CRANFIELD UNIVERSITY

Anietie Nnana Umofia

Risk-based Reliability Assessment of Subsea Control module for Offshore Oil and Gas production

School of Engineering (SoE)
Department of Offshore, Process and Energy Engineering
PhD School of Engineering

PhD
Academic Year: 2011 - 2014

Supervisor: Dr. A. Kolios and Prof. F. Brennan

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This thesis is submitted in partial fulfilment of the requirements for the degree of Degree of Doctor of Philosophy (PhD)

ABSTRACT

Offshore oil and gas exploitation is principally conducted using dry or wet tree systems, otherwise called the subsea Xmas tree system. Due to the shift to deeper waters, subsea production system (SPS) has come to be a preferred technology with attendant economic benefits. At the centre of the SPS is the subsea control module (SCM), responsible for the proper functioning and monitoring of the entire system. With increasing search for hydrocarbons in deep and ultra-deepwaters, the SCM system faces important environmental, safety and reliability challenges and little research has been done in this area.

Analysis of the SCM reliability then becomes very fundamental due to the huge cost associated with failure. Several tools are available for this analysis, but the FMECA stands out due to its ability to not only provide failure data, but also showcase the system's failure modes and mechanisms associated with the subsystems and components being evaluated. However, the technique has been heavily challenged in various literatures for several reasons. To close this gap, a novel multi-criteria approach is developed for the analysis and ranking of the SCM failures modes.

This research specifically focusses on subsea tree-mounted electro-hydraulic (E-H) SCM responsible for the underwater control of oil and gas production. A risk identification of the subsea control module is conducted using industry experts. This is followed by a comprehensive component based FMECA analysis of the SCM conducted with the conventional RPN technique, which reveals the most critical failure modes for the SCM. A novel framework is developed using multi-criteria fuzzy TOPSIS methodology and applied to the most critical failure modes obtained from the FMECA evaluation using unconventional parameters. Finally, a validation of these results is performed using a stochastic input evaluation and SCM failure data obtained from the offshore industry standard reliability database, OREDA.

Keywords: Reliability Assessment, SCM, API 17N, FMECA, Risk priority Number (RPN), Fuzzy TOPSIS, SPS.

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Dedication

Η καρδιά μου είναι γεμάτη με χαρά σε αυτό το τεράστιο επίτευγμα.

Είμαι πολύ ευγνώμων στον Θεό για την καλοσύνη, έλεος, χάρη, την παροχή και την αγάπη του για μένα.

Αφιερώνω αυτό το διδακτορικές σπουδές στο Θεό για να καταστήσει δυνατή.

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ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
CA	Criticality assessment
CAPS	Communication and Power Syste
CIV	Chemical Injection Valve
COPS	Communication On Power System
Comms	Communication
DP	Drill Pipe
DCSM	Dummy Subsea Control Module
DCV	Directional Control Valve
DHPT	Downhole Pressure Temperature Transducers
EFL	Electrical Flying Lead
E-H	Electro-hydraulic
EPU	Electrical Power Unit
ESD	Emergency shutdown
ETU	Electronic Test Unit
FAT	Factory Acceptance Test
FCV	Flow Control Valve
FM	Failure mode
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FPSO	Floating Production Storage and Offloading
FTA	Failure Tree Analysis
HFL	Hydraulic Flying Lead
HP	High Pressure
HPU	Hydraulic Power Unit
IWCV	Intelligent Well Completion Valve
LP	Low Pressure
LS	Landing String
MCDM	Multi-criteria decision making
MCDA	Multi-criteria decision analysis
MCS	Master Control Station
MF	Membership Function

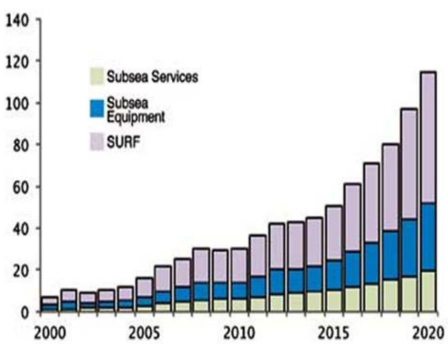
MIV	Methanol Injection Valve
MTBF	Mean time between failure
MTTF	Mean time to failure
MQC	Multi Quick Connector
NCR	Non-conformance report
NDT	Non Destructive Test
OEM	Original Equipment Manufacturer
PCV	Production Choke Valve
PSU	Power Supply unit
PMV	Production Master Valve
PWV	Production Wing Valve
RAM	Reliability Availability Maintainability
QA/QC	Quality Assurance / Quality Control
RBD	Reliability block diagrams
RCR	Remote Component Replacement
RPN	Risk Priority Number
ROV	Remote Operated Vehicle
SCM	Subsea Control Module
SCMMB	Subsea Control Module Mounting Base
SCS	Subsea Control System
SCSSV	Surface Controlled Subsurface Safety Valve
SDU	Subsea Distribution Unit
SEM	Subsea Electronic Module
SFT	Surface Flow Tree
SIT	System Integration Test
SPS	Subsea Production System
SRT	Site Receiving Test
SSTT	SubSea Test Tree
SUTA	Subsea Umbilical Termination Assembly
T/F	Test and Flushing
TFN	Triangular fuzzy numbers
TH	Tubing Hanger
TOPSIS	Technique for order performance by similarity to ideal solution
TRT	Tree Running Tool
TT	Torque Tool
TTA	Torque Tool Adaptor

TUTU	Topside Umbilical Termination Unit
UPS	Uninterruptible Power Supply
UTA	Umbilical Termination Assembly
UDW	Ultra-deepwater
WP	Work Package
WROV	Work ROV
XMT	Xmas tree
XOV	Crossover Valve
XT	Xmas Tree

1 INTRODUCTION

1.1 Background of the research

The easy oil has been found! Hydrocarbon search is witnessing a dramatic drive into remote, deep and ultra-Deepwater arena with attendant safety, environmental and reliability challenges (Mahler 2014). Deepwater conditions inherently dictate the development of oil and gas fields by means of subsea production systems (SPS), since traditional surface facilities such as steel-piled jacket are either technically unfeasible or uneconomical due to the water depth. According to the Douglas-Westwood (DW) forecasts, the total global subsea hardware Capex is $117 billion (bn) between 2014 and 2018. Compared to the previous period five years period, this represents a growth of more than 80% (See figure 1). The figure also shows a worldwide statistics for offshore production facilities ranging from floaters, fixed platforms to subsea wells with four thousand five hundred and four (4,504) subsea wells operational today, four hundred and six (406) under development and over six thousand being planned for 2014 onwards (Morgan 2014).



	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

(a) (b)

Figure 1 – (a) Subsea market forecast 2014 to 2018, (Douglass Westwood 2014).

(b) Statistic of Offshore production systems worldwide operational and 2014 onwards (Morgan 2014).

The shift to Deepwater presents a huge challenge to the subsea systems demanding reliability at its best. This calls for a need for a reliability assessment of the subsea control module (SCM), being the heart of a typical SPS, considering the high cost associated with failure.

A subsea production system (SPS) comprises a wellhead, valve tree (‘x-mas tree’) equipment, pipelines, structures and a piping system, etc., and, in many instances, a number of wellheads have to be controlled from a single location (Haritonov 2009, Wang 2012). It ranges in complexity from a single satellite well with a flowline linked to a fixed platform, FPSO or an onshore installation, to several wells on a cluster or template on a tie-back to fixed or floating systems piped directly to an onshore facility. Figure 1 is a typical subsea field development layout on a tie-back to an FPSO.

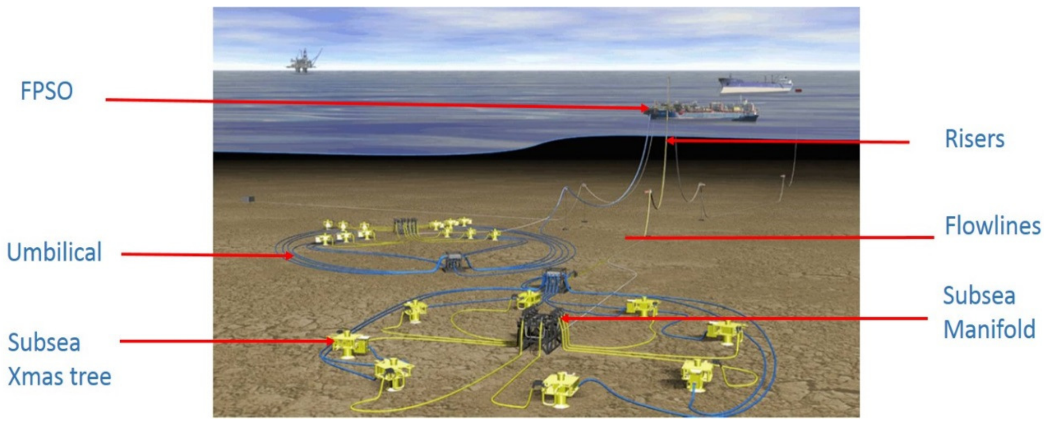


Figure 2 Subsea development field layout (Pedram 2008)

A subsea control module (SCM) is the main ‘’brain’’ of a typical electro-hydraulic SPS. Normally mounted on the system to be controlled (tree, manifold, SDU…etc), it delivers multiplexed control power to the appropriate system unit. A tree-mounted SCM (see figure 3) is responsible for the control of all tree valves and sensors including the downhole intelligent valves and their instrumentation. It is also responsible for relaying all signals from the topside to the appropriate units and vice versa for efficient condition monitoring of the entire SPS. Common functions of a tree-mounted SCM are as follows:

- Control of subsea tree valves
- Control of chemical injection valves
- Monitoring of the tree system functions
- Control of the SCSSV
- Control of the intelligent control valves
- Monitoring of downhole instrumentation

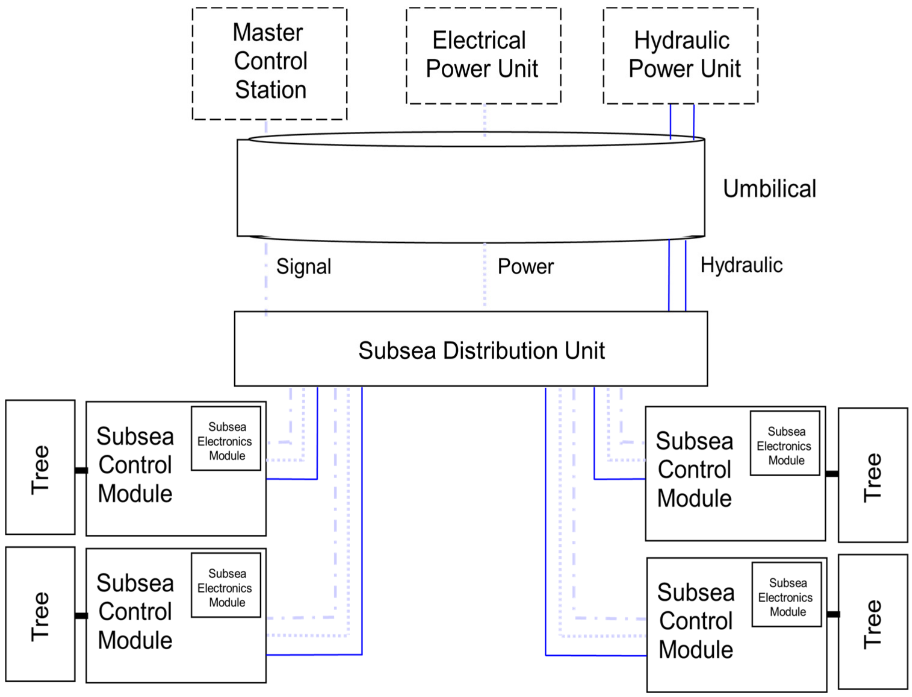


Figure 3 E-H multiplexed SPS showing a tree-mounted SCM, self-addition

The above functions are so critical to a subsea production system (SPS) and normally require embedded redundancy as failure or loss in any of those will typically lead to very severe consequences. Common failures typical experienced in the SCM during offshore oil and gas production offshores are (Mamman 2009, Broadbent 2010):

- Leakages in the different valve units in the SCM
- Inability to operate the SCM valve units from their last position
- Loss of signal from the SCM unit
- Loss of power from the its SEM unit
- Water ingress into in to the SCM housing

The failure consequences are further amplified by environment and increased water depth as a well support vessel (WSV) and a remote operated vehicle (see figure 4) at very exorbitant cost are normally required for the SCM retrieval, repair and replacement.

