.1, 0.31, 0.5)	(0.1, 0.37, 0.6)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Choke and Kill Valves External Leakage	F_{20}	(0.1, 0.35, 0.5)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Shuttle Valve External Leakage	F_{21}	(0.4, 0.5, 0.6)	(0.5, 0.67, 0.9)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0.8, 0.9, 1)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Shuttle Valve Coupling and Tubing Blockage	F_{22}	(0.2, 0.3, 0.4)	(0.2, 0.3, 0.4)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)	(0.6, 0.7, 0.8)	(0, 0.1, 0.2)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Riser BOP Flexible Joint External Leakage	F_{23}	(0, 0.17, 0.3)	(0.2, 0.3, 0.4)	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0, 0.1, 0.2)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
Small Bore Hydraulic tubing Leakage	F_{24}	(0.4, 0.68, 0.9)	(0.1, 0.2, 0.3)	(0.3, 0.4, 0.5)	(0.5, 0.6, 0.7)	(0.5, 0.6, 0.7)	(0.1, 0.2, 0.3)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)
Annular Preventer Internal Leakage	F_{25}	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Subsea Accumulators Loss of Pre-charge gas	F_{26}	(0, 0.1, 0.2)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)
Blind Shear Ram Internal leakage	F_{27}	(0.3, 0.45, 0.6)	(0.3, 0.44, 0.8)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	(0.1, 0.38, 0.8)	(0.1, 0.29, 0.4)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Blind Shear Ram Failts to Shear and Close well	F_{29}	(0.2, 0.3, 0.4)	(0.1, 0.23, 0.5)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Annular Preventer External Leakage	F_{30}	(0.2, 0.3, 0.4)	(0.1, 0.27, 0.4)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Check Valve Internal Leakage	F_{31}	(0.1, 0.2, 0.3)	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)	(0.4, 0.5, 0.6)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Annular Preventer Fails to Close/seal	F_{32}	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Choke and Kill Valves Fails to Close	F_{33}	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Choke and Kill Valves Fails to Open	F_{34}	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)
Check Valve Stuck Closed	F_{35}	(0, 0.13, 0.3)	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0, 0.12, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
Fixed Pipe Ram Internal leakage	F_{36}	(0.1, 0.36, 0.5)	(0.2, 0.3, 0.4)	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0.6, 0.7, 0.8)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)

Table 4-9: Aggregate Crisp Expert Decision Matrix (Defuzzified Data)

Failure Modes	Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	0.305	0.565	0.200	0.800	0.800	0.700	0.900	0.700	0.100
Fixed Pipe Ram External Leakage	F_2	0.630	0.825	0.500	1.200	0.700	0.500	0.700	0.300	0.100
Single Acting SPM Valve External Leakage	F_3	0.340	0.580	0.400	1.200	0.800	0.200	0.800	0.200	0.100
Single Acting SPM Valve Internal Leakage	F_4	0.400	0.420	0.400	1.200	0.800	0.200	0.800	0.200	0.100
Solenoid Valve Fail to Close	F_5	0.400	0.500	0.400	0.800	0.900	0.900	0.400	0.100	0.100
Solenoid Valve fail to Operate-low voltage	F_6	0.530	0.400	0.400	0.800	0.700	0.900	0.400	0.100	0.100
Choke and Kill Valve Internal Leakage	F_7	0.600	0.700	0.200	1.200	0.600	0.800	0.100	0.100	0.100
Blind Shear Ram External Leakage	F_8	0.300	0.200	0.100	0.800	0.300	0.100	0.700	0.300	0.100
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	0.100	0.500	0.200	0.800	0.800	0.700	0.900	0.700	0.100
Fixed Pipe Ram Fail to Close	F_{10}	0.700	0.700	0.200	0.800	0.300	0.500	0.100	0.100	0.100
Shuttle Valve coupling and Tubing External leakage	F_{11}	0.700	0.435	0.300	0.400	0.600	0.600	0.800	0.500	0.100
Shuttle Valve coupling and Tubing - Post SV to BOP External leakage	F_{12}	0.700	0.400	0.300	0.400	0.600	0.100	0.900	0.800	0.100
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	0.900	0.700	0.600	2.000	0.900	0.100	0.900	0.800	0.900
Hydraulic Connectors Spuriously Unlatches	F_{14}	0.900	0.700	0.600	2.000	0.900	0.100	0.900	0.600	0.500
Double Acting SPM Valve External Leakage	F_{15}	0.325	0.400	0.700	2.400	0.300	0.500	0.800	0.400	0.100
Double Acting SPM Valve Internal Leakage	F_{16}	0.505	0.700	0.500	2.400	0.500	0.500	0.800	0.400	0.100
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	0.330	0.400	0.200	0.800	0.900	0.400	0.400	0.200	0.100
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	0.300	0.330	0.200	0.800	0.900	0.400	0.400	0.200	0.100
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	0.305	0.360	0.200	0.800	0.900	0.400	0.400	0.200	0.100
Choke and Kill Valves External Leakage	F_{20}	0.325	0.300	0.100	1.600	0.800	0.500	0.400	0.200	0.100
Shuttle Valve External Leakage	F_{21}	0.500	0.685	0.100	1.600	0.400	0.100	0.900	0.200	0.100
Shuttle Valve Coupling and Tubing Blockage	F_{22}	0.300	0.300	0.300	0.400	0.700	0.100	0.800	0.200	0.100
Riser BOP Flexible Joint External Leakage	F_{23}	0.160	0.300	0.300	1.600	0.800	0.100	0.200	0.100	0.100
Small Bore Hydraulic tubing Leakage	F_{24}	0.665	0.200	0.400	2.400	0.600	0.200	0.400	0.400	0.100
Annular Preventer Internal Leakage	F_{25}	0.500	0.300	0.200	2.000	0.700	0.900	0.200	0.200	0.100
Subsea Accumulators Loss of Pre-charge gas	F_{26}	0.100	0.100	0.400	1.600	0.800	0.800	0.900	0.800	0.500
Blind Shear Ram Internal leakage	F_{27}	0.450	0.495	0.200	2.000	0.800	0.200	0.200	0.200	0.100
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	0.415	0.270	0.200	2.000	0.800	0.200	0.200	0.200	0.100
Blind Shear Ram Failts to Shear and Close well	F_{29}	0.300	0.265	0.200	2.000	0.800	0.200	0.200	0.200	0.100
Annular Preventer External Leakage	F_{30}	0.300	0.260	0.200	2.000	0.800	0.900	0.200	0.200	0.100
Check Valve Internal Leakage	F_{31}	0.200	0.300	0.400	0.800	0.400	0.700	0.500	0.200	0.100
Annular Preventer Fails to Close/seal	F_{32}	0.700	0.700	0.200	2.000	0.800	0.200	0.200	0.200	0.100
Choke and Kill Valves Fails to Close	F_{33}	0.300	0.400	0.100	1.600	0.800	0.500	0.500	0.200	0.100
Choke and Kill Valves Fails to Open	F_{34}	0.300	0.400	0.100	1.600	0.800	0.500	0.500	0.400	0.100
Check Valve Stuck Closed	F_{35}	0.140	0.300	0.400	0.800	0.800	0.500	0.135	0.200	0.100
Fixed Pipe Ram Internal leakage	F_{36}	0.330	0.300	0.500	1.200	0.700	0.500	0.700	0.300	0.100

Table 4-10: Normalised Crisp Expert Decision Matrix

Failure Mode	Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	0.1087	0.2011	0.1189	0.0906	0.1850	0.2310	0.2528	0.3112	0.0783
Fixed Pipe Ram External Leakage	F_2	0.2246	0.2936	0.2525	0.1359	0.1619	0.1650	0.1966	0.1334	0.0783
Single Acting SPM Valve External Leakage	F_3	0.1212	0.2064	0.2020	0.1359	0.1850	0.0660	0.2247	0.0889	0.0783
Single Acting SPM Valve Internal Leakage	F_4	0.1426	0.1495	0.2020	0.1359	0.1850	0.0660	0.2247	0.0889	0.0783
Solenoid Valve Fail to Close	F_5	0.1426	0.1779	0.2020	0.0906	0.2081	0.2970	0.1123	0.0445	0.0783
Solenoid Valve fail to Operate-low voltage	F_6	0.1890	0.1424	0.2020	0.0906	0.1619	0.2970	0.1123	0.0445	0.0783
Choke and Kill Valve Internal Leakage	F_7	0.2139	0.2491	0.1010	0.1359	0.1387	0.2640	0.0281	0.0445	0.0783
Blind Shear Ram External Leakage	F_8	0.1070	0.0712	0.0505	0.0906	0.0694	0.0330	0.1966	0.1334	0.0783
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	0.0357	0.1779	0.1010	0.0906	0.1850	0.2310	0.2528	0.3112	0.0783
Fixed Pipe Ram Fail to Close	F_{10}	0.2496	0.2491	0.1010	0.0906	0.0694	0.1650	0.0281	0.0445	0.0783
Shuttle Valve coupling and Tubing External leakage	F_{11}	0.2496	0.1548	0.1515	0.0453	0.1387	0.1980	0.2247	0.2223	0.0783
Shuttle Valve coupling and Tubing - Post SV to BOP External leakage	F_{12}	0.2496	0.1424	0.1515	0.0453	0.1387	0.0330	0.2528	0.3556	0.0783
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	0.3209	0.2491	0.3030	0.2266	0.2081	0.0330	0.2528	0.3556	0.7049
Hydraulic Connectors Spuriously Unlatches	F_{14}	0.3209	0.2491	0.3030	0.2266	0.2081	0.0330	0.2528	0.2667	0.3916
Double Acting SPM Valve External Leakage	F_{15}	0.1159	0.1424	0.3536	0.2719	0.0694	0.1650	0.2247	0.1778	0.0783
Double Acting SPM Valve Internal Leakage	F_{16}	0.1800	0.2491	0.2525	0.2719	0.1156	0.1650	0.2247	0.1778	0.0783
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	0.1177	0.1424	0.1010	0.0906	0.2081	0.1320	0.1123	0.0889	0.0783
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	0.1070	0.1174	0.1010	0.0906	0.2081	0.1320	0.1123	0.0889	0.0783
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	0.1087	0.1281	0.1010	0.0906	0.2081	0.1320	0.1123	0.0889	0.0783
Choke and Kill Valves External Leakage	F_{20}	0.1159	0.1068	0.0505	0.1813	0.1850	0.1650	0.1123	0.0889	0.0783
Shuttle Valve External Leakage	F_{21}	0.1783	0.2438	0.0505	0.1813	0.0925	0.0330	0.2528	0.0889	0.0783
Shuttle Valve Coupling and Tubing Blockage	F_{22}	0.1070	0.1068	0.1515	0.0453	0.1619	0.0330	0.2247	0.0889	0.0783
Riser BOP Flexible Joint External Leakage	F_{23}	0.0570	0.1068	0.1515	0.1813	0.1850	0.0330	0.0562	0.0445	0.0783
Small Bore Hydraulic tubing Leakage	F_{24}	0.2371	0.0712	0.2020	0.2719	0.1387	0.0660	0.1123	0.1778	0.0783
Annular Preventer Internal Leakage	F_{25}	0.1783	0.1068	0.1010	0.2266	0.1619	0.2970	0.0562	0.0889	0.0783
Subsea Accumulators Loss of Pre-charge gas	F_{26}	0.0357	0.0356	0.2020	0.1813	0.1850	0.2640	0.2528	0.3556	0.3916
Blind Shear Ram Internal leakage	F_{27}	0.1604	0.1762	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	0.1480	0.0961	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
Blind Shear Ram Failts to Shear and Close well	F_{29}	0.1070	0.0943	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
Annular Preventer External Leakage	F_{30}	0.1070	0.0925	0.1010	0.2266	0.1850	0.2970	0.0562	0.0889	0.0783
Check Valve Internal Leakage	F_{31}	0.0713	0.1068	0.2020	0.0906	0.0925	0.2310	0.1404	0.0889	0.0783
Annular Preventer Fails to Close/seal	F_{32}	0.2496	0.2491	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
Choke and Kill Valves Fails to Close	F_{33}	0.1070	0.1424	0.0505	0.1813	0.1850	0.1650	0.1404	0.0889	0.0783
Choke and Kill Valves Fails to Open	F_{34}	0.1070	0.1424	0.0505	0.1813	0.1850	0.1650	0.1404	0.1778	0.0783
Check Valve Stuck Closed	F_{35}	0.0596	0.1068	0.2020	0.0906	0.1850	0.1650	0.0379	0.0889	0.0783
Fixed Pipe Ram Internal leakage	F_{36}	0.1405	0.1068	0.2525	0.1359	0.1619	0.1650	0.1966	0.1334	0.0783

Table 4-11: Criteria Weights derived from Expert Decision by Entropy Method

Criteria		Weight
Improper maintenance- LOCS	C_1	0.1020
Occurrence Inspection/testing ineffectivenes	C_2	0.1047
Improper maintenance- LOCM	C_3	0.1077
System or Component Complexity	C_4	0.1088
Safeguards from Detectibility	C_5	0.1031
Safeguards from Redundancy	C_6	0.1213
Loss of a function (ANOTHER)	C_7	0.1067
Loss of Multiple functions	C_8	0.1176
Loss of all functions	C_9	0.1281

The crisp weight as shown in Table 4-11 was inputted directly to different MCDA algorithms developed using excel with the exception of the PROMETHEE in which Palisade Visual PROMETHEE software was used to generate ranks. The weights were rounded off to 2 decimal places by the software as seen in the preferences in Table 4-12.

Table 4-12: Preference functions and associated criteria parameters assigned.

Preferences	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
active	yes	yes	yes	yes	yes	yes	yes	yes	yes
Min/Max	max	max	max	max	min	min	max	max	max
Weight	0.1	0.1	0.11	0.11	0.1	0.12	0.11	0.12	0.13
Preference function	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual

The unicriterion flows and multi criteria flows for the PROMETHEE analysis are shown in Appendix B. Also the distance measures, relative closeness coefficients used to generate the ranks of the different methods are shown in the Appendix B.

4.6 MCDA Ranking outcomes

A summary of the ranking outcomes from the different MCDA techniques applied is shown in Table 4-13. The rankings from the FMECA are also shown alongside for easy comparison. Details of the findings are discussed in Chapter 5.

Table 4-13: Failure Modes ranking outcomes from FMECA and MCDAs

FAILURE MODE	Failure Mode ID	FMECA-RPN	PROMETHEE	FUZZY TOPSIS-INTERVAL	FUZZY TOPSIS	TOPSIS
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	10	6	11	9	12
Fixed Pipe Ram External Leakage	F_2	4	7	8	6	9
Single Acting SPM Valve External Leakage	F_3	11	11	10	15	11
Single Acting SPM Valve Internal Leakage	F_4	11	13	12	11	13
Solenoid Valve Fail to Close	F_5	6	32	35	26	34
Solenoid Valve fail to Operate-low voltage	F_6	13	27	31	24	29
Choke and Kill Valve Internal Leakage	F_7	3	24	26	23	25
Blind Shear Ram External Leakage	F_8	15	18	20	19	17
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	15	20	16	14	15
Fixed Pipe Ram Fail to Close	F_{10}	15	19	22	17	20
Shuttle Valve coupling and Tubing External leakage	F_{11}	8	10	14	7	14
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	8	3	4	5	4
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	17	1	1	1	1
Hydraulic Connectors Spuriously Unlatches	F_{14}	17	2	2	2	2
Double Acting SPM Valve External Leakage	F_{15}	1	5	6	4	5
Double Acting SPM Valve Internal Leakage	F_{16}	1	4	5	3	6
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	9	31	28	30	27
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	9	33	32	33	33
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	9	35	27	29	31
Choke and Kill Valves External Leakage	F_{20}	11	25	30	28	32
Shuttle Valve External Leakage	F_{21}	18	9	9	13	8
Shuttle Valve Coupling and Tubing Blockage	F_{22}	12	17	19	18	16
Riser BOP Flexible Joint External Leakage	F_{23}	19	29	23	36	22
Small Bore Hydraulic tubing Leakage	F_{24}	12	8	7	12	7
Annular Preventer Internal Leakage	F_{25}	5	26	33	31	30
Subsea Accumulators Loss of Pre-charge gas	F_{26}	9	14	3	8	3
Blind Shear Ram Internal leakage	F_{27}	14	16	15	22	18
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	10	21	18	27	21
Blind Shear Ram Failts to Shear and Close well	F_{29}	20	28	21	32	23
Annular Preventer External Leakage	F_{30}	21	36	36	35	36
Check Valve Internal Leakage	F_{31}	2	23	29	21	28
Annular Preventer Fails to Close/seal	F_{32}	36	12	13	16	10
Choke and Kill Valves Fails to Close	F_{33}	36	30	25	25	26
Choke and Kill Valves Fails to Open	F_{34}	36	22	24	20	24
Check Valve Stuck Closed	F_{35}	36	34	34	34	35
Fixed Pipe Ram Internal leakage	F_{36}	36	15	17	10	19

5 DISCUSSION

Following an initial failure modes and effect analysis of the BOP system in Chapter 4, a further analysis was carried out using comparable MCDA methods, which include the conventional TOPSIS technique, Fuzzy-TOPSIS, Fuzzy-TOPSIS interval method and PROMETHEE technique. Table 4-13 shows the ranking outcomes for a select critical failure mode list using the previously mentioned methods. It is intended to discuss the overall results in general to present a holistic picture of research results. A collation of analysis outcomes from the failure identification and evaluation (in Section 4.1) and the MCDA analysis is discussed in this chapter. The advantage of MCDA assessment over the FMECA RPN rankings is made obvious in Table 4-13, as there are no ties in the ranking outcomes given there is a clear preference (based on criticality from experts input) of one failure mode over another. The table is colour coded from red to dark green depicting more critical to less critical. Comparing the MCDA ranking outcomes indicates that there is some degree of similarity in the different technique's outcome. The TOPSIS and the fuzzy-interval TOPSIS techniques give very close ranks with a given failure mode being a rank or two higher or lower. However, if the ranks were to be grouped as shown by the colour coding, it can be seen that the critical failure modes fall in nearly similar criticality bands with some exceptions. An example is F23 is ranked 36th and F36 is ranked 10th from the fuzzy TOPSIS and as such slightly higher band given they are at least above five ranks deviated from the ranks of other 3 techniques. The sensitivity of these failure modes is to be investigated later on this chapter. However, a discussion of the top critical failure modes relative to their root causes identified from the FMECA is presented to establish the importance of the criteria used for the assessment. While some discussion has been provided in chapter 4, this section would provide more general detail of critical component failures, as the cumulative picture is hereby presented.

It can be deduced from Table that Wellhead connector failure (F13) and the LMRP connector failure (F14) are the top 2 critical failures from the MCDA analysis. These failures are associated with risk of a leakage to the environment with severe consequences.

The MCDA analysis shows the connector is the most component and this is also established in the sensitivity discussed later in the chapter upon inspection of the variation on the importance weights assigned to assessment criteria its failure mode relative to the used in this study. The connectors are known to have a much lower failure frequency but are also very critical to the overall performance of the BOP system and they do share similarities in the way they can be detected. While returning cuttings through wellhead to surface (rig), if there is small leakage/ seepages, it would not be detected except an ROV is hovering around the area. The other possible medium of detection is during a function test, however these tests are not directly meant to test the connectors directly. Since if a cup type tester is run in hole and installed in a profile in the Wellhead housing (sealing), fluid can be pumped through the choke and kill lines to test each ram by closing the ram across the test pipe but there is no way to test the connection below the flex joint. The same applies to a wellhead connector as well. So in the event of a leak between at that point, even a pressure test would not detect it. What the operator would want to ascertain is that the BOP holds pressure (when sealing element is tested after installation or periodically) meaning the BOP can be used to isolate a well, thereafter the riser can be drained and any repair effected on the connection.

The LMRP is tensioned hooked up and connected to a telescopic joint which allows it to balance out heave. So, if the LMRP connector disconnects the telescopic joint will retract and this should be easily known to the driller due to loss of weight on the tensioner. Also the fluid level will drop and consequently a drop in pressure. In addition if circulating fluid in the system, the stand pipe pressure will drop due to less friction in the system. This will easily be noticed and thus for the score thus the rationale for the low detection score in the FMECA. It is also not surprising that a spurious unlatching or parting of the LMRP from the BOP stack due to connector failure would lead to an environmental leakage of fluid to the environment. The consequence can be severe if it occurs during drilling and worst if in an overpressure zone or new reservoir. This is costly as it could result in a blowout potentially with often associated downtime and threat to personnel safety. A connector unlatch can be the result of a mechanical component (e.g. bolts, flanges, studs) failing due to fatigue or corrosion. Chloride and hydrogen-induced Stress Corrosion Cracking have led to the fracturing of the installed bolts.

Root-cause analysis from previous bolt related failures have shown that while the formation of a complete hermitic seal by paint coating on subsea structures is impossible, the impact of an absence of coating or paint on hydrogen generation on cathodically protected structures cannot be ignored. The hydrogen generation arising from an increase in current drawn from the CP anode system, due to unpainted segments on structures can contribute to hydrogen embrittlement corrosion. Hydrogen embrittlement can be influenced by type of alloy material is made of and its production method, method of heat treatment, discontinuities in the metal, temperature and pressure. Also when drilling through casing with bit going through the wellhead housing, it is standard practice for a wear bushing to be installed to avoid the rotating pipe wearing across the wellhead generating tiny metallic metals. This can cause wearing as it damages or can cause degradation of connector gaskets due to steel swarfs passing through the BOP. This is a potential leakage root cause.

Another failure mode of the LMRP connector is a case of failure to unlatch (this was ranked same as the spuriously unlatching in the FMECA) especially when associated with a drift-off by vessel either due to bad weather or the occurrence of a black-out when drilling from a DP vessel. The consequence can be severe with considerable downtime as the risers can be damaged. A failure of hydraulic or control related system failure (e.g. solenoid valve failure) is a potential case of this failure mode.

It is important for the connectors to be rated correctly during qualification and manufacture to the internal pressure and specified temperature envelope. This is to ensure extended life and reliability of sealing elements and the split ring retractors which pulls away the latching segments from the other connecting item (e.g. wellhead). Quality assurance and control (QA/QC) in installation procedure is of importance and also Operators need to ensure all directly contracted and sub-contracted equipment vendors QA/QC programs are routinely reviewed to ascertain conformance to specifications (e.g. material specification requirement such as material hardness, and yield strength) and current standards. Also Drilling contractors to ensure due diligence during inspection, maintenance and testing BOP components. These are also confirmed in QC-FIT (2014) report which identified the following concerns (most of which mentioned already) to be contributing factors to the failure or threat on the integrity of connectors in general: bolt material hardness and strength; quality control systems/subcontractor controls; coatings; cathodic protection; paint coating; and installation torque procedures.

The connectors failure modes was not ranked amongst the most critical failure mode in the chapter 4 FMECA RPN based analysis due to the low detection score but it had a low to moderate occurrence rating and was acknowledged to be critical as depicted given its the severity ranking. It was only the BSEE FMECA 1 report (ABS, 2013b) that had a connector failure (corrosion/erosion and loss of general function) amongst the highest ranking failure modes.

The next set of critical failures (failure modes of Accumulators, Double Acting SPM Valve, Shuttle Valve tubing and coupling, Shuttle Valve) are controls system related. The control system is central to the BOP system and its failure can lead to costly consequences as seen in the FMECA. The failure of a number of components that can lead to a loss of function at varying degrees (one or multiple functions to complete or partial loss (e.g. delay of a function) is what constitutes the majority of control system failures.

The top critical control failure mode is the loss of a pre-charge of the subsea accumulator with identified possible cause such as a leakage through the end caps and fittings, seal damage, and corrosion for the piston type analysed. The consequence is a deviation in the available volume of hydraulic fluid to be supplied to activate a function which means the function activation and should the loss of pre-charge continues, it could lead to the damage of piston or bladder for a bladder type accumulator. The seal material make-up of a piston accumulator are not compatible with some fluid, hence the need for corrosion-resistant materials to survive extreme environments and as also they have to be periodically replaced. It is essential for the accumulator to be pre-charged correctly to propel the hydraulic fluid and this is dependent on the equipment function to be operated and environment. This failure mode has a low probability of occurrence but can occur with the root cause traced to improper maintenance or low attentiveness of operating personnel. Its criticality was influenced by the scores for detection and severity assigned in the FMECA with worst case considered when associated with a failure to activate a shear ram or annular preventer

The SPM valve external leakage is a critical failure with potential catastrophic consequence should power fluid not been available to the respective shuttle valve for supply to activate a function. The nature of cause of this failure would be mechanical damage to the valve body assembly and seals deterioration. The mechanisms associated with damage to the valve body assembly would be a less likely wear or the effect of corrosion. OEM would need to look at the material selection and operational conditions and environment of the valve should wear be the main reason for leaks. Also vibrational effect of operation could lead to valve seal failure and collapsing of connecting hose. Another failure cause is the separation of tubing connection. The requirement of the SPM to close and open in a quick manner for the delivery of fluid in a high pressure system often causes pressure surge, hydraulic shock or water hammer effect that can affect lines. These effects need be taken into consideration by OEMS and also operators need to be aware of these root causes when conducting/planning maintenance activities.

The failure of the tubing or hose that connects or supply’s functional fluid to the shuttle valve was considered very critical. Failure of tubing/hoses have been mentioned already in the SPM discussion above, however it is important for stacking to be done properly with due consideration for usage condition and material selection (hard piping or hose).

The shuttle valve external leakage was the next critical item and is known to be a single point failure with severe and potential catastrophic consequences depending on the associated function. Mechanical damage was known to be the main cause resulting to an external leak. The shuttle valve like any other valve would experience leakage through deteriorated or damaged seals. The fasteners of the shuttle valve connection can be loosened following vibration effect from the oscillation of the shuttle from on end to another when high flow fluid is been passed through it. The

FMECA shows a relatively low occurrence however it cannot be dismissed to be critical should the right valve sizing and selection be made.

Fixed pipe ram external leakage failure was identified as the next critical failure mode and the associated causes are worn sealing elements (bonnet, top, door), damage to gaskets, pistons, ram packer element, ram body bonnet/housing and misalignment issues which are mostly mechanical failures. These identified possible damaged items need replacement when a leak is observed. These are easily noticeable when prior to normal drilling operation testing (stump or installation) is carried out and with the help an ROV inspection at any time. The consequence can be severe as seen in the FMECA severity ranking. These failure causes are common to other failure modes of the pipe ram and any other ram and the annular preventer

Typical stressors or failures that can affect seals and gaskets are mechanical failure related (from compression or distortion of ring or bolting configuration), chemical (corrosion) and thermal (hardening and embrittlement for non-metal seals). It is expected that a proper pressure-tight seal between secured mating parts should be able to survive normal and possible emergency loads. However should an adjacent part loosen, giving way for an exposure to process fluid initiate corrosion can which damaging the sealing capability and consequently result into a leakage or parting of connection. Thermal cycling as well depending on the usage of the BOP can cause loosening of bolts. Intermediate flange can be damaged when replacing damaged seal, a case of improper maintenance and these procedures are usually stated in the Operating and maintenance manuals. In addition, it is important for BOP maintenance personnel to follow procedures for screwing the bolts, as these would contain the closing torque requirements in line with the lubricant used for the threads. However, the only test of seals/gaskets is to ascertain if they hold pressure that way it is considered functional. Januarilham, (2012) work reported the flange and gasket to be 4th most critical component of the BOP system

Besides the ram connections, related aspects mentioned above potential causes responsible for a pipe ram failure to perform a closing or opening function would be a loss of supply of hydraulic to activate function.

The top set of critical failure modes as identified by the MCDA analysis have been discussed, however this is not mean the lower rank of critical failures are not important as well as they also do form part of the BOP system. The Blind shear ram related failure was not amongst the top 10 failures ranks based on the MCDA analysis in this work. No doubt the associated consequence of the Blind shear ram failure can be catastrophic, as seen in the very high severity ranking in the FMECA (though had a low detection score in this work) and the ranking assigned to the loss of function related criteria in the MCDA analysis. However, its final ranking from the MCDA considering all the assessment criteria saw other failures of more criticality in order of priority. While reviewing the results with experts who contributed to the study, they were not surprised given from their knowledge and experience the blind shear ram is very critical and important relative to prevention to a well control, however there are other components whose functionality are required to manage drilling scenarios prior to the need for the activation of a BSR. Also The BSEE FMECA 1(ABS, 2013b) report reported the Blind shear ram to be the most critical component based on the RPN score which was influenced by a high detection score. It is not wrong for “mechanical failure” as a failure mode (as identified in the BSEE FMECA) to be assumed hard to detect if it is having to do with microstructure of material of ram body or component, however it is open to varying possibilities/interpretations. In this thesis, failures considered are functional failures, hence low detection score (noticeable) and as such consistent with the other BSEE FMECA.

Also the choke and kill line is another important component that was observed from the FMECA analysis that was not amongst the top failures in the MCDA analysis. The FMECA analysis shows the Choke and Kill lines to be more critical than the Choke and kill valves. The failure mode responsible for the high importance was the possibility of an external leakage, which is however with a low likelihood of occurrence. The potential cause of such a failure is majorly mechanical damage at the riser-attached, jumper-attached or BOP-attached line segment. Other possible causes are at connection points due to bad seals or packing elements, and possible external shock e.g. bad weather. The capability for both lines being interchangeable in terms of choking or killing function makes was responsible for the scores the experts assigned. A possible worst case considered is if the kill line goes below the BOP, it cannot be used for choke function.

Experts mentioned besides been able to detect a failure, of importance to better preventing incidents are the need to ensure procedures are followed accordingly, company polies are adhered to, maintenance, testing, and inspection are carried out effectively and the need for due-diligence in specification and managing BOP system during a drilling campaign.

It is interesting to note how the criteria used in the MCDA assessment are relevant in the prior discussion of the failure causes associated with critical BOP components failure modes. Maintenance is of essence to improve and sustain the BOP System and its components performance, however it is important that they are executed effectively to assure they are fit for purpose, hence the criteria for assessment "improper Maintenance effectiveness". There is need for company to have procedures and policies in place guiding well control with consideration for improvements following changes or updating of standards and recommended practice. There should be an in-house training assessment to ensure personnel are up to date with technology and best practice besides the statutory certifications specified as required by industry. This has a direct influence on the effectiveness of the maintenance practices and routine operational testing and inspections carried out on BOP system. This will help curtail unnecessary problems e.g. Using another or a not verified supplier instead of OEM replacements parts such as elastomeric seals could result in costly problems when they are faced with special condition(s) they were not designed for.

Inspection for wear and potential damage through close visual check should be carried out for BOP components as frequent as possible if weather permits. Proper maintenance is a recommended mitigation for corrosion prevention. Also seals and packing that have been damaged needs be replaced as soon as possible. In addition to good inspection, effective testing compliments is required e.g. testing of wellbore can also help detect cavity wear of rams in good time before it becomes catastrophic. While testing of the BOP System has been acknowledged as an option to improve safety and in turn reliability level of a safety critical system, it can also impair reliability if too frequent than required. Regulatory standards or recommended practices and company policies can suffice for these concerns. Diagnostic capabilities improvement in the BOP system similar to those of the subsea production systems (e.g. valve signature, trend analysis) would help in early detection of incipient damage mechanisms and increase BOP system availability. As such unnecessary replacements can be done earlier making maintenance more effective.

The root causes identifiable so far are as follows:

- wrong specification (e.g. material) for a component in relation to operation condition or usage scenarios,
- component usage outside of its operating envelope,
- lack of standards or guidelines for some failure modes testing that could reveal the initiation or development of some failure mode mechanism,
- faults from manufacturing process, and
- possible lack of training of operators (given an inaction in terms of conducting maintenance/testing or operating nature/envelope an item is subjected to has been identified as a possible cause of a failure).

5.1 Technology Qualification/Engineered component(s) to reduce Subsea BOP System's risk and associated downtime.

The recent calls for improvements in certain aspects of the BOP design as discussed earlier has seen informed OEMs new designs of engineered components or functions, in addition to their continuous product improvement and development plans. Technology qualification activities are intrinsic to the success of the design development outcome. (Rahimi and Rausand, 2015) stated that "A well-designed Technology Qualification Process (TQP) increases the probability of success and ensures the maturity and readiness of a new product/technology before it enters the operational phase" and this translates to reducing uncertainty in the development and use of new products. There are a number of TQP approaches proposed in literature with slight variants in their implementation or levels of maturity assessment.

Example guidelines for qualification process include the Det Norske Veritas (DNV, 2008; DNV, 2011) and the subsea industry (API 17N, 2009).

Qualification activities provide the opportunity to address design weakness at the parameter (e.g. temperature and pressure) level that are associated with the mechanisms and associated root cause of the component failure modes. It is important for suitable materials to be selected for specific components construction with clear reliability requirements with consideration of parameters such as associated fluid properties and contamination effects, temperature (inclusive of thermal shock) and pressure envelope, flow rate and any erosion/turbulence effect. It is of essence to conduct the parameter testing/study individually and in combination with others. Also considerations of mitigations for mechanisms that threat to the integrity of the component should be done during the design stage and in operation. A good example is protective coatings that wears off or damaged can cause corrosion which can initiate failure of a component (e.g. bolt) and the increased loading and bending moment on component due to say jarring operation can result in increased fracture. Another example is the effect of erosion on the elements (e.g. packers) which lead to an annular BOP failure and that of the bending of the drill pipe due to compressive forces that prevented hang-off of the pipe on the deepwater horizon BOP. Besides peculiar operation instances that can be considered during design, other aspects such as the swelling softening and brittleness of non-metallic seals that occurs over time which OEMs are familiar with also do need some consideration when addressing new requirements or during improvement opportunities. This can be carried out through or during a design review exercise as part of the qualification process.

Design verification and validation are present in the qualification process of the API RP 17N with capabilities to highlight associated risk through the Technology Readiness Level (TRL) process. In addition, the qualification testing as part of the TQP can help to demonstrate functional requirement, screen out faults and manufacturing/assembly defects and improve robustness and reliability. There is a real need for the industry to develop a framework for qualification of subsea BOP system and components, especially with the new drilling limits for prospective wells e.g. HPHT and Ultra-HPHT wells. These operating conditions would require a whole new elastomeric sealing technology given in current drilling BOP limits seals have to be replaced nearly every run. Electronics would need some revolution for reliable performance with increased reservoir temperature. In summary key aspects besides organisational and obsolescence issues which should be addressed through the qualification and improvement process are material properties (mostly mechanical), operating and environmental conditions, and maintenance and inspection practices.

5.2 Sensitivity Analysis

A sensitivity analysis of the multi-criteria assessment of the Subsea BOP system by way of critical failure modes was carried out to see how the ranking outcome will vary. The analyses carried out are:

- in consideration of the correlation of criteria (leave one criterion out and see the result)
- sensitivity analysis of the effect of weights of each criterion (increase one criterion’s weight by 15%, leave the rest the same, compare with benchmark study)

The first sensitivity (omit a criterion and observe the ranking outcome) was repeated for the various criteria and then for the two negative criteria (redundancy and detectability) used in the analysis. A sample raw TOPSIS and fuzzy TOPSIS methods ranking outcome using the following omission of one criteria is shown in Table_Apx C-1 and Table_Apx C-2. It can be observed in Table_Apx C-2 that without consideration for complexity and improper testing the Double SPM valve external leakage criticality ranking dropped from a more critical (4th place) to a lesser critical item (7th and 9th respectively), as these factors influence the scores. While the raw outcome are clear, it is of importance to understand what criteria dominates ranking outcomes for a particular failure mode or in general and as such the deviations rather would be used to describe the sensitivity outcome.

Sensitivity analysis results carried out whereby a criterion is omitted from the analysis using the Fuzzy-Interval TOPSIS technique is shown in Figure 5-1 (see

Appendix C those of TOPSIS, Fuzzy TOPSIS). A comparison of the ranking outcomes of the three different techniques indicates all the criteria are sensitive and with relatively marginal importance for majority of the failure modes as seen in their degree of influence on the failure mode ranking. The results indicates criteria C_1 to C_3 (maintenance and testing related) to be the most important or influencing factors for all three analysis approach. The fuzzy interval TOPSIS approach also had criterion C_6 to be very important with the combination of C_5 and C_6 also showing an influence in the ranking outcome (this is driven by mostly $C_{6,}$ though the combination effect cannot be ignored). However, for the fuzzy TOPSIS ranking sensitivity analysis criteria C_5 and C_6 and consequently their combination had little or no impact on the failure modes rankings. It is possible this outcome is due to the computational approach, but the ranking outcomes are relatively not far from the other techniques.

It can be seen that the omission of any one of C_1 to C_3 can influence the ranking outcome of the external leakage of the Blind shear ram i.e. F8 from an original rank to a lesser rank which means it becomes more critical . The implication of this is that testing and maintenance Is not a dominating criteria for improving the blind shear ram. While this can be arguable, the sensitivity also indicates redundancy C_6 to be correlated, as its omission results in an increase in rank outcome, which can be interpreted as redundancy can contribute to the ram's functionality improvement. The annular preventer external leakage (F32), choke and kill valve fails to close F33), choke and kill valves external leakage (F20), shuttle valve coupling and tubing external (F12), Fixed pipe ram fails to close (F10) failure mode shows an increase in ranking suggesting their becoming less critical upon omission of C_1. This implies there is a correlation between the failure modes and the criteria a requirement or importance of C_1 for an improved component associated with the failure mode.

Failure modes F2, F6, F16, and F33 correlates with all C_1 to C_3 criteria and the sensitivity results show that the failure modes all marginally become less critical implying the requirement for testing and maintenance for improving function of BOP system components associated with the failure modes. Other deductions can be made from the analysis Figure 5-1. Figure 5-2 shows one of the results of the sensitivity analysis where specific criterion weight has been varied by way of a percentage increase to understand the impact on the ranking outcome. The ranking outcome in general indicates that was little or no effect observed for a 15% increase in weight of a criterion in several instances. This can be associated with the very small range of the set of criteria weights presenting a view that all criteria are important. This informed the decision to further increase the weight by 30%, 50% and 100% respectively. The external leakage of the blind shear ram (F8), fixed pipe ram fails to close (F10) and internal leakage of the fails safe check valves (F31) ranking outcome are correlated with criteria C5. This correlation is seen for all four different weight increases (ranging from 15% to 100% in) as depicted in Figure 5-3. The increase in weight of C5 results in these failure modes becoming more critical, implying the requirement for proper detection in the components associated with these failure modes. There were a good number of failure modes (F1, F3, F4, F5, F13, F14, and F26) whose ranking outcomes was not influenced by the increase in the weights of the criteria.

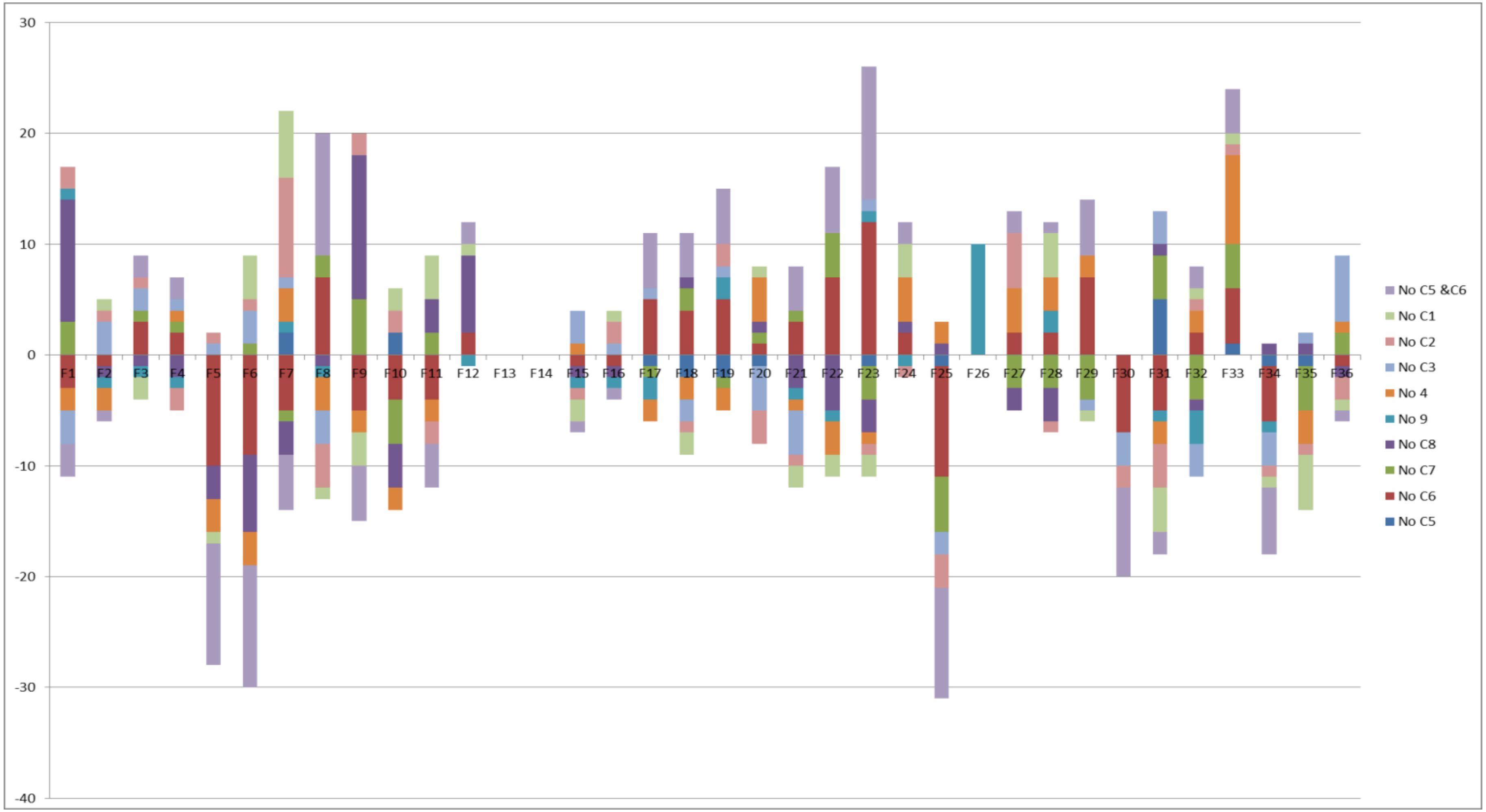


Figure 5-1: Sensitivity analysis with the omission of one criterion to see the impact on failure mode ranks using the Fuzzy Interval TOPSIS approach.

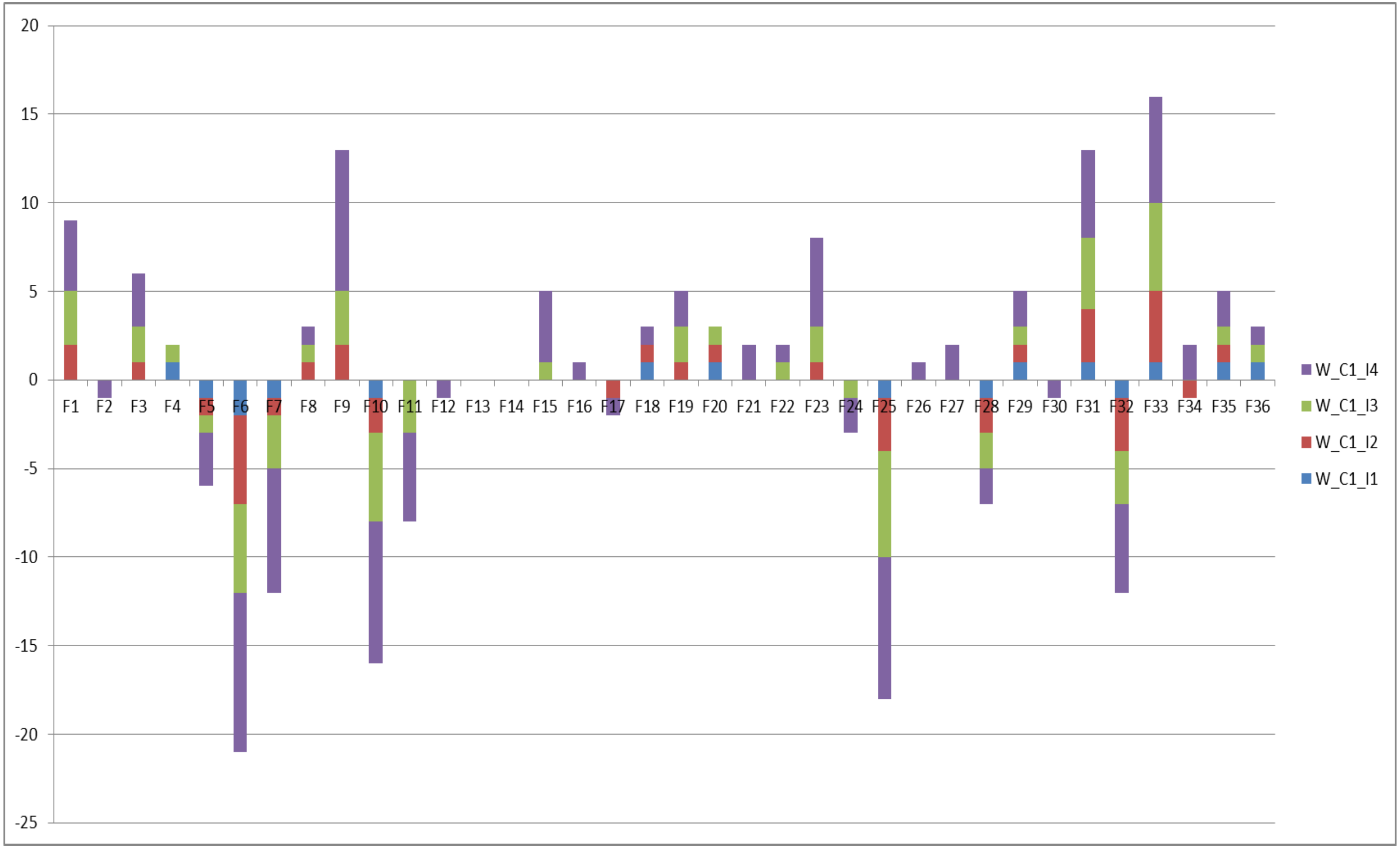


Figure 5-2: Sensitivity analysis of an increase in criterion 1's weight using the Fuzzy-interval TOPSIS

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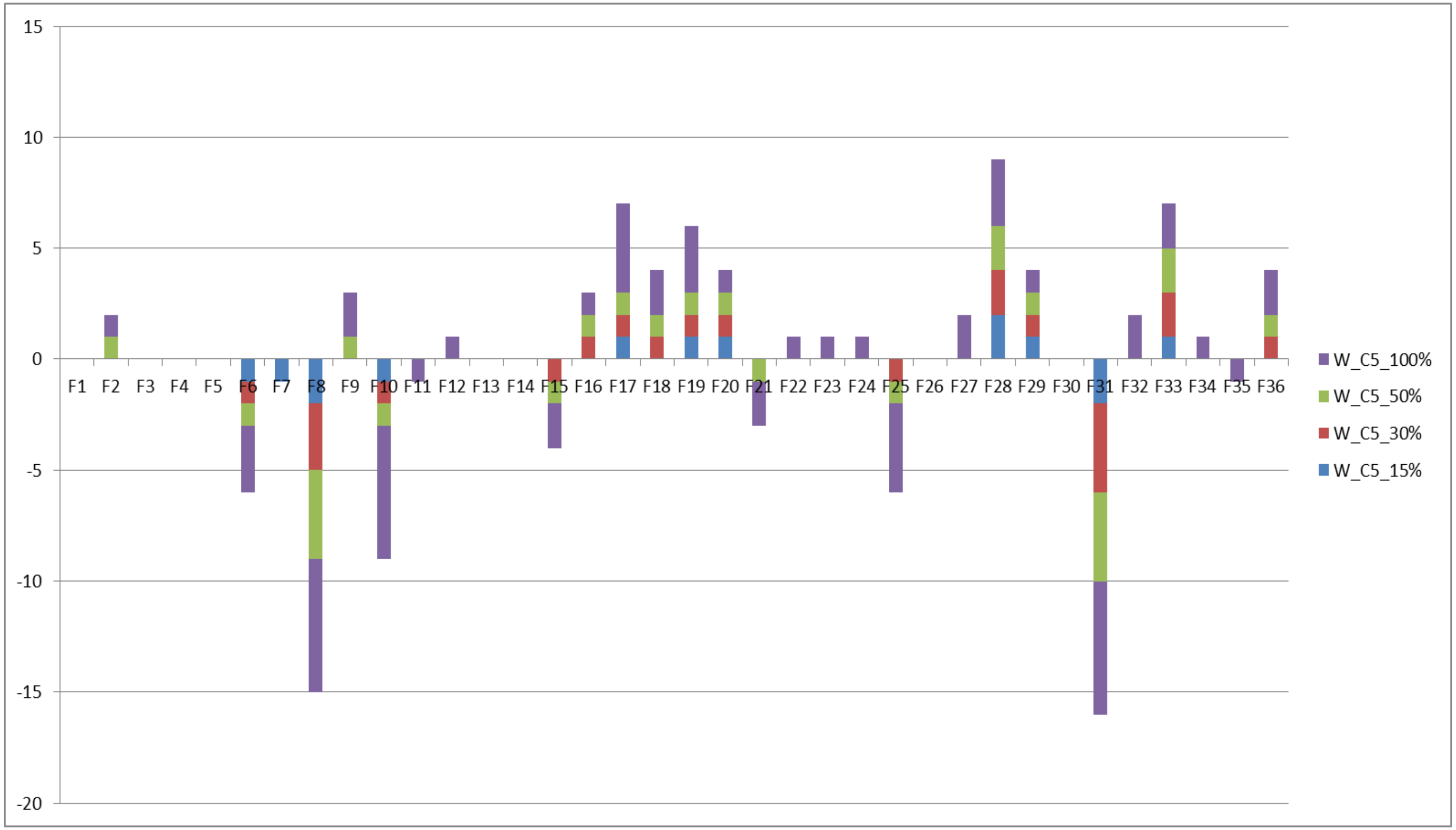

Figure 5-3: Sensitivity analysis of an increase in criterion 5's weight using the Fuzzy-interval TOPSIS

It is evident that the sensitivity of the criteria weight increase to each of the failure modes ranking outcome are varied and unique. The impact on the failure mode ranking outcome is different with respect to each criterion and the incremental criterion weights (see Figures in Appendix C).

To further understand the effect of the criteria weights, fuzzy weights was varied using the Fuzzy TOPSIS technique and ranking outcomes observed. This was to represent human linguistic representation of sensitivity but in this case with more than one criterion weight been altered (increased and decreased). Figure 5-4 shows the sensitivity analysis outcome considering set criteria (group) fuzzy weight being varied. The four set of variations are: (a) Criteria C_1, C_2 and C_3 was assigned a Medium (M) score while others were left as normal (Absolutely high- AH and Very high- VH); (b). C_1, C_2 and C_3 assigned an AH weight with others kept constant; (c). C_1, C_2 and C_3 assigned an M weight with other criteria assigned VH and (d). All criteria assigned equal weight of AH and VH.

It was observed that assigning all criteria equal weight of AH or VH did have a similar impact on the ranking outcome of failure modes. This also establishes the impact or contribution of criterion weight on the ranking outcomes, given some failure modes became less critical or more critical as seen in the deviations. Also the sensitivity of assigning a Medium weight to the severity related criteria C_7 to C_9 showed that the greatest deviations (even distribution between failure modes that became less critical (e.g. F8, F9, F22, F26) and those that became more critical (e.g. F7, F25, F32)) in majority of the failure modes except those of F13 and F14 and F16. These criteria are not failure drivers but a measure of the consequence offered following these failures and the sensitivity shows they are sensitive and important. It was expected that these would change the dominance of F13 and F14 as most critical item given they were assigned high scores relative to C_7 to C_9 but the analysis have shown that even when these criteria are made of lesser importance they still stand out to be topmost critical failure modes given contributions from other 6 criteria.

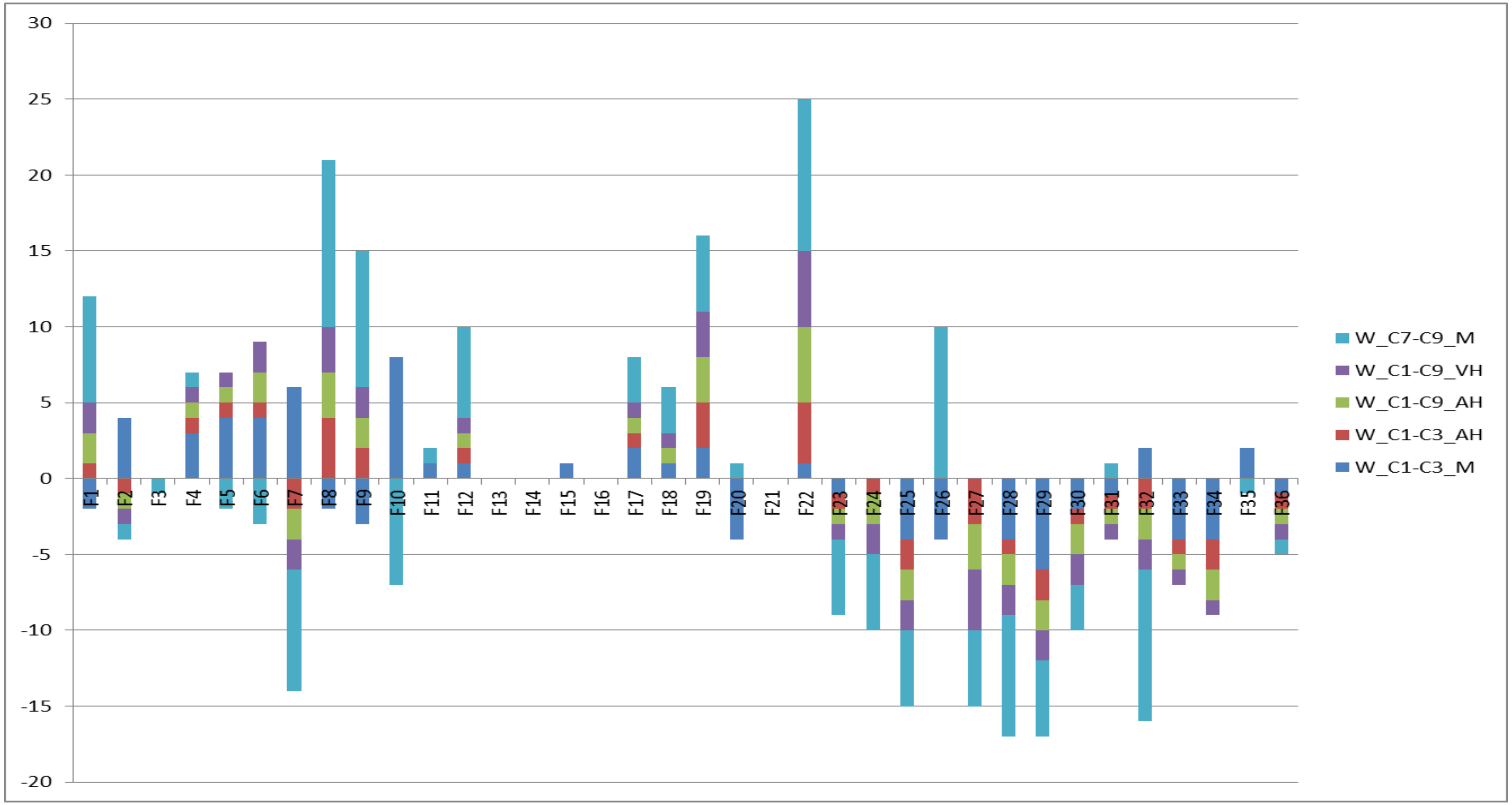

Figure 5-4: Relative changes in criteria fuzzy weight to understand impact on failure modes outcome

The maintenance and testing related criteria (C1 to C3) have shown to be a sensitive contributor to the ranking of a BOP system component failure mode. An indication from the Figure 5-4 is that the external leakages of the choke and kill lines, shuttle valve coupling and tubing showed minor deviation of one rank step towards less criticality. While the failure to close and external leakage of the pipe ram (F10 and F2), internal leakages of the choke and kill valve and single acting SPM valve (F4 and F7) moved at least 3 and above ranks towards less criticality. Similarly, a minor decrease in rank change towards being more risk critical was observed for a number of failure modes.

The sensitivity analysis confirms spurious unlatching of the wellhead hydraulic connector to be the most critical failure considering the several risk criteria as their ranks were preserved. While the ranking outcomes for the different sensitivity scenarios are nearly similar, a few deviations observed for some failure modes and these are owing to the influence of a criterion on that failure mode. It is important to note that the lower ranked failure modes in terms of criticality

5.3 Research outcome validation

To ensure the robustness of the identified failure mode evaluation in this research work, testing by way of comparison amongst different ranking outcomes and/or against established viewpoint is required to establish the findings. Several methods for validation exist for substantiating any research methodology such as sensitivity analysis and comparison with real world/verifiable data. While an end-end verification means of validation (progressive assurance explaining objective and presenting outcome) has been applied for every segment of this work, this section provides a confirmation of the validity of the research methodology and the findings against intended objectives.

Weights can be assigned to the different experts to compensate for their degree of competency with a domain area of knowledge of the system under analysis.

These can be used to appropriate the evaluations in the failure analysis. Direct rating methods, Eigen-vector, point allocation or Delphi methods can be used to assign weights of experts (Chin et al, 2009). Sensitivity analysis can be carried out for varying combinations of expert weights to ascertain the influence on failure mode ranking outcome. However, equal weights can be considered for all experts contributing to the analysis if there is no sufficient rationale for disparity in their abilities (Liu, H et al 2014). In this research, a minimum benchmark (IWCF certification) was set for competence of the experts and some operational experience (in this case minimum of 5 years' experience). Another way of sensitivity could have been to add more criteria. However to avoid overlap rendering criteria not independent, this was not considered as it could make sensitivity difficult.

MCDA method application spanned the use of traditional tested technique such as the TOPSIS with variations in its algorithm formulation and PROMETHEE. This consisted how the weights were normalised (vector or linear), importance weight of criteria were assigned/and or obtained (directly from experts and use of Entropy method for generation), how the data is perceived and inputted (Fuzzy numbers considered as intervals or typical triangular shaped numbers or de-fuzzified fuzzy or crisp data).

Similar or fairly different outcomes can often be generated using different MCDA techniques and exact same data, and this is due to the different computational and preference modelling structure of the techniques. None is better or worse but only one that performs better in some conditions, however, it these techniques have similarities in theories used for ranking alternatives. Hence, when some deviations are observed in the alternatives ranking, then the ranking results can be aggregated. The research goal in this thesis is to demonstrate efficiently the application of MCDA for better decision aiding for stakeholders. Furthermore, it is important to emphasise that MCDA techniques are decision support tools and not a decision tool. They are best guide to help decision makers have an outcome to compare with their expert opinion/ existing knowledge/prior conceived viewpoints in order to make an informed judgement.

The outcome of the Multi-criteria analysis of the BOP system clearly shows failures of the Wellhead connector, LMRP hydraulic connector and Control system related failure as the Top 3 most critical failure with respect to a well control. The next in line are those of the ram and Annular preventer, which is closely consistent with the concluding coarse failure mode ranking (see Section 2.9.3) in Holand and Awan, (2012). Also the discussion presented earlier showed some comparison with the outcome from ABS FMECAs(ABS, 2013d), however it is important to state that each analysis in themselves are correct with their outcome dependent on the experience and knowledge of the experts applied and also the approach of the analysis.

6 CONCLUSION AND RECOMMENDATION

6.1 Summary

This thesis entails multi-criteria assessment of the Subsea Blowout preventer (BOP) system. It has applied a combination of a traditional semi-quantitative risk analysis technique and MCDA techniques to understand in more detail the failure risk associated with the BOP System. This chapter culminates the reporting of the findings of this doctoral research. The research significance, contribution to knowledge, challenges, and limitations of the applied methodology restated with some emphasis on salient points. Also presented is an additional area of scholarship, which may be explored by future researchers. A high-level pointed conclusion established from the research, presented in this thesis, is thus summarised as follows:

- BOP System is intrinsically a complex system
- Traditional techniques used to assess non-complex system reliability (e.g. RBD with failure rates or general statistical or quantitative approach) are unable to capture the stochastic variations and uncertainties associated with complex systems.
- Hence a more robust or multi-dimensional approach would be necessary to assess the BOP system and understand the risk of a loss of function at component level arising from an unreliability.
- This need is driven by the relevance of the BOP System and the cost of its consequence; the drive for oil exploitation in deeper waters offering harsh environment, technical challenges and greater uncertainty; specific field challenges requiring modifications, e.g. HPHT wells
- In this thesis traditional systematic risk assessment technique, FMECA has been applied to understand the weakness associated with the BOP system.
- Also a major contribution to knowledge was made to the above understanding by the application of MCDA to the Subsea BOP System for a more representative failure risk ranking.

A critical failure mode list has been identified and the complicity associated with detectability of a failure mode seen from risk assessment rank outcome presented in Table 4-6. Extracted from the FMECA analysis were also critical Subsea BOP system components in Table 4-5. The analysis showed in Figure 4-3, that the control systems contribute 46% of the aggregated component identified failure modes RPNs. The control systems are vital with great consequence however of lower risk consequently given the level of redundancy designed into the system.

From the identified failure modes select critical list of 36 failure modes were further analysed using MCDA techniques and nine different criteria address the limitation of the FMECA technique. Table 8-1 shows a list of critical failure of component/subsystem from severity-based ranking and a representative listing from the MCDA analysis following the discussion of results. The research outcome shows results, which are not far from reality.

Table 6-1 : Critical Component extract from MCDA analysis and Severity based coarse ranking

Extract Critical Component	
Severity based Coarse list	MCDA analysis ranking list
Wellhead Connector	Wellhead Connector
LMRP Hydraulic Connector	LMRP Hydraulic Connector
Control System	Controls Set 1 (Accumulators, Double Acting SPM Valve, Shuttle Valve tubing and coupling, Shuttle Valve)
Blind shear Ram	Fixed Pipe Ram *
Pipe Ram	Annular Preventer
Flexible Joint	Controls Set 2 (Single Acting SPM Valve, Manifold HPR, Annular HPR)
Annular Preventer	Blind Shear Ram
Choke and Kill Line	

*** Recall in this thesis Pipe Ram was considered to represent both Fixed and variable bore types**

Also it can be seen from the failure data that from a component perspective, the controls system is the most critical, having the least mean time to fail (MTTF). Though it has about the least average downtime per failure, it has the highest downtime per BOP-days –given its largest contribution to the total number of failures (represented across the three failure data tables). The FMECA analysis confirms the controls having the largest cumulative failure contribution and as such not a surprise it comes in the Top 3 critical failure list of the BOP System.

Besides the controls, the next component critical failure mode/component set common to all three BOP failure data set are those of choke and kill lines, annular preventer and ram preventers. Beyond these three component failures, there exists no further common consistent rank amongst this data set. This can be compared with the FMECA outcome and it is not surprising, as outcome does not align perfectly with the MCDA rankings, which is more representative to measure risk of a failure mode in a system as against the conventional 3-parameter FMECA assessment.

The ranking outcome following the assessment of experts has provided a better ranking view point of the failure modes even as it does address the weakness of the FMECA technique. Most obvious improvement is providing a more encompassing outcome giving the spread of criteria and no ties in the ranks of the failure modes.

6.2 Research Contribution

This significance of this research is critical to the sustainability of the offshore industry specifically its drilling activities. The desire for a catastrophic event-free activity is closely related to an improved understanding of the BOP system as established in Chapter 1 and 2. Currently the price of oil is down which affects the cost of field developments and production, suggesting the level of risk tolerance is limited. Unreliability in the BOP system, which results in a failure with potential for a complete loss of well control, is a risk that would be undesirable. This work has added a new dimension to assessing the risk of failure associated with the BOP system. It presents criteria for assessing the risks by way of failure modes identified from a failure modes and effect analysis.

In this research, we reviewed risk and reliability analysis, its process, the different techniques, and its application in the offshore industry across different stages. The role and use of the FMECA was reviewed with the gains and drawbacks presented. While these are known knowledge, this work presents it uniquely from a practical point of view by showing the misgivings in analysis outcome depending on what quantitative computation approach is used for criticality ranking (classical risk definition or RPN). The limitations in the ranking outcome of FMECA using RPN, the confinement to assessment based on three criteria and the consideration of equal importance for the criteria was shown and discussed elaborately suggesting the need for improvement using multiple criteria decision analysis.