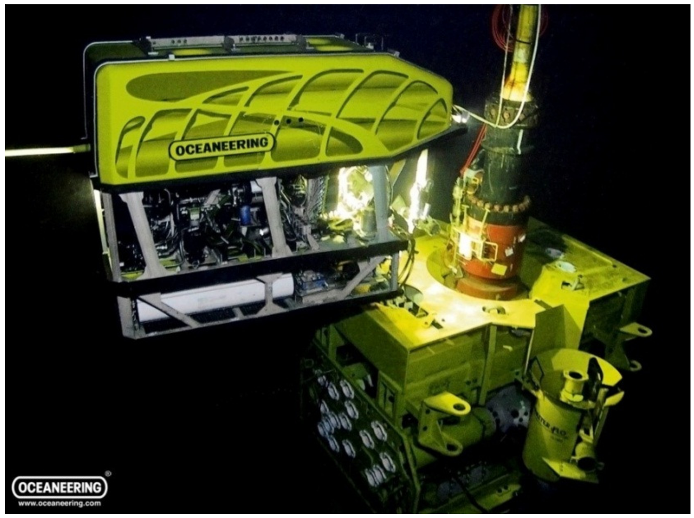


Figure 4 ROV during a subsea operation on a Xmas Tree, courtesy of Oceaneering.

The obvious gap associated in the operation of the SCM in an SPS for offshore oil and gas exploitation and the limited associated research demands a study into this area.

1.2 Motivation for the Project

The brain of a typical subsea control system (SCS) in an SPS is the subsea control module (SCM). It is controlled by the master control station (MCS) located topside on a platform or floating vessel. Usually mounted in an Xmas tree, manifold or SDU, the SCM contains electronics, instrumentation, and hydraulics for safe and efficient operation of subsea valves, chokes and also provides condition monitoring functions. Figure 5 shows the various parts of the SCM.

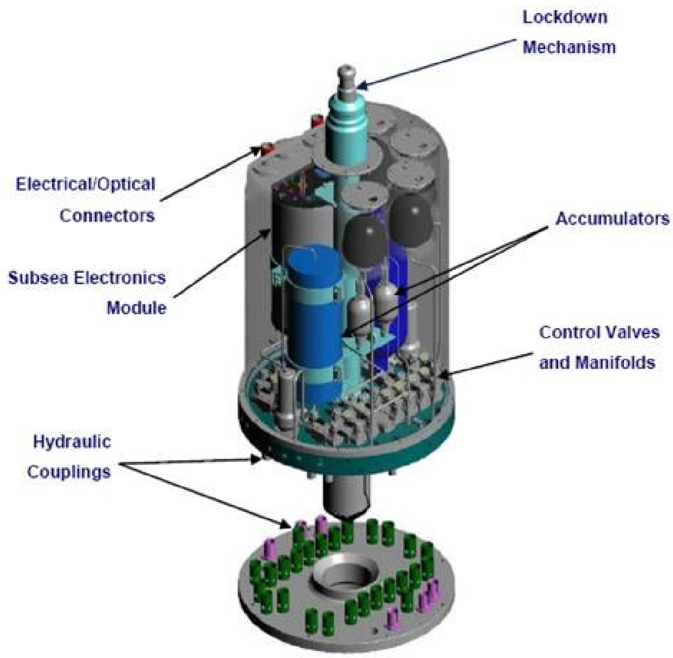


Figure 5 Subsea Control module (SCM), courtesy of Aker

It is no secret in the industry that the SCM is one of the systems with the biggest reliability challenges (Brandt 2001). A recent industry study by a top oil and gas producer firm (name withheld, for confidentiality reasons) shows that the SCM as being responsible for the highest production loss in the SPS (See figure 6). The study showed the SCM as being responsible for 30.4% of production loss, far above any other system in the SPS. This, at the least is very alarming and deserves the highest attention possible to reduce such a rate system malfunction.

Today, the SCM is required to provide controls at tieback distances as much as a 100km, water depths of 3000m with a pressure rating at 15,000psi. This requires more complex systems, accurate data collection, fast response time and overall improved performance posing unprecedented challenges to the module. Well interventions in subsea deepwater wells cost over $200,000 per day, with a typical cost of $10,000,000 per intervention including operations usually being conducted by a floating deepwater drilling rig (Pedram 2008). Failure of this system leads to a huge loss in production, environmental issues and may lead to an uneconomical field development with significant safety concerns.

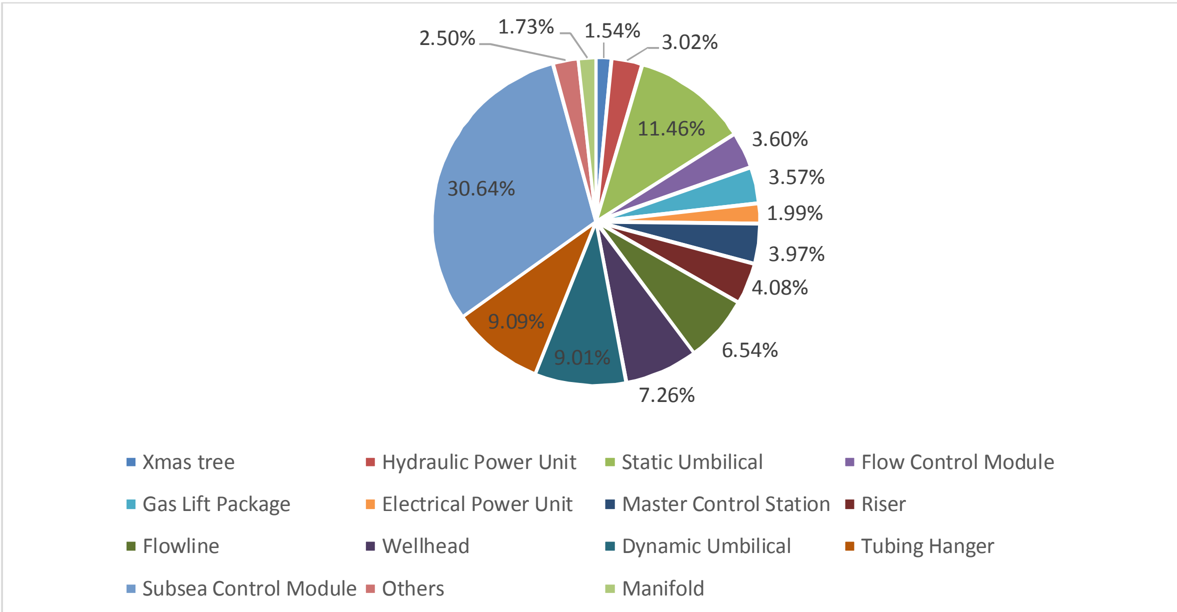


Figure 6 Main causes of production Loss divided in the SPS

The sensitivity, remoteness and high cost of intervention, repair and maintenance makes the reliability of subsea control module (SCM) a priority in the offshore oil and gas industry. However, little research has been done in this area.

This PhD research is focussed on risk-based reliability assessment of the subsea control module (SCM) used for the production of hydrocarbons in subsea oil and gas production. A review of the challenges in deepwater water oil and gas development is conducted. Also in the thesis, the features, merits and limitations of various techniques used in reliability assessment are being explored with a focus on failure mode and effect criticality analysis (FMECA). FMECA is known to be one of the widely used engineering tools for analysing systems reliability (Hekmatpanah 2011). An FMECA with a thorough risk identification analysis of the subsea control module (SCM) is being analysed in this report. A criticality assessment of its failure modes is then performed using the RPN methodology. Considering some limitations associated with the RPN methodology, a novel multi-criteria fuzzy TOPSIS evaluation of the SCM failure modes is conducted using unconventional parameters, derived from expanding the criterion used in the conventional RPN. A sensitivity analysis based on the elimination of one risk factor at a time is also conducted. A validation of the results is performed using a stochastic evaluation and analysis of data obtained from the industry (OREDA database). In line with recent developments in subsea controls, a comparative analysis of the electro-hydraulic and all-electric SCM is performed using the fuzzy TOPSIS methodology. This study highlights the prospect of the all-electric system as a possible replacement technology for the electro-hydraulic (EH) system considering its attendant merits.

1.3 Aims and Objectives of the Research

The subsea control system constitutes a vital part of the overall subsea production equipment, and its reliability is paramount in order to achieve safe and undisturbed production (Grude 1994). The overall aim of this project is to develop an effective methodology for assessing the reliability of subsea control modules (SCM) in deepwater oil and gas production systems.

The project has the following objectives:

- To conduct a critical literature review on reliability assessment with a focus on the subsea offshore industry in order to find knowledge gaps.
- Perform comprehensive failure mode and effect criticality analysis (FMECA) for the SCM to establish the effect of the failures and here identify risks
- To conduct a study on possible causes of failures in SCM with a focus on deep waters and the results validated with data collected from the field or expert opinions.
- To develop a novel method for assessing SCM reliability using relevant multi-criteria decision making methods.
- Perform a sensitivity analysis and validation of the model obtained.

1.4 Research Methodology

An overview of the methodology being used in this study, highlighting the main stages is shown in figure 7. The first step in this methodology is a full description of the subsea production system (SPS). Here, a high-level description of the SPS and the subsea control system (SCS) is provided showing the different sections and the position of the subsea control module (SCM), which is the heart of the SCS.

In stage 2, the SCM full identity including its functionality and boundary in the SCS will be provided. The material, operational and environmental characteristics of the SCM will also be provided.

Stage 3 of this study consists of a clear identification of all failure modes and failure mechanisms associated with the failure of the SCM. This stage involves developing of an understanding of failure modes characteristics of the SCM. Failure Modes Effect and Criticality Analysis (FMECA) technique will be used for this. The worksheet to be used in this analysis will consist of the following categories:

- Component Identification and classification
- Failure Causes
- Failure Effects
- Failure Modes

A failure influencing diagram will be derived showing the effect of each of the failure mechanisms.

Criticality assessment of the subsea control module will be performed in stage 4 considering the system features, failures modes, causes, effects and ranking based on conventional and enhanced methodologies. Modelling the reliability of the SCM requires consideration of a complex set of underlying mechanism and processes in relation to its components, operation and the environment.

In stage 5, a survey is conducted using subsea experts is conducted to access the importance of risk factors that influence the reliability of the subsea control module. A questionnaire is designed with two sections. The first section evaluates the importance of the risk factors in SCM reliability while the second rates the risk factors against the SCM failure modes. The results obtained feeds the multi-criteria evaluation performed in stage6. A deep multi-criteria evaluation of the criticality model is performed by expanding the conventional FMECA risk factors from three to ten.

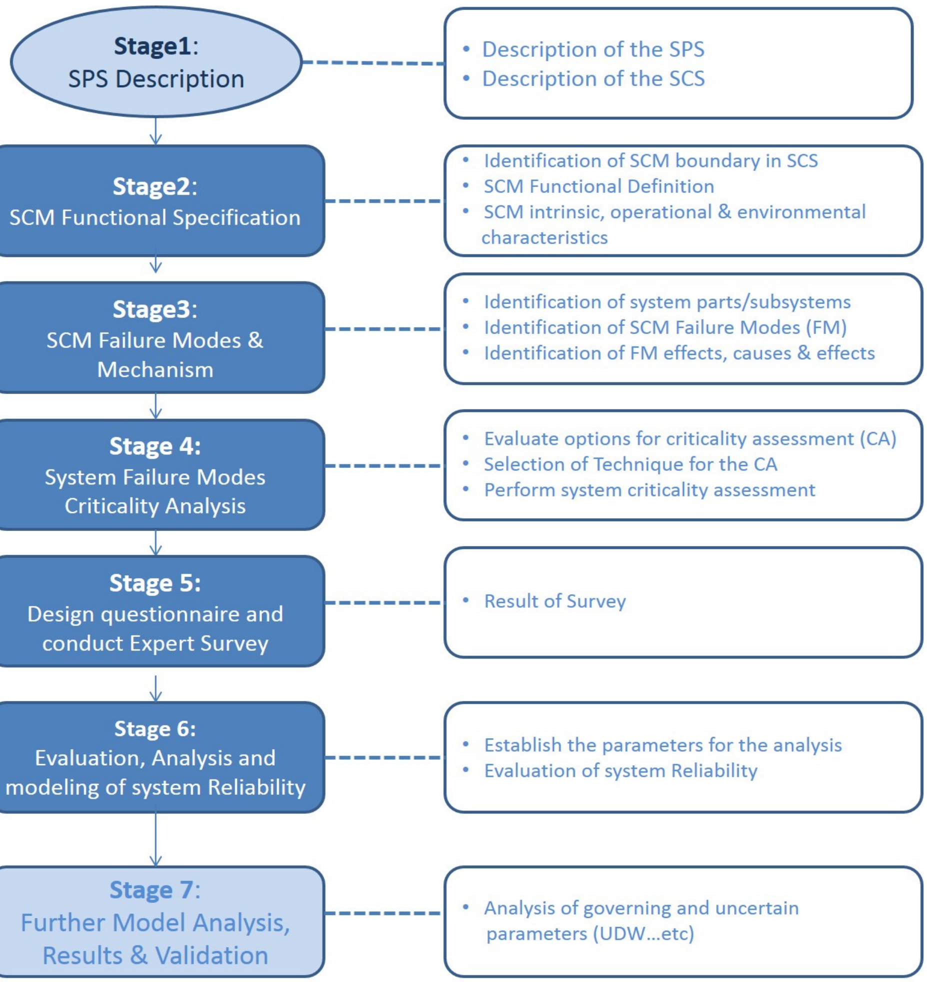


Figure 7 Research Methodology

In stage 7, the SCM reliability model testing, sensitivity analysis and validation will be performed. The main objective of the model testing will be to assess the reliability characteristic of the SCM for the extraction of hydrocarbon in Deepwater as the available technologies approach their threshold.

A considerable amount of data is needed to complete these analyses. When searching for data, several databases and papers were reviewed. Ocean properties data have also been obtained from the industry including failure rates. A vast amount of data was also obtained from the offshore Reliability database (OREDA), which contains key information for the reliability analysis performed, such as probability of failure and time to repair. OREDA compiles offshore equipment data from several petroleum companies through 20years (Osteb0 2001, OREDA 2009). Additional data is also obtained through expert elicitation by conducting a survey using key specialists in the industry covering the operators group, equipment manufacturers including controls engineering and consulting firms.

The reliability data considered in this study are those of the subsea control module (SCM) installed on subsea Xmas tree for the purpose of well control for the production of oil and gas. A horizontal tree (HT) control is being assumed though the functionality is similar to those employed for the vertical tree system. Controls used for subsea pipelines, SDU and manifolds are outside the scope of this report. A semi-quantitative approach is adopted in this research, capturing data through expert elicitation and those from recognised industry databases.

1.5 Structure of the Thesis

Chapter one of this report commences with a general background to the research project. It defines subsea production system (SPS) and explains the role of the subsea control module (SCM) in an SPS for oil and gas production. The common function of the SCM and a high-level list of common failures in the SCM is also provided. The justification for carrying out the research is clearly explained highlighting the significance of the SCM in an SPS as a chosen technology. Aims and objectives including the study methodology are also provided in this chapter.

Chapter two looks into risks assessment in the subsea industry. It commences with a review on the attendant risks associated with offshore oil and gas production in the face of increasing water depth. Deepwater subsea controls is discussed next along with subsea challenges and risks. The classification of water depth into shallow, deepwater and ultra-deepwater is also showcased. The industry standard for managing risk, API17N, is also explained along with equipment qualification, a requirement for unproven systems and components deployment in the subsea industry. This chapter highlights the first principle of reliability and mentions the need for a study into SCM reliability. The chapter also looks into common flow assurance challenges in the offshore subsea industry including subsea and equipment qualification. Uncertainty as a key bsis for risk is discussed along with systems reliability. A comprehensive review of reliability assessment techniques is then performed from the high-level full probabilistic approach to the component –based techniques like FTA, RBD and FMECA. A section in this chapter is dedicated to subsea production system (SPS) including subsea control system (SCS). Subsea Xmas tree, which is the heart of an SPS, is explained showing the breakdown of different types and features. The different types of subsea control systems including the all-electric SCS are also explained and tabularised

Chapter three focuses on the subsea control module (SCM) and associated risk for its operability. The chapter commences with a historical background of the SCM, explains the SCM system architecture including its function in subsea oil and gas production. Parts of the SCM are also listed and classified. The chapter explains the principle and application of FMEA along with its criticality analysis (FMECA). A comprehensive Failure modes and effect criticality analysis (FMECA) for SCM is performed. Finally, the inherent gaps in FMECA methodology are highlighted.

Considering the gaps inherent in the application of FMECA, chapter four looks at the framework for multi-criteria assessment of SCM reliability. Various methods for bridging the gap are mentioned. A recommendation for the fuzzy TOPSIS methodology for criticality assessment is explained. Data gathering strategy and the survey conducted for this study is explained along with a characterisation of the experts that participated. A novel fuzzy TOPSIS analysis of the SCM failure modes is implemented using unconventional parameters and a sensitivity analysis performed.

In chapter five, a stochastic modelling of the subsea control module failure modes is performed. The analysis reveals the ten most critical failures modes in the SCM.

Chapter six discusses the comparative analysis between the commonly used electro-hydraulic (EH) SCM and the new all-electric SCM, with the industry struggling to make a switch to this promising technology. Parameters such as technology, OPEX, CAPEX, technology and schedule for delivery are used in the analysis.

In chapter seven, a discussion of all the analysis conducted in this research is performed. Results from the SCM FMECA criticality analysis, stochastic input modelling are all discussed and the validation explained regarding those obtained from the fuzzy TOPSIS methodology. A realistic comparison of the results obtained is also compared to those from the industry de-factor reliability database OREDA for the validation of the results. Finally, a case with on a subsea control module (SCM) for a given deployment condition is presented. The inter-relation between system component and failure modes is also discussed. The study highlights how the failure in one component could lead to the failure of an inter-related component eventually leading to a total failure of the entire SCM system and a loss in production with huge OPEX.

Conclusion, novelty/contribution of this study, recommendation and a listing of possible further work emanating from the research is provided in chapter eight. Figure 8 is a diagrammatic representation of the analysis conducted in this research project.

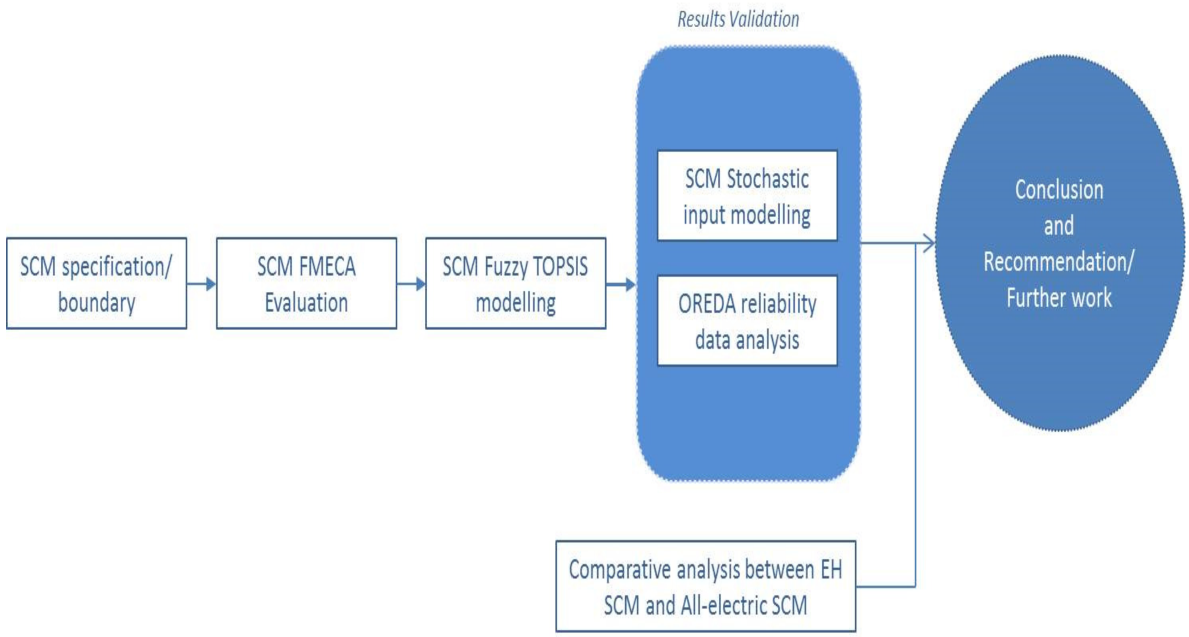


Figure 8 – Diagrammatic representation all the project analysis and flow.