Critical components of the BOP system have been identified following criticality ranking of the modes of component failures using the FMECA and four different MCDA (TOPSIS, Fuzzy TOPSIS, Fuzzy TOPSIS-interval data, and PROMETHEE) methods for consistency.

The connectors were found to be the most critical with that of the wellhead as number one. This is not surprising as it is of higher pressure rating than the LMRP connector. The next critical set are control system related components, followed by Fixed and variable pipe rams and then the annular preventer. In the list is then another set of control items and then the Blind shear ram. The criticality of the control system and its component to the reliability and usefulness of the BOP system as barrier for the prevention of a loss of well control is again established and validates literature with field data.

Findings from sensitivity analysis further validated analysis findings in addition to those of actual field data.

The multicriteria analysis methodology shown in this thesis can help identify criteria that are important to understanding a technology or system and the areas of risk (failure modes) requiring attention or to be addressed by subject matter experts. The analysis in this thesis shows value in the application of MCDA to assessing technology or risk in technology as substantial correlation information between the assessment criteria and the alternatives can be derived from the decision outcome. An interactive sensitivity analysis using variation sin weight of criteria can also provide a much better decision aiding to the decision maker.

Despite the established benefits that can accrue from a risk assessment, it may not translate to a risk reduction if the assessment is considered as an end in itself. It is important for the process to be applied with an end-goal in mind and the outcomes in the form of understanding and actions be utilised to inform design, operation or procedural improvement, maintenance activities. Also this decision outcomes be communicated amongst stakeholders and logged in a register/ management which can be assesed by different responsible parties with traceability of how they are addressed. Root causes and their failure associated mechanisms have been discussed indentifying aspects of BOP system components that need frequent review or improvement given varied operational scenarios.

It is also important that a guideline be developed specifying when these assessments will be conducted and how the outcome will be managed. Company policy need to ensure a thorough review of BOP systems and its components prior to their use for a drilling or any other campaign. Modifications or changes in specifications/requirements (e.g minimum design pressure, well bore presure) for different scenarios have to be assessed in a workshop to understand thier impact on equipment reliability and operations. This can take the form of a technical risk categorisation and technology readiness level assessment process as described in API 17N (API 17N, 2009).

6.3 Publication from PhD

There are a number of publications from this work. Most of which are under review with Society of Underwater Technology (SUT) Journal, Ships and Offshore Structures Journal, and the International Journal of Systems Engineering and Assurance.

Initials findings of this work were presented in the Mathematical Modelling in Maintenance and reliability Conference, Oxford University, (MIMAR) 2014.

6.4 Recommendation for future work

This method may be adopted for analysis of more specific designs when necessary with suitable criteria, as identified, peculiar to the design and intended decision problem to be resolved.

Two experts who declined to complete questionnaire on the basis of “not expert enough to contribute to the study” would have preferred to be part of the study within a group context. It is important to state that these two experts meet the requirements having requisite certifications, training and experience but were not confident enough due to the safety-critical nature of the Subsea BOP system. These echoes the gain of group decision making in the context of obtaining a broader view of the assessment given the variation of the different expert’s experiences. However group decision-making is not without challenges (not the subject of this work though) but in the course of this research, such an approach would be expensive, given limited funding, to bring together group of experts within a room. In this work an individual decision assessment has been utilised to reduce bias, however the analysis in itself is can be classified as a group decision-making framework. However when large number of criteria and alternatives are involved the complexity can be increased with more time required. Further work can be done to compare the outcome from both approaches within the context of MCDA implementation approach. This would be rather at subsystem or component level, otherwise decision outcome may be impaired due to experts being likely to be fatigued from the process. Alternatively, the use of an on-line individual voting system in group-decision making suggested by French (2007) can be explored.

Also worth mentioning is the major constraint with increased depth is the issue of response time to activate a function, and control signal delivery (electrical or hydraulic). There are indications that all-electric controlled BOP system may be the trend in the near future. It would be of benefit to do a similar analysis on such a system.

Again while software systems are an improvement option, they can also fail which is a subject of concern for their use in a safety-critical embedded application as in the BOP system. Thus during the development of software, new versions may be released with new functions added given the need for improved performance or addressing bugs. It is important that new defects are not added or created, which can be multiplicity depending on the complexity of the software architecture. Hence rigorous testing, verification and validation are required prior to deployment. In addition, fault tolerance is another unique feature that software should have as mentioned in the previous sub-section. This also apply to the entire BOP system, as there is need for stakeholders to assess and agree what is essential and create specific standards for their development and improvement options given new drilling operational challenges. This way unnecessary addition of items e.g. three pods being considered by an OEM, or additional blind shear ram or even new technology software applications with greater foot print to achieve increased reliability would be optimised. Thus it would be ideal to have a single component that work, if a ram should be designed and can tested for all possible operational scenarios.

While a good number of root causes have been identified, more attention should be directed to understanding Component functional capability such as using Finite element analysis to assess ram shearing performance for different scenarios, sealing performance of BOP. It may be interesting to see their performance relative to depth and material properties- this and above could help inform development of approaches and pointers for failure identification and evaluation.

When specification are presented for drilling rigs which normally have the BOP systems on them (sometimes one or two), there needs to be clear specification on the BOP system and this should consist not just compliance with API 53 but also requirements should be made on the performance. It should incorporate the well owners experience or expert input for the required drilling operation rig is sought for. This is important as often BOP systems which can be re-dressed to address some special concerns, e.g. if a well control situation is expected, or not and they are used as present on available drilling rig with dependence on rig crew experience/competence to address issues as they arise.

All innovative ideas should be assessed using API17N and Technology readiness level assessment be conducted for improvement in BOP system functionality (e.g. a full subsea BOP control using acoustic communication rather than as a back-up for emergency situations amidst challenge with refraction of sound waves, multi path and reflection or signal to noise in water concerns) or improvement in specific component design (e.g. an improved ram that can have multiple functionalities to seal annular, shear and seal or a ram with capability to shear any type of tubing). Certificates can be provided and updated periodically following a change in associated technical risk category.

Qualification activities need to be reinforced and reports of executed activities be requested by users of the equipment for assurance process and also stringent regimes be placed with penalties for the failure of maintenance and testing systems, inclusive of the personnel and organisational input. The API 17N process for technical risk management can be adapted for applications to the BOP system for specific use of a BOP system on a drilling rig for a new field.

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APPENDICES

Appendix A: Blowout Preventer Technology

Appendix B: Addendum to MCDA of Subsea BOP

Appendix C: Sensitivity Analysis

Appendix D: Initial Assessment Criteria

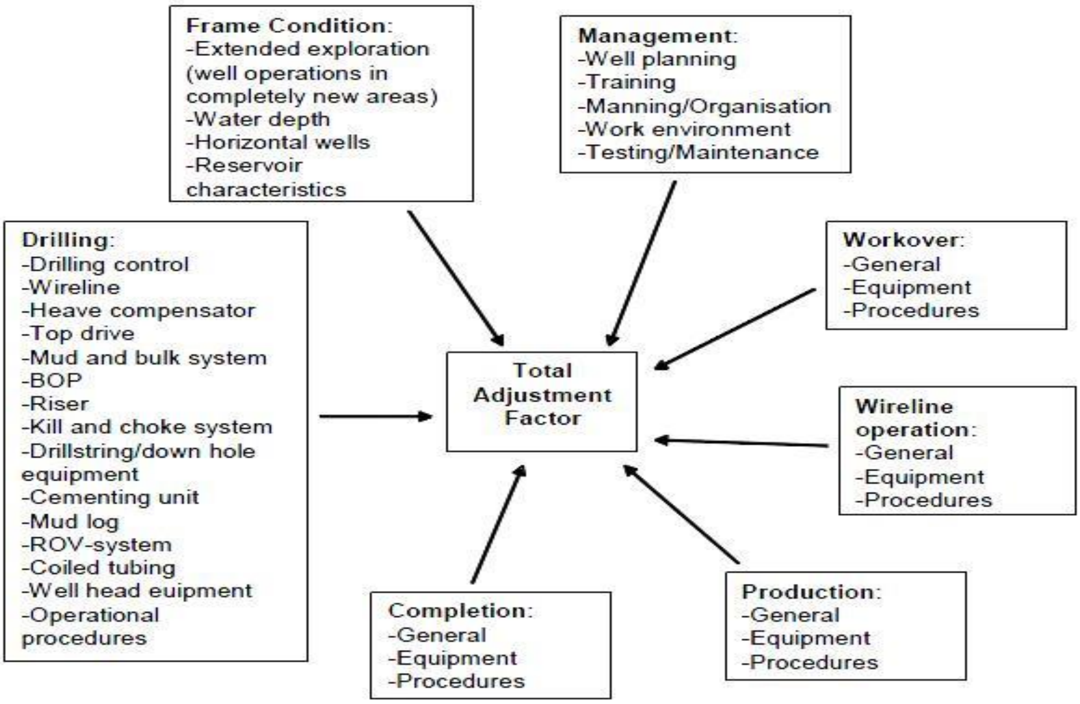
Appendix E: Risk Assessment Annex

Appendix A Blowout Preventer Technology

A.1 Drilling and Well control theory

A.1.1 Blowout contributing elements

(Dervo and Blom-Jensen, 2004) presented the need for adjustment factor that would consider other elements that forms the basis for the kick frequency, rather than the traditional assessment approach that utilises reliability data. Several elements contributing to blowout risk as used in the BlowFAM assessment approach is shown in Figure_Apx A_1



Figure_Apx A-1: Schematic showing contributing elements to blowout risks ((Dervo and Blom-Jensen, 2004)**).**

A.2 BOP System and components

A.2.1 BOP System

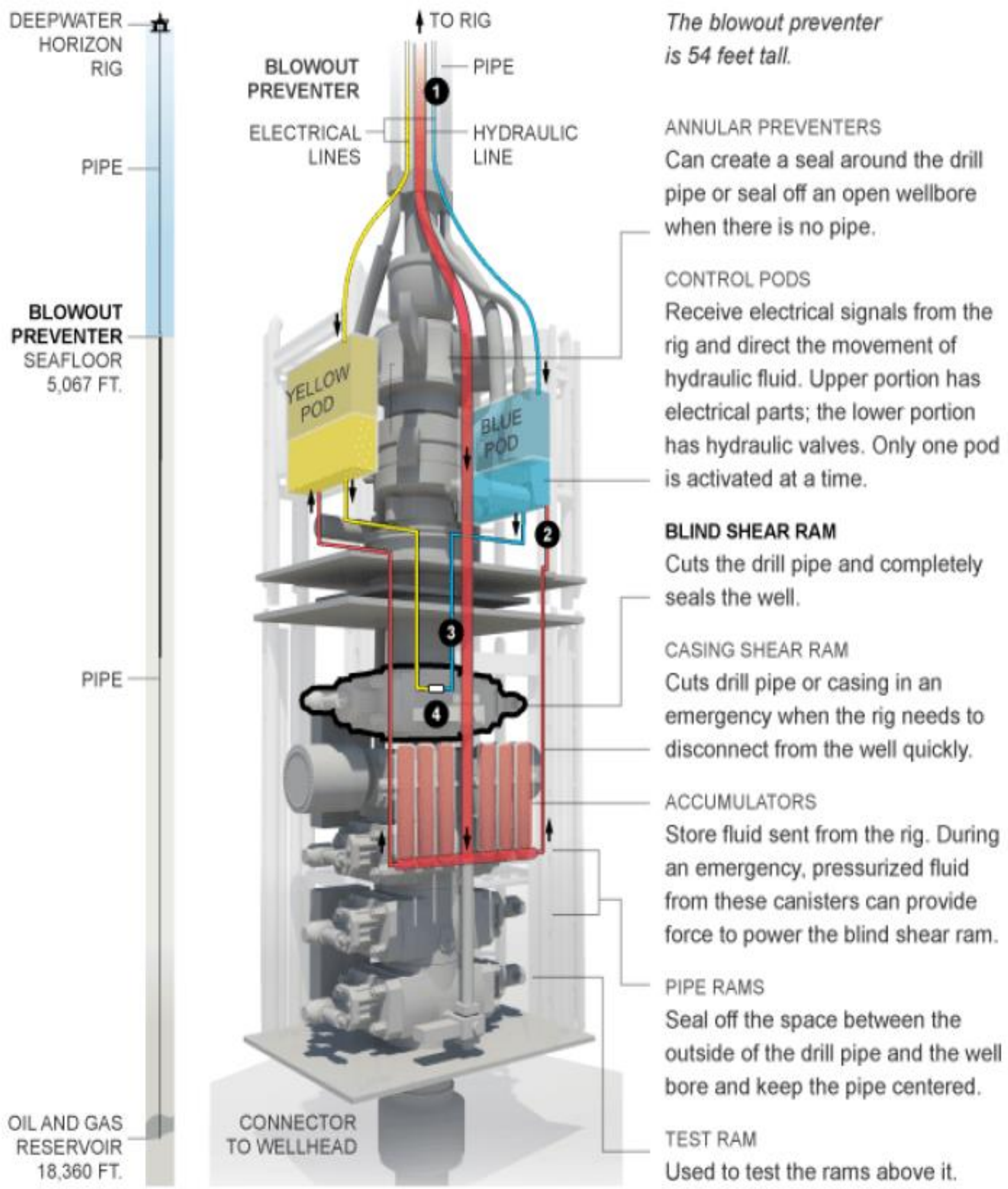


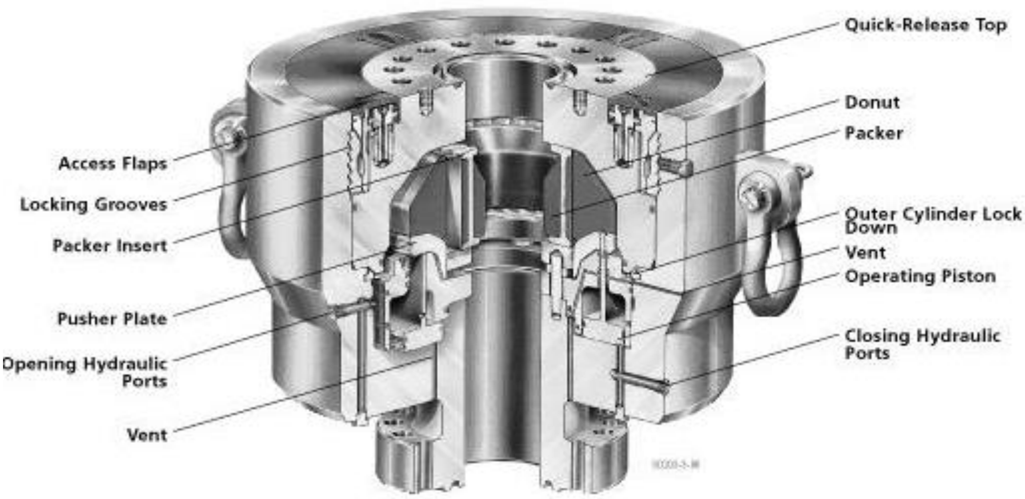
Figure 4.19 BOP control system in Macondo Deepwater Horizon (Gröndahl, M., et al., 2010)

Figure_Apx A-2: The Macondo Deepwater Horizon BOP System (Grondahl, M. et al., 2010)

A.2.2 Annular BOP

- **Cameron DL Annular BOP (shown in Figure 4-10)**

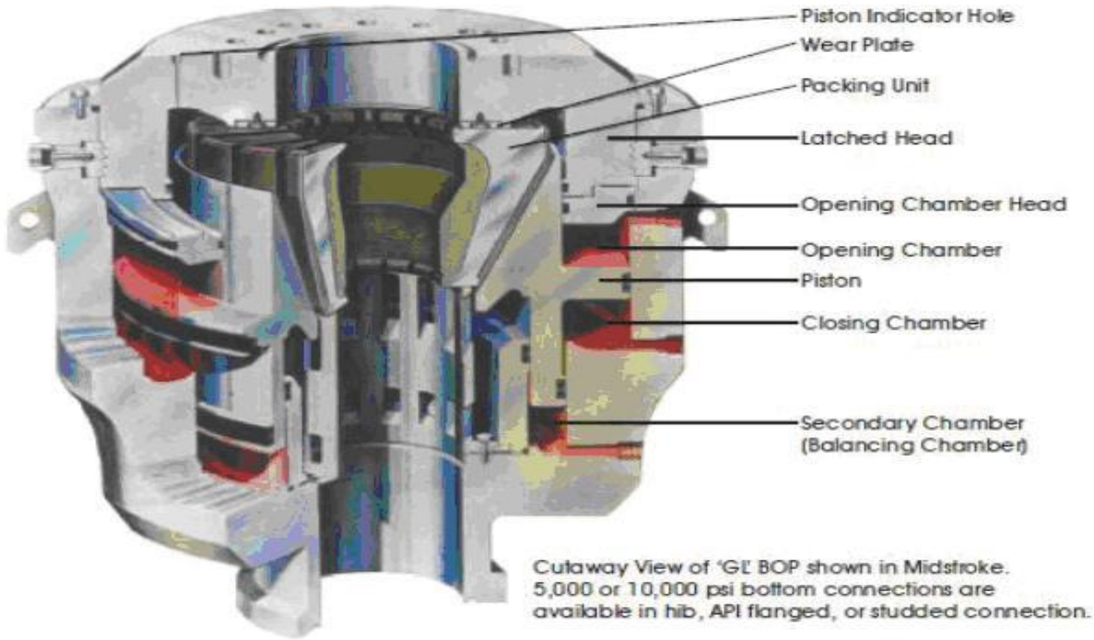
This is a shorter in height BOP compared to other annular preventers. It is uniquely designed such that the operating piston and pusher plate is forced upward by closing pressure to displace the solid elastomer and compel the inward-closing of the packer. Besides stripping a pipe, the DL BOP is capable of closing and sealing an open hole as well as an object of any shape and size that can fit into the wellbore. It is available in size range of 7-1/16" to 21-1/4" and in working pressure range of 2000 to 20000 psi. Figure 4-10 shows a typical Cameron DL BOP.



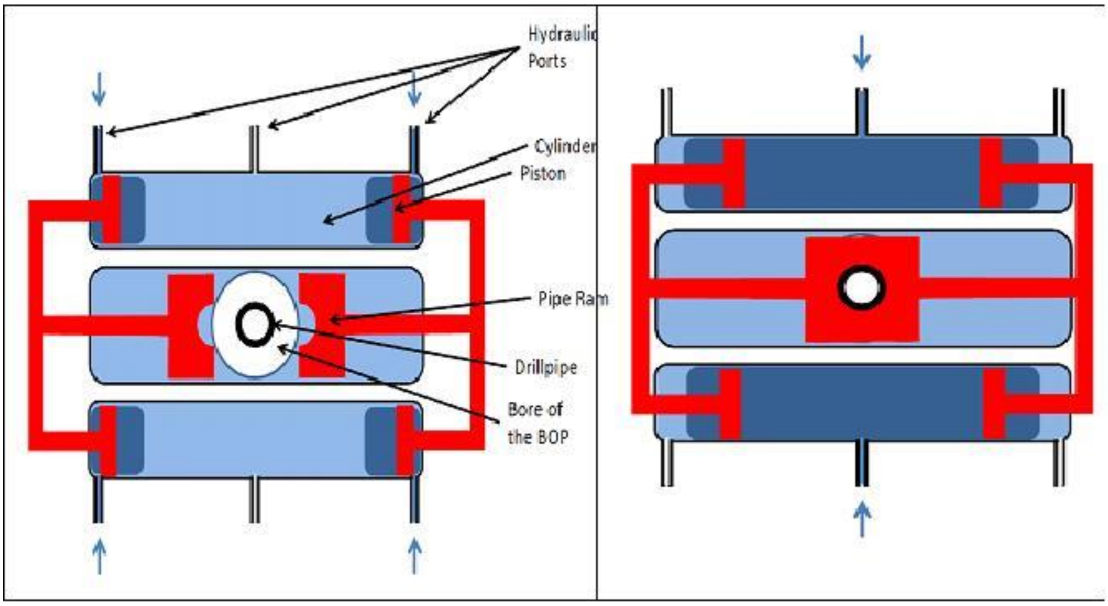
Figure_Apx A-3: The Cameron DL BOP

- **The Hydril GL Annular Blowout Preventers**

The Hydril Pressure control blowout preventer is designed with a long piston to provide balance, ease of operation and reliable operation. It is designed with a long-life packing unit, a latched head and operational capability of extending the intervals between packing unit and shop repairs for increased uptime. Greater flexibility for control hook-up is provided by the secondary chamber, offering a reduced closing pressure and volumes for closing and opening. Figure 4-11 shows a typical Hydril GL Annular preventer.

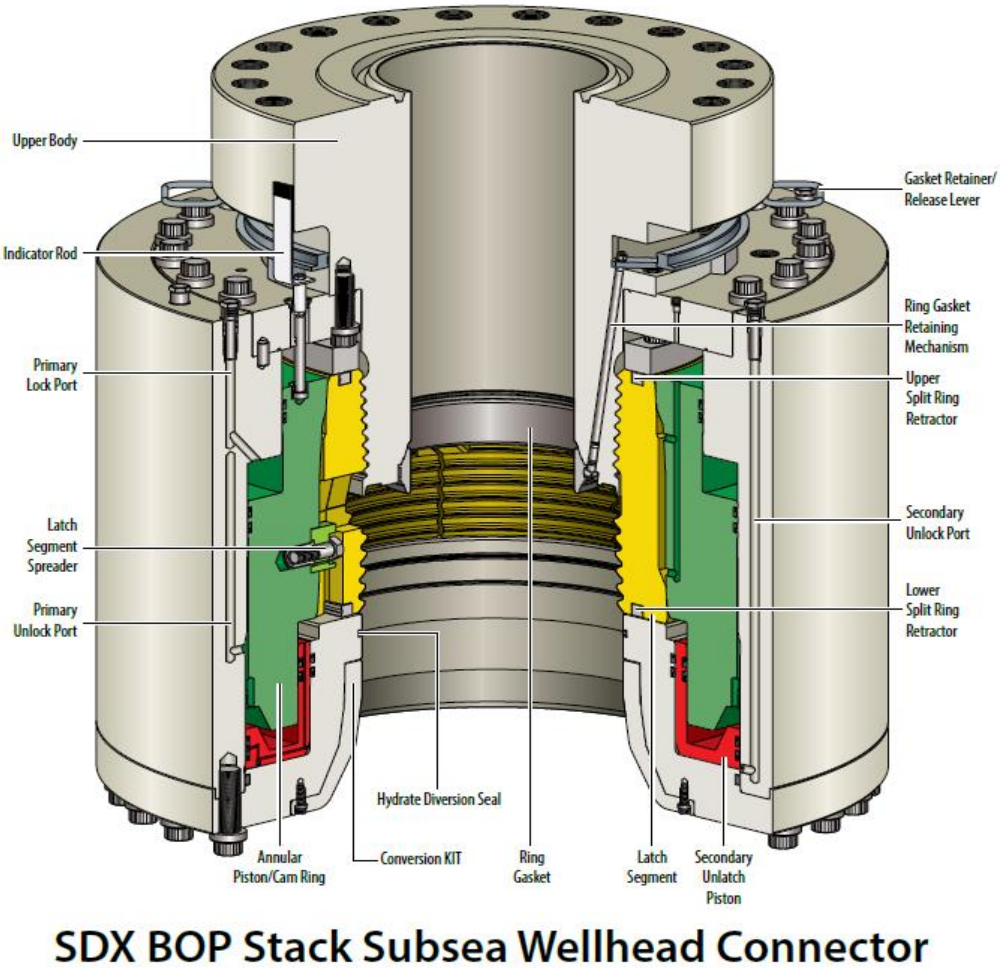


Figure_Apx A-4: Hydril GL Annular Preventer (Rig Train, 2001)



Figure_Apx A-5: **Plan View of the BOP Pipe ram before and upon demand (Rees, A. 2011).**

A.2.3 Subsea Wellhead Connector



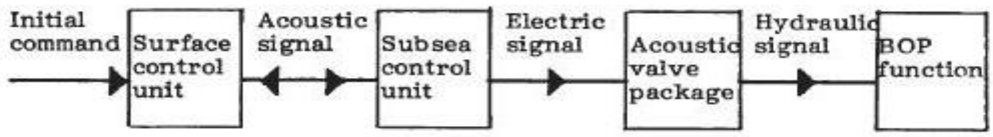
Figure_Apx A-6: SDX Stack Subsea Wellhead Connector

A.2.4 Acoustic Control

This control system type provides a back-up operational support for critical BOP functions (during normal drilling activity and in emergency) and is independent of the loss of primary control system. The emergency situation includes unplanned disconnect of the riser or loss of BOP control arising from other accidents. Water depth capability is specified by acoustic BOP control systems based on the assumptions of normal noise levels. Most new generation acoustic

BOP has operational water depth capability greater than 10000 ft. The Acoustic control system is mostly found on Offshore Norway Mobile Offshore Drilling Units (MODU) (Childers et al., 2004).

A surface control unit with a receiver which communicates with a pod at the lower stack makes up the control system. Upon initiation of the function at surface, hydro-acoustic coded signals is sent from the top transducer (mounted in the water beneath the hull of the rig) to the transducer on the BOP stack. The received acoustic signal is converted to electrical signal at the subsea control to activate the solenoid valve for the specific BOP function. The sequence for signal transmission for the acoustic system is described in Figure_Apx A-7 below.



Figure_Apx A-7: Signal Sequence for acoustic control systems (Hals and Moines, 1984)

There are innovations currently been made concerning the possibility of a full subsea BOP control using acoustic communication rather than as a back-up for emergency situations (given the highly advanced nature of available digital systems and technology in modern times) with a capability to offer reliability, integrity, and security at an appropriate level. This translates to a BOP without an umbilical with a number of benefits for MUX communication. The obvious benefits are the requirement for very little equipment on topside which increases available deck space, a reduction in transportation and handling cost since it can be quickly moved from one rig to another and umbilical with reels eliminated, respectively. This would reduce the total system downtime, as umbilical damage induced loss time is eliminated. Also as the riser run out, the moonpool handling of the umbilical is eliminated, thus improving the health and safety of system operations. This new thinking is not without challenges hence the use of technology qualification programme. Some of the challenges of the subsea acoustic systems design are (MacLeod and Jaffrey, 2009):

- Refraction issues: as sound waves do not travel through water in straight lines
- Interference concerns: acoustic systems used for supporting other subsea applications including vessel position may interfere with each other and this is not desired.
- Multi path effects resulting from reflections of hard surfaces and water layer.
- Bandwidth and range concern, as low frequencies are required for large range and thus high data rates are not supported.
- Signal to noise ratio issue, given the presence of noise in the water under a rig.

Given this is for emergency or back-up the functions are very few.

A.2.5 The Automatic Disconnect Function

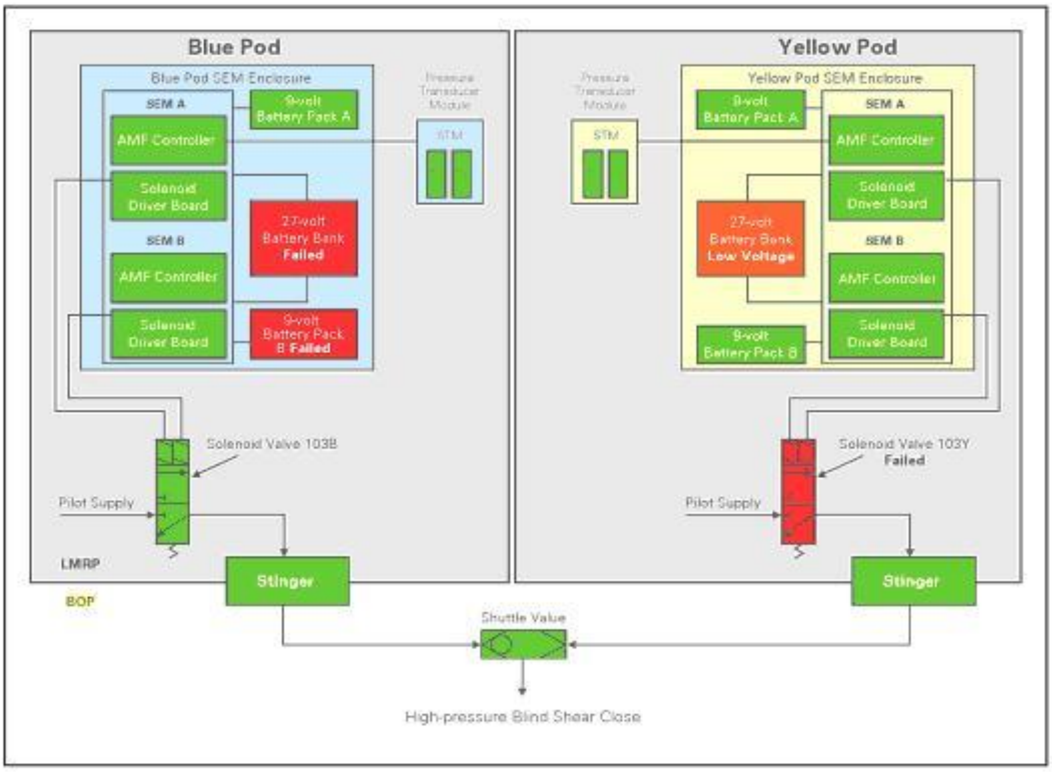
In the event of an unplanned separation of the drilling riser from the BOP, the blind shear rams of the BOP stack can be closed using an automatic mode function (AMF) of the subsea control system. The wellbore can be secured should there be a loss of hydraulic power, electric power, and electronic communication between pods, through a sequence of functions are initiated by the AMF. It is able to achieve this as it monitors the connectivity of the surface control system to the BOP stack (Transocean, 2011). The AMF system consists of Subsea Electric Modules housed electrical circuitry and uses existing hardware such as valves, solenoids, pressurized hydraulic fluid to control the BOP.

The AMF system consists of Subsea Electric Modules housed electrical circuitry and uses existing hardware such as valves, solenoids, pressurized hydraulic fluid to control the BOP. The AMF cards are designed to be independent. The components that make up the AMF system include (Transocean, 2010):

- An AMF processor board (one per SEM, two per pod and four in the BOP system)

- Dedicated 9-volt (V) DC battery pack per AMF
- 27V DC battery pack shared for both SEM A and B (one per pod and two in BOP system).
- Subsea hydraulic accumulators dedicated for operating AMF system functions
- A custom software file added to the PLC in each of the SEMs that defines the hydraulic activation sequence and timing instructions
- A bi-stable “latching” relay in each AMF card. Once the relay is latched in either the arm or disarm mode, it will remain in that mode whether it is powered or not.

The schematic shown in Figure_Apx A 8 is a simplified AMF control system for the GOM Deepwater Horizon showing constituting components for descriptive purposes. However, the colours in the schematic besides the blue and yellow (for pod identification) shows the working condition of the components at the time of the blowout on the rig: green to mean working, red corresponding to failed state and orange for lower performance. In providing power to the SEM PLC, solenoid driver card, solenoids, AMF card and Subsea Transducer Module for the AMF sequence, non-rechargeable battery packs are used by every Cameron AMF system. A battery type with a flat discharge curve is used for this application by Cameron, implying that constant output voltage is supplied by the battery until it reaches the end of life. Hence, by merely measuring the voltage offers no practical way for predicting the battery life. Thus a replacement of the batteries is recommended by Cameron after one year of operation or 33 AMF actuations, or within 5 years of shelf-life.