2 Risk Assessment in the Subsea Industry

2.1 Field development concepts, Equipment and Effects of water depth

Though offshore fields present opportunities for increasing oil reserves, they present huge technological and economic challenges. Reduced capital cost is a key factor that allows for a profitable development of an offshore oil and gas field. To achieve this, a careful study of the development concept has to be conducted. According to (Maryam 2011), key parameters for concept considerations of oilfield development includes reservoir characteristics, distance to shore, drilling/installation and well intervention plan, topside weight, utilities, field layout, flow assurance, accessibility, regional influences, financials, well count and HSE considerations with water depth as a major player for offshore field concept selection.

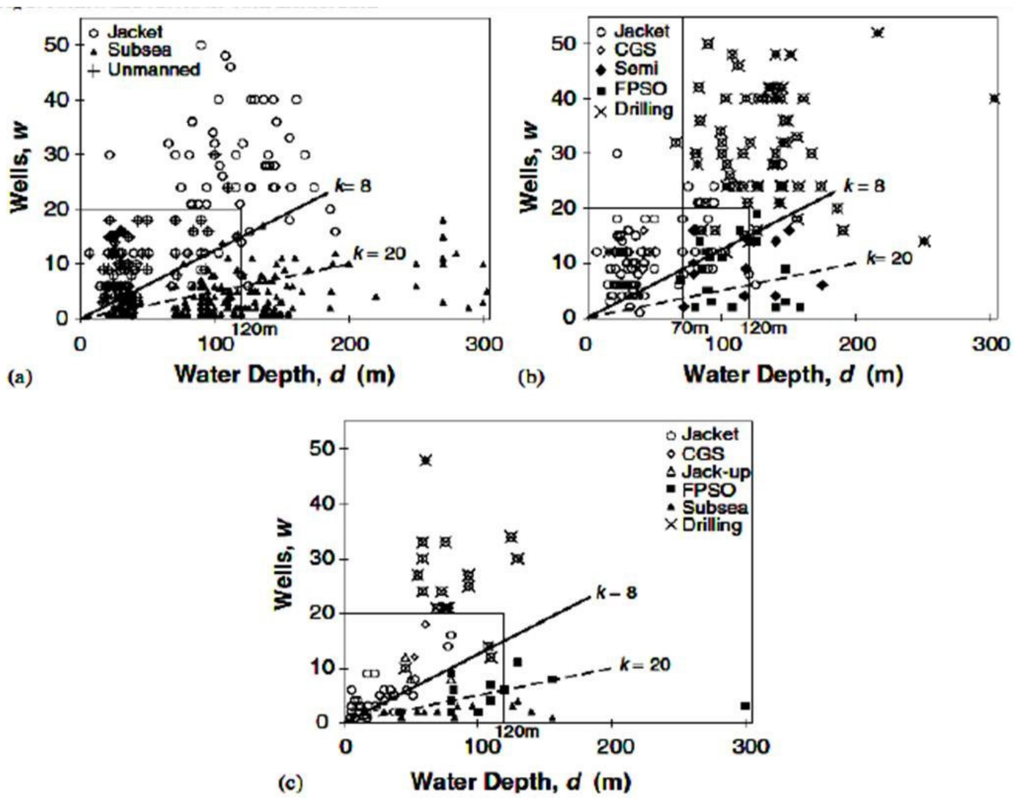


Figure 9 Worldwide deepwater facilities (a) dry tree platforms (b) floaters and (c) subsea satellites (Miriam 2011).

In a study of the development concepts in the North Sea (figure 9a & b above), the study clearly shows that for shallow water, jackets and remote tiebacks were earlier favoured. The study also shows that subsea tiebacks are more for deeper water deployments as a result of a dramatic increase of jacket costs at these depths while the cost of subsea is principally dependent on well count. In the same study, we see that fixed platforms and compliant towers are prominent in shallow waters; TLPs are relatively favoured in deepwaters but disadvantaged in economics while the FPSOs take the upper hand in deep and ultra-deepwater developments as they are greatly even for marginal fields (Wensheng Lu 2006, Zhiyong Su 2014).

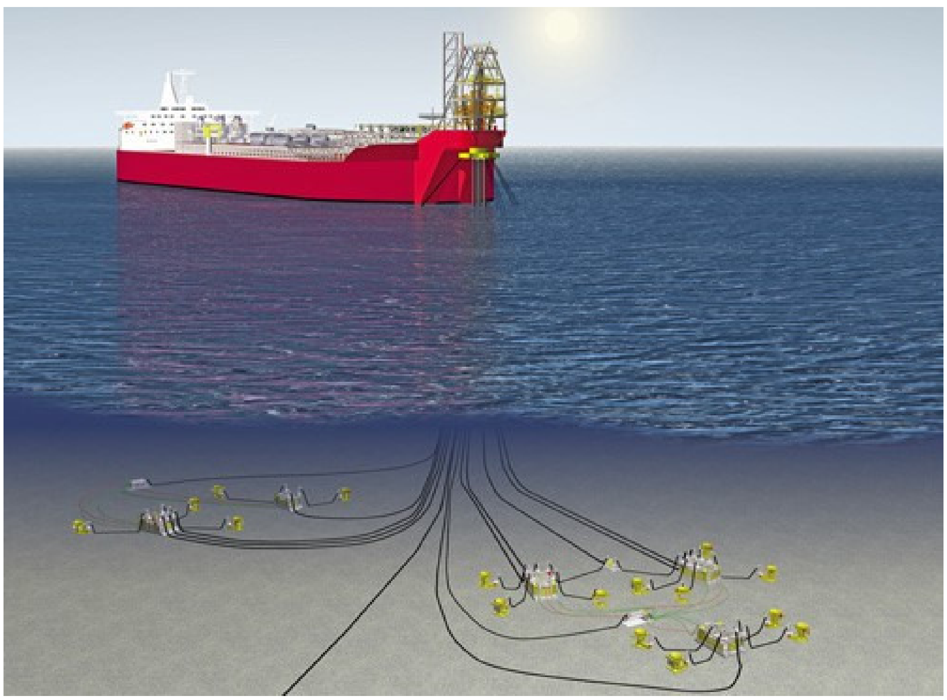


Figure 10 A typical Ultra-deepwater architecture using an FPSO, courtesy of Modec

Deepwater conditions inherently dictate the development of oil and gas fields by means of subsea production systems, since traditional surface facilities such as steel-piled jacket might be either technically unfeasible or uneconomical due to the water depth. Figure 10 shows the deployment an FPSO for a deepwater development.

For riser systems, migration into ultra-deepwaters introduces increase in system weight, flow assurance (heat and pressure management) issues, installation difficulty, station-keeping challenge and increased vortex-induced vibrations. (Fabrice 2001) demonstrates that in order to qualify flexible pipelines for ultra-deepwater operation of 3000m, hyperbaric test and deep immersion performance (DIP) tests are required. Similarly, (Zhang Y 2003) confirms that collapse and axial compression are key challenges on flexible deployed in deepwater environments due to hydrostatic pressures.

According to Pedram (2008), below are the five major issues to be tackled with respect to ultra-deepwater developments.

1. Impact of Ultra-Deepwater Environment on Subsea Equipment Reliability
2. Technical Challenges to Assuring Reliable Performance of Subsea Equipment
3. Utilizing Novel Subsea Technology
4. Flow Assurance: Deep Water Challenges
5. High Cost of Subsea Interventions

The above list obviously shows that reliability is paramount in any subsea development with a significant correlation to environmental parameters. Figure 11 shows a collapsed rig in an offshore field due to a subsea system failure. Deepwater invariably means very high hydrostatic pressure and low temperature which fluctuates around 4ºC. The low temperature poses a huge flow assurance during operations and even worse during startup and shutdown operations.

Figure 11 A semi-sub rig collapses in ultra-deepwaters (UDW Report 2005).

For conventional systems, Reliability, Availability and Maintenance (RAM) analysis can be successfully applied to demonstrate the commercial performance of a given concept (Brandt 2009). A RAM model basically gives a prediction on the expected system performance on a probabilistic system model built on experiential data. These models form the basis for the evaluation of different development scenarios and predict the expected performance of the design options.

A reasonable economics is required for an ultra-deepwater field development. Hence, deployment at this depth poses a huge challenge due to the demand for acceptable financial metrics in today's uncertain and unstable oil and gas environment (Bradley 2001). Reliable equipment that will ensure production availability and minimum offshore subsea intervention is the only answer to this.

Reflection on the root causes of failure suggest that failures are far from inevitable and in many cases could have been anticipated and prevented had sufficient attention been placed on their identification, assessment and management at the design stage (Caroline 2009).

2.2 Deep and Ultra-deepwater Controls

The term "Deepwater" is subject to different interpretation, but in general it is assumed to be beyond the reach of current saturation diving technology. A typical classification of subsea water depths and number of installations for offshore facilities in each class planned between 2014 and 2018 is shown in table 1.

Table 1 Subsea water depth classification and number of installations worldwide (Ostebo 2001, Offshore Engineer September 2014).

Classification	Water Depth	No of Installations Worldwide planned between 2014 and 2018
Shallow Water	<500m	207
Deepwater	500-1000m	86
Ultra-Deepwater	>1500m	94

Operations in Deepwater is strictly with the use of remote operated vehicles (ROVs) as no diver has access to this depth. Figure 4 shows an ROV during a subsea operation on an Xmas tree). During installation or equipment retrieval, the high depth implies longer, more tasking and expensive offshore campaign.

Equipment failure or loss at this depth could be very difficult if not impossible to recover due to the nature of the seabed. Analysing the risks associated in shallow and deepwater oil and gas exploration requires a deep understanding of the variation in the ocean parameters with depth. Figure 12 gives a schematic of the ocean reliability influencing factors. These parameters vary from region to region and with changing water depths (Paulinus 2012).