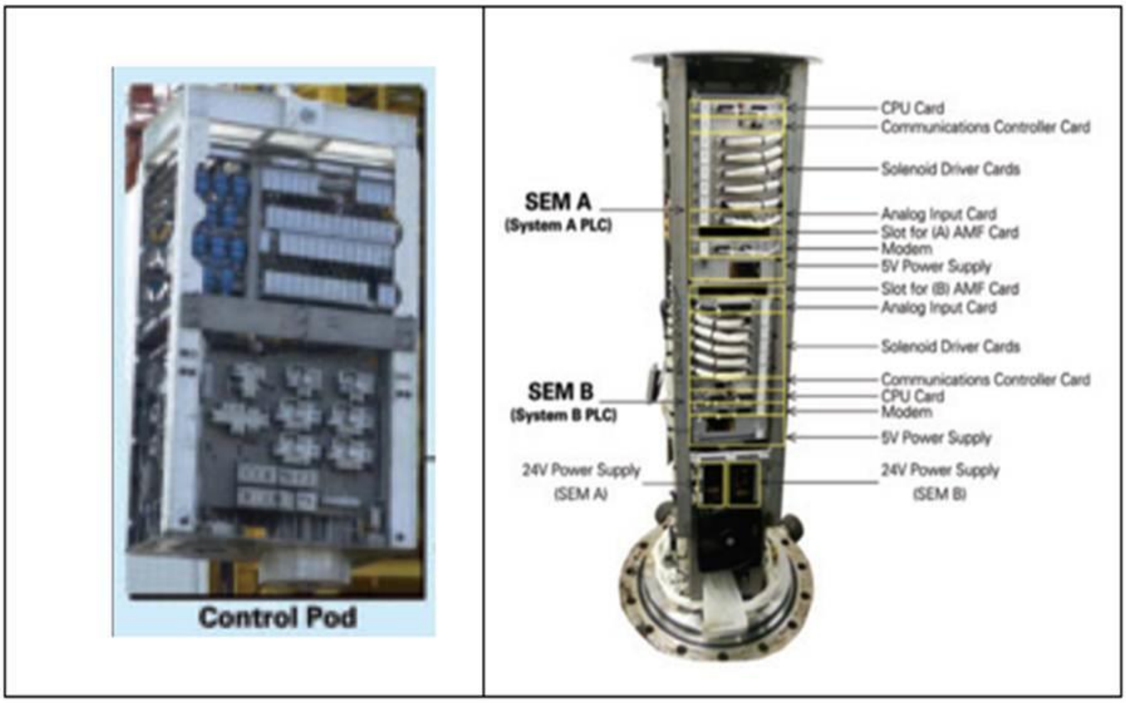
Figure_Apx A-8: **A simplified schematic of the AMF control system** (BP, 2010)

A.2.6 Remote Operated Vehicle Intervention

The Remote operated vehicle (ROV) has been very useful for intervening within the offshore environment especially for deepwater environments, where use of divers constitutes a risk. Considering the operation of the BOP and drilling operation, the ROV can be used for inspections and also a number of interventions to execute certain BOP functions such as:

- Wellhead connector unlock
- Riser connector unlock (primary and secondary)
- Pipe ram "open" and ST-lock "lock"
- BSR Ram close – auto shear arm
- BSR Close and Open
- LRMP connector opening/unlock

Hydraulic pressure can be provided to the BOP stack by the ROV through a hot stab panel, while other function simply entails a mechanical means of controlling valves. The AMF function and the autoshear function can be activated by the ROV and as such ROV intervention has been found in most rigs (e.g. drill ships and anchored semi-sub) with different BOP control systems.



Figure_Apx A-9: The BOP Pod and a typical Cameron 'Mark I' SEM Housing located in each Pod (Transocean, 2010)

A.2.7 Choke and Kill line and Valves

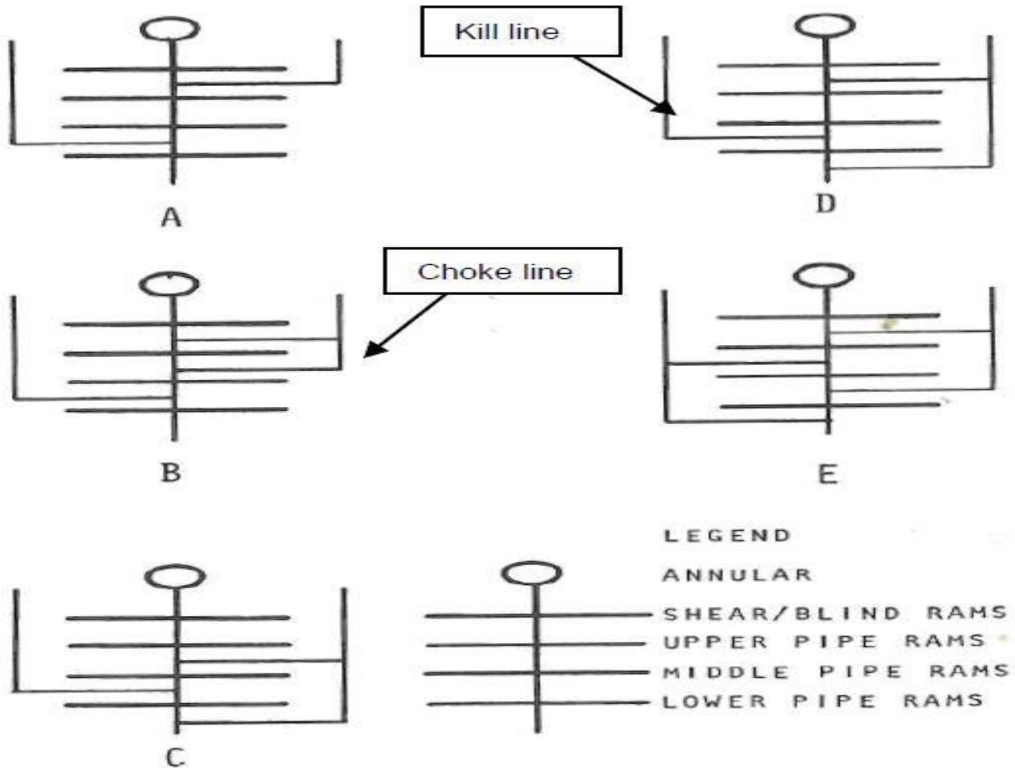
Given the increase in drilling activities for greater depths, addition functions are prompted for the subsea BOP system, such as:

- To enable static pressure monitoring in the BOP stack using the Kill line.
- To use both lines as parallel choke lines for reducing pressure due to friction from circulation.

According to Hawker, D. (2001), some requirements for chokes and kill line includes:

- The kill line working pressure should be equal to or greater than that of the BOPs.

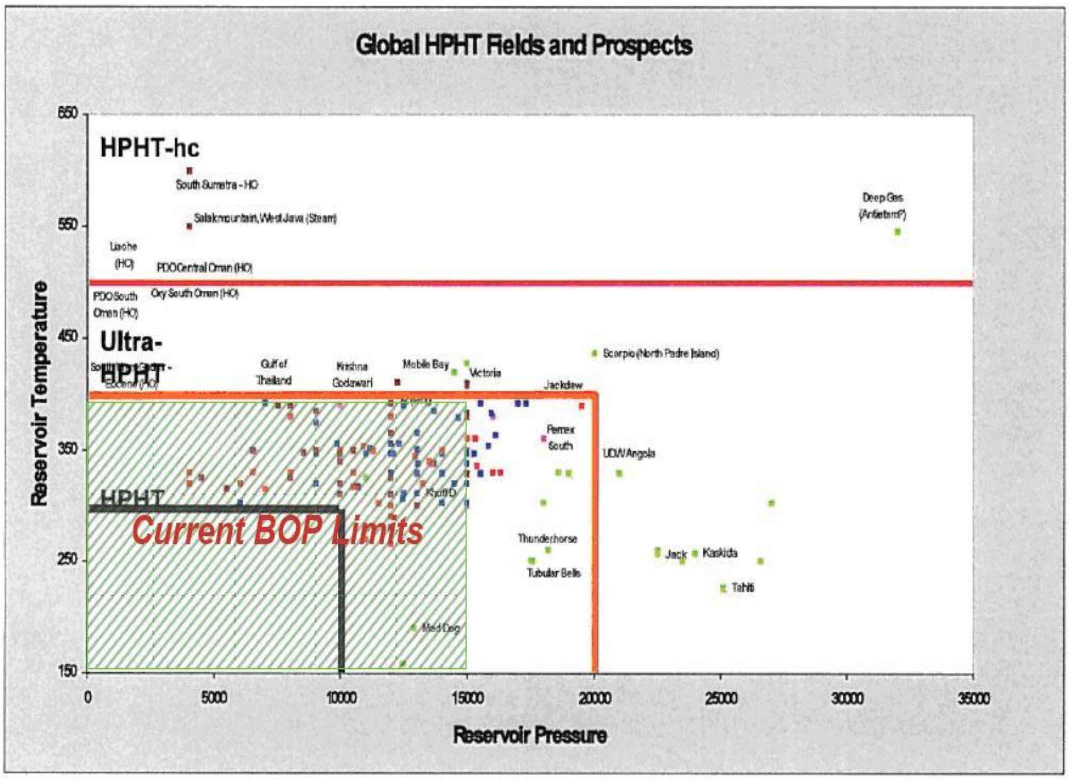
- The rated BOP stack operating pressure should have a pressure capacity as the manifold.
- In isolating equipment(s) needing repairs, downstream the choke line, there should be alternative flare and flow routes.
- The choke line should be as straight as possible and firmly anchored.



Figure_Apx A-10: Typical configurations of the choke and kill lines

A.2.8 BOP and HPHT Drilling Limits

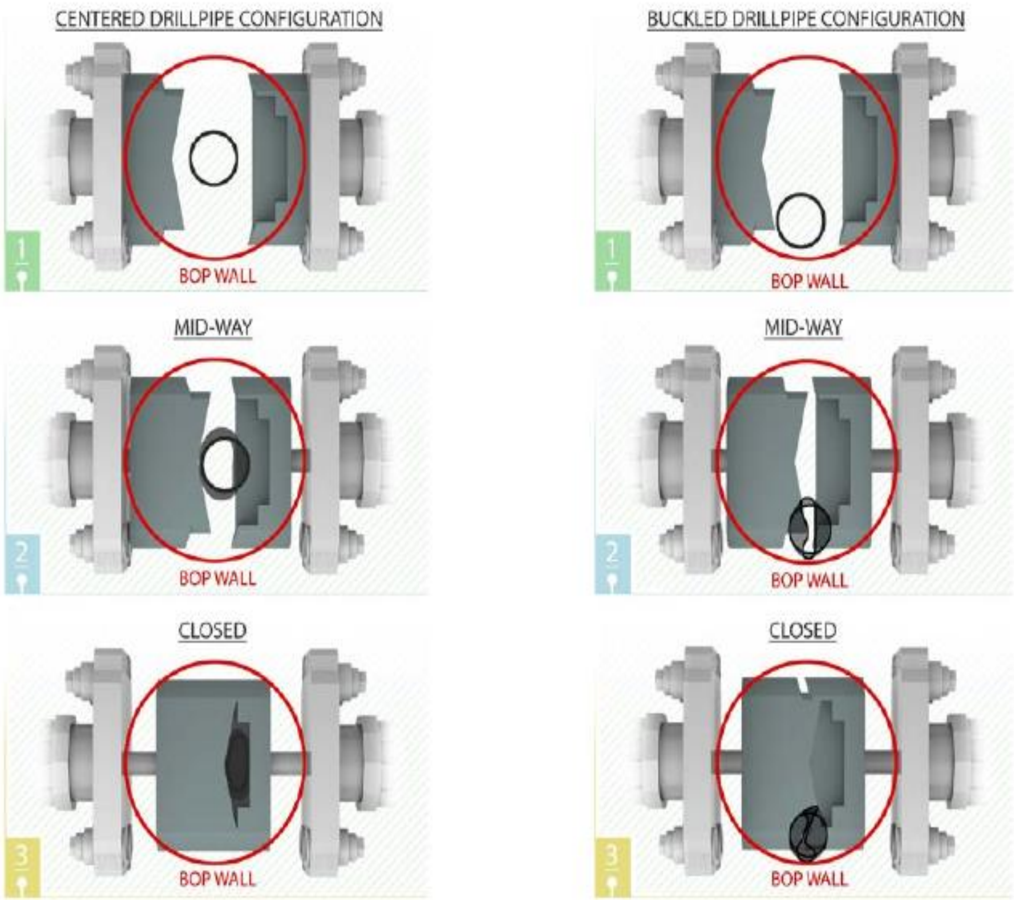
Limitations offered by HPHT Environments while global HPHT fields have been categorized to show the current BOP limits and future challenge in Figure_Apx A-11.



Figure_Apx A-12: BOP Limits and HPHT Drilling limits for Global Fields and Prospects (Source: Lobo, F. (2010))

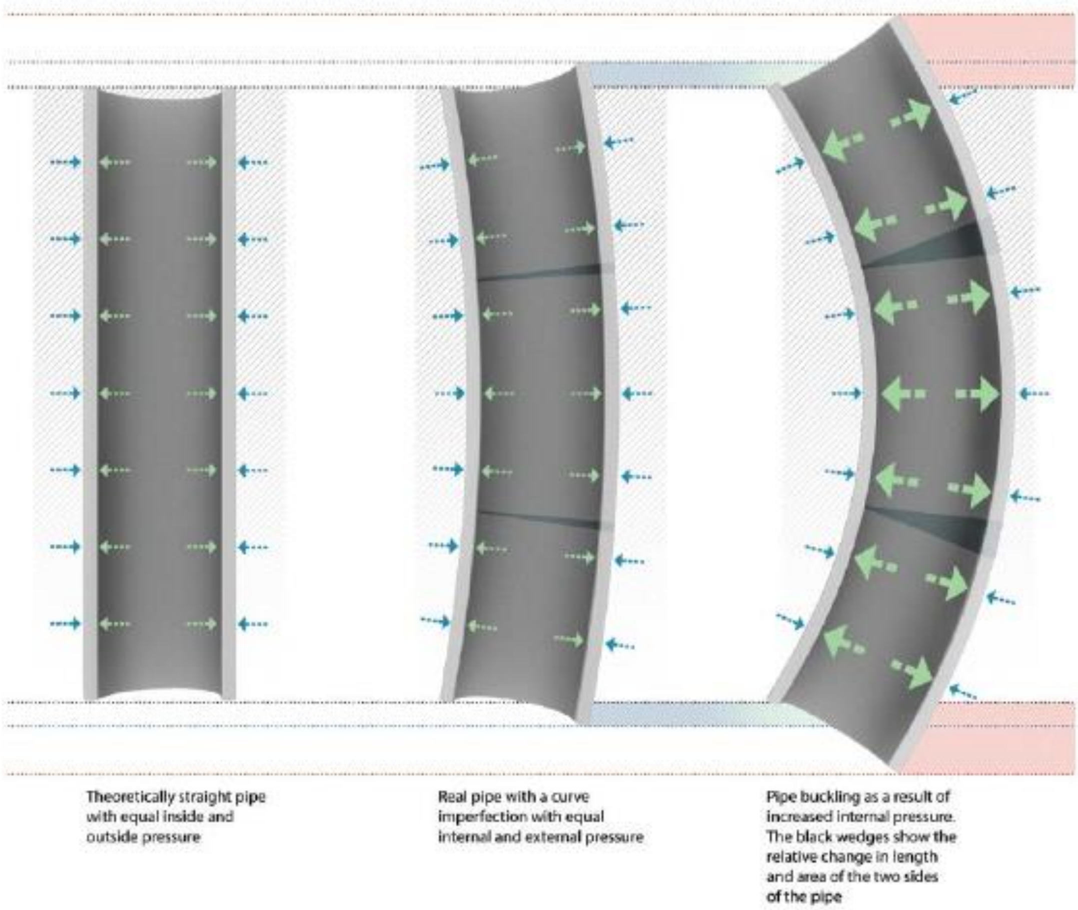
A.3 The Deepwarer Macondo related Diagrams

A.3.1 BSR and drill-pipe position



Figure_Apx A-13: Deepwater Horizon BOP as designed to shear a centred drill-pipe in the BSR and seal well (left). The drill-pipe found off-centre causing partial closure of the BSR leaving well unsealed.

A.3.2 Pressure effect on Drill-pipe



Figure_Apx A-14: The effect of the resultant between internal and external pressures on drill pipe.

Appendix B Addendum to MCDA of Subsea BOP

B.1 BOP MULTI CRITERIA ANALYSIS QUESTIONNAIRE AND SAMPLE DATA SET

BOP MULTICRITERIA ANALYSIS

Thank you for considering to assist me in my research work, it is highly appreciated.

I intend to Assess the BOP System using a Multicriteria Analysis method.
A select Critical failure mode list have been obtained from a FMECA analysis.
This Analysis is not far from a FMECA analysis but considers more criteria. Please make an attempt to scale these failure modes and where you have concerns you can make notes on the side- this would be highly appreciated.

I need you to help me score the failure modes relative to a set of criteria as shown in sheet 2.
The Scores/weights to be used are linguistic as shown below ranging from Absolutely high to Very Low.

I have modified the criteria list and provided this definition following initial consultation and agreement. Also for the assessment you can assume a BOP system with one Blind shear Ram, two annular preventers say 3 Pipe rams and a Casing shear ram.

This is entirely academic and so the gain may not be obvious at the outset.
While I understand the rigour involved, whatever attempt can be made would be appreciated.

Absolutely High	**AH**
Very High	**VH**
Fairly High	**FH**
Slightly High	**SH**
Medium High	**MH**
Medium	**M**
Medium Low	**ML**
Low	**L**
Very Low	**VL**

However before you proceed to Sheet 2 can you assign a level of importance (using the scale above or on a rank of 1 to 10) for the following criteria, listed below, in assessing the BOP system

Criteria	**Score/weight**
Improper maintenance 1- LOCS	
Improper maintenance 2- LOCM	
Occurrence Inspection/testing ineffectivenes	
System or Component Complexity	
Safeguards from Detectibility	
Safeguards from Redundancy	
Loss of a function (ANOTHER)	
Loss of Multiple functions	
Loss of all functions	

Criteria	Description
Improper maintenance-LOCS	Improper maintenance 1 (C1): This measures the chances for an inability to restore the system to a functional state (i.e. the failure mode condition effected) with contribution from a lack of supervision (Maintenance includes spares and consumables replacement).
Improper maintenance-LOCM	Improper maintenance 2 (C2): The chances for an inability to restore the system to a functional state but with contributions from a lack of competence by management (Maintenance includes spares and consumables replacement). Management captures all the personnel related profiling such as trainings received, job/shift factors etc.)
Occurrence Inspection/testing ineffectiveness	Occurrence due to Inspection/testing ineffectiveness (C3): This refers to the ability for the system to be tested or effectively inspected and assure perform its function as intended (this includes the testing interval contribution to effectiveness). This criterion is a positive variable, thus a lower score or weight would be assigned should a testing effectiveness most likely prevent failure mode occurrence and the contrary, would be a higher weight.
System or Component Complexity	System or Component Complexity (C4): This measures the level of complication in the system due to increased interaction from more components, or combination of components from different manufacturers and its effect on the proper functioning of the equipment. E.g. more hydraulic supply routes, more tubing or complex stacking of hydraulic pipes from a multi shuttle valve assembly, which can create more leak paths.

Criteria	Description
Safeguards from Detectability	Detectability (C5): This implies the ease of detecting a failure without it being hidden, i.e. the likelihood of a component or system functional state (working or not faulty) being noticed by a detection mechanism following an identified failure mode occurring. It is a negative variable.
Safeguards from Redundancy	Safeguards from Redundancy (C6): This is a measure of the system ability to recover from the occurrence of a fault or have alternative means or medium to ensure a fired function towards achieving well control is executed, i.e. a likelihood of a component or system function being safeguarded by redundancy following an identified failure mode occurring. This is a negative variable.
Loss of a function (ANOTHER)	Loss of a function (ANOTHER) (C7): The potential for this failure mode to lead to loss of another function.
Loss of Multiple functions	Loss of Multiple functions (C8): The potential for this failure mode to lead to loss of more than one function.
Loss of all functions	Loss of all functions (C9): The potential for this failure mode to lead to a complete loss of well control system function

		Improper maintenance- LOCS C_1									
Failure Modes	Failure Mode ID	ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	ML	ML	M	ML	ML	ML	M	ML	ML	L
Fixed Pipe Ram External Leakage	F_2	MH	FH	FH	FH	SH	FH	SH	FH	FH	FH
Single Acting SPM Valve External Leakage	F_3	ML	M	ML	ML	M	ML	ML	ML	M	ML
Single Acting SPM Valve Internal Leakage	F_4	M	ML	M	M	M	M	M	MH	M	M
Solenoid Valve Fail to Close	F_5	M	M	M	M	M	M	M	M	M	M
Solenoid Valve fail to Operate-low voltage	F_6	MH	MH	MH	SH	MH	MH	MH	MH	MH	MH
Choke and Kill Valve Internal Leakage	F_7	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Blind Shear Ram External Leakage	F_8	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Fixed Pipe Ram Fail to Close	F_{10}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Shuttle Valve coupling and Tubing External leakage	F_{11}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Shuttle Valve coupling and Tubing - Post SV to BOP External leal	F_{12}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Hydraulic Connectors Spuriously Unlatches	F_{14}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Double Acting SPM Valve External Leakage	F_{15}	M	ML	M	ML	M	M	M	M	L	ML
Double Acting SPM Valve Internal Leakage	F_{16}	SH	L	SH	SH	SH	FH	SH	SH	MH	SH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	ML	ML	M	ML	ML	ML	ML	ML	ML	ML
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	ML	M	L	L	M	ML	M	ML	M	L
Choke and Kill Valves External Leakage	F_{20}	M	M	L	M	M	ML	M	M	ML	ML
Shuttle Valve External Leakage	F_{21}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Shuttle Valve Coupling and Tubing Blockage	F_{22}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Riser BOP Flexible Joint External Leakage	F_{23}	VL	L	L	L	VL	L	L	VL	L	L
Small Bore Hydraulic tubing Leakage	F_{24}	FH	SH	FH	FH	FH	MH	FH	FH	VH	FH
Annular Preventer Internal Leakage	F_{25}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Subsea Accumulators Loss of Pre-charge gas	F_{26}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Blind Shear Ram Internal leakage	F_{27}	MH	M	M	M	MH	MH	MH	M	MH	M
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	ML	ML	SH	ML	ML	MH	ML	FH	ML	L
Blind Shear Ram Failts to Shear and Close well	F_{29}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Annular Preventer External Leakage	F_{30}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Check Valve Internal Leakage	F_{31}	L	L	L	L	L	L	L	L	L	L
Annular Preventer Fails to Close/seal	F_{32}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Choke and Kill Valves Fails to Close	F_{33}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Choke and Kill Valves Fails to Open	F_{34}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Check Valve Stuck Closed	F_{35}	L	VL	VL	L	VL	L	VL	VL	VL	VL
Fixed Pipe Ram Internal leakage	F_{36}	ML	M	ML	M	M	M	M	M	L	M

		Improper maintenance- LOCM C_2									
Failure Modes	Failure Mode ID	ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	AH	ML	FH	ML	ML	AH	ML	MH	ML	VH
Fixed Pipe Ram External Leakage	F_2	AH	AH	AH	AH	FH	AH	AH	VH	AH	FH
Single Acting SPM Valve External Leakage	F_3	ML	ML	ML	ML	VH	ML	FH	VH	AH	AH
Single Acting SPM Valve Internal Leakage	F_4	ML	ML	ML	FH	ML	ML	ML	ML	ML	ML
Solenoid Valve Fail to Close	F_5	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Solenoid Valve fail to Operate-low voltage	F_6	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valve Internal Leakage	F_7	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Blind Shear Ram External Leakage	F_8	L	L	L	L	L	L	L	L	L	L
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Fixed Pipe Ram Fail to Close	F_{10}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Shuttle Valve coupling and Tubing External leakage	F_{11}	M	M	M	M	MH	M	M	M	M	MH
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	M	M	M	M	M	M	M	M	M	M
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Hydraulic Connectors Spuriously Unlatches	F_{14}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Double Acting SPM Valve External Leakage	F_{15}	M	M	M	M	M	M	M	M	M	M
Double Acting SPM Valve Internal Leakage	F_{16}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	M	M	ML	M	M	M	ML	M	L	M
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	M	MH	M	M	ML	M	M	M	ML	L
Choke and Kill Valves External Leakage	F_{20}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Shuttle Valve External Leakage	F_{21}	FH	FH	SH	SH	SH	FH	SH	VH	VH	SH
Shuttle Valve Coupling and Tubing Blockage	F_{22}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Riser BOP Flexible Joint External Leakage	F_{23}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Small Bore Hydraulic tubing Leakage	F_{24}	L	L	L	L	L	L	L	L	L	L
Annular Preventer Internal Leakage	F_{25}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Subsea Accumulators Loss of Pre-charge gas	F_{26}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Blind Shear Ram Internal leakage	F_{27}	M	M	M	FH	M	M	M	MH	M	M
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	ML	ML	ML	L	ML	ML	ML	ML	ML	ML
Blind Shear Ram Failts to Shear and Close well	F_{29}	L	L	L	L	L	L	L	ML	L	M
Annular Preventer External Leakage	F_{30}	ML	L	ML	ML	ML	ML	L	ML	ML	L
Check Valve Internal Leakage	F_{31}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Annular Preventer Fails to Close/seal	F_{32}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Choke and Kill Valves Fails to Close	F_{33}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valves Fails to Open	F_{34}	M	M	M	M	M	M	M	M	M	M
Check Valve Stuck Closed	F_{35}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Fixed Pipe Ram Internal leakage	F_{36}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML

Failure Modes	Failure Mode ID	Inspection/testing ineffectivenes C_3									
		ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	L	L	L	L	L	L	L	L	L	L
Fixed Pipe Ram External Leakage	F_2	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Single Acting SPM Valve External Leakage	F_3	M	M	M	M	M	M	M	M	M	M
Single Acting SPM Valve Internal Leakage	F_4	M	M	M	M	M	M	M	M	M	M
Solenoid Valve Fail to Close	F_5	M	M	M	M	M	M	M	M	M	M
Solenoid Valve fail to Operate-low voltage	F_6	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valve Internal Leakage	F_7	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram External Leakage	F_8	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	L	L	L	L	L	L	L	L	L	L
Fixed Pipe Ram Fail to Close	F_{10}	L	L	L	L	L	L	L	L	L	L
Shuttle Valve coupling and Tubing External leakage	F_{11}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Hydraulic Connectors Spuriously Unlatches	F_{14}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Double Acting SPM Valve External Leakage	F_{15}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Double Acting SPM Valve Internal Leakage	F_{16}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves External Leakage	F_{20}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle Valve External Leakage	F_{21}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle Valve Coupling and Tubing Blockage	F_{22}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Riser BOP Flexible Joint External Leakage	F_{23}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Small Bore Hydraulic tubing Leakage	F_{24}	M	M	M	M	M	M	M	M	M	M
Annular Preventer Internal Leakage	F_{25}	L	L	L	L	L	L	L	L	L	L
Subsea Accumulators Loss of Pre-charge gas	F_{26}	M	M	M	M	M	M	M	M	M	M
Blind Shear Ram Internal leakage	F_{27}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Failts to Shear and Close well	F_{29}	L	L	L	L	L	L	L	L	L	L
Annular Preventer External Leakage	F_{30}	L	L	L	L	L	L	L	L	L	L
Check Valve Internal Leakage	F_{31}	M	M	M	M	M	M	M	M	M	M
Annular Preventer Fails to Close/seal	F_{32}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves Fails to Close	F_{33}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Choke and Kill Valves Fails to Open	F_{34}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Check Valve Stuck Closed	F_{35}	M	M	M	M	M	M	M	M	M	M
Fixed Pipe Ram Internal leakage	F_{36}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH

Failure Modes	Failure Mode ID	System or Component Complexity C_4									
		ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	L	L	L	L	L	L	L	L	L	L
Fixed Pipe Ram External Leakage	F_2	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Single Acting SPM Valve External Leakage	F_3	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Single Acting SPM Valve Internal Leakage	F_4	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Solenoid Valve Fail to Close	F_5	L	L	L	L	L	L	L	L	L	L
Solenoid Valve fail to Operate-low voltage	F_6	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valve Internal Leakage	F_7	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Blind Shear Ram External Leakage	F_8	L	L	L	L	L	L	L	L	L	L
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	L	L	L	L	L	L	L	L	L	L
Fixed Pipe Ram Fail to Close	F_{10}	L	L	L	L	L	L	L	L	L	L
Shuttle Valve coupling and Tubing External leakage	F_{11}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Hydraulic Connectors Spuriously Unlatches	F_{14}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Double Acting SPM Valve External Leakage	F_{15}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Double Acting SPM Valve Internal Leakage	F_{16}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves External Leakage	F_{20}	M	M	M	M	M	M	M	M	M	M
Shuttle Valve External Leakage	F_{21}	M	M	M	M	M	M	M	M	M	M
Shuttle Valve Coupling and Tubing Blockage	F_{22}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Riser BOP Flexible Joint External Leakage	F_{23}	M	M	M	M	M	M	M	M	M	M
Small Bore Hydraulic tubing Leakage	F_{24}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Annular Preventer Internal Leakage	F_{25}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Subsea Accumulators Loss of Pre-charge gas	F_{26}	M	M	M	M	M	M	M	M	M	M
Blind Shear Ram Internal leakage	F_{27}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Blind Shear Ram Failts to Shear and Close well	F_{29}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Annular Preventer External Leakage	F_{30}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Check Valve Internal Leakage	F_{31}	L	L	L	L	L	L	L	L	L	L
Annular Preventer Fails to Close/seal	F_{32}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Choke and Kill Valves Fails to Close	F_{33}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valves Fails to Open	F_{34}	M	M	M	M	M	M	M	M	M	M
Check Valve Stuck Closed	F_{35}	L	L	L	L	L	L	L	L	L	L
Fixed Pipe Ram Internal leakage	F_{36}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML

		Detectibility C_6									
Failure Modes	Failure Mode ID	ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Fixed Pipe Ram External Leakage	F_2	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Single Acting SPM Valve External Leakage	F_3	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Single Acting SPM Valve Internal Leakage	F_4	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Solenoid Valve Fail to Close	F_5	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Solenoid Valve fail to Operate-low voltage	F_6	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Choke and Kill Valve Internal Leakage	F_7	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Blind Shear Ram External Leakage	F_8	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Fixed Pipe Ram Fail to Close	F_{10}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Shuttle Valve coupling and Tubing External leakage	F_{11}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Hydraulic Connectors Spuriously Unlatches	F_{14}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Double Acting SPM Valve External Leakage	F_{15}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Double Acting SPM Valve Internal Leakage	F_{16}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Choke and Kill Valves External Leakage	F_{20}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Shuttle Valve External Leakage	F_{21}	M	M	M	M	M	M	M	M	M	M
Shuttle Valve Coupling and Tubing Blockage	F_{22}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Riser BOP Flexible Joint External Leakage	F_{23}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Small Bore Hydraulic tubing Leakage	F_{24}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Annular Preventer Internal Leakage	F_{25}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Subsea Accumulators Loss of Pre-charge gas	F_{26}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Blind Shear Ram Internal leakage	F_{27}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Blind Shear Ram Failts to Shear and Close well	F_{29}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Annular Preventer External Leakage	F_{30}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Check Valve Internal Leakage	F_{31}	M	M	M	M	M	M	M	M	M	M
Annular Preventer Fails to Close/seal	F_{32}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Choke and Kill Valves Fails to Close	F_{33}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Choke and Kill Valves Fails to Open	F_{34}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Check Valve Stuck Closed	F_{35}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Fixed Pipe Ram Internal leakage	F_{36}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH

		Safeguards from Redundancy C_8									
Failure Modes	Failure Mode ID	ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Fixed Pipe Ram External Leakage	F_2	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Single Acting SPM Valve External Leakage	F_3	L	L	L	L	L	L	L	L	L	L
Single Acting SPM Valve Internal Leakage	F_4	L	L	L	L	L	L	L	L	L	L
Solenoid Valve Fail to Close	F_5	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Solenoid Valve fail to Operate-low voltage	F_6	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Choke and Kill Valve Internal Leakage	F_7	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Blind Shear Ram External Leakage	F_8	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Fixed Pipe Ram Fail to Close	F_{10}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Shuttle Valve coupling and Tubing External leakage	F_{11}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Hydraulic Connectors Spuriously Unlatches	F_{14}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Double Acting SPM Valve External Leakage	F_{15}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Double Acting SPM Valve Internal Leakage	F_{16}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valves External Leakage	F_{20}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Shuttle Valve External Leakage	F_{21}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle Valve Coupling and Tubing Blockage	F_{22}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Riser BOP Flexible Joint External Leakage	F_{23}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Small Bore Hydraulic tubing Leakage	F_{24}	L	L	L	L	L	L	L	L	L	L
Annular Preventer Internal Leakage	F_{25}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Subsea Accumulators Loss of Pre-charge gas	F_{26}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Blind Shear Ram Internal leakage	F_{27}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Failts to Shear and Close well	F_{29}	L	L	L	L	L	L	L	L	L	L
Annular Preventer External Leakage	F_{30}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Check Valve Internal Leakage	F_{31}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Annular Preventer Fails to Close/seal	F_{32}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves Fails to Close	F_{33}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Choke and Kill Valves Fails to Open	F_{34}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Check Valve Stuck Closed	F_{35}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Fixed Pipe Ram Internal leakage	F_{36}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH