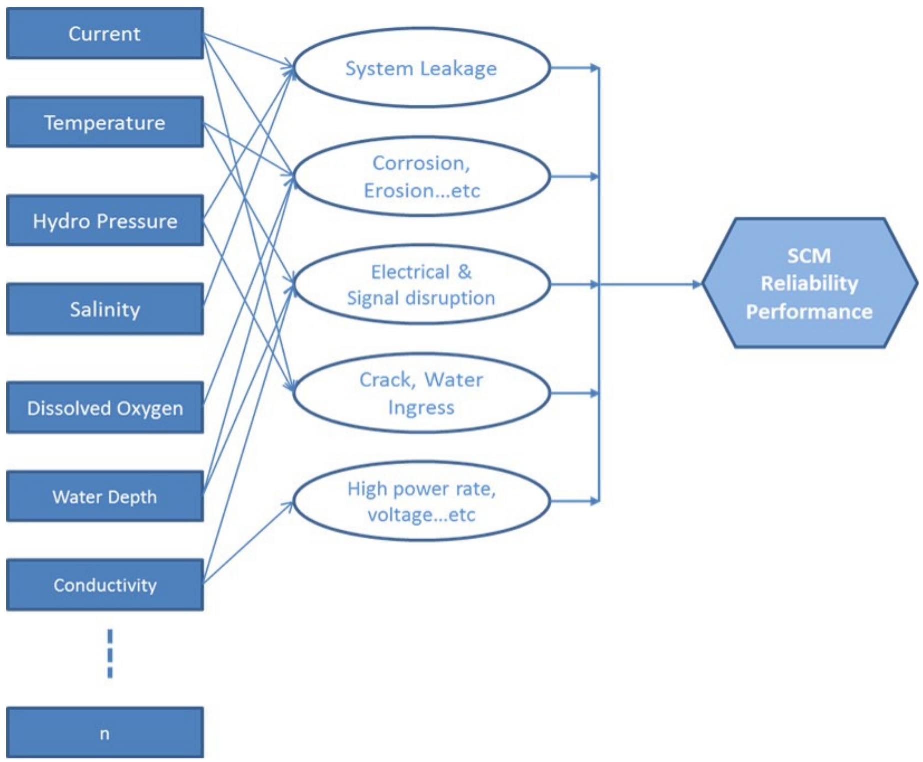


Figure 12 Ocean properties reliability influencing factors (Paulinus 2012).

(Paulinus 2012) confirms that Deepwater environment is defined by a number of variables which encompass temperature gradient, hydrostatic pressures, dissolved gases, salt, pollution, salinity, microbial organisms, carbon-dioxide and mineral deposits. Figure 13 shows the variation of some of these parameters with depth.

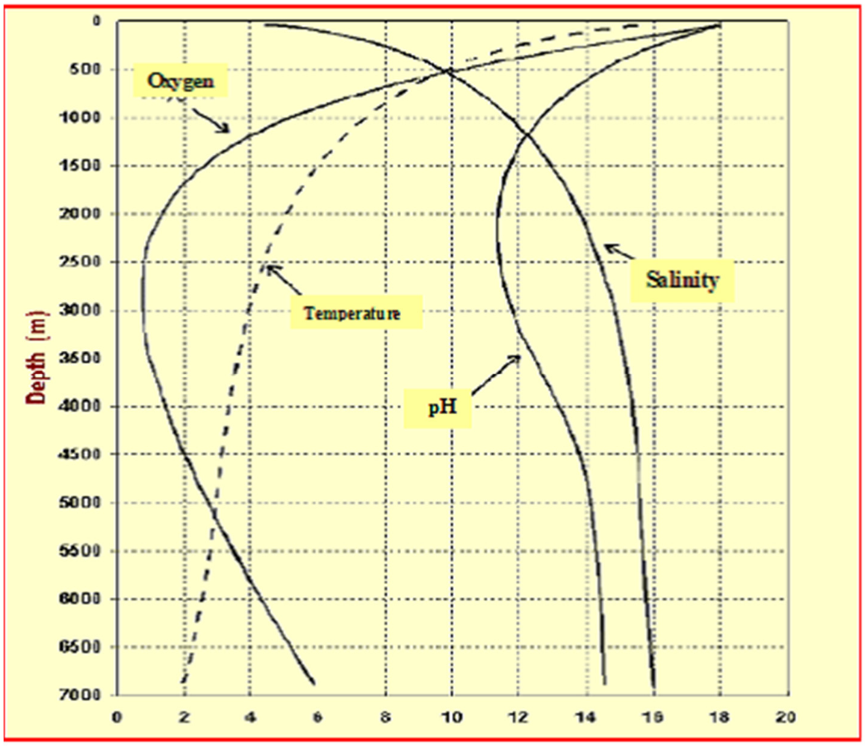


Figure 13 Variation of Temperature (°C), Salinity (ppt), Oxygen (ml/l) and pH with Depth (m), courtesy Paulinus 2012

The figure depicts a rapid increase in ocean salinity with depth in the shallow water region and a slow increase in the deepwater region. The behaviour of temperature is exactly opposite that of the salinity curve as the seabed temperature is typically 4°C and decreases with depth as shown on the curve. The ocean temperature exhibits a rapid decline in the shallow water region and a slow reduction in the deepwater region. The Oxygen and PH curves are very similar in behaviour to that of temperature, showing a rapid decrease in shallow waters and increasing with the ocean water depth. A study conducted on shallow to deepwater facilities and flow assurance challenges in offshore Newfoundland (Ewida 2004) also shows the extreme wind speeds wave heights for deepwater being slightly lower than those of shallow waters (see table 2).

Table 2 Typical/Indicative environmental parameters for shallow water Field (Grand Banks) and deepwater location (Ewida A.A. (2004).

Parameter	Grand Banks	Deepwater
Minimum Water Temperature @seabed (°C)	~1.7	~3
100 Year Extreme Wind Speed (1hr mean) (m/s)	~40	~30
100 Year Significant Wave Height (H_s) (m)	~16	~15
100 Year Maximum Wave Height (H_{max})(m)	~30	~27
100 Year Maximum Current Speed (near surface) (m/s)	~1.30	More or less severe depending on location
Annual Mean Iceberg Fux per Degree Square	~50	More or less severe depending on location
Potential for Pack Ice	Yes	Yes

(Mark A 2004) explains the variation of control requirements with water depth. He explains that controls in shallow waters could be effectively executed with direct hydraulics principle by basically charging and discharging of the hydraulic lines. However, with increased water depth, the absolute control system pressure at the actuator increases and depending on the actuator configuration, the “fail-safe” return spring may need to provide a greater force to ensure valve closure. Also, for shallow water depths, remote accumulator systems are tolerable. With increasing water depth, hydraulic systems require local accumulation to store energy to operate a valve once the directional control valve (DCV) in the subsea control module has functioned electrically with lower power. Although the 'gauge' pressure across the actuator does not change as the water depth increases, the absolute pressure does. This raises accumulator precharge requirements and hence, the pressure at which the gas has to operate. Unfortunately, as the pressure of the gas increases, it starts to behave more like liquid, thus the amount of stored energy for a given volume decreases with depth. This is mitigated by increasing the amount of subsea accumulation, resulting in larger assemblies/modules. The key concern in situations where limited effective accumulation is present is that the opening of a valve can "pull down" the available hydraulic pressure needed to keep other system valves open. The control of opening time to maintain system pressure when limited accumulation is present can be readily achieved by applying a restriction orifice to the flow either upstream of the DCV in the SCM or downstream using a venting check valve.

Modern subsea control systems are generally electro-hydraulic multiplexed (EH-Mux) systems, whereby hydraulic power is generated at the surface and transmitted to one, or more, subsea control pods by means of an umbilical. In essence, a control pod comprises of a number of solenoid-operated hydraulic pilot valves such that the hydraulic fluid may be directed to the various hydraulic actuators which control the relevant subsea equipment (valves, rams, chokes etc) (Clayton 1998).

In summary, the move from shallow to deepwater implies a huge risk with attendant economic penalty for delayed/lost production. This risk becomes increased with the application of novel and prototype technologies.

In ultra-deepwater subsea development, the application of the processes in API 17N with the right assumptions, inputs, during the project lifecycle is very critical to achieving a reliable offshore oil and gas system. Novel and unproven technologies with little or no data find much application in ultra-deepwater developments. DNV-RP-A203 provides a sound framework for their qualification. The strategy is to identify and assess the level of technical risk in the project, followed by the use of API 17N in driving the project. The processes should be used consistently throughout the subsea project lifecycle.

There is a need for a close integration between reliability and engineering for a successful ultra-deepwater project. Equipment's have the highest probability of achieving reliability at the design phase. From this phase through the engineering, procurement, testing, installation and operations, serious attention should be given to avoid the introduction of defects along the equipment lifecycle.

2.3 Subsea challenges and risks

The search for hydrocarbon is witnessing a dramatic move from shallow and deepwater into the ultra-deep arena. According to industry statistics (see table 3), ultra-deepwater Greenfields have a whopping reserve of 19, 520.75 million boe barrels of oil and 6,466 subsea wells globally planned from 2014 representing about 25% of oil production forecast within this period (Morgan 2014).

Table 3 Greenfield reserves forecast 2014 to 2018 (Morgan 2012).

Water Depth	Field Numbers	Liquid Reserves (mmbbl)	Gas Reserves (bcf)
Shallow	1214	46,150.75	770,028.05
Deep	161	12,621.98	97,509.77
Ultra-deep	107	19,520.75	54,507.00
Total	1,482	78,293.48	922,044.82

This shift to ultra-deepwater presents a huge challenge with attendant risk and associated hazard. According to Maryam Maddahi (2011), hazards typically considered, studied and prevented during an offshore oil and gas field life

Table 4 Environmental Stress and typical effects

Environmental Stress	Typical Effects
Temperature	Change in viscosity, physical expansion, cracking, thermal aging, oxidation, ice formation, brittleness and variation in materials properties such as resistance, inductance and capacitance.
Vibration	Reduction in material strength, electrical signal interference, cracking, leakage etc.
Thermal cycling	Alteration in electrical properties, Cracking etc.
Shock	Cracking, Leakage, delamination, ruptured seals, mechanical function impairment etc.
Pressure	Compression, Leakage, Water ingress etc.
Humidity	Leakage, Creates electrical leakage paths, oxidation, corrosion, embrittlement.
Electromagnetic radiation	Surious and Erroneous signal, disconnection in communication, inaccuracy in measurements etc.
Sand	Contamination of lubricants, erosion of mechanical parts, clogging of orifices, increased friction, abrasion etc.
Nuclear/Cosmic Radiation	Heating and thermal aging, Electrical, chemical and electrical properties alteration, oxidation and discoloration of surfaces, damage to electrical and electronic components etc.

includes jacking, trawl, blowout, collapse, capsize, subsidence, landslide, earthquakes, fire, explosion, lightning, heavy weather, winds and storms, tsunamis, workmanship, mechanical failure, pipe laying, piping operations, trenching, stuck drill stem, collision and corrosion. For a successful development of an oil and gas field, a careful evaluation of each of these hazards is required.

For the purpose of this research, ultra-deepwater refers to deployments above 1500m. At a mile depth, water squeezes everything at more than one ton per square inch (Pedram 2008). According to Shifler (2005), parameters that affect systems in seawater includes temperature, dissolved oxygen content, hydrostatic pressure, salinity, water chemistry, pH, bio-fouling, pollution/contamination, galvanic interactions, fluid velocity characteristics and mode, alloy composition, alloy surface films, geometry, surface roughness, and heat transfer rate. Table 4 depicts environmental loads and typical effects. A clear understanding of the interaction of these factors offers optimum system design which ensures a reliable system design.