		Loss of a function (ANOTHER) C_7									
Failure Modes	Failure Mode ID	ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Fixed Pipe Ram External Leakage	F_2	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Single Acting SPM Valve External Leakage	F_3	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Single Acting SPM Valve Internal Leakage	F_4	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Solenoid Valve Fail to Close	F_5	M	M	M	M	M	M	M	M	M	M
Solenoid Valve fail to Operate-low voltage	F_6	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valve Internal Leakage	F_7	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Blind Shear Ram External Leakage	F_8	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Fixed Pipe Ram Fail to Close	F_{10}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle Valve coupling and Tubing External leakage	F_{11}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Hydraulic Connectors Spuriously Unlatches	F_{14}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Double Acting SPM Valve External Leakage	F_{15}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Double Acting SPM Valve Internal Leakage	F_{16}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Valves External Leakage	F_{20}	M	M	M	M	M	M	M	M	M	M
Shuttle Valve External Leakage	F_{21}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Shuttle Valve Coupling and Tubing Blockage	F_{22}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Riser BOP Flexible Joint External Leakage	F_{23}	L	L	L	L	L	L	L	L	L	L
Small Bore Hydraulic tubing Leakage	F_{24}	M	M	M	M	M	M	M	M	M	M
Annular Preventer Internal Leakage	F_{25}	L	L	L	L	L	L	L	L	L	L
Subsea Accumulators Loss of Pre-charge gas	F_{26}	AH	AH	AH	AH	AH	AH	AH	AH	AH	AH
Blind Shear Ram Internal leakage	F_{27}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Failts to Shear and Close well	F_{29}	L	L	L	L	L	L	L	L	L	L
Annular Preventer External Leakage	F_{30}	L	L	L	L	L	L	L	L	L	L
Check Valve Internal Leakage	F_{31}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Annular Preventer Fails to Close/seal	F_{32}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves Fails to Close	F_{33}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Choke and Kill Valves Fails to Open	F_{34}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Check Valve Stuck Closed	F_{35}	VL	VL	L	VL	VL	L	VL	VL	VL	VL
Fixed Pipe Ram Internal leakage	F_{36}	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH

Failure Modes	Failure Mode ID	Loss of Multiple functions C_8									
		ED_1	ED_2	ED_3	ED_4	ED_5	ED_6	ED_7	ED_8	ED_9	ED_{10}
Manifold Hydraulic Pressure Regulator Unstable output pressu	F_1	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Fixed Pipe Ram External Leakage	F_2	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Single Acting SPM Valve External Leakage	F_3	L	L	L	L	L	L	L	L	L	L
Single Acting SPM Valve Internal Leakage	F_4	L	L	L	L	L	L	L	L	L	L
Solenoid Valve Fail to Close	F_5	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Solenoid Valve fail to Operate-low voltage	F_6	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Choke and Kill Valve Internal Leakage	F_7	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Blind Shear Ram External Leakage	F_8	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
Annular Hydraulic Pressure Regulator Unstable output pressu	F_9	FH	FH	FH	FH	FH	FH	FH	FH	FH	FH
Fixed Pipe Ram Fail to Close	F_{10}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle Valve coupling and Tubing External leakage	F_{11}	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Shuttle Valve coupling and Tubing - Post SV to BOP External lea	F_{12}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Hydraulic Connectors Spuriously Unlatches	F_{14}	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
Double Acting SPM Valve External Leakage	F_{15}	M	M	M	M	M	M	M	M	M	M
Double Acting SPM Valve Internal Leakage	F_{16}	M	M	M	M	M	M	M	M	M	M
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves External Leakage	F_{20}	L	L	L	L	L	L	L	L	L	L
Shuttle Valve External Leakage	F_{21}	L	L	L	L	L	L	L	L	L	L
Shuttle Valve Coupling and Tubing Blockage	F_{22}	L	L	L	L	L	L	L	L	L	L
Riser BOP Flexible Joint External Leakage	F_{23}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Small Bore Hydraulic tubing Leakage	F_{24}	M	M	M	M	M	M	M	M	M	M
Annular Preventer Internal Leakage	F_{25}	L	L	L	L	L	L	L	L	L	L
Subsea Accumulators Loss of Pre-charge gas	F_{26}	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Blind Shear Ram Internal leakage	F_{27}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	L	L	L	L	L	L	L	L	L	L
Blind Shear Ram Failts to Shear and Close well	F_{29}	L	L	L	L	L	L	L	L	L	L
Annular Preventer External Leakage	F_{30}	L	L	L	L	L	L	L	L	L	L
Check Valve Internal Leakage	F_{31}	L	L	L	L	L	L	L	L	L	L
Annular Preventer Fails to Close/seal	F_{32}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves Fails to Close	F_{33}	L	L	L	L	L	L	L	L	L	L
Choke and Kill Valves Fails to Open	F_{34}	M	M	M	M	M	M	M	M	M	M
Check Valve Stuck Closed	F_{35}	L	L	L	L	L	L	L	L	L	L
Fixed Pipe Ram Internal leakage	F_{36}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML

B.2 BOP System Failure mode ranking data sheets

Table_Apx B-1: Vector normalised weights of expert crisp decision matrix (TOPSIS)

Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
F_1	0.1087	0.2011	0.1189	0.0906	0.1850	0.2310	0.2528	0.3112	0.0783
F_2	0.2246	0.2936	0.2525	0.1359	0.1619	0.1650	0.1966	0.1334	0.0783
F_3	0.1212	0.2064	0.2020	0.1359	0.1850	0.0660	0.2247	0.0889	0.0783
F_4	0.1426	0.1495	0.2020	0.1359	0.1850	0.0660	0.2247	0.0889	0.0783
F_5	0.1426	0.1779	0.2020	0.0906	0.2081	0.2970	0.1123	0.0445	0.0783
F_6	0.1890	0.1424	0.2020	0.0906	0.1619	0.2970	0.1123	0.0445	0.0783
F_7	0.2139	0.2491	0.1010	0.1359	0.1387	0.2640	0.0281	0.0445	0.0783
F_8	0.1070	0.0712	0.0505	0.0906	0.0694	0.0330	0.1966	0.1334	0.0783
F_9	0.0357	0.1779	0.1010	0.0906	0.1850	0.2310	0.2528	0.3112	0.0783
F_{10}	0.2496	0.2491	0.1010	0.0906	0.0694	0.1650	0.0281	0.0445	0.0783
F_{11}	0.2496	0.1548	0.1515	0.0453	0.1387	0.1980	0.2247	0.2223	0.0783
F_{12}	0.2496	0.1424	0.1515	0.0453	0.1387	0.0330	0.2528	0.3556	0.0783
F_{13}	0.3209	0.2491	0.3030	0.2266	0.2081	0.0330	0.2528	0.3556	0.7049
F_{14}	0.3209	0.2491	0.3030	0.2266	0.2081	0.0330	0.2528	0.2667	0.3916
F_{15}	0.1159	0.1424	0.3536	0.2719	0.0694	0.1650	0.2247	0.1778	0.0783
F_{16}	0.1800	0.2491	0.2525	0.2719	0.1156	0.1650	0.2247	0.1778	0.0783
F_{17}	0.1177	0.1424	0.1010	0.0906	0.2081	0.1320	0.1123	0.0889	0.0783
F_{18}	0.1070	0.1174	0.1010	0.0906	0.2081	0.1320	0.1123	0.0889	0.0783
F_{19}	0.1087	0.1281	0.1010	0.0906	0.2081	0.1320	0.1123	0.0889	0.0783
F_{20}	0.1159	0.1068	0.0505	0.1813	0.1850	0.1650	0.1123	0.0889	0.0783
F_{21}	0.1783	0.2438	0.0505	0.1813	0.0925	0.0330	0.2528	0.0889	0.0783
F_{22}	0.1070	0.1068	0.1515	0.0453	0.1619	0.0330	0.2247	0.0889	0.0783
F_{23}	0.0570	0.1068	0.1515	0.1813	0.1850	0.0330	0.0562	0.0445	0.0783
F_{24}	0.2371	0.0712	0.2020	0.2719	0.1387	0.0660	0.1123	0.1778	0.0783
F_{25}	0.1783	0.1068	0.1010	0.2266	0.1619	0.2970	0.0562	0.0889	0.0783
F_{26}	0.0357	0.0356	0.2020	0.1813	0.1850	0.2640	0.2528	0.3556	0.3916
F_{27}	0.1604	0.1762	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
F_{28}	0.1480	0.0961	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
F_{29}	0.1070	0.0943	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
F_{30}	0.1070	0.0925	0.1010	0.2266	0.1850	0.2970	0.0562	0.0889	0.0783
F_{31}	0.0713	0.1068	0.2020	0.0906	0.0925	0.2310	0.1404	0.0889	0.0783
F_{32}	0.2496	0.2491	0.1010	0.2266	0.1850	0.0660	0.0562	0.0889	0.0783
F_{33}	0.1070	0.1424	0.0505	0.1813	0.1850	0.1650	0.1404	0.0889	0.0783
F_{34}	0.1070	0.1424	0.0505	0.1813	0.1850	0.1650	0.1404	0.1778	0.0783
F_{35}	0.0596	0.1068	0.2020	0.0906	0.1850	0.1650	0.0379	0.0889	0.0783
F_{36}	0.1405	0.1068	0.2525	0.1359	0.1619	0.1650	0.1966	0.1334	0.0783

Table_Apx B-2: Weighted normalised weights of expert crisp decision matrix (TOPSIS)

Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
F_1	0.0111	0.0210	0.0128	0.0099	0.0191	0.0280	0.0270	0.0366	0.0100
F_2	0.0229	0.0307	0.0272	0.0148	0.0167	0.0200	0.0210	0.0157	0.0100
F_3	0.0124	0.0216	0.0218	0.0148	0.0191	0.0080	0.0240	0.0105	0.0100
F_4	0.0145	0.0156	0.0218	0.0148	0.0191	0.0080	0.0240	0.0105	0.0100
F_5	0.0145	0.0186	0.0218	0.0099	0.0215	0.0360	0.0120	0.0052	0.0100
F_6	0.0193	0.0149	0.0218	0.0099	0.0167	0.0360	0.0120	0.0052	0.0100
F_7	0.0218	0.0261	0.0109	0.0148	0.0143	0.0320	0.0030	0.0052	0.0100
F_8	0.0109	0.0075	0.0054	0.0099	0.0072	0.0040	0.0210	0.0157	0.0100
F_9	0.0036	0.0186	0.0109	0.0099	0.0191	0.0280	0.0270	0.0366	0.0100
F_{10}	0.0255	0.0261	0.0109	0.0099	0.0072	0.0200	0.0030	0.0052	0.0100
F_{11}	0.0255	0.0162	0.0163	0.0049	0.0143	0.0240	0.0240	0.0261	0.0100
F_{12}	0.0255	0.0149	0.0163	0.0049	0.0143	0.0040	0.0270	0.0418	0.0100
F_{13}	0.0327	0.0261	0.0326	0.0246	0.0215	0.0040	0.0270	0.0418	0.0903
F_{14}	0.0327	0.0261	0.0326	0.0246	0.0215	0.0040	0.0270	0.0314	0.0502
F_{15}	0.0118	0.0149	0.0381	0.0296	0.0072	0.0200	0.0240	0.0209	0.0100
F_{16}	0.0184	0.0261	0.0272	0.0296	0.0119	0.0200	0.0240	0.0209	0.0100
F_{17}	0.0120	0.0149	0.0109	0.0099	0.0215	0.0160	0.0120	0.0105	0.0100
F_{18}	0.0109	0.0123	0.0109	0.0099	0.0215	0.0160	0.0120	0.0105	0.0100
F_{19}	0.0111	0.0134	0.0109	0.0099	0.0215	0.0160	0.0120	0.0105	0.0100
F_{20}	0.0118	0.0112	0.0054	0.0197	0.0191	0.0200	0.0120	0.0105	0.0100
F_{21}	0.0182	0.0255	0.0054	0.0197	0.0095	0.0040	0.0270	0.0105	0.0100
F_{22}	0.0109	0.0112	0.0163	0.0049	0.0167	0.0040	0.0240	0.0105	0.0100
F_{23}	0.0058	0.0112	0.0163	0.0197	0.0191	0.0040	0.0060	0.0052	0.0100
F_{24}	0.0242	0.0075	0.0218	0.0296	0.0143	0.0080	0.0120	0.0209	0.0100
F_{25}	0.0182	0.0112	0.0109	0.0246	0.0167	0.0360	0.0060	0.0105	0.0100
F_{26}	0.0036	0.0037	0.0218	0.0197	0.0191	0.0320	0.0270	0.0418	0.0502
F_{27}	0.0164	0.0184	0.0109	0.0246	0.0191	0.0080	0.0060	0.0105	0.0100
F_{28}	0.0151	0.0101	0.0109	0.0246	0.0191	0.0080	0.0060	0.0105	0.0100
F_{29}	0.0109	0.0099	0.0109	0.0246	0.0191	0.0080	0.0060	0.0105	0.0100
F_{30}	0.0109	0.0097	0.0109	0.0246	0.0191	0.0360	0.0060	0.0105	0.0100
F_{31}	0.0073	0.0112	0.0218	0.0099	0.0095	0.0280	0.0150	0.0105	0.0100
F_{32}	0.0255	0.0261	0.0109	0.0246	0.0191	0.0080	0.0060	0.0105	0.0100
F_{33}	0.0109	0.0149	0.0054	0.0197	0.0191	0.0200	0.0150	0.0105	0.0100
F_{34}	0.0109	0.0149	0.0054	0.0197	0.0191	0.0200	0.0150	0.0209	0.0100
F_{35}	0.0061	0.0112	0.0218	0.0099	0.0191	0.0200	0.0040	0.0105	0.0100
F_{36}	0.0143	0.0112	0.0272	0.0148	0.0167	0.0200	0.0210	0.0157	0.0100

Table_Apx B-3 : Distance measures, relative closeness coefficients, and ranking for failure modes (TOPSIS)

Failure modes	Failure Mode ID	D^+_i	D^-_i	RCi	Ranking
Manifold Hydraulic Pressure Regulator Unstable c	F_1	0.0937	0.0454	0.3264	12
Fixed Pipe Ram External Leakage	F_2	0.0891	0.0488	0.3539	9
Single Acting SPM Valve External Leakage	F_3	0.0926	0.0449	0.3266	11
Single Acting SPM Valve Internal Leakage	F_4	0.0930	0.0434	0.3182	13
Solenoid Valve Fail to Close	F_5	0.1018	0.0267	0.2077	33
Solenoid Valve fail to Operate-low voltage	F_6	0.1011	0.0276	0.2147	28
Choke and Kill Valve Internal Leakage	F_7	0.1015	0.0320	0.2398	24
Blind Shear Ram External Leakage	F_8	0.0982	0.0419	0.2990	17
Annular Hydraulic Pressure Regulator Unstable o	F_9	0.0965	0.0436	0.3114	15
Fixed Pipe Ram Fail to Close	F_{10}	0.0991	0.0386	0.2803	19
Shuttle Valve coupling and Tubing External leakag	F_{11}	0.0922	0.0427	0.3165	14
Shuttle Valve coupling and Tubing - Post SV to B	F_{12}	0.0888	0.0609	0.4069	4
Welhead Hydraulic Connectors Spuriously Unlatc	F_{13}	0.0167	0.1089	0.8668	1
Hydraulic Connectors Spuriously Unlatches	F_{14}	0.0447	0.0798	0.6408	2
Double Acting SPM Valve External Leakage	F_{15}	0.0885	0.0549	0.3827	5
Double Acting SPM Valve Internal Leakage	F_{16}	0.0867	0.0532	0.3803	6
Choke and Kill Line (Jumper hoseline) External L	F_{17}	0.0991	0.0275	0.2174	26
Choke and Kill Line (Riser Attached Line) Externa	F_{18}	0.0997	0.0262	0.2083	32
Choke and Kill Line (BOP Attached Line) Externa	F_{19}	0.0995	0.0267	0.2115	30
Choke and Kill Valves External Leakage	F_{20}	0.1002	0.0267	0.2102	31
Shuttle Valve External Leakage	F_{21}	0.0940	0.0517	0.3549	8
Shuttle Valve Coupling and Tubing Blockage	F_{22}	0.0973	0.0417	0.3002	16
Riser BOP Flexible Joint External Leakage	F_{23}	0.1002	0.0379	0.2744	21
Small Bore Hydraulic tubing Leakage	F_{24}	0.0898	0.0497	0.3565	7
Annular Preventer Internal Leakage	F_{25}	0.1017	0.0273	0.2115	29
Subsea Accumulators Loss of Pre-charge gas	F_{26}	0.0669	0.0635	0.4869	3
Blind Shear Ram Internal leakage	F_{27}	0.0960	0.0403	0.2957	18
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	0.0976	0.0376	0.2782	20
Blind Shear Ram Failts to Shear and Close well	F_{29}	0.0985	0.0366	0.2706	22
Annular Preventer External Leakage	F_{30}	0.1035	0.0234	0.1845	35
Check Valve Internal Leakage	F_{31}	0.0992	0.0271	0.2148	27
Annular Preventer Fails to Close/seal	F_{32}	0.0942	0.0471	0.3335	10
Choke and Kill Valves Fails to Close	F_{33}	0.0993	0.0288	0.2248	25
Choke and Kill Valves Fails to Open	F_{34}	0.0965	0.0324	0.2512	23
Check Valve Stuck Closed	F_{35}	0.1005	0.0254	0.2014	34
Fixed Pipe Ram Internal leakage	F_{36}	0.0926	0.0381	0.2916	19

B.2.1 BOP System Failure mode ranking Using Fuzzy TOPSIS

Table_Apx B-4 : Normalised Aggregate Fuzzy Expert Decision Matrix

Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
F_1	(0.1, 0.31, 0.5)	(0.2, 0.53, 1)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0, 0.1, 0.2)
F_2	(0.4, 0.66, 0.8)	(0.6, 0.85, 1)	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0, 0, 0)	(0, 0, 0)	(0.6, 0.7, 0.8)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)
F_3	(0.2, 0.33, 0.5)	(0.2, 0.56, 1)	(0.3, 0.4, 0.5)	(0.2, 0.3, 0.4)	(0, 0, 0)	(0, 0, 0)	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_4	(0.2222, 0.4444, 0.6)	(0.2222, 0.3778, 0.8889)	(0.3333, 0.4444, 0.5556)	(0.2222, 0.3333, 0.4444)	(0, 0, 0)	(0, 0, 0)	(0.7778, 0.8, 1)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_5	(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
F_6	(0.4, 0.51, 0.7)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.3, 0.4, 0.5)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
F_7	(0.5556, 0.6667, 0.7)	(0.6667, 0.7778, 0.8889)	(0.1111, 0.2222, 0.3333)	(0.2222, 0.3333, 0.4444)	(0, 0, 0)	(0, 0, 0)	(0, 0.1, 0.2222)	(0, 0.1111, 0.2222)	(0, 0.1111, 0.2222)
F_8	(0.25, 0.375, 0.4)	(0.125, 0.25, 0.375)	(0, 0.125, 0.25)	(0.125, 0.25, 0.375)	(0, 0, 0)	(0, 0, 0)	(0.75, 0.7, 1)	(0.25, 0.375, 0.5)	(0, 0.125, 0.25)
F_9	(0, 0.1, 0.2)	(0.4, 0.5, 0.6)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0, 0.1, 0.2)
F_{10}	(0.75, 0.875, 0.8)	(0.75, 0.875, 1)	(0.125, 0.25, 0.375)	(0.125, 0.25, 0.375)	(0, 0, 0)	(0, 0, 0)	(0, 0.1, 0.25)	(0, 0.125, 0.25)	(0, 0.125, 0.25)
F_{11}	(0.6667, 0.7778, 0.8)	(0.3333, 0.4667, 0.6667)	(0.2222, 0.3333, 0.4444)	(0, 0.1111, 0.2222)	(0, 0, 0)	(0, 0, 0)	(0.7778, 0.8, 1)	(0.4444, 0.5556, 0.6667)	(0, 0.1111, 0.2222)
F_{12}	(0.6, 0.7, 0.8)	(0.3, 0.4, 0.5)	(0.2, 0.3, 0.4)	(0, 0.1, 0.2)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0, 0.1, 0.2)
F_{13}	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0, 0.9, 1)
F_{14}	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.5, 0.6, 0.7)	(0, 0.5, 0.6)
F_{15}	(0.1111, 0.3889, 0.5)	(0.3333, 0.4444, 0.5556)	(0.6667, 0.7778, 0.8889)	(0.5556, 0.6667, 0.7778)	(0, 0, 0)	(0, 0, 0)	(0.7778, 0.8, 1)	(0.3333, 0.4444, 0.5556)	(0, 0.1111, 0.2222)
F_{16}	(0.1111, 0.6222, 0.8)	(0.6667, 0.7778, 0.8889)	(0.4444, 0.5556, 0.6667)	(0.5556, 0.6667, 0.7778)	(0, 0, 0)	(0, 0, 0)	(0.7778, 0.8, 1)	(0.3333, 0.4444, 0.5556)	(0, 0.1111, 0.2222)
F_{17}	(0.2, 0.31, 0.5)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_{18}	(0.2, 0.3, 0.4)	(0.1, 0.36, 0.5)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_{19}	(0.1, 0.31, 0.5)	(0.1, 0.37, 0.6)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_{20}	(0.1111, 0.3889, 0.5)	(0.2222, 0.3333, 0.4444)	(0, 0.1111, 0.2222)	(0.3333, 0.4444, 0.5556)	(0, 0, 0)	(0, 0, 0)	(0.3333, 0.4, 0.5556)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{21}	(0.4, 0.5, 0.6)	(0.5, 0.67, 0.9)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_{22}	(0.2222, 0.3333, 0.4)	(0.2222, 0.3333, 0.4444)	(0.2222, 0.3333, 0.4444)	(0, 0.1111, 0.2222)	(0, 0, 0)	(0, 0, 0)	(0.7778, 0.8, 1)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{23}	(0, 0.1889, 0.3)	(0.2222, 0.3333, 0.4444)	(0.2222, 0.3333, 0.4444)	(0.3333, 0.4444, 0.5556)	(0, 0, 0)	(0, 0, 0)	(0.1111, 0.2, 0.3333)	(0, 0.1111, 0.2222)	(0, 0.1111, 0.2222)
F_{24}	(0.4444, 0.7556, 0.9)	(0.1111, 0.2222, 0.3333)	(0.3333, 0.4444, 0.5556)	(0.5556, 0.6667, 0.7778)	(0, 0, 0)	(0, 0, 0)	(0.3333, 0.4, 0.5556)	(0.3333, 0.4444, 0.5556)	(0, 0.1111, 0.2222)
F_{25}	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0, 0, 0)	(0, 0, 0)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_{26}	(0, 0.1, 0.2)	(0, 0.1, 0.2)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0, 0, 0)	(0, 0, 0)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0, 0.5, 0.6)
F_{27}	(0.3333, 0.5, 0.6)	(0.3333, 0.4889, 0.8889)	(0.1111, 0.2222, 0.3333)	(0.4444, 0.5556, 0.6667)	(0, 0, 0)	(0, 0, 0)	(0.1111, 0.2, 0.3333)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{28}	(0.1111, 0.4222, 0.8)	(0.1111, 0.3222, 0.4444)	(0.1111, 0.2222, 0.3333)	(0.4444, 0.5556, 0.6667)	(0, 0, 0)	(0, 0, 0)	(0.1111, 0.2, 0.3333)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{29}	(0.2222, 0.3333, 0.4)	(0.1111, 0.2556, 0.5556)	(0.1111, 0.2222, 0.3333)	(0.4444, 0.5556, 0.6667)	(0, 0, 0)	(0, 0, 0)	(0.1111, 0.2, 0.3333)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{30}	(0.2, 0.3, 0.4)	(0.1, 0.27, 0.4)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0, 0, 0)	(0, 0, 0)	(0.1, 0.2, 0.3)	(0.1, 0.2, 0.3)	(0, 0.1, 0.2)
F_{31}	(0.125, 0.25, 0.3)	(0.25, 0.375, 0.5)	(0.375, 0.5, 0.625)	(0.125, 0.25, 0.375)	(0, 0, 0)	(0, 0, 0)	(0.5, 0.5, 0.75)	(0.125, 0.25, 0.375)	(0, 0.125, 0.25)
F_{32}	(0.6667, 0.7778, 0.8)	(0.6667, 0.7778, 0.8889)	(0.1111, 0.2222, 0.3333)	(0.4444, 0.5556, 0.6667)	(0, 0, 0)	(0, 0, 0)	(0.1111, 0.2, 0.3333)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{33}	(0.2222, 0.3333, 0.4)	(0.3333, 0.4444, 0.5556)	(0, 0.1111, 0.2222)	(0.3333, 0.4444, 0.5556)	(0, 0, 0)	(0, 0, 0)	(0.4444, 0.5, 0.6667)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{34}	(0.2222, 0.3333, 0.4)	(0.3333, 0.4444, 0.5556)	(0, 0.1111, 0.2222)	(0.3333, 0.4444, 0.5556)	(0, 0, 0)	(0, 0, 0)	(0.4444, 0.5, 0.6667)	(0.3333, 0.4444, 0.5556)	(0, 0.1111, 0.2222)
F_{35}	(0, 0.1444, 0.3)	(0.2222, 0.3333, 0.4444)	(0.3333, 0.4444, 0.5556)	(0.1111, 0.2222, 0.3333)	(0, 0, 0)	(0, 0, 0)	(0, 0.12, 0.3333)	(0.1111, 0.2222, 0.3333)	(0, 0.1111, 0.2222)
F_{36}	(0.125, 0.45, 0.5)	(0.25, 0.375, 0.5)	(0.5, 0.625, 0.75)	(0.25, 0.375, 0.5)	(0, 0, 0)	(0, 0, 0)	(0.75, 0.7, 1)	(0.25, 0.375, 0.5)	(0, 0.125, 0.25)

Table_Apx B-5 : Weighted Normalised Aggregate Fuzzy Expert Decision Matrix

Failure Mode ID	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
F_1	(0.07, 0.248, 0.45)	(0.12, 0.371, 0.8)	(0.07, 0.16, 0.27)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.48, 0.63, 0.8)	(0, 0.09, 0.2)
F_2	(0.28, 0.528, 0.72)	(0.36, 0.595, 0.8)	(0.28, 0.4, 0.54)	(0.06, 0.12, 0.2)	(0, 0, 0)	(0, 0, 0)	(0.48, 0.63, 0.8)	(0.16, 0.27, 0.4)	(0, 0.09, 0.2)
F_3	(0.14, 0.264, 0.45)	(0.12, 0.392, 0.8)	(0.21, 0.32, 0.45)	(0.06, 0.12, 0.2)	(0, 0, 0)	(0, 0, 0)	(0.56, 0.72, 0.9)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_4	(0.1556, 0.3556, 0.54)	(0.1333, 0.2644, 0.7111)	(0.2333, 0.3556, 0.5)	(0.0667, 0.1333, 0.2222)	(0, 0, 0)	(0, 0, 0)	(0.6222, 0.72, 1)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_5	(0.21, 0.32, 0.45)	(0.24, 0.35, 0.48)	(0.21, 0.32, 0.45)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.24, 0.36, 0.5)	(0, 0.09, 0.2)	(0, 0.09, 0.2)
F_6	(0.28, 0.408, 0.63)	(0.18, 0.28, 0.4)	(0.21, 0.32, 0.45)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.24, 0.36, 0.5)	(0, 0.09, 0.2)	(0, 0.09, 0.2)
F_7	(0.3889, 0.5333, 0.63)	(0.4, 0.5444, 0.7111)	(0.0778, 0.1778, 0.3)	(0.0667, 0.1333, 0.2222)	(0, 0, 0)	(0, 0, 0)	(0, 0.09, 0.2222)	(0, 0.1, 0.2222)	(0, 0.1, 0.2222)
F_8	(0.175, 0.3, 0.36)	(0.075, 0.175, 0.3)	(0, 0.1, 0.225)	(0.0375, 0.1, 0.1875)	(0, 0, 0)	(0, 0, 0)	(0.6, 0.63, 1)	(0.2, 0.3375, 0.5)	(0, 0.1125, 0.25)
F_9	(0, 0.08, 0.18)	(0.24, 0.35, 0.48)	(0.07, 0.16, 0.27)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.48, 0.63, 0.8)	(0, 0.09, 0.2)
F_{10}	(0.525, 0.7, 0.72)	(0.45, 0.6125, 0.8)	(0.0875, 0.2, 0.3375)	(0.0375, 0.1, 0.1875)	(0, 0, 0)	(0, 0, 0)	(0, 0.09, 0.25)	(0, 0.1125, 0.25)	(0, 0.1125, 0.25)
F_{11}	(0.4667, 0.6222, 0.72)	(0.2, 0.3267, 0.5333)	(0.1556, 0.2667, 0.4)	(0, 0.0444, 0.1111)	(0, 0, 0)	(0, 0, 0)	(0.6222, 0.72, 1)	(0.3556, 0.5, 0.6667)	(0, 0.1, 0.2222)
F_{12}	(0.42, 0.56, 0.72)	(0.18, 0.28, 0.4)	(0.14, 0.24, 0.36)	(0, 0.04, 0.1)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.56, 0.72, 0.9)	(0, 0.09, 0.2)
F_{13}	(0.56, 0.72, 0.9)	(0.36, 0.49, 0.64)	(0.35, 0.48, 0.63)	(0.12, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.56, 0.72, 0.9)	(0, 0.81, 1)
F_{14}	(0.56, 0.72, 0.9)	(0.36, 0.49, 0.64)	(0.35, 0.48, 0.63)	(0.12, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.4, 0.54, 0.7)	(0, 0.45, 0.6)
F_{15}	(0.0778, 0.3111, 0.45)	(0.2, 0.3111, 0.4444)	(0.4667, 0.6222, 0.8)	(0.1667, 0.2667, 0.3889)	(0, 0, 0)	(0, 0, 0)	(0.6222, 0.72, 1)	(0.2667, 0.4, 0.5556)	(0, 0.1, 0.2222)
F_{16}	(0.0778, 0.4978, 0.72)	(0.4, 0.5444, 0.7111)	(0.3111, 0.4444, 0.6)	(0.1667, 0.2667, 0.3889)	(0, 0, 0)	(0, 0, 0)	(0.6222, 0.72, 1)	(0.2667, 0.4, 0.5556)	(0, 0.1, 0.2222)
F_{17}	(0.14, 0.248, 0.45)	(0.18, 0.28, 0.4)	(0.07, 0.16, 0.27)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.24, 0.36, 0.5)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_{18}	(0.14, 0.24, 0.36)	(0.06, 0.252, 0.4)	(0.07, 0.16, 0.27)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.24, 0.36, 0.5)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_{19}	(0.07, 0.248, 0.45)	(0.06, 0.259, 0.48)	(0.07, 0.16, 0.27)	(0.03, 0.08, 0.15)	(0, 0, 0)	(0, 0, 0)	(0.24, 0.36, 0.5)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_{20}	(0.0778, 0.3111, 0.45)	(0.1333, 0.2333, 0.3556)	(0, 0.0889, 0.2)	(0.1, 0.1778, 0.2778)	(0, 0, 0)	(0, 0, 0)	(0.2667, 0.36, 0.5556)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{21}	(0.28, 0.4, 0.54)	(0.3, 0.469, 0.72)	(0, 0.08, 0.18)	(0.09, 0.16, 0.25)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_{22}	(0.1556, 0.2667, 0.36)	(0.1333, 0.2333, 0.3556)	(0.1556, 0.2667, 0.4)	(0, 0.0444, 0.1111)	(0, 0, 0)	(0, 0, 0)	(0.6222, 0.72, 1)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{23}	(0, 0.1511, 0.27)	(0.1333, 0.2333, 0.3556)	(0.1556, 0.2667, 0.4)	(0.1, 0.1778, 0.2778)	(0, 0, 0)	(0, 0, 0)	(0.0889, 0.18, 0.3333)	(0, 0.1, 0.2222)	(0, 0.1, 0.2222)
F_{24}	(0.3111, 0.6044, 0.81)	(0.0667, 0.1556, 0.2667)	(0.2333, 0.3556, 0.5)	(0.1667, 0.2667, 0.3889)	(0, 0, 0)	(0, 0, 0)	(0.2667, 0.36, 0.5556)	(0.2667, 0.4, 0.5556)	(0, 0.1, 0.2222)
F_{25}	(0.28, 0.4, 0.54)	(0.12, 0.21, 0.32)	(0.07, 0.16, 0.27)	(0.12, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.08, 0.18, 0.3)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_{26}	(0, 0.08, 0.18)	(0, 0.07, 0.16)	(0.21, 0.32, 0.45)	(0.09, 0.16, 0.25)	(0, 0, 0)	(0, 0, 0)	(0.64, 0.81, 1)	(0.56, 0.72, 0.9)	(0, 0.45, 0.6)
F_{27}	(0.2333, 0.4, 0.54)	(0.2, 0.3422, 0.7111)	(0.0778, 0.1778, 0.3)	(0.1333, 0.2222, 0.3333)	(0, 0, 0)	(0, 0, 0)	(0.0889, 0.18, 0.3333)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{28}	(0.0778, 0.3378, 0.72)	(0.0667, 0.2256, 0.3556)	(0.0778, 0.1778, 0.3)	(0.1333, 0.2222, 0.3333)	(0, 0, 0)	(0, 0, 0)	(0.0889, 0.18, 0.3333)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{29}	(0.1556, 0.2667, 0.36)	(0.0667, 0.1789, 0.4444)	(0.0778, 0.1778, 0.3)	(0.1333, 0.2222, 0.3333)	(0, 0, 0)	(0, 0, 0)	(0.0889, 0.18, 0.3333)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{30}	(0.14, 0.24, 0.36)	(0.06, 0.189, 0.32)	(0.07, 0.16, 0.27)	(0.12, 0.2, 0.3)	(0, 0, 0)	(0, 0, 0)	(0.08, 0.18, 0.3)	(0.08, 0.18, 0.3)	(0, 0.09, 0.2)
F_{31}	(0.0875, 0.2, 0.27)	(0.15, 0.2625, 0.4)	(0.2625, 0.4, 0.5625)	(0.0375, 0.1, 0.1875)	(0, 0, 0)	(0, 0, 0)	(0.4, 0.45, 0.75)	(0.1, 0.225, 0.375)	(0, 0.1125, 0.25)
F_{32}	(0.4667, 0.6222, 0.72)	(0.4, 0.5444, 0.7111)	(0.0778, 0.1778, 0.3)	(0.1333, 0.2222, 0.3333)	(0, 0, 0)	(0, 0, 0)	(0.0889, 0.18, 0.3333)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{33}	(0.1556, 0.2667, 0.36)	(0.2, 0.3111, 0.4444)	(0, 0.0889, 0.2)	(0.1, 0.1778, 0.2778)	(0, 0, 0)	(0, 0, 0)	(0.3556, 0.45, 0.6667)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{34}	(0.1556, 0.2667, 0.36)	(0.2, 0.3111, 0.4444)	(0, 0.0889, 0.2)	(0.1, 0.1778, 0.2778)	(0, 0, 0)	(0, 0, 0)	(0.3556, 0.45, 0.6667)	(0.2667, 0.4, 0.5556)	(0, 0.1, 0.2222)
F_{35}	(0, 0.1156, 0.27)	(0.1333, 0.2333, 0.3556)	(0.2333, 0.3556, 0.5)	(0.0333, 0.0889, 0.1667)	(0, 0, 0)	(0, 0, 0)	(0, 0.108, 0.3333)	(0.0889, 0.2, 0.3333)	(0, 0.1, 0.2222)
F_{36}	(0.0875, 0.36, 0.45)	(0.15, 0.2625, 0.4)	(0.35, 0.5, 0.675)	(0.075, 0.15, 0.25)	(0, 0, 0)	(0, 0, 0)	(0.6, 0.63, 1)	(0.2, 0.3375, 0.5)	(0, 0.1125, 0.25)

Table_Apx B-6 : Distance measures, relative closeness coefficients, and ranking for failure modes (Fuzzy-TOPSIS)

Failure Mode ID	D^+_i	D^-_i	RC_i	Ranking
F_1	7.1005	3.0295	0.2991	9
F_2	6.8735	3.1465	0.3140	6
F_3	7.3720	2.6930	0.2676	15
F_4	7.2856	2.8289	0.2797	11
F_5	7.7300	2.0200	0.2072	26
F_6	7.7160	2.0790	0.2123	24
F_7	7.6939	2.1044	0.2148	23
F_8	7.5788	2.2888	0.2319	19
F_9	7.1700	2.6400	0.2691	14
F_{10}	7.4863	2.3613	0.2398	17
F_{11}	6.8100	3.1167	0.3140	7
F_{12}	6.6600	3.2100	0.3252	5
F_{13}	5.5900	4.8000	0.4620	1
F_{14}	5.9400	4.2300	0.4159	2
F_{15}	6.7344	3.2961	0.3286	4
F_{16}	6.5911	3.5856	0.3523	3
F_{17}	7.9310	1.8340	0.1878	30
F_{18}	8.0090	1.7710	0.1811	33
F_{19}	8.0365	1.8635	0.1882	29
F_{20}	7.9311	1.9328	0.1959	28
F_{21}	7.2105	2.6895	0.2717	13
F_{22}	7.5067	2.3067	0.2351	18
F_{23}	8.1567	1.6450	0.1678	36
F_{24}	7.2233	2.7706	0.2772	12
F_{25}	7.9150	1.8250	0.1874	31
F_{26}	6.9450	3.0750	0.3069	8
F_{27}	7.7778	2.1978	0.2203	22
F_{28}	8.0117	2.0206	0.2014	27
F_{29}	8.0317	1.8261	0.1852	32
F_{30}	8.1055	1.6445	0.1687	35
F_{31}	7.6063	2.2725	0.2300	21
F_{32}	7.3489	2.5000	0.2538	16
F_{33}	7.7528	2.0494	0.2091	25
F_{34}	7.5639	2.2606	0.2301	20
F_{35}	8.1549	1.6912	0.1718	34
F_{36}	7.0925	2.9388	0.2930	10

B.2.2 BOP System Failure mode ranking Using Fuzzy TOPSIS - Interval method

Table_Apx B-7 : Fuzzy Expert interval decision matrix

	C_1 (L)	C_1 (U)	C_2 (L)	C_2 (U)	C_3 (L)	C_3 (U)	C_4 (L)	C_4 (U)	C_5 (L)	C_5 (U)	C_6 (L)	C_6 (U)	C_7 (L)	C_7 (U)	C_8 (L)	C_8 (U)	C_9 (L)	C_9 (U)
	0.101978427		0.104674271		0.107727557		0.108785552		0.10310746		0.121272412		0.106743027		0.117563964		0.128147328	
F_1	0.1	0.5	0.2	1	0.1	0.3	0.1	0.3	0.7	0.9	0.6	0.8	0.8	1	0.6	0.8	0	0.2
F_2	0.4	0.8	0.6	1	0.4	0.6	0.2	0.4	0.6	0.8	0.4	0.6	0.6	0.8	0.2	0.4	0	0.2
F_3	0.2	0.5	0.2	1	0.3	0.5	0.2	0.4	0.7	0.9	0.1	0.3	0.7	0.9	0.1	0.3	0	0.2
F_4	0.2	0.6	0.2	0.8	0.3	0.5	0.2	0.4	0.7	0.9	0.1	0.3	0.7	0.9	0.1	0.3	0	0.2
F_5	0.3	0.5	0.4	0.6	0.3	0.5	0.1	0.3	0.8	1	0.8	1	0.3	0.5	0	0.2	0	0.2
F_6	0.4	0.7	0.3	0.5	0.3	0.5	0.1	0.3	0.6	0.8	0.8	1	0.3	0.5	0	0.2	0	0.2
F_7	0.5	0.7	0.6	0.8	0.1	0.3	0.2	0.4	0.5	0.7	0.7	0.9	0	0.2	0	0.2	0	0.2
F_8	0.2	0.4	0.1	0.3	0	0.2	0.1	0.3	0.2	0.4	0	0.2	0.6	0.8	0.2	0.4	0	0.2
F_9	0	0.2	0.4	0.6	0.1	0.3	0.1	0.3	0.7	0.9	0.6	0.8	0.8	1	0.6	0.8	0	0.2
F_{10}	0.6	0.8	0.6	0.8	0.1	0.3	0.1	0.3	0.2	0.4	0.4	0.6	0	0.2	0	0.2	0	0.2
F_{11}	0.6	0.8	0.3	0.6	0.2	0.4	0	0.2	0.5	0.7	0.5	0.7	0.7	0.9	0.4	0.6	0	0.2
F_{12}	0.6	0.8	0.3	0.5	0.2	0.4	0	0.2	0.5	0.7	0	0.2	0.8	1	0.7	0.9	0	0.2
F_{13}	0.8	1	0.6	0.8	0.5	0.7	0.4	0.6	0.8	1	0	0.2	0.8	1	0.7	0.9	0.8	1
F_{14}	0.8	1	0.6	0.8	0.5	0.7	0.4	0.6	0.8	1	0	0.2	0.8	1	0.5	0.7	0.4	0.6
F_{15}	0.1	0.5	0.3	0.5	0.6	0.8	0.5	0.7	0.2	0.4	0.4	0.6	0.7	0.9	0.3	0.5	0	0.2
F_{16}	0.1	0.8	0.6	0.8	0.4	0.6	0.5	0.7	0.4	0.6	0.4	0.6	0.7	0.9	0.3	0.5	0	0.2
F_{17}	0.2	0.5	0.3	0.5	0.1	0.3	0.1	0.3	0.8	1	0.3	0.5	0.3	0.5	0.1	0.3	0	0.2
F_{18}	0.2	0.4	0.1	0.5	0.1	0.3	0.1	0.3	0.8	1	0.3	0.5	0.3	0.5	0.1	0.3	0	0.2
F_{19}	0.1	0.5	0.1	0.6	0.1	0.3	0.1	0.3	0.8	1	0.3	0.5	0.3	0.5	0.1	0.3	0	0.2
F_{20}	0.1	0.5	0.2	0.4	0	0.2	0.3	0.5	0.7	0.9	0.4	0.6	0.3	0.5	0.1	0.3	0	0.2
F_{21}	0.4	0.6	0.5	0.9	0	0.2	0.3	0.5	0.3	0.5	0	0.2	0.8	1	0.1	0.3	0	0.2
F_{22}	0.2	0.4	0.2	0.4	0.2	0.4	0	0.2	0.6	0.8	0	0.2	0.7	0.9	0.1	0.3	0	0.2
F_{23}	0	0.3	0.2	0.4	0.2	0.4	0.3	0.5	0.7	0.9	0	0.2	0.1	0.3	0	0.2	0	0.2
F_{24}	0.4	0.9	0.1	0.3	0.3	0.5	0.5	0.7	0.5	0.7	0.1	0.3	0.3	0.5	0.3	0.5	0	0.2
F_{25}	0.4	0.6	0.2	0.4	0.1	0.3	0.4	0.6	0.6	0.8	0.8	1	0.1	0.3	0.1	0.3	0	0.2
F_{26}	0	0.2	0	0.2	0.3	0.5	0.3	0.5	0.7	0.9	0.7	0.9	0.8	1	0.7	0.9	0.4	0.6
F_{27}	0.3	0.6	0.3	0.8	0.1	0.3	0.4	0.6	0.7	0.9	0.1	0.3	0.1	0.3	0.1	0.3	0	0.2
F_{28}	0.1	0.8	0.1	0.4	0.1	0.3	0.4	0.6	0.7	0.9	0.1	0.3	0.1	0.3	0.1	0.3	0	0.2
F_{29}	0.2	0.4	0.1	0.5	0.1	0.3	0.4	0.6	0.7	0.9	0.1	0.3	0.1	0.3	0.1	0.3	0	0.2
F_{30}	0.2	0.4	0.1	0.4	0.1	0.3	0.4	0.6	0.7	0.9	0.8	1	0.1	0.3	0.1	0.3	0	0.2
F_{31}	0.1	0.3	0.2	0.4	0.3	0.5	0.1	0.3	0.3	0.5	0.6	0.8	0.4	0.6	0.1	0.3	0	0.2
F_{32}	0.6	0.8	0.6	0.8	0.1	0.3	0.4	0.6	0.7	0.9	0.1	0.3	0.1	0.3	0.1	0.3	0	0.2
F_{33}	0.2	0.4	0.3	0.5	0	0.2	0.3	0.5	0.7	0.9	0.4	0.6	0.4	0.6	0.1	0.3	0	0.2
F_{34}	0.2	0.4	0.3	0.5	0	0.2	0.3	0.5	0.7	0.9	0.4	0.6	0.4	0.6	0.3	0.5	0	0.2
F_{35}	0	0.3	0.2	0.4	0.3	0.5	0.1	0.3	0.7	0.9	0.4	0.6	0	0.3	0.1	0.3	0	0.2
F_{36}	0.1	0.5	0.2	0.4	0.4	0.6	0.2	0.4	0.6	0.8	0.4	0.6	0.6	0.8	0.2	0.4	0	0.2

Table_Apx B-8: Weighted normalised fuzzy expert interval decision matrix

	C_1 (L)	C_1 (U)	C_2 (L)	C_2 (U)	C_3 (L)	C_3 (U)	C_4 (L)	C_4 (U)	C_5 (L)	C_5 (U)	C_6 (L)	C_6 (U)	C_7 (L)	C_7 (U)	C_8 (L)	C_8 (U)	C_9 (L)	C_9 (U)
F_1	0.00243	0.01215	0.00489	0.02446	0.00257	0.00770	0.00334	0.01001	0.01154	0.02845	0.01644	0.02193	0.01641	0.02051	0.02125	0.02833	0.00000	0.01281
F_2	0.00972	0.01944	0.01468	0.02446	0.01027	0.01540	0.00667	0.01334	0.00989	0.02529	0.01096	0.01644	0.01231	0.01641	0.00708	0.01417	0.00000	0.01281
F_3	0.00486	0.01215	0.00489	0.02446	0.00770	0.01284	0.00667	0.01334	0.01154	0.02845	0.00274	0.00822	0.01436	0.01846	0.00354	0.01062	0.00000	0.01281
F_4	0.00486	0.01458	0.00489	0.01957	0.00770	0.01284	0.00667	0.01334	0.01154	0.02845	0.00274	0.00822	0.01436	0.01846	0.00354	0.01062	0.00000	0.01281
F_5	0.00729	0.01215	0.00978	0.01468	0.00770	0.01284	0.00334	0.01001	0.01319	0.03161	0.02193	0.02741	0.00615	0.01025	0.00000	0.00708	0.00000	0.01281
F_6	0.00972	0.01701	0.00734	0.01223	0.00770	0.01284	0.00334	0.01001	0.00989	0.02529	0.02193	0.02741	0.00615	0.01025	0.00000	0.00708	0.00000	0.01281
F_7	0.01215	0.01701	0.01468	0.01957	0.00257	0.00770	0.00667	0.01334	0.00824	0.02213	0.01918	0.02467	0.00000	0.00410	0.00000	0.00708	0.00000	0.01281
F_8	0.00486	0.00972	0.00245	0.00734	0.00000	0.00513	0.00334	0.01001	0.00330	0.01264	0.00000	0.00548	0.01231	0.01641	0.00708	0.01417	0.00000	0.01281
F_9	0.00000	0.00486	0.00978	0.01468	0.00257	0.00770	0.00334	0.01001	0.01154	0.02845	0.01644	0.02193	0.01641	0.02051	0.02125	0.02833	0.00000	0.01281
F_{10}	0.01458	0.01944	0.01468	0.01957	0.00257	0.00770	0.00334	0.01001	0.00330	0.01264	0.01096	0.01644	0.00000	0.00410	0.00000	0.00708	0.00000	0.01281
F_{11}	0.01458	0.01944	0.00734	0.01468	0.00513	0.01027	0.00000	0.00667	0.00824	0.02213	0.01370	0.01918	0.01436	0.01846	0.01417	0.02125	0.00000	0.01281
F_{12}	0.01458	0.01944	0.00734	0.01223	0.00513	0.01027	0.00000	0.00667	0.00824	0.02213	0.00000	0.00548	0.01641	0.02051	0.02479	0.03187	0.00000	0.01281
F_{13}	0.01944	0.02430	0.01468	0.01957	0.01284	0.01797	0.01334	0.02001	0.01319	0.03161	0.00000	0.00548	0.01641	0.02051	0.02479	0.03187	0.05126	0.06407
F_{14}	0.01944	0.02430	0.01468	0.01957	0.01284	0.01797	0.01334	0.02001	0.01319	0.03161	0.00000	0.00548	0.01641	0.02051	0.01771	0.02479	0.02563	0.03844
F_{15}	0.00243	0.01215	0.00734	0.01223	0.01540	0.02054	0.01668	0.02335	0.00330	0.01264	0.01096	0.01644	0.01436	0.01846	0.01062	0.01771	0.00000	0.01281
F_{16}	0.00243	0.01944	0.01468	0.01957	0.01027	0.01540	0.01668	0.02335	0.00660	0.01897	0.01096	0.01644	0.01436	0.01846	0.01062	0.01771	0.00000	0.01281
F_{17}	0.00486	0.01215	0.00734	0.01223	0.00257	0.00770	0.00334	0.01001	0.01319	0.03161	0.00822	0.01370	0.00615	0.01025	0.00354	0.01062	0.00000	0.01281
F_{18}	0.00486	0.00972	0.00245	0.01223	0.00257	0.00770	0.00334	0.01001	0.01319	0.03161	0.00822	0.01370	0.00615	0.01025	0.00354	0.01062	0.00000	0.01281
F_{19}	0.00243	0.01215	0.00245	0.01468	0.00257	0.00770	0.00334	0.01001	0.01319	0.03161	0.00822	0.01370	0.00615	0.01025	0.00354	0.01062	0.00000	0.01281
F_{20}	0.00243	0.01215	0.00489	0.00978	0.00000	0.00513	0.01001	0.01668	0.01154	0.02845	0.01096	0.01644	0.00615	0.01025	0.00354	0.01062	0.00000	0.01281
F_{21}	0.00972	0.01458	0.01223	0.02202	0.00000	0.00513	0.01001	0.01668	0.00495	0.01580	0.00000	0.00548	0.01641	0.02051	0.00354	0.01062	0.00000	0.01281
F_{22}	0.00486	0.00972	0.00489	0.00978	0.00513	0.01027	0.00000	0.00667	0.00989	0.02529	0.00000	0.00548	0.01436	0.01846	0.00354	0.01062	0.00000	0.01281
F_{23}	0.00000	0.00729	0.00489	0.00978	0.00513	0.01027	0.01001	0.01668	0.01154	0.02845	0.00000	0.00548	0.00205	0.00615	0.00000	0.00708	0.00000	0.01281
F_{24}	0.00972	0.02187	0.00245	0.00734	0.00770	0.01284	0.01668	0.02335	0.00824	0.02213	0.00274	0.00822	0.00615	0.01025	0.01062	0.01771	0.00000	0.01281
F_{25}	0.00972	0.01458	0.00489	0.00978	0.00257	0.00770	0.01334	0.02001	0.00989	0.02529	0.02193	0.02741	0.00205	0.00615	0.00354	0.01062	0.00000	0.01281
F_{26}	0.00000	0.00486	0.00000	0.00489	0.00770	0.01284	0.01001	0.01668	0.01154	0.02845	0.01918	0.02467	0.01641	0.02051	0.02479	0.03187	0.02563	0.03844
F_{27}	0.00729	0.01458	0.00734	0.01957	0.00257	0.00770	0.01334	0.02001	0.01154	0.02845	0.00274	0.00822	0.00205	0.00615	0.00354	0.01062	0.00000	0.01281
F_{28}	0.00243	0.01944	0.00245	0.00978	0.00257	0.00770	0.01334	0.02001	0.01154	0.02845	0.00274	0.00822	0.00205	0.00615	0.00354	0.01062	0.00000	0.01281
F_{29}	0.00486	0.00972	0.00245	0.01223	0.00257	0.00770	0.01334	0.02001	0.01154	0.02845	0.00274	0.00822	0.00205	0.00615	0.00354	0.01062	0.00000	0.01281
F_{30}	0.00486	0.00972	0.00245	0.00978	0.00257	0.00770	0.01334	0.02001	0.01154	0.02845	0.02193	0.02741	0.00205	0.00615	0.00354	0.01062	0.00000	0.01281
F_{31}	0.00243	0.00729	0.00489	0.00978	0.00770	0.01284	0.00334	0.01001	0.00495	0.01580	0.01644	0.02193	0.00820	0.01231	0.00354	0.01062	0.00000	0.01281
F_{32}	0.01458	0.01944	0.01468	0.01957	0.00257	0.00770	0.01334	0.02001	0.01154	0.02845	0.00274	0.00822	0.00205	0.00615	0.00354	0.01062	0.00000	0.01281
F_{33}	0.00486	0.00972	0.00734	0.01223	0.00000	0.00513	0.01001	0.01668	0.01154	0.02845	0.01096	0.01644	0.00820	0.01231	0.00354	0.01062	0.00000	0.01281
F_{34}	0.00486	0.00972	0.00734	0.01223	0.00000	0.00513	0.01001	0.01668	0.01154	0.02845	0.01096	0.01644	0.00820	0.01231	0.01062	0.01771	0.00000	0.01281
F_{35}	0.00000	0.00729	0.00489	0.00978	0.00770	0.01284	0.00334	0.01001	0.01154	0.02845	0.01096	0.01644	0.00000	0.00615	0.00354	0.01062	0.00000	0.01281
F_{36}	0.00243	0.01215	0.00489	0.00978	0.01027	0.01540	0.00667	0.01334	0.00989	0.02529	0.01096	0.01644	0.01231	0.01641	0.00708	0.01417	0.00000	0.01281

Table_Apx B-9 : Distance measures, relative closeness coefficients, and ranking for failure modes (Fuzzy-TOPSIS-interval method)

	Failure Mode ID	D^+	D^-	RC	Ranking
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	0.0531	0.0833	0.3892	10
Fixed Pipe Ram External Leakage	F_2	0.0526	0.0789	0.3999	9
Single Acting SPM Valve External Leakage	F_3	0.0521	0.0828	0.3865	11
Single Acting SPM Valve Internal Leakage	F_4	0.0507	0.0828	0.3797	14
Solenoid Valve Fail to Close	F_5	0.0363	0.0892	0.2893	36
Solenoid Valve fail to Operate-low voltage	F_6	0.0391	0.0874	0.3089	32
Choke and Kill Valve Internal Leakage	F_7	0.0419	0.0857	0.3282	25
Blind Shear Ram External Leakage	F_8	0.0496	0.0812	0.3793	15
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	0.0481	0.0829	0.3668	17
Fixed Pipe Ram Fail to Close	F_{10}	0.0472	0.0825	0.3636	18
Shuttle Valve coupling and Tubing External leakage	F_{11}	0.0493	0.0797	0.3824	13
Shuttle Valve coupling and Tubing - Post SV to BOP External leakage	F_{12}	0.0598	0.0757	0.4414	4
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	0.0913	0.0366	0.7136	1
Hydraulic Connectors Spuriously Unlatches	F_{14}	0.0728	0.0530	0.5788	2
Double Acting SPM Valve External Leakage	F_{15}	0.0562	0.0761	0.4246	6
Double Acting SPM Valve Internal Leakage	F_{16}	0.0571	0.0764	0.4277	5
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	0.0393	0.0866	0.3123	31
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	0.0386	0.0877	0.3059	33
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	0.0401	0.0883	0.3127	30
Choke and Kill Valves External Leakage	F_{20}	0.0400	0.0865	0.3165	28
Shuttle Valve External Leakage	F_{21}	0.0562	0.0779	0.4191	7
Shuttle Valve Coupling and Tubing Blockage	F_{22}	0.0467	0.0837	0.3582	19
Riser BOP Flexible Joint External Leakage	F_{23}	0.0440	0.0867	0.3368	24
Small Bore Hydraulic tubing Leakage	F_{24}	0.0546	0.0780	0.4115	8
Annular Preventer Internal Leakage	F_{25}	0.0398	0.0866	0.3149	29
Subsea Accumulators Loss of Pre-charge gas	F_{26}	0.0623	0.0657	0.4865	3
Blind Shear Ram Internal leakage	F_{27}	0.0488	0.0834	0.3691	16
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	0.0475	0.0856	0.3569	20
Blind Shear Ram Failts to Shear and Close well	F_{29}	0.0451	0.0851	0.3463	22
Annular Preventer External Leakage	F_{30}	0.0374	0.0890	0.2958	35
Check Valve Internal Leakage	F_{31}	0.0409	0.0844	0.3265	26
Annular Preventer Fails to Close/seal	F_{32}	0.0505	0.0810	0.3838	12
Choke and Kill Valves Fails to Close	F_{33}	0.0406	0.0850	0.3232	27
Choke and Kill Valves Fails to Open	F_{34}	0.0430	0.0830	0.3415	23
Check Valve Stuck Closed	F_{35}	0.0374	0.0881	0.2981	34
Fixed Pipe Ram Internal leakage	F_{36}	0.0451	0.0824	0.3538	21

B.2.3 BOP System Failure mode ranking Using PROMETHEE

Table_Apx B-10 : Unicriterion flows matrix

	Unicriterion flows								
Failure Modes	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
F_1	-0.2571	0.4857	-0.3714	1	1	-0.6	0.8286	0.8	-0.0857
F_2	0.5429	1	0.7714	-0.1429	0.2571	-0.2	0.2	0.3143	-0.0857
F_3	-0.0286	0.5429	0.4571	-0.1429	-0.2857	0.4286	0.4571	-0.2571	-0.0857
F_4	0.0571	0.2	0.4571	-0.1429	-0.2857	0.4286	0.4571	-0.2571	-0.0857
F_5	0.0571	0.4	0.4571	-0.5714	-0.8571	-0.9143	-0.2571	-0.8857	-0.0857
F_6	0.4286	0	0.4571	-0.5714	0.2571	-0.9143	-0.2571	-0.8857	-0.0857
F_7	0.4857	0.8	-0.3714	-0.1429	0.5143	-0.7429	-0.9714	-0.8857	-0.0857
F_8	-0.4857	-0.9143	-0.8857	-0.5714	0.8857	0.8286	0.2	0.3143	-0.0857
F_9	-0.9714	0.4	-0.3714	-0.5714	-0.2857	-0.6	0.8286	0.8	-0.0857
F_{10}	0.8	0.8	-0.3714	-0.5714	0.8857	-0.2	-0.9714	-0.8857	-0.0857
F_{11}	0.8	0.2571	0.1143	-0.9429	0.5143	-0.4857	0.4571	0.6571	-0.0857
F_{12}	0.8	0	0.1143	-0.9429	0.5143	0.8286	0.8286	0.9429	1
F_{13}	0.9714	0.8	0.9143	0.5714	-0.8571	0.8286	0.8286	0.9429	0.9143
F_{14}	0.9714	0.8	0.9143	0.5714	-0.8571	0.8286	0.8286	0.7143	-0.0857
F_{15}	-0.2	0	1	0.8857	0.8857	-0.2	0.4571	0.5143	-0.0857
F_{16}	0.3714	0.8	0.7714	0.8857	0.6571	-0.2	0.4571	0.5143	-0.0857
F_{17}	-0.1143	0	-0.3714	-0.5714	-0.8571	0.1429	-0.2571	-0.2571	-0.0857
F_{18}	-0.4857	-0.2571	-0.3714	-0.5714	-0.8571	0.1429	-0.2571	-0.2571	-0.0857
F_{19}	-0.8	-0.2	-0.3714	-0.5714	-0.8571	0.1429	-0.2571	-0.2571	-0.0857
F_{20}	0.6286	-0.4857	-0.8857	0.1714	-0.2857	-0.2	-0.2571	-0.2571	-0.0857
F_{21}	0.2857	0.6	-0.8857	0.1714	0.7429	0.8286	0.8286	-0.2571	-0.0857
F_{22}	-0.4857	-0.4857	0.1143	-0.9429	0.2571	0.8286	0.4571	-0.2571	-0.0857
F_{23}	-0.8	-0.4857	0.1143	0.1714	-0.2857	0.8286	-0.6571	-0.8857	-0.0857
F_{24}	0.6286	-0.9143	0.4571	0.8857	0.5143	0.4286	-0.2571	0.5143	-0.0857
F_{25}	0.2857	-0.4857	-0.3714	0.5714	0.2571	-0.9143	-0.6571	-0.2571	-0.0857
F_{26}	-0.9714	-1	0.4571	0.1714	-0.2857	-0.7429	0.8286	0.9429	0.9143
F_{27}	0.2	0.3143	-0.3714	0.5714	-0.2857	0.4286	-0.6571	-0.2571	-0.0857
F_{28}	0.1429	-0.7143	-0.3714	0.5714	-0.2857	0.4286	-0.6571	-0.2571	-0.0857
F_{29}	-0.4857	-0.7714	-0.3714	0.5714	-0.2857	0.4286	-0.6571	-0.2571	-0.0857
F_{30}	-0.4857	-0.8286	-0.3714	0.5714	-0.2857	-0.9143	-0.6571	-0.2571	-0.0857
F_{31}	-0.7143	-0.4857	0.4571	-0.5714	0.7429	-0.6	0.0286	-0.2571	-0.0857
F_{32}	0.8	0.8	-0.3714	0.5714	-0.2857	0.4286	-0.6571	-0.2571	-0.0857
F_{33}	-0.4857	0	-0.8857	0.1714	-0.2857	-0.2	0.0286	-0.2571	-0.0857
F_{34}	-0.4857	0	-0.8857	0.1714	-0.2857	-0.2	0.0286	0.5143	-0.0857
F_{35}	-0.8857	-0.4857	0.4571	-0.5714	-0.2857	-0.2	-0.8857	-0.2571	-0.0857
F_{36}	-0.1143	-0.4857	0.7714	-0.1429	0.2571	-0.2	0.2	0.3143	-0.0857

Table_Apx B-11: Multicriteria flows (failure modes in decreasing order of criticality)

	Multicriteria flows		
Failure Modes	**Phi**	**Phi+**	**Phi-**
F_{13}	0.672	0.7826	0.1105
F_{14}	0.517	0.6517	0.1347
F_{12}	0.4723	0.6892	0.217
F_{16}	0.4429	0.6227	0.1798
F_{15}	0.349	0.5759	0.2269
F_{1}	0.2952	0.5563	0.261
F_{2}	0.2772	0.5445	0.2674
F_{24}	0.241	0.5161	0.2751
F_{21}	0.2395	0.4979	0.2584
F_{11}	0.1274	0.481	0.3536
F_{3}	0.1177	0.4192	0.3015
F_{32}	0.0986	0.384	0.2853
F_{4}	0.0906	0.4042	0.3137
F_{26}	0.0611	0.4753	0.4142
F_{36}	0.0546	0.4229	0.3682
F_{27}	-0.0134	0.3398	0.3532
F_{22}	-0.0561	0.3372	0.3932
F_{8}	-0.0637	0.3594	0.4231
F_{10}	-0.0886	0.3278	0.4164
F_{9}	-0.0901	0.3275	0.4176
F_{28}	-0.1269	0.2831	0.41
F_{34}	-0.1275	0.3064	0.4339
F_{31}	-0.1709	0.2874	0.4583
F_{7}	-0.1781	0.3058	0.4839
F_{20}	-0.1859	0.2551	0.441
F_{25}	-0.1953	0.2569	0.4522
F_{6}	-0.1961	0.2842	0.4803
F_{29}	-0.197	0.2393	0.4363
F_{23}	-0.2157	0.2653	0.481
F_{33}	-0.2182	0.2393	0.4574
F_{17}	-0.2535	0.2264	0.48
F_{5}	-0.307	0.2318	0.5388
F_{18}	-0.3183	0.1942	0.5125
F_{35}	-0.3436	0.176	0.5196
F_{19}	-0.3444	0.1885	0.5329
F_{30}	-0.3658	0.1601	0.5259