2.3.1 API 17N and Subsea projects Risks/Reliability

The key to successful reliability management system is to develop understanding and control of all the diverse elements (or risks) which may prevent the design, manufacture, installation and operation of reliable subsea system (Caroline 2009). Typical hazards associated with oil and gas facilities are listed below (API RP 14J 2001):

- Blowouts
- Riser/pipeline leaks
- Process leaks
- Non-process spills
- Marine collisions
- Structural events
- Marine events

- Dropped objects
- Transport accidents
- Personal (or occupational) accidents
- Construction accidents
- Attendant vessel accidents and
- Diving accidents

The American Petroleum Institute created a recommended practice (17N) as a central guidance on the implementation of reliability management systems for the subsea industry (Haritnov 2009). The RP is based on an initial work done in Cranfield University in the late 1990s. The principle of API 17N is that the level of reliability effort for a project is fundamentally a function of the level of technical risk for which the project is exposed to. Essentially, API 17N advocates that the technical risks in subsea projects should be evaluated and reliability efforts applied accordingly.

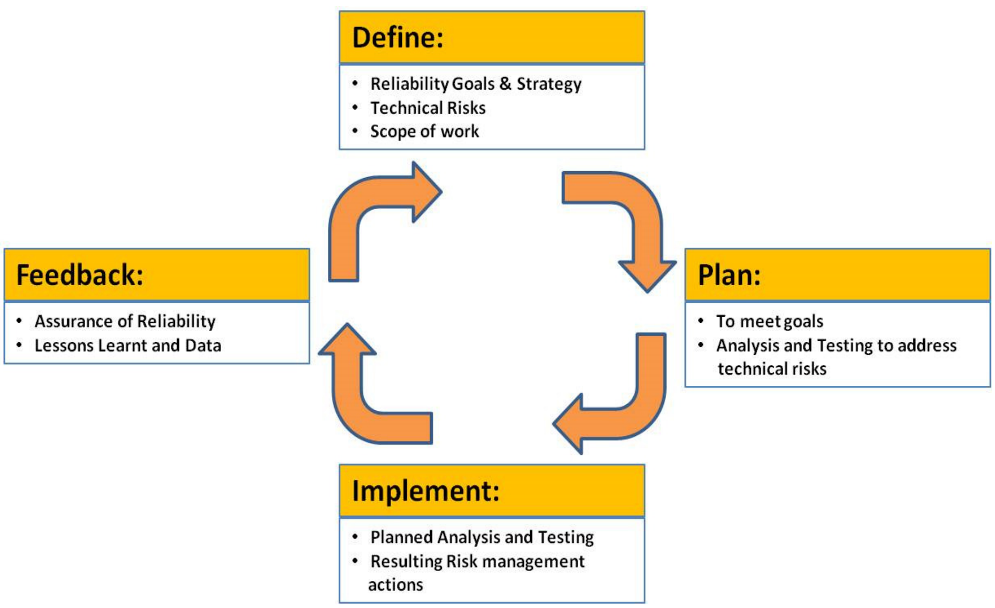


Figure 14 Define-plan-Implement-Feedback Cycle as presented by API RP 17N

API 17N provides a standard framework for the implementation of reliability management system in subsea projects. It is built on twelve (12) key processes that cuts across definition of Availability Goals and Requirements, organizing/planning for availability, design and manufacturing for availability, reliability assurance, risk and availability Analysis, verification and validation, project risk Management, reliability qualification and testing, performance tracking and data management, supply chain management, management of change down to organizational learning. These processes arranged into four basic steps of define, plan, implement and feedback as shown in the figure 14. The approach encourages a stop-and-think attitude all through the activities. Subsea project development is divided into 5 project stages as shown below:

1. feasibility;
2. concept selection;
3. front end engineering design (FEED);
4. detail design and manufacture;
5. System integration test (SIT), installation, commissioning and operations.

At every stage of the project development, the API 17N reliability processes are applied from feasibility through design to operations.

2.3.2 Flow assurance

The increasing water depth along with the demand for system operability such as hydraulic flow instability in the riser system becomes a major concern due to the demand for the transportation of multiphase production from the wellbore to the topside facilities. Deeper water wells require higher energy to flow to their facilities and have higher losses. Even for high pressure wells, with reservoir depletion, the energy to move the hydrocarbon to the surface dwindles. According to Ewida (2004), system pressure drops for shallow water are dictated by tubing head losses, whilst in deepwater pressure drops are largely a function of riser head losses. In shallow water, artificial lift applying wellbore gas lift system may be sufficient to boost gas-liquid ratios for shallow water systems. This is different for deepwater operations as wellbore gas lift combined with riser base gas lift is typically applied not only for boosting production, but for reducing riser-induced slugging at turndown flow conditions and assisting startup. (Frank Close 2008), suggest the application of sub-mudline technologies like electric submersible pumps (ESP), hydraulic submersible pumps (HSP) and seabed boosting for increasing production and ultimate well recovery in deep and ultra-deepwaters.

In deep and ultra-deepwater wells, temperature and wax management is a huge task as the subsea systems are exposed to very low temperatures typically 4ºC. Flow assurance challenges at this depth include:

- Slug challenges
- Hydrate formation
- Wax/Paraffin
- Asphaltenes/Naphthalene
- Scales
- Erosion/Corrosion
- Emulsion/Viscosity…etc

Figure 15 Hydrate formation flow challenge in ultra-deepwaters

Figure 15 shows hydrate being retrieved from a blocked pipeline. Drilling techniques used in shallow waters are often not applicable in deepwaters. From (Luiz Alberto S 2003), you see that the temporary guide bases (TGB) commonly used for well spudding operation is not applicable as it often inclines or sinks into the mudline during the 36' hole operation. Other challenges with a move into deep and ultra-deep water drilling includes spud in the well, geohazards, small tolerance between pore pressure and fracture pressure gradient and borehole instability.

2.3.2.1 Hydrates

Gas hydrates typically form when water molecules react with smaller hydrocarbon molecules such as methane, ethane, propane, isobutene, butane etc. at conditions of high pressure and low temperature to form ice-like structures. Crucial factors for hydrate formation are the appropriate temperature, pressure and at/below its water dew point (Vienna et al 2013). The deep and ultra deep water environment are particularly prone to the formation of hydrates due to the low subsea temperatures of 0 to 3 degrees Celsius. At these temperatures, hydrates tend to form unless the fluid is sufficiently inhibited. Hydrates may form during continuous flow mode as well as during shut in and have high tendency to deposit on pipe walls thus plugging up the pipes. Removal of hydrate plugs within subsea lines can be complicated, therefore a key management strategy is minimizing the risk of operating within the hydrate region. This can be achieved by continuous injection of mono ethylene glycol (MEG). Key indicators to formation of hydrates plugs are MEG injection failure or insufficient MEG inhibition. (Wilson et al 2004). Another possible strategy for mitigating hydrates is to reduce heat loss using insulation and production flow rate (Kopps et al 2007)

2.3.2.2 Wax/Parrafin

Waxes are basically n-paraffins in the range of n-c20 to n-c80 or higher. As the fluid temperature drops below the ‘cloud point’ or wax appearance temperature (WAT), paraffin precipitate within the fluid. Thermal, chemical and mechanical methods are available for wax management. Active heating is a means of maintaining temperature in the flowline, thereby preventing wax deposition and hydrate plugging. This is achieved by maintaining temperatures above the WAT and hydrate formation temperature. Periodic pigging is also a preferred method for dewaxing (Koops et al 2007).

2.3.2.3 Slugging

Slugging is a multiphase flow pattern that is considered to be a hydrodynamic instability in a pipeline system. It can result from terrain changes, hydrodynamic conditions, severe pipe turns such as risers and can typically lead to harsh transient pressures and flow that could lead to equipment damage and operational problems. General means of mitigating slugging include slug catchers, oversized separators and automatic control of topside choke or use of pressure and flow measurement along the pipeline to regulate back pressure (Viana et al 2013)

2.3.2.4 Asphaltene/ Napthenates

Asphaltenes are black, gummy and slick substances that typically precipitate out of crude as flocculation pressure moves down the well bore tuning. Dispersant chemicals are used for mitigating asphaltenes by ensuring that chemical injection points are at reservoir depths and carried out at high-injection pressure and rate. (Brown 2002). Asphaltenes present in crude are made of large aromatic structures insoluble in non-polar solvents like pentane and hexane but are soluble in aromatic solvents (Jordan et al 2008).

Presence of naphthenic acids in crude, high total acid number (TAN) and presence of high bicarbonate and calcium values within the formation brines can lead to formation of napthenates. (Sorbie et al 2005). Recent control methods include PH modification, chelation and demulsification (Jordan et al 2008).

2.3.2.5 Salt and Scale Precipitation

Inorganic scale formation is closely linked to brine chemistry, as this is related to the type and amount of scales formed. Brine compatibility with chemicals is also crucial to its control (Jordan et al 2008). A key factor in managing scales is to understand how the brine chemistry changes over the life cycle of the field for each well and take measures to place scale control strategy upstream its predicted occurrence point (Jordan et al 2001). This is also dependent on the water sources. Three major water sources in the oil field environment are produced water, de-sulphated seawater and seawater with different ratios of calcium and magnesium ions, which has been shown to have significant impact on scale performance and inhibitor performance. Programs for scale prediction are used to predict the types, likelihood and amount of mineral scales that could occur. Pressure and temperature changes within the flow are used to predict the highest super saturation point and/or its deposit mass (Jordan et al 2008).

2.3.3 Subsea and Equipment Qualification

DNV-RP-A203 is a recommended practice for qualification of new technology developed by Det Norske Veritas. It is intended for offshore oil and gas industry but its main principles can be used in different application areas. DNV-RP-A203 identifies failure modes, recommends changes for design improvement and provides the confidence that the new and required technology will function within the acceptable technological limits. DNV-RP-A203 recommends the application of detailed simulation and testing techniques for components, sub-assemblies and the entire system. Though the process involves some element of reliability assessment, it does not provide towards the prediction of the system field performance.

Technology readiness level (TRL) is used to illustrate the level of the stage of the technology in the industry. It can be defined for both a component and a system. The scale ranges from unproven concept to field proven. See table 5 for the different levels TRL.

Table 5 Definition of Technology Readiness Levels (TRLs), courtesy API17N.

	TRL	Development Stage Completed	Definition of Development Stage
Concept	0	Unproven Concept	Basic scientific/engineering principles observed and reported. No analysis or testing completed and no design history.
Proof of Concept	1	Proven Concept	Concept formulated and functionality proven analysis. Essentially paper work and may be R&D experimentation
	2	Validated	Concept validated by a physical model, a

		Concept	system mock up or functionality testing in the laboratory.
Prototype	3	Prototype Tested	Prototype built and put through functionality and performance tests.
	4	Environment tested	System meets all TRL3 requirements. The system is designed and built as a production unit. The unit is then put through a simulated environment (e.g. hyperbaric environment) or actual operating environment.
	5	System Tested	Meets all TRL4 requirements; System built as a production unit and integrated into its intended operating environment with full interface and functionality tests, but outside the intended field environment.
Field Qualified	6	System Installed	Meets all TRL5. Built as a production unit. Full interface and function test performed in the intended (or closely simulated) environment and operated for less than 3yrears.
	7	Field Proven	Production unit now integrated into the intended operating system., installed and operating for more than 3years with acceptable reliability, showing low risk of early life failures in the field.