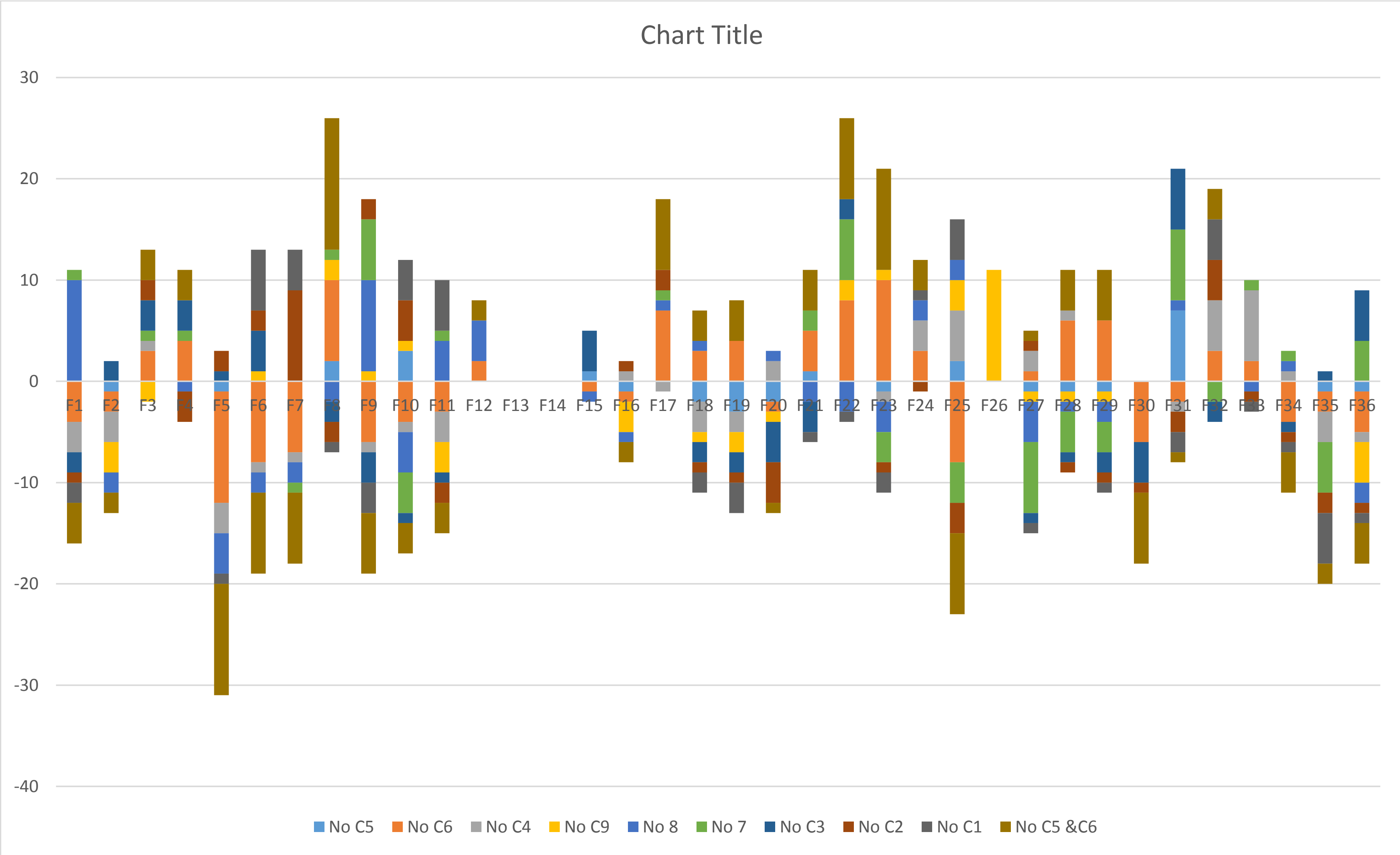
Appendix C Sensitivity Analysis

Table_Apx C-1 : TOPSIS Failure modes criticality sensitivity analysis

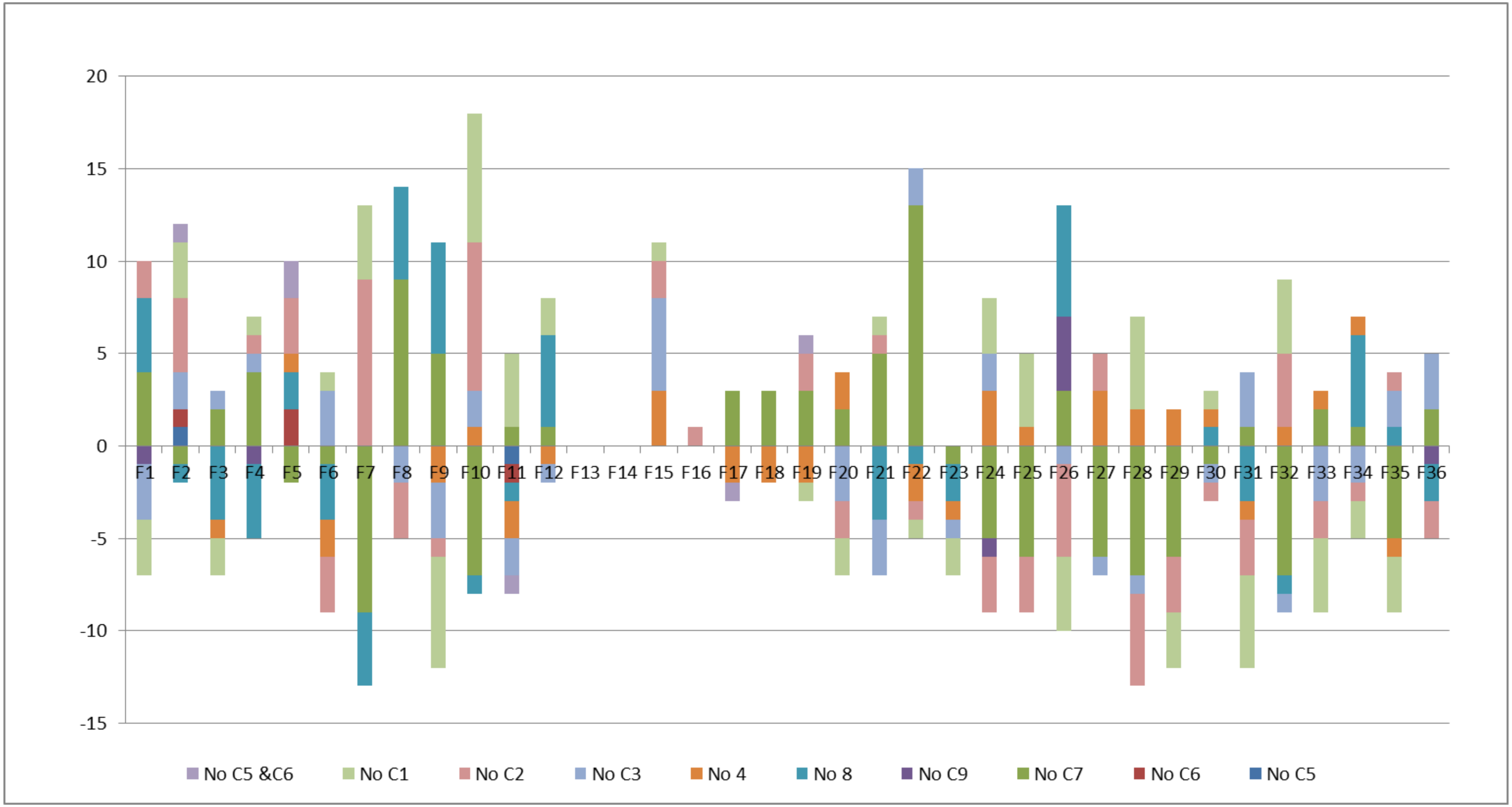
Failure Modes	Failure Mode ID	Criteria considered (No CX means All without Criteria X)										
		All	No C5	No C6	No C4	No C9	No 8	No 7	No C3	No C2	No C1	No C5 &C6
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	12	12	8	9	12	22	13	10	11	10	8
Fixed Pipe Ram External Leakage	F_2	9	8	7	6	6	7	9	11	9	9	7
Single Acting SPM Valve External Leakage	F_3	11	11	14	12	9	11	12	14	13	11	14
Single Acting SPM Valve Internal Leakage	F_4	13	13	17	13	13	12	14	16	10	13	16
Solenoid Valve Fail to Close	F_5	34	33	23	31	34	30	34	35	36	33	23
Solenoid Valve fail to Operate-low voltage	F_6	29	29	21	28	30	27	29	33	31	35	21
Choke and Kill Valve Internal Leakage	F_7	25	25	18	24	25	23	24	25	34	29	18
Blind Shear Ram External Leakage	F_8	17	19	25	17	19	15	18	15	15	16	30
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	15	15	9	14	16	24	21	12	17	12	9
Fixed Pipe Ram Fail to Close	F_{10}	20	23	16	19	21	16	16	19	24	24	17
Shuttle Valve coupling and Tubing External leakage	F_{11}	14	14	11	11	11	18	15	13	12	19	11
Shuttle Valve coupling and Tubing - Post SV to BOP External leakage	F_{12}	4	4	6	4	4	8	4	4	4	4	6
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	1	1	1	1	1	1	1	1	1	1	1
Hydraulic Connectors Spuriously Unlatches	F_{14}	2	2	2	2	2	2	2	2	2	2	2
Double Acting SPM Valve External Leakage	F_{15}	5	6	4	5	5	4	5	9	5	5	5
Double Acting SPM Valve Internal Leakage	F_{16}	6	5	5	7	3	5	6	6	7	6	4
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	27	27	34	26	27	28	28	27	29	27	34
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	33	31	36	30	32	34	33	31	32	31	36
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	31	28	35	29	29	31	31	29	30	28	35
Choke and Kill Valves External Leakage	F_{20}	32	30	31	34	31	33	32	28	28	32	31
Shuttle Valve External Leakage	F_{21}	8	9	12	8	8	6	10	5	8	7	12
Shuttle Valve Coupling and Tubing Blockage	F_{22}	16	16	24	16	18	13	22	18	16	15	24
Riser BOP Flexible Joint External Leakage	F_{23}	22	21	32	21	23	19	19	22	21	20	32
Small Bore Hydraulic tubing Leakage	F_{24}	7	7	10	10	7	9	7	7	6	8	10
Annular Preventer Internal Leakage	F_{25}	30	32	22	35	33	32	26	30	27	34	22
Subsea Accumulators Loss of Pre-charge gas	F_{26}	3	3	3	3	14	3	3	3	3	3	3
Blind Shear Ram Internal leakage	F_{27}	18	17	19	20	17	14	11	17	19	17	19
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	21	20	27	22	20	20	17	20	20	21	25
Blind Shear Ram Failts to Shear and Close well	F_{29}	23	22	29	23	22	21	20	21	22	22	28
Annular Preventer External Leakage	F_{30}	36	36	30	36	36	36	36	32	35	36	29
Check Valve Internal Leakage	F_{31}	28	35	26	27	28	29	35	34	26	26	27
Annular Preventer Fails to Close/seal	F_{32}	10	10	13	15	10	10	8	8	14	14	13
Choke and Kill Valves Fails to Close	F_{33}	26	26	28	33	26	25	27	26	25	25	26
Choke and Kill Valves Fails to Open	F_{34}	24	24	20	25	24	25	25	23	23	23	20
Check Valve Stuck Closed	F_{35}	35	34	33	32	35	35	30	36	33	30	33
Fixed Pipe Ram Internal leakage	F_{36}	19	18	15	18	15	17	23	24	18	18	15

Table_Apx C-2: Fuzzy TOPSIS Failure modes criticality sensitivity analysis

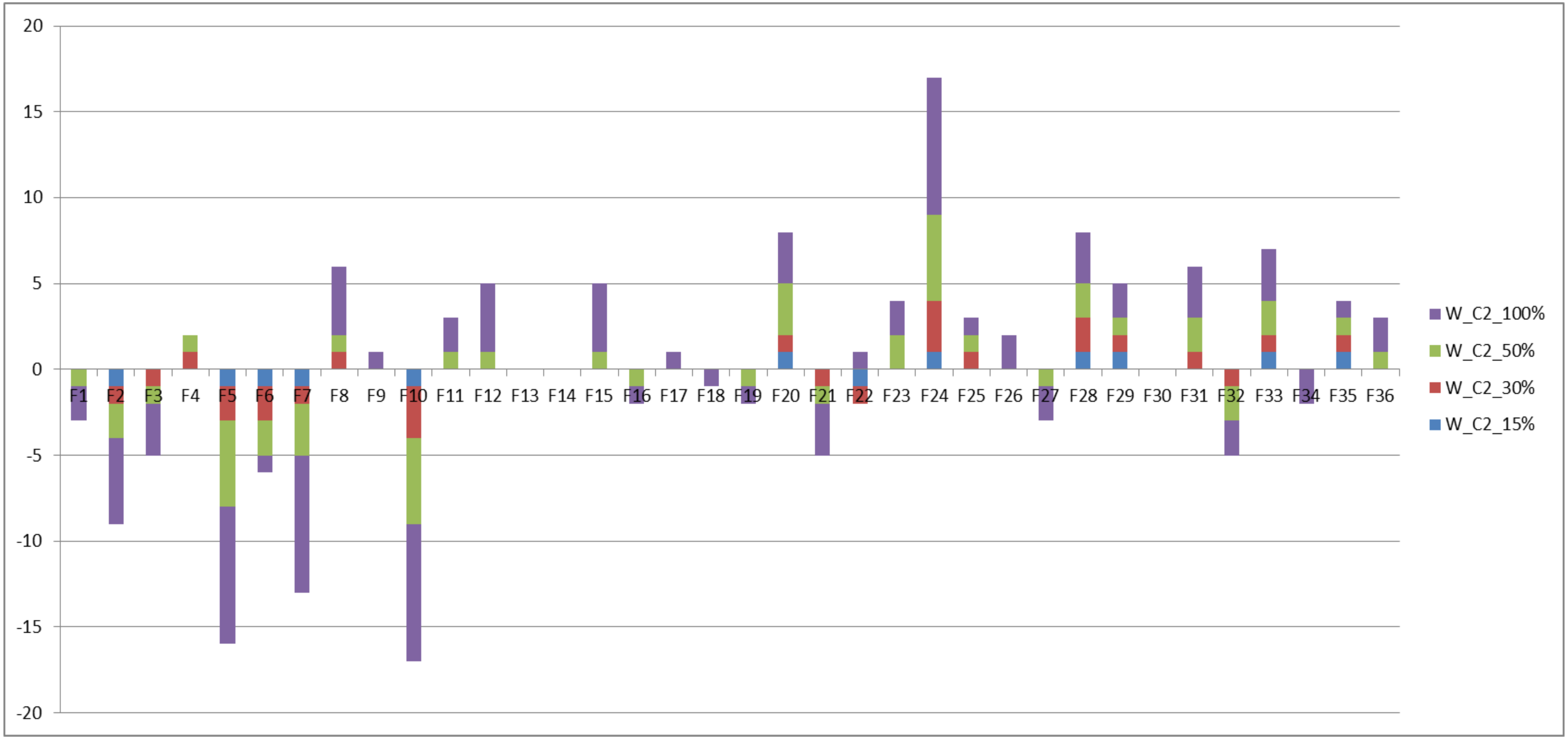
Failure Modes	Failure Mode ID	Criteria considered (No CX means All without Criteria X)										
		All	No C5	No C6	No C7	No C9	No 8	No 4	No C3	No C2	No C1	No C5 &C6
Manifold Hydraulic Pressure Regulator Unstable output pressure	F_1	9	9	9	13	8	13	9	6	11	6	9
Fixed Pipe Ram External Leakage	F_2	6	7	7	5	6	5	6	8	10	9	7
Single Acting SPM Valve External Leakage	F_3	15	15	15	17	15	11	14	16	15	13	15
Single Acting SPM Valve Internal Leakage	F_4	11	11	11	15	10	7	11	12	12	12	11
Solenoid Valve Fail to Close	F_5	26	26	26	24	26	23	24	28	27	23	26
Solenoid Valve fail to Operate-low voltage	F_6	24	24	24	23	24	21	22	27	21	25	24
Choke and Kill Valve Internal Leakage	F_7	23	23	23	14	23	19	23	23	32	27	23
Blind Shear Ram External Leakage	F_8	19	19	19	28	19	24	19	17	16	19	19
Annular Hydraulic Pressure Regulator Unstable output pressure	F_9	14	14	14	19	14	20	12	11	13	8	14
Fixed Pipe Ram Fail to Close	F_{10}	17	17	17	10	17	16	18	19	25	24	17
Shuttle Valve coupling and Tubing External leakage	F_{11}	7	6	6	8	7	6	5	5	7	11	6
Shuttle Valve coupling and Tubing - Post SV to BOP External leakage	F_{12}	5	5	5	6	5	10	4	4	5	7	5
Welhead Hydraulic Connectors Spuriously Unlatches	F_{13}	1	1	1	1	1	1	1	1	1	1	1
Hydraulic Connectors Spuriously Unlatches	F_{14}	2	2	2	2	2	2	2	2	2	2	2
Double Acting SPM Valve External Leakage	F_{15}	4	4	4	4	4	4	7	9	6	5	4
Double Acting SPM Valve Internal Leakage	F_{16}	3	3	3	3	3	3	3	3	4	3	3
Choke and Kill Line (Jumper hoseline) External Leakage	F_{17}	30	30	30	33	30	30	28	30	30	30	29
Choke and Kill Line (Riser Attached Line) External Leakage	F_{18}	33	33	33	36	33	33	31	33	33	33	33
Choke and Kill Line (BOP Attached Line) External Leakage	F_{19}	29	29	29	32	29	29	27	29	31	28	30
Choke and Kill Valves External Leakage	F_{20}	28	28	28	30	28	28	30	25	26	26	28
Shuttle Valve External Leakage	F_{21}	13	13	13	18	13	9	13	10	14	14	13
Shuttle Valve Coupling and Tubing Blockage	F_{22}	18	18	18	31	18	17	16	20	17	17	18
Riser BOP Flexible Joint External Leakage	F_{23}	36	36	36	35	36	34	35	35	36	34	36
Small Bore Hydraulic tubing Leakage	F_{24}	12	12	12	7	11	12	15	14	9	15	12
Annular Preventer Internal Leakage	F_{25}	31	31	31	25	31	31	32	31	28	35	31
Subsea Accumulators Loss of Pre-charge gas	F_{26}	8	8	8	11	12	14	8	7	3	4	8
Blind Shear Ram Internal leakage	F_{27}	22	22	22	16	22	22	25	21	24	22	22
Blind Shear Ram Fails to Close (seal open-hole)	F_{28}	27	27	27	20	27	27	29	26	22	32	27
Blind Shear Ram Failts to Shear and Close well	F_{29}	32	32	32	26	32	32	34	32	29	29	32
Annular Preventer External Leakage	F_{30}	35	35	35	34	35	36	36	34	34	36	35
Check Valve Internal Leakage	F_{31}	21	21	21	22	21	18	20	24	18	16	21
Annular Preventer Fails to Close/seal	F_{32}	16	16	16	9	16	15	17	15	20	20	16
Choke and Kill Valves Fails to Close	F_{33}	25	25	25	27	25	25	26	22	23	21	25
Choke and Kill Valves Fails to Open	F_{34}	20	20	20	21	20	25	21	18	19	18	20
Check Valve Stuck Closed	F_{35}	34	34	34	29	34	35	33	36	35	31	34
Fixed Pipe Ram Internal leakage	F_{36}	10	10	10	12	9	8	10	13	8	10	10



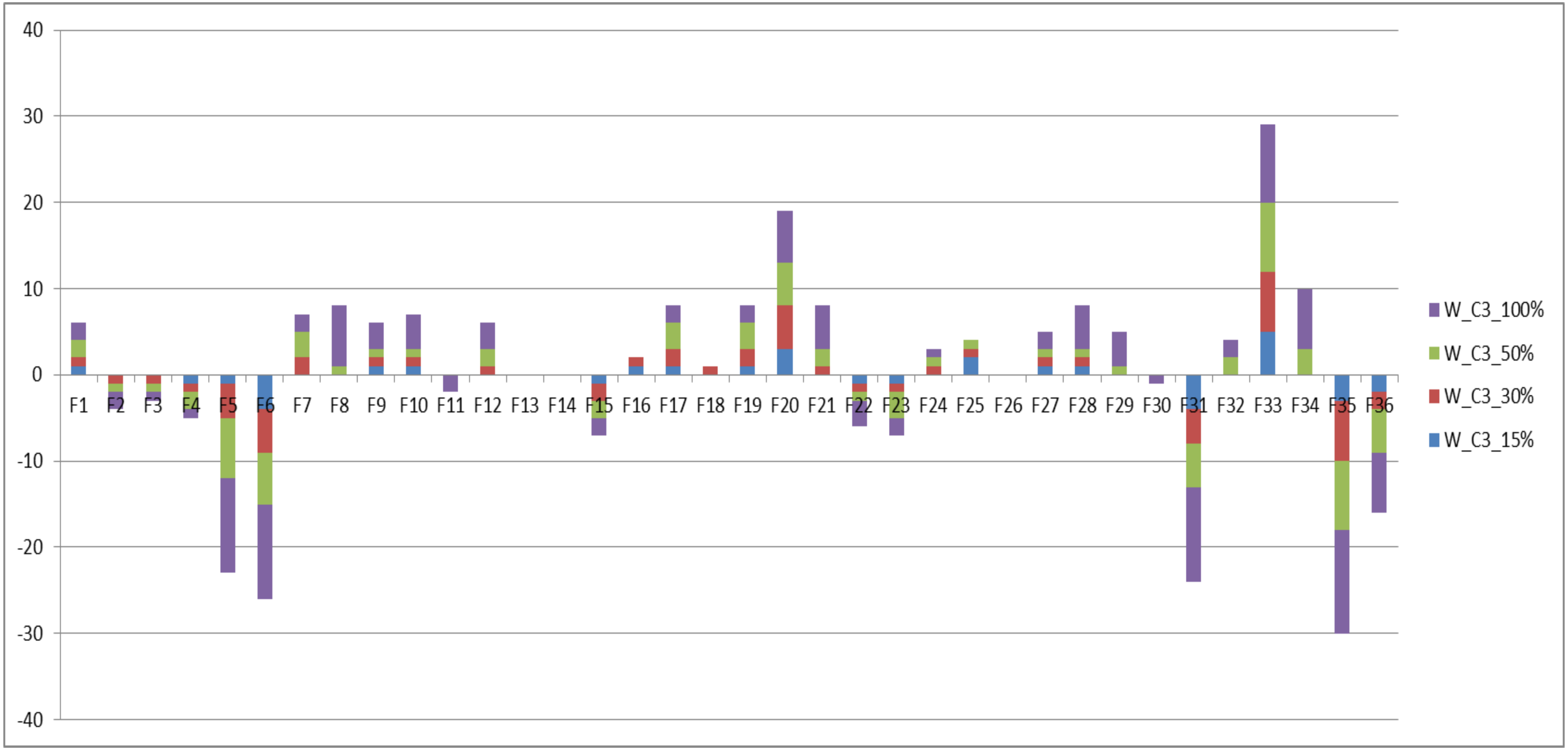
Figure_Apx C-1: Sensitivity analysis of criteria omission using the TOPSIS technique.



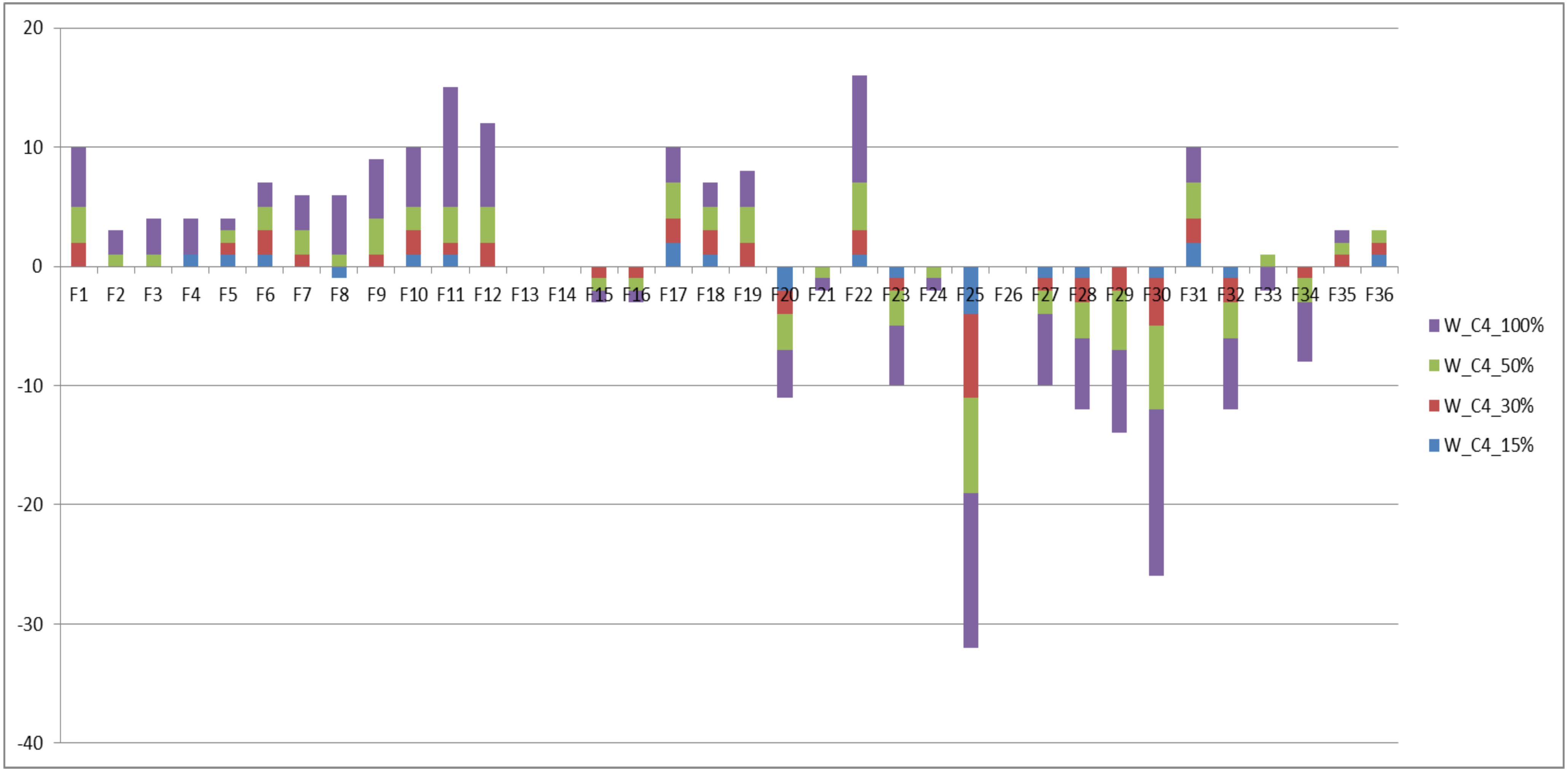
Figure_Apx C-2: Sensitivity analysis of a criterion omission using the Fuzzy TOPSIS technique.



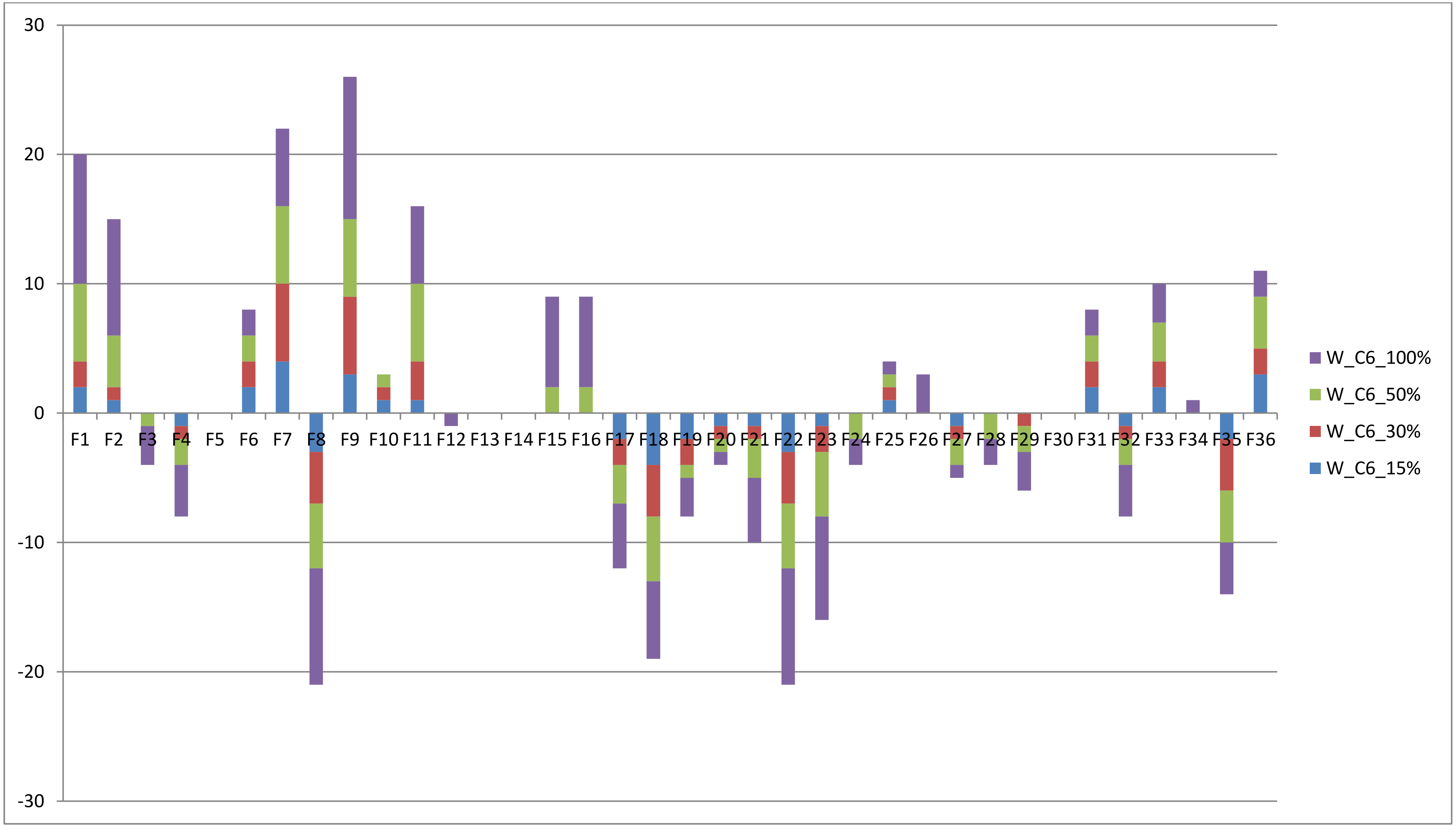
Figure_Apx C-3: Sensitivity analysis of an increase in criterion 2's weight using the Fuzzy-interval TOPSIS



Figure_Apx C-4: Sensitivity analysis of an increase in criterion 3's weight using the Fuzzy-interval TOPSIS

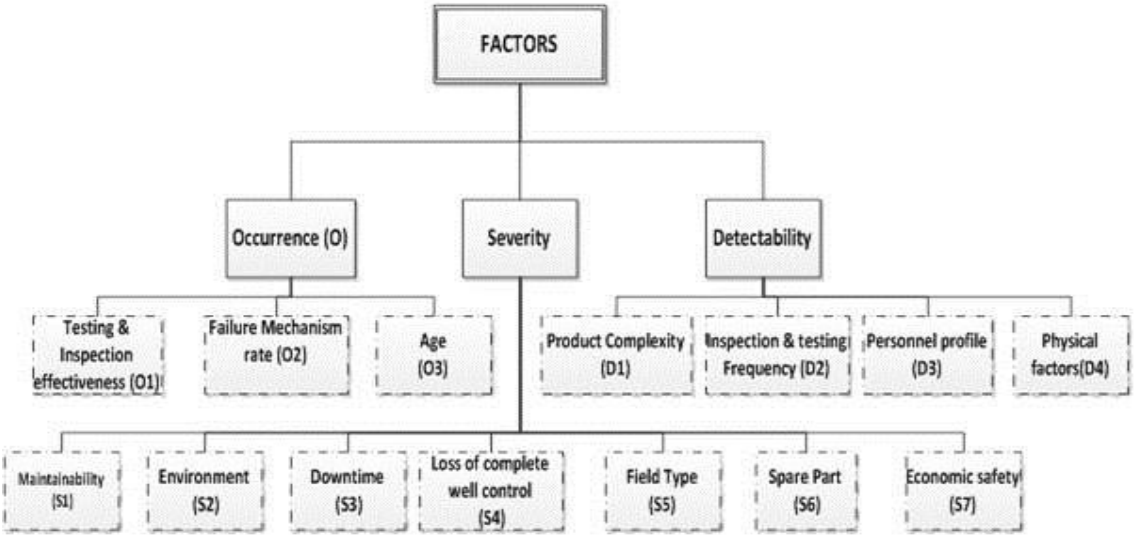


Figure_Apx C-5: Sensitivity analysis of an increase in criterion 4's weight using the Fuzzy-interval TOPSIS



Figure_Apx C-6: Sensitivity analysis of an increase in criterion 6's weight using the Fuzzy-interval TOPSIS

Appendix D Initial Assessment Criteria Hierarchy



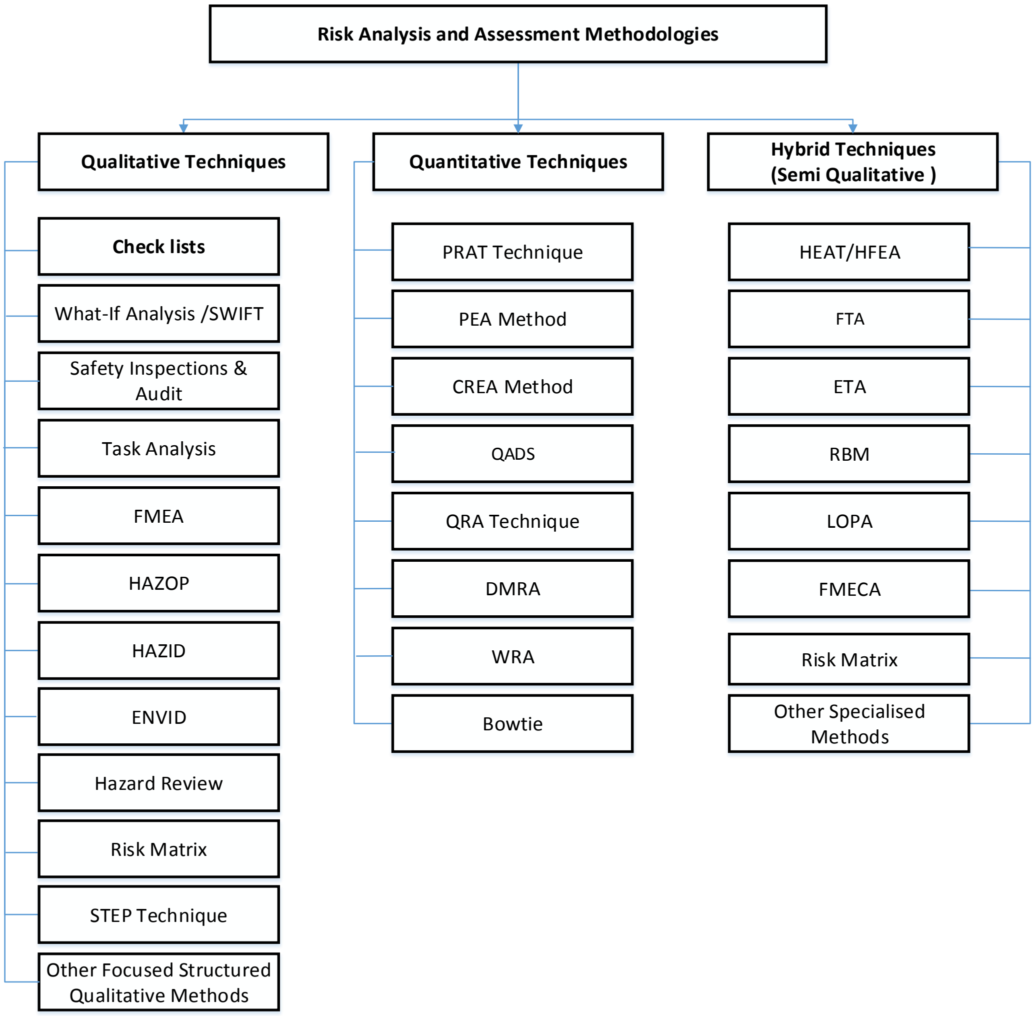
Appendix E Risk Assessment Annex

E.1 Risk Assessment Methodologies

While risk analysis tries to satisfy the goal of identifying possible accident scenarios, their likelihood and consequences to provide details of the overall risk to the system, it also identifies the contributors to risks to inform optimal changes or improvement actions (geared towards risk reduction). Risk assessment could be qualitative, quantitative or semi- quantitative (a mixture of both). These classes can be also be grouped into deterministic, probabilistic and a combination of both approaches based on the output data. This however depends on the goal of the analysis, amount and type of data available and/or experts' judgement.

A spectrum of risk analysis methods exists, which fall into these classes mentioned above, however not all are able to conduct a combination of all three unique elements amongst other as described in Figure 2-1: identification, assessment, and hierarchisation/ management/control. Figure_ApxE-1 showcases different risk analysis and assessment techniques under three main categories namely the qualitative, quantitative and semi-qualitative/hybrid or combination techniques.

Most of the known qualitative risk methods, though structured, are simple, descriptive, and fundamentally used for hazard/risk identification, while some extend to include some qualitative evaluation and categorisation based on some relative judgement, which is mostly subjective. In this method likelihood of occurrence and severity determined are entirely qualitative. Most of these techniques identify hazards or risks depending on the perspective being considered in the analysis. These can be generic/scenario, system, environment or activities based, however it is important for an adequate technique to be applied.



Figure_Apx E-1: Risk Analysis and Assessment Methodologies Classification (Adapted from (Marhavilas et al., 2011)

(Marhavilas et al., 2011) give a good overview of qualitative methods such as Failure modes and Effect Analysis (FMEA), Checklist, Hazard Identification (HAZID)/ Environmental Impact identification (ENVID), Hazard review, What –If Analysis, Task Analysis, Hazard and Operability Study (Labovský et al., 2007; Reniers et al., 2005), Sequential Timed Event Plotting (STEP) (Kontogiannis et al., 2000).

Semi-Quantitative risk methods have likelihood of occurrence and severity approximately quantified over a range. The relevance of risk analysis methods that fall in this class entails their suitability for analysing/assessing risk from a wide range and combination of equipment failures, failure and accident scenarios or events, human error, and other external situations. However, implementation of the process of these techniques can be time-consuming and complicated and challenging when applied to complex systems. Examples include FMECA, Fault tree analysis (FTA) and Event tree analysis (ETA).

In Quantitative Risk Assessment method, likelihood of occurrence and potential severity level are fully quantified for scenarios considered or identified. This would often require the use of existing failure/loss in integrity data and even computation models for simulating such events. In the offshore industry, such assessment includes fire and collision modelling, dropped object analysis, evacuation modelling, blowout risk modelling, etc. From Figure 3-3, amongst the methods shown, it appears there exist a number of methods and variants, however the QRA would be discussed in a little more detail.

Decision Matrix Risk Assessment (DMRA) is a systematic technique which evaluates risk or a risk ranking using a combination of consequence/severity and likelihood range. Following the identification of hazards, a risk matrix is constructed and/or applied to describe the risk level and inform management decision. Risk assessment by way of a risk matrix is easy, the only challenge is having the right and suitable one, which varies from one organisation to another (Haimes, 2009). QRA as tool to safety engineering is like process simulation to process engineering and finite elements to structural engineering. It starts usually with a formal qualitative risk assessment in identifying hazards and then an evaluation of the risks components should data be available. The matrix will be quantitative in its categories description, however where it is qualitative, then the DMRA would be a qualitative one.

Other Quantitative methods includes Weighted risk analysis -WRA (Suddle, 2009), Proportional Risk Assessment technique-PRAT (Marhavilas and Koulouriotis, 2012) Societal risk estimation -SRE (Risktec, 2007) Clinical Risk and Error analysis- CRE (Trucco and Cavallin, 2006), Predictive Epistemic Approach–PEA (Vaidogas, 2006), Quantitative assessment of domino scenarios - QADS (Marhavilas et al., 2011). Besides the established qualitative methods for purely risk/hazard identification, commonly used methods are FMEA, FMECA, FTA and HAZOP (Bernardi et al., 2013).

The FMEA is a systematic method of identifying potential failure modes and what their effects are locally and globally. It is a technique designed to reveal weakness in a system, design and can support other more detailed risk assessment techniques. (See Section 2.2 for more details). FMECA is the quantitative form of FMEA. While the methodology remains the same the only difference being the quantification failure modes criticality. It has found extensive use and has been recommended as the first approach to carry out in a structured reliability program as it helps identify weakness in design. It also feeds into several other analysis such as the FTA, technology qualification given identified weakness or as part of a development process, spare parts requirements and maintenance analysis, (see the next section for more detail).

Fault Tree Analysis follows a top-down approach to provide a detailed and acceptable way of predicting quantified system failures (Top Events) frequency. FTA uses a digital logic to represent how a Top Event can occur or ways in which a system can fail. Probabilities of system failing or frequencies of events can be calculated at a point in time and/or under certain conditions. Events and gates (e.g. AND gate, OR gate) are used to construct fault trees in depicting possible logical combinations of human errors, equipment failures, and other external events that can cause specific accidents or Top Events. When either of two or more events are required to give rise to an intermediate event, an OR gate is used. An AND gate is used when both or all of the initial events are required to cause an intermediate event. Fault tree modelling for reliability purpose, can consist of a combination of repairable and non-repairable failures, and how they can affect reliability of the system over its lifetime (i.e., if it's relatively constant, increases or decreases with time). It can help establish maintenance task and intervals. Also while safeguards can be defined from the fault tree, for more complex trees visualising safeguards can be challenging and common cause failures (a single failure that can setback two or more safeguards or affect multiple devices operation that should be considered as independent) may be concealed. Hence Minimal Cut Set analysis, Common Cause Failure Analysis (CCFA), Sensitivity and Importance Measures Analysis have been developed to help identify minimal cut-sets and dominant failures. For more details on FTA see Rausand, (2004).

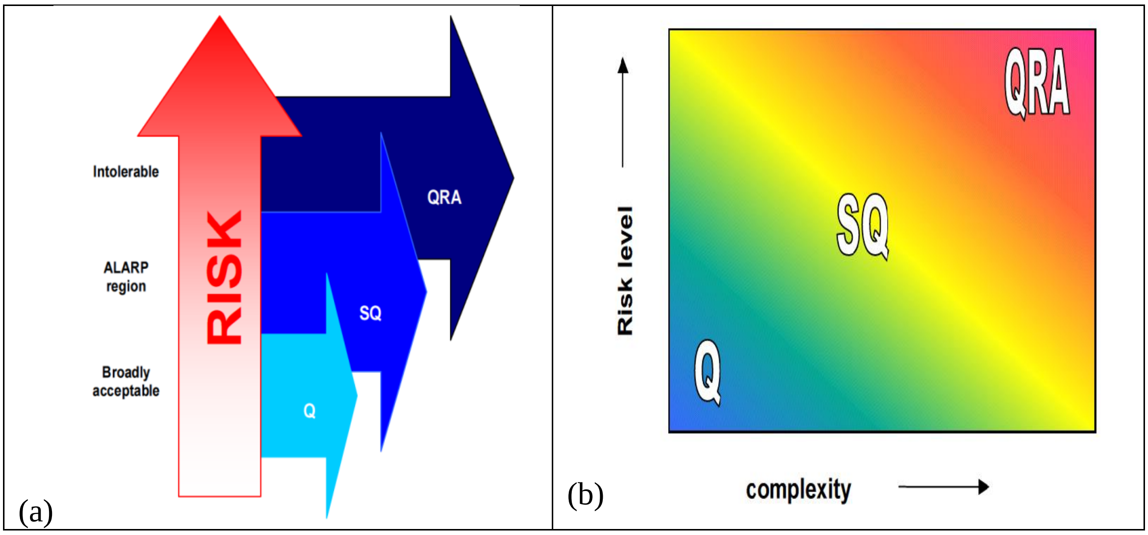
HAZOP is a systematic technique that uses guide words (e.g. more flow or less pressure) to identify deviations from normal operating conditions of a process or design and evaluates their effect. A multidisciplinary team of experts is required for the process and proper planning and management of the process and identified hazard/risk requiring actions is necessary for effective outcome. A version of HAZOP applied to drilling, heavy-lifts, which are considered safety critical is called Procedural HAZOP (CMPT, 1999).

Other Specialised Techniques includes risk analysis techniques extensions being developed and utilised that combines multiple attributes of the different techniques discussed so far. Another approach is to view the application of risk analysis techniques for frequency or/and consequence modelling. For some hazards (e.g. marine hazards), there is interdependence between the frequencies and consequence. In such scenarios the hazards are considered specifically hence specialised analysis e.g. collision analysis, reliability analysis, and structural analysis. Reliability analysis (RA) techniques application does not consider consequence but almost only the failure likelihood of a system under consideration. Examples of methods used for RA includes FTA, ETA, FMECA, reliability simulation, and human reliability analysis (which considers a human operator as an item to be analysed).

Fixed offshore platforms structural safety assessment have used risk principles quite independently and basically known as Structural reliability analysis (SRA). The loads on structures and their resistance in a probabilistic manner is the focus of SRA. Though the goals of SRA and QRA are similar, they have had quite different evolution. For Offshore Structures, CMPT (1999) pointed out the challenges in integrating SRA analysis into QRA despite the potentials. All types of uncertainties, especially those from human error are not included in SRA; Probabilities from actuarial or field data are used in QRA and such data for structural failures are difficult to obtain and usually not available; Non-structural failures as well their interaction with structure component failures are not accounted for in SRA. (Basu and Bhattacharya, 2001) presented a case that failures could arise from interactions (involving structural and non-structural failures) and that such probability data be made available for better risk assessment.

E.1.1 Choice of technique and the drift from/to Qualitative ones

The complexity and size of the risk influences the selection of a method to be used. When the complexity and risk levels are high QRA is preferred, when the complexity and risk levels are both low then qualitative risk assessments can be used. Also considering the risk level i.e. if intolerable or broadly acceptable, qualitative risk assessments or QRA can be used respectively. This is depicted by the diagram in Figure_Apx E-2 as described, where Q is qualitative, SQ is Semi-quantitative



Figure_Apx E-3: Proportionate risk assessment and an alternative description of the approach to risk assessment as a function of risk level and complexity (HSE 2006).

When performing a risk management exercise, there should not be an over dependence on QRA results alone. QRAs are subjective and uncertain in terms of the validity of their input and assumptions. As a risk comparison technique, QRAs are valuable as a means expressing the differences in relative risk levels for considered options. On the other hand a good understanding of the acceptability of risk and risk profile with the efficiency of controls in place can be achieved through qualitative risk assessment. However, for certain system aspects requiring in-depth analysis qualitative risk assessments should not be used in isolation.

E.2 Risk Assessment Application in the Offshore Industry- Brief Note

Risk analysis has found application in offshore project development from the concept to decommissioning. This section presents a select detail of relevant studies on the use of Risk assessment on individual components and systems (see Table_Apx E 1) as well as on operational procedures at different stages within the offshore marine and subsea industries

At the feasibility or appraisal stage, the Qualitative techniques are likely very suitable or a high level form of any detailed method (quantitative or semi-quantitative) would apply. This includes SWIFT, HAZID, Risk matrix or even a high-level System FMECA. At the design stage QRA have been used to screen out high risk alternatives along with high cost options, and undertake design audits of systems with critical functions (e.g. the BOP and its associated control systems) with the goal of meeting desired business expectations which also includes the minimization of danger to personnel and prevention of severe damage to environment. Other useful techniques include FTA, SWIFT, HAZOP, Hazard review, HAZID, and other specialised techniques. Though at the early (concept or front end) design phase, similar studies on previous designs can be modified in a risk assessment workshop. Also detailed risk quantification may not be considered at this stage for standard concepts or design.

Upon the completion of the design concept selection and a detailed stage, the project team can then move to installing the manufactured/procured system and its components.The outcome of the risk analysis (e.g. FMECA) have assisted in justifying actions in the inspection maintenance and repair dossier. The improvement of system performance (e.g. by way of upgrade or debottlenecking works) have also been supported with risk analysis/assessment to ensure activities do not introduce new risk or weaken barrier performance. Beyond Production also presented in applications is the case of life extension activities and decommissioning. For decommissioning it has been applied to demonstrating ALARP, assessing removal options and risk to different personnel (Kierans et al., 2004). This includes addressing environmental issues and those of safety not previously considered. SWIFT, hazard review, SRE (considering political and societal aspects) and ETA would be ideal techniques for this phase.

Risk assessment has been seamlessly integrated into drilling programs with a goal of understanding weakness or limitations in design or project plan, to improve decision making, minimize cost and loss rime to system. One of such is the development of flexible structured hierarchical risk assessment models for drilling operations (Khatlan et al., 2007). Risk analysis has been applied to understanding and improving well integrity for preventing risk of a blowout- a major contributor to the total risk profile of offshore oil and gas installations, with a significant consequence in relation to loss of lives, asset integrity and environment damage.

Currently there is an increased attention on the challenges and risks of drilling into high pressure high temperature (HPHT) fields, following the Macondo well blow-out in the GOM; highlighting concerns such as managing pressure and temperature for field life, cement/sealant long term integrity for corrosive environment, testing equipment issues for wells, proppant function and chemical control and electrical/power battery limits (Mazero, 2012; Proehl, 2006) This has opened up discussions and plans of developing technologies to match these challenges. Most of the HPHT wells are located in deepwater environments characterised by pervasive complexity in its operations and cost especially from rig rental and long trip times. This can be amplified for ultra-deepwater fields showing how technical capabilities are stretched which can often result to increased risk with excessive equipment wear and tear. With such high cost and risks requiring only the biggest and most favourable deep prospects be drilled, a continued application of risk analysis would be seen.

The benefits of risk reduction measures incorporation into the design of facilities, which were informed by risk analysis has been established. This helped with achieving operator’s risk management benchmark and compliance with regulators. See (Overfield and Collins, 2002)

Table_Apx E-1: Review of Risk Assessment Application in the Offshore Industry

No	Paper Citation	Technique Name/ Software Used	Application/System/Scenario	Lifecycle Phase	Comments/Points to note
1	Risk Assessment of a BOP and Control System for 10,000' Water Depths (Quilici et al., 1998)	QRA-FTA	Drilling/ Design Audit of BOP	Design	The results of the assessment identified a combination of component failures, operator errors, and environmental conditions required for the BOP failure. This informed design changes that improved the control system reliability.
2	Risk Management in Exploration Drilling (Thorogood et al., 2000)	Checklist, Qualitative and Quantitative risk methods applied in different context (see Comments)	Drilling /Project, well, location-specific, environmental and operational risk assessment	Through-life	There is an emphasis on the significance of lesson learned as an input into the assessment to buttress the evolving and dynamic nature of the model. Risk Analysis context considered includes: Environmental risk Assessment, Operational risk assessment, Well risk assessment (technical), project risk assessment (political, schedule, financial or political)
3	Focused Risk Management Brings a Step-Change Improvement in Drilling Performance at Sakhalin's Oduptu ERD Development (Mohammed et al., 2006)	Qualitative and some specialised quantitative modelling of consequence and frequency		Design and in-Use for Drilling	Strategy for drilling operations risk management was developed using cavity formation events refined for wells. It identified threats , post event consequences and then used expert personnel experience to identify threat mitigation barriers/strategies
4	An Integrated System for Risk Assessment of Drilling Operations in OIl and Gas Wells (Khatlan et al., 2007)	Hierarchial Drilling Operation Risk Assessment (DORA)- brainstorming technique, Delphi and the Matrix method	Drilling /Project, well, location-specific, environmental and operational risk assessment	Design and in-Use for Drilling	The goal is to provide information required for decision making and minimizing cost, loss time to the system. The risk considered were those emanating from man, machine and earth. The last phase of the DORA process model is one of a dynamic risk assessment and revise plan. This recognises the fact that changes to the program or risks can occur and thus data from monitoring devices in place would be used for updating before a new evaluation.
5	Dynamically Positioned Completion Operations Risk Analysis (Barrilleaux et al., 2001)	Quantitative approach- probabilistic Approach, Uncertainty analysis/ Decision Analysis by Tree Age - DATA software-speadsheet	DP completion operations	Operations	The risk analysis was to ascertain potential financial exposure incurrable when conducting completion operations from DP vessels, compared to a moored vessel.
6	Application of a Deepwater Riser Risk Analysis to Drilling Operations and Riser Design (Ambrose et al., 2001)	Specialised Quantitative risk analysis technique- Drive-off, storm occurrence per activity, failure per activity probabilities	Drilling/ Riser	Design and in-Use for Drilling	The risk assessment entailed amongst others, determinining the percentage of time that the vessel is exposed to various seas and swell from 0 to 90- degree headings The analysis considered several scenarios and results showed risk sensitivity to vessel type used.
7	Comparison of Quantitative Blowout Risk Assessment Approaches (Dervo and Blom-Jensen, 2004)	BLOFAM Quantitative risk analysis approach	Drilling/ Blowout Risk	Design and in-Use for Drilling	The BLOWFAM approach is compared with traditional approach to blowout risk assessment. BLOWFAM combines well specific well and installation information. Unlike traditional approaches BLOWFAM requires risk analyst to have good knowledge and understanding of drilling and blowout parlance.
8	Dynamically Positioned Completion Operations Risk Analysis (Overfield and Collins, 2002)	QRA- ETA /FLACS (Flame acceleratoor simulation,	FPSO installations	Conceptual and detailed design stage	Design features influenced the risk contributions from the hazards QRA used to demonstrate risk-acceptance criteria as defined by an operator. QRA outcome informed the design basis and used for a verification basis.
9	Comparative Risk Analysis of Two FPSO Mooring Configurations (Stiff and Ferrari, 2003)	HAZID and Structural Reliability Assessment techniques	FPSO (spread-moored & turret-morrred configuartions)	Concept selection/ Design Phase	Risk analysis was applied to provide information concerning the relative risk and potential differences between the two configurations.

No	Paper Citation	Technique Name/ Software Used	Application/System/Scenario	Lifecycle Phase	Comments/Points to note
10	Risk Assessment of offshore Engineering Equipment Projects- A Case Study of Fall Pipe Vessel in China (Zhao et al., 2011)	Fuzzy-Analytical Hierachy Process	Fall pipe vessel	Design and Operations	Experts opinion was vital to completion: Interviews and field study was used.
11	Risk & Reliability Based Fitness for Service (FFS) Assessment for Subsea Pipelines (Mustapha, and Bai, 2011)	QRA, SRA	Subsea Pipelines	Throughlife	It attempts to address using risk assessment to inform pipeline segments reliability targets and contribute input for FFS. A unique synergy of QRA and SRA is demonstrated.
12	Lessons learnt from recent Deepwater Riser Projects (Saint-Marcoux et al., 2010)	FMECA	Procurement, fabrication or installation scenarios for a Hybrid Riser Towers (HRT) for DW Production	Manufacturing, Installation and Commisioning Phase	Only a few parameters could be analyzed as the FMECA covers a range of concepts and so difficult to cascade into a detailed quantitative analysis. The outcome of the FMECA helped justified actions in the inspection maintenance and repair dossier.
13	Assessing the Risk of Riser and Piepline Failures on Offshore Installations (Comer, et al., 1991)	QRA -Frequency estimation,Consequence Modelling and Impact Assessment	Riser Pipeline System failure	Operations	This paper is over 20 years old and as such the calculatiosn were done using spreadsheet. Risk presentation was mainly the Potential loss of life (PLL)and F-N plots was used to show different fatality incident levels contributions to the PLL. The results showed varied outcomes in risk reduction potential of an SSIV for different installation cases considered and hence the need for risk analysis tool to be applied to unique cases.
14	Risk Assessment as a Tool in establishing the requirement of Subsea isolation Valves in Subsea Pipelines (Dhar, R.. 2009)	QRA -Frequency estimation, ETA, Consequence Modelling and Impact Assessment-Quantitative and Qualitative	Riser Pipeline System failure	Though Generic but applicable in Design Stage.	Quantitative Assessment- Personnel risk, PLL Risk, Asset Risk (e.g. Structural failure of platform leg or lower deck), and Environmental. Qualitative Assessment- Cases where no data is available or risk potential exist in the future. E.g Dropped object Challenges in consequence Assessment (e.g erronous results may be generated from softwares for large hole size release cases) and risk assessment (e.g. frequency influences th eoverall risk greatly and can be misleading) were presented.
15	Addresing the integration and Installation HSE Risks for Deepwater Project (Warwick and Grant, 2006)	HAZID with risk Matrix ETA- for more detailed assesment involving scenarios with interrelated issues /SACS was used for impact load and damage to pipe works , CFD for gas dispersion modelling	Offshore riser-pipeline system (a case of introduction of buy-back gas to the facility during hook-up and commisiioning)	Installation and commissioning	Existing risk analysis techniques need adaptation to address new risk posed by newly understood complexity in the offshore industry e.h those associated with integration and installation
16	BlowFlow - a New Tool Within Blowout Risk Management (Arild et al., 2008)	Quantitative approach- probabilistic Approach, Uncertainty analysis/ BlowFlow	Drilling Risk	Throughlife	Monte carlo Simulation technique is used to provide several potential blowout rate and durations As known uncertainty exist with decision support system using probabilistic distribution, environmental risk analysis would suffer a drawback given implictness with what blowout rate to use (expected, weighted, worst case?)

No	Paper Citation	Technique Name/ Software Used	Application/System/Scenario	Lifecycle Phase	Comments/Points to note
17	Risk Analysis Techniques Applied to Floating Oil production in Deepwater Offshore Environments (Carpignano et al., 1998).	QRA-FMEA (for wellhead) and HAZOP (for turret and flowlines) were used hazard identification, Risk matrix approach was used to estimate the accident probabilities and consequences. Event tree to describe the sequence for different operative stage (spontaneous and artificial-lift)	FPSO- DW and Ultra DW	Throughlife	In this study, databanks were initially investigated to identify initiating events (e.g. crane accidents, anchor system failures, falling loads and blow out) for accidents involving FPSO, in addition to data for different working conditions (i.e. drilling to operations) to provide a general overview
18	Risk Assessment of Platform Decommisioning and Removal (Kierans et al., 2004)	Quantitative, Bowtie /Custom-made Excel spreadsheet	Platform removal (Frigg field)	Decommissioning/ Removal	Overall risk puture was developed from occupational related risk, residual hydrocarbon risk and other major hazard that are concept dependent and otherwise. Demonstrating ALARP, the effectiveness of barriers, and a measure of how the risks vary for different personnel and different removal options was the focus of the work. In the course of the study, where no/insufficient data is available, certain risk level evaluations required were made by experts.
19	Conceptual Framework: Semi-PSS for Sustainable Decommissioning of Offshore Platforms in Malaysia (Lun, et al. 2012)	Hazard function concept, Risk matrix, DRMA	Offshore Jacket Platforms	Decommissioning/ Removal	Fully Quantutative methods for assessing aeging structires may not be feasible, hence the use of other evaluation mediums such as competent engineering judgement, detailed analysis from similar platforms or reference data.
20	Appllication of Fuzzy Sets Theory in Qualitative and Quantitative Risk Assessment (Anatoly, B. , et al., 2002)	Risk matrix (ALARP Criteria) / Fuzzy St Theory	Offshore lifting/ towing Operation	Installation	Where databases that are reliable are not available and ascertaining outcome probabilities is challenging for analysisng certain operations fuzzy set theory can be adapted to traditional risk analysis. Experts judgement was relied on for assessing uncertainty levels. The need to obtain real data from operations via data collection, or Inspection and monitoring was emphasised.
21	Holistic Approach to Subsea Integrity management and Reliability and Their Application to Greenfield and Brownfield Projects.	HAZID , Checklist - Throughlife; Bowtie -Design stage; HAZOP-Detailed design, Installation and commissioning	Subsea production System (new and Old developments)	Throughlife	The approach is geared towards a subsea intergrity management program development and implementation. This emphasises the use of risk assessment tool or risk-based approaches. The importance or transparency and tractibility in efficiently sharing knowledge and lessons learnt from different projects/facilities was emphasised.
22	The Longannet to Goldeneye project: Challenges in Developing and End-to-End CCS Scheme (Garnham, andTucker, 2012)	HAZID, HAZOP and Bowtie	Carbon Capture and Storage System (Onshore and Offshore)	Throughlife	Initial Risk register was pivotal to initial commercial negotiations which included what risk were business as usual ordemonstrated risk and how they would be adressed. Bowtie was used to analyse containment risk- identified mitigation barries (natural, engineered and reactive)
23	Risk -Based Classification of offshore Production Systems (Tremblay et al., 2007)	HAZID, QRA, HAZOP, and /or FMEA	Offshore production System	Throughlife	The potential of classification via risk-based verification (RBV) was demonstrated, despite the typical prescriptive classification methods . RBV provided a project specific view to understanding risk that are critical to a facility and inform an installation specific Class plan Integral to the approach is knowing what the overall performance criteria for the facility is,against which safety critical elements can be assesed. A major impedement could arise from an absence of key stakeholders commitment

No	Paper Citation	Technique Name/ Software Used	Application/System/Scenario	Lifecycle Phase	Comments/Points to note
24	Risk-based Assessment for the Existed Submarine Pipeline (Zhao and Wang, 2010	HAZID, Risk Matrix, DRMA	Subsea Pipeline system	Operations	It emphasises the role of data to assessing and categorsing risk levels, how such information can be time dependent and why asset managers need to update risk levels Qualitative, quantitative and semi-quantitative risk analysis methods can be applied to operating pipelines based on current technology and data
25	Preliminary Hazard Analysis of Fire Systems of Tankers (Martins and Goyano, 2007)	Checklist, HAZID, Risk matrix, FTA, ETA, Delphi	Tankers Fire System (Marine)	Throughlife	IMO (2002) guidelines for Formal Safety Assessment is presented and the first step (hazard identification) applied to the system of interest. Hazard Scenarios were classified using five frequency classes and four Severity classes - IMO's seven frequency classes were modified based on Ship's operational life and owner's experience in relation to the associated hazards. The need for personnel competence (vis-avis good training) and clear procedures for operators was emphasised.
26	Safety and Risk Analysis of Natural Gas Hydrate Pellet Carrier (Kaehler, and Hamann, 2012)	HAZID-FMECA	Gas-Hydrate Carrier (Marine)	Throughlife	An alternative to conventional LNG carrier was systematically assesed and results showed diverse comparative advantages for different scenarios considered. Scenarios considered included PLL, Potential loss of cargo, fire risk, and societial risk. Results also gave indicative directions for further studies and sensitivity/optimisation analysis to fully understand and verify the technology option.
27	Environmental Risk Assessment Utilising Bowtie Methodology (Jones and Israni, 2012)	HAZID and ENVID by way of a Bow-tie	Offshore LNG Platform	Throughlife	In addition to the establihed benefits of Bowtie methodology, attention was drawn to its utility for reviewing production start-up and difficult challenges with specific process stream.
28	Risk assessment of aging ship hull structures in the presence of corrosion and fatigue (Akpan, et al. 2002)	Structural Reliability Analysis - Analytical Model (Ultimate limit Strength, Second order reliability model)	Hull Structure	Ageing Stage	Risk associated with an aeging asset was better assessed using time dependent random functions reliability model as it had lower reliability values than those of instantaneous reliability. The accuracy of the models used for the assessment of ultimate strength determines the qulaity of the results would be and also numerical models are considered to be of more quality than analytical models.
29	Use of Fuzzy Sets Theory in Qualitative and Quantitative RiskAssessment (Zolotukin and Gudmestan, 2000)	ETA/Fuzzy St Theory	Towing operaion failure to assess consquence (damage or Loss of deck)	Installation	Same as below
30	Assessment of existing offshore structures for asset extension (Ersdal G. 2005)	HAZID, HAZOP, SRA- Collapse Analysis, Damage strength and reserve free board ratio, Probabilistic Structural Model Simulation	Offshore Structures	Life- Extension	Risk evaluation is integral to any assessment of an asset for life extension consideration. Bothe Quantitative and Qualitative methods are useful and uncertainties exist in the degradation mechnaisms and their estimation, data available, risk screening techniques, risk reduction means and acceptance criteria, and competence of analyst..