Equipment qualification through TRL provides a means of verification and validation by highlighting the associated risk in the system. According to API17N, testing is performed during qualification for three main purposes names:

1. To demonstrate functional requirement
2. To screen out faults and manufacturing/assembly defects and
3. To improve robustness and reliability

An outline of component and system qualification process is as shown in figure 16.

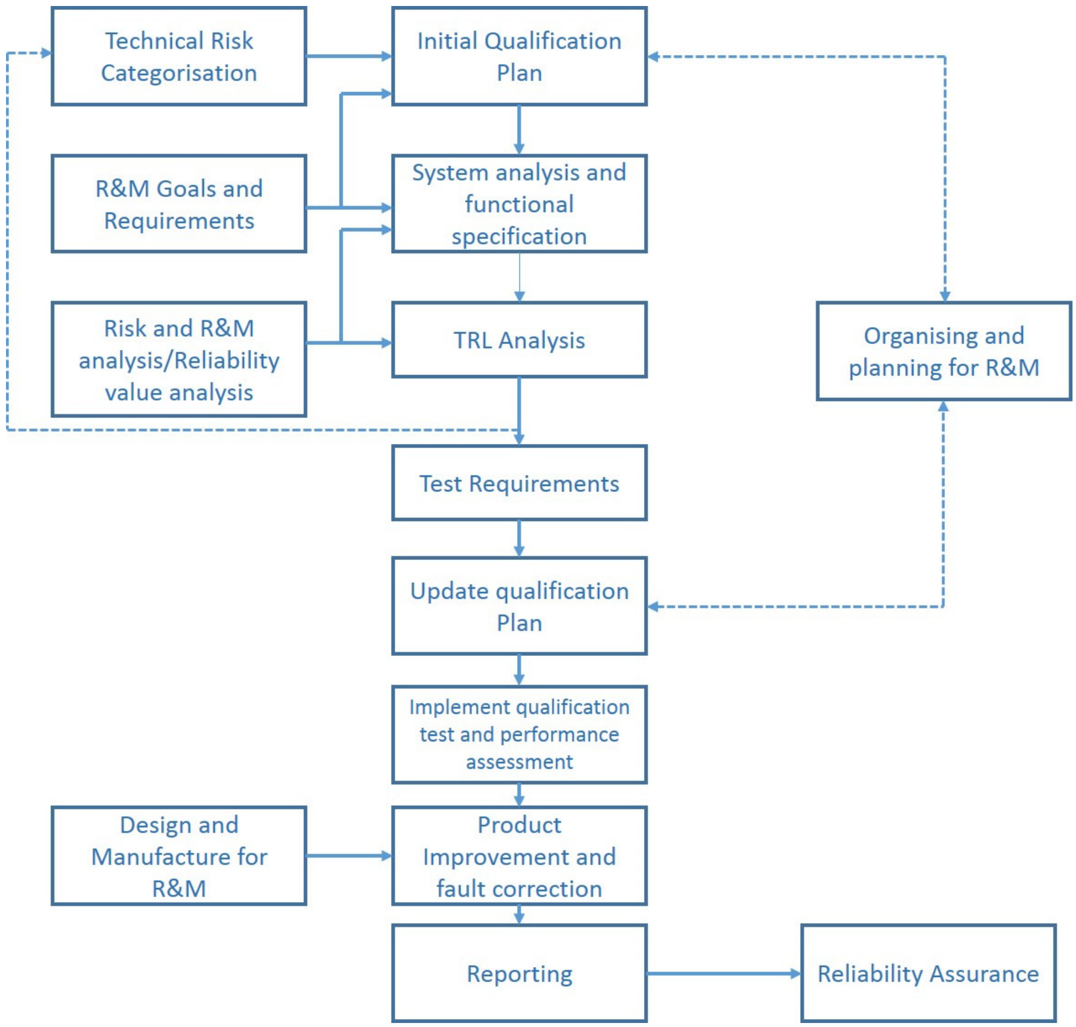


Figure 16 Outline of qualification process, courtesy API17N.

Other relevant standards reliability analysis are ISO14224, ISO20815, API17Q and API Q1 (ISO29001). ISO14224 defines the minimum requirements of data to be collected, details of the process of data collection to ensure quality in the process. API QI (ISO29001) provides standard for quality delivery of subsea systems. API17Q is the American version of DNV RP A203.

2.4 Uncertainty and Systems Reliability

2.4.1 Uncertainty

Uncertainty is a state of having a limited knowledge and where is virtually impossible to exactly describe the existing state or future outcomes (API 17N). In application to equipment functionality and operation, this state demands an understanding and assessment of the technical risks that could influence or affect the operation of the equipment in question. This assessment depends on the amount of information or data available. The result helps in a clear priotisation of the defined action to ensure performance and minimise the risk that may affect the reliability and availability of the system. Potential sources of uncertainty are:

- Physical environment
- Company Experience
- Novel technology requirement
- Reliability expectation to meet financial goals

According to (DNV 1992), uncertainty could be classified into:

- Physical uncertainty
- Measurement uncertainty
- Statistical uncertainty and
- Model uncertainty

Physical (intrinsic or inherent) uncertainty describes the natural randomness of a quantity. Typical examples of this type are the yield stress affected by production variability (manufacturing defects) or the variability in the wave and wind loading. Measurement uncertainty which is caused by errors in instruments or instrumental configurations and sample disturbance due to external factors (eg. ‘noise’ in experimental measurements). Statistical uncertainty which occurs due to inadequate data or information such as a limited number of samples. Model uncertainty due to imperfections and idealizations made in the physical model, formulations for load and resistance variables as well as the allocation of statistic distribution to the main variables.

Uncertainty is normally one of the first activity in a project stage along with technical risk assessment. At this stage, the associated technical risk is identified and categorised.

2.4.1.1 Technical Risk Categorisation

Technical risk categorisation applies to the design stages of a project, from feasibility through the detailed stage. This is a qualitative process that identifies the factors that could lead to the failure of the project. The five risk factors commonly assessed, accordingly to API17N are:

- Reliability
- Technology
- Architecture
- Environment and
- Organisation

Table 6 shows technical risk categorisation. The categorisation, however, does not consider criticality.

Table 6 Technical Risk categorisation (API 17N)

	Technical System Scale and Complexity			Operating Envelope	Organisational Scale/Complexity
Key Words	Reliability	Technology	Architecture/ Configuration	Environment	Organisation
	Reliability requirements, Maintainability, Availability, Failure Modes, Risk, Uncertainty	Materials, Dimensions, Design life, , Design concept, Stress limits, Temperature limits, Corrosion, Duty Cycle	Equipment, layout, interfaces, Complexity, Driver/ROV, Deployment/ Intervention, Tooling	Field location, Water depth, Seabed conditions, Reservoir conditions, Environmental loadings, Test location, Storage	Location, Company, Contractor, Supply chain, Design, Manufacture, Install, Operate, Maintain

A (Very high)	Reliability improvements; significant improvement requiring change in technology	Novel technology or new design concepts to be qualified during project	Novel application; change in architecture or configuration previously applied by supplier	New Environment; Project pushing environmental boundaries such as pressure, temperature, severe met conditions.	Whole new Team; new project team working with a new supplier in a new location.
B (High)	Reliability improvement: change to design, not change to technology	Major modifications; known technology with major modifications such as material changes, conceptual changes, manufacturing changes or upgrades.	Orientation and Capacity changes; significant architectural modification such as size, orientation and layout.	Significant environmental changes.	Significant team changes
C (Medium)	Minor Reliability Improvement	Minor modifications	Interface changes	Similar environmental conditions	Minor team changes
D (Low)	Unchanged Reliability	Field proven technology	Unchanged	Same environmental conditions	Same team as previous

API17N advocates that projects with high uncertainty of technical risk demands more detailed reliability effort while those with low technical risk or uncertainty should be given little reliability effort beyond good engineering and management practices.

2.4.2 Systems Reliability

Reliability is about dependability, successful operation and performance without failures. DNV-RP-A203 defines failure as the loss of the ability of an item to perform the required (specified) function within the limits set for its intended use. Across the industries, several definitions reliability exist. In one context, reliability of a component or system is viewed as the probability that it does not fail during a certain interval of time *(0, t).* In an equivalent way, reliability is defined as the probability that the component or system is still in operation at that time, t (Helder et al 2004). In another close definition, Reliability is defined as the probability that a system will perform its intended function for at least a given period of time when operated under some specified conditions (DNV-RP-A203 2011). In the context of this study, the authors are correct as they all emphasise the ability of an entity to function when required without failure.

Basically, reliability is based on the concept of a random variable – *time (t),* its probability density functions (PDF) and cumulative density functions (CDF). Reliability relationship is focused on the probability that the time to failure *T* is in some interval$(t + \Delta t)$.

$$P(t \leq T \leq t + \Delta t) \equiv probabilitythat\ t \leq T \leq t + \Delta t \qquad (1.1)$$

The above probability can be related to the density and distribution functions, and the results are:

$$P(t \leq T \leq t + \Delta t) = f(t)\Delta t = F(t + \Delta t) - F(t) \qquad (1.2)$$

Where, F(t) and f(t) are the cdf and pdf (or the failure density function) respectively. If we divide by Δt in Equation 1.2 and let Δt→0, we obtain from the fundamental definition of the derivative the fact that the density function is the derivative of the distribution function:

$$f(t) = \frac{dF(t)}{dt} \qquad (1.3)$$

Clearly, the distribution function is then the integral of the density function:

$$F(t) = \int_0^t f(x)dx \tag{1.4}$$

This function is the probability of failure by time *t*. Since the random variable *T* is defined only for the interval $0 \; to \; \infty$. From Equation 1.2,

$$F(t) = P(0 \leq T \leq t) = \int_0^t f(x)dx \tag{1.5}$$

From 1.5, the probability of success at time *t, R(t),* for time to failure larger than t (that is *T*>*t*):

$$R(t) = P(T > t) = 1 - F(t) = \int_t^\infty f(x)dx \tag{1.6}$$

Where R(t) is the reliability function.

Traditionally, systems reliability has been specified qualitatively rather than quantitatively. Quantitative methods include FTA and RBD (Magnno 2012). FMECA is an examples of a qualitative reliability assessment technique (Todinov 2005, Wardt 2011). In non-critical systems, this is perfectly acceptable. However, in critical systems like subsea, a quantitative measure is required. According to Byrne (1994), a quantitative reliability specification should include the following clauses:

- The criteria for failure.
- Appropriate reliability characteristics
- The required value of the reliability characteristics.
- The time during which, and the conditions in which the system is required to perform its function.

Common approaches for evaluating systems reliability is using random events and variables (Todinov 2005). For a system with statistically independent components arranged in series (see figure 17), let S signify that the event system is working and C_k symbolise the event k*th* component is working.

Figure 17 System Components in series

In this configuration, the event S is an intersection of all events C_k, k=1, 2,…,n, since the system will only work if all the components work. Hence,

$$S = C_1 \cap C_2 \cap \ldots \cap C_n \tag{1.7}$$

Accordingly, the probability that the system will be working is

$$P\ (S) = P(C_1)P(C_2)P(C_3)\ldots P(C_n) \tag{1.8}$$

Being a product of the probabilities of the individual components will be working. Since the system reliability R = P(S) and the k*th* components reliability, R_k = $P(C_k)$, the reliability is the series arranges system:

$$R = R_1 \times R_2 \times \ldots \times R_n \tag{1.9}$$

Invariably, the more moments in a series, the less the reliability of the system. Another key derivation is that the reliability of the least reliable components is bigger than that of the system as $R_1 \times R_2 \times \ldots \times R_n < R_k$. Practically, this implies that the reliability of the least reliable component has to be improved for the reliability of the system to be improved in a series arrangement. Increasing the reliability of a component with an already high reliability has no effect on the system reliability if the reliability of the least reliable component is not increased. In the same way, for a parallel arranged (see figure 18), the event S (for a working system) is a union of the events C_k for the k*th* components working.

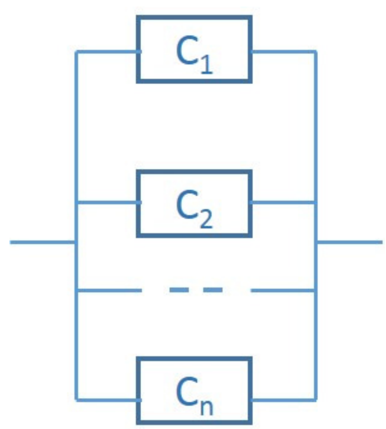


Figure 18 Systems with components in parallel

Mathematically,

$$S = C_1 \cup C_2 \cup \ldots \cup C_n \qquad (1.10)$$

Reasoning in terms of failure, the system will only fail if all the components fail. That is:

$$\bar{S} = \overline{C_1} \cap \overline{C_2} \cap \ldots \cap \overline{C_n} \qquad (1.11)$$

Hence, the probability of a system failure,

$$P(\bar{S}) = P(\overline{C_1}) \times P(\overline{C_2}) \times \ldots \times P(\overline{C_n}) \qquad (1.12)$$

Since the reliability of a system, $R = 1 - P(\bar{S})$ and the reliability of the components, R_i, where $i = 1, 2, \ldots. n$.

$$R = 1 - (1-R_1) \times \ldots \times (1-R_n) \times (1-R_{n+1}) \qquad (1.13)$$

and since $R_{n+1}<1$,

$$1 - (1-R_1) \times \ldots \times (1-R_n) < 1 - (1-R_1) \times \ldots \times (1-R_n) \times (1-R_{n+1}) \qquad (1.13)$$

This evaluation shows that the reliability of a system with components arranged in parallel is greater that the reliability of its most reliable component. Mathematically,

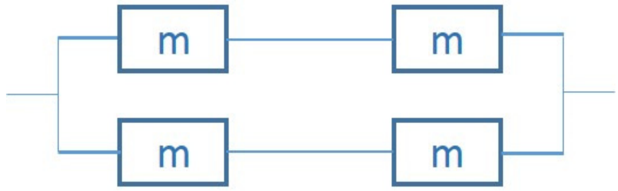
$$1 - (1-R_1) \times \ldots \times (1-R_i) \times \ldots \times (1-R_n) > R_i. \qquad (1.14)$$

Two possible ways of increasing the reliability of a system are (Todino 2005):

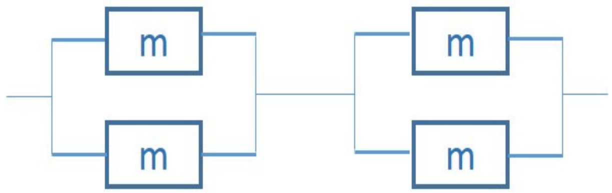
1. Inclusion of active redundancy at a system level and
2. Inclusion of active redundancy at a component level

Consider a system with two identical components, m, as show in figure 19a.

a.



b.



c.

Figure 19 a, b, c Reliability through redundancy

For 17b arrangement, the reliability of the system,

$$R_1 = m^2 (2\text{-}m^2) \qquad (1.15)$$

For the c arrangement,

$$R_2 = m^2 (2 - m)^2 \qquad (1.16)$$

Since $R_2 - R_1 = 2m^2 (m - 1)^2 > 0$, the arrangement in figure 19b has a lower reliability than that in figure 19c. This illustrates that redundancy at a component level is more effective than redundancy at a system level.

2.5 Reliability assessment techniques

The performance of materials in the subsea environment has many influences and determining the long-term effects of seawater under multiple stress conditions can be a daunting task (Mudge 2009). Reliability assessment techniques help in addressing this challenge. Across the industries, several techniques have been developed for assessing components and systems reliability to ensure optimum performance.

According to Haroonaadi (2007), there are basically two approaches to system reliability assessment – analytical techniques and stochastic simulation. The analytical techniques represent the system by analytical models and evaluate the reliability indices from these models using mathematical solutions. Stochastic simulation, however, involves real time simulation of the systems. Here the simulation is performed by mimicking the actual process and random behavior of the system. Fu (2009) reviews three methods of assessing reliability – The taylor series method, Rosenbleuth point estimation method and the Monte Carlo method. The Taylor method applies to linear functions, but produces lots of errors with nonlinear functions. The Rosenbleuth method on the other hand is for symmetrically distributed random variables. The monte carlo method is principallyf based on the laws of large numbers in mathematics and depends heavily on data availability.

Basile (2006) examines the estimation of complex mechanical systems reliability based on the reliability of its components subjected to variable loads with the use of Reliabilitix, a Matlab library. The author reveals that loads acting on system components are not independent of each other. This is true because a particular failure mode may be caused by a combination of several failure mechanisms.

Onoufriou (2001) examines methods for reliability in offshore structures and associated characteristics with a focus on system resistance and comes out with methods ranging from A to E as shown in figure 20. A, being full probabilistic, B-search Algorithms, C-pushover, D-Simplified models while E is component-based. The Probabilistic analysis methods include the first and second-order reliability methods, Monte Carlo simulation, Importance sampling, Latin Hypercube sampling, and stochastic expansions (Choi 2007).

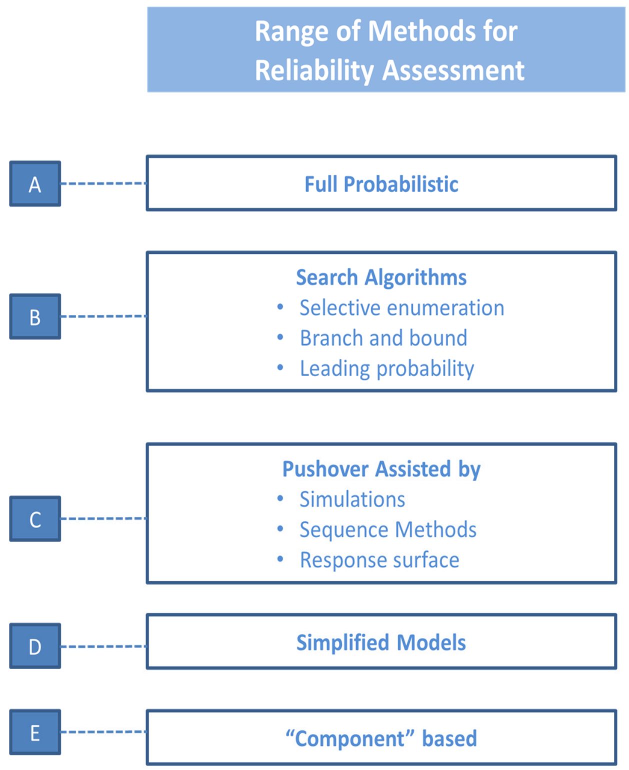


Figure 20 Systems Reliability methods (Onoufriou 2001)

Here, the author proposes that within the five groups from A to E, methods closer to A are associated with a higher level of complexity and recommends that methods close to E are most suitable for research purposes. In this research, a level E method was adopted.

For the system to be evaluated as a multi-component system reliability data for each of its components is required. The approach involves the use of techniques such as fault tree analysis (FTA), failure mode and effect analysis (FMEA) and reliability block diagrams (RBDs) for generating the system reliability values. These systems are briefly explained in section 2.5.1.

2.5.1 Reliability Block Diagram (RBD)

The reliability of complex systems can be assessed using well established methods like reliability block diagrams and fault tree analysis (Vintr 2007). Application of RBDs requires a deep understanding of system functionality, failure modes and redundancy matrix for a reliable operation of the system.

This method basically involves the analysis of systems into their different components and establishing their interdependencies and redundancy. Catelani, M (2014) and Dahmani, O (2014) are examples of the application of reliability block diagram (RBD) in modelling systems reliability.

Common interdependencies in the RBDs are the series, parallel and the m-out-of-n redundancies. Figure 21 shows an RBD representation of a system with components in series.

Figure 21 RBD with components in series

In the series configuration, if one component fails, the whole system fails. RBDs are best for analysing and comparing systems options instead of looking for absolute values of reliability. This helps in obtaining better design options by introducing good redundancies or eliminating weak links in systems design.

2.5.2 Fault Tree Analysis (FTA)

A fault tree is a graphical representation of the relationships between component level faults and system level failures or top level undesired (Moore, 2007, Maqnno 2009). An FTA is a top-down deductive approach for evaluating the failure of a single system by exploring all the possible causes of that failure.

Hiraoka, Y et al (2014) and Murakami (2009) give examples on the application of the FTA in analysing and visualising events. FTA is particularly useful for highly complex systems or processes in which the outcome of one or more non-critical, lower-level events may produce an undesired critical event. This is particularly true in application especially to the subsea industry where failure results in very high offshore intervention cost. Figure 22 shows a typical fault-tree diagram with input events A and B, producing C as the failure event.

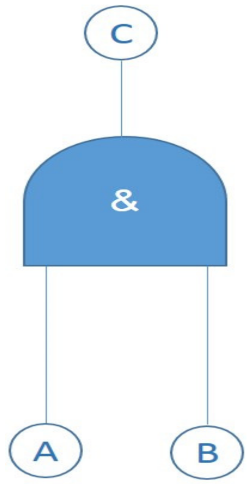


Figure 22 A typical fault tree diagram with an an-gate

Much like FMECA, reliability data is quite fundamental to its quantitative analysis. The fault tree explicitly shows all the associated events and relationships that lead to the top event. It reveals the logic behind the cause of the top event. It also provides a framework for a quantitative as well as qualitative evaluation of the top event. Two of the biggest issues with FTA are complexity and inaccuracy in component fault rate estimation. Other limitations of the FTA are:

Highly dependent on subjective opinions with risk of inaccurate information

- A wrong failure source identification would result in wrong results
- It is not very effective for complex systems
- For very large systems, a a quantitative software analysis may be required

2.5.3 FMECA

FMECA is one of the most popular tools for assessing systems reliability among others like FTA and RBD (Adnan (2012). Application of FMEA dates back to the 1950/60s (Arhagba 2010, Liu 2013) and since then has been used in a wide range of industries including nuclear, aerospace, mechanical, automotive, medical, electronics and the onshore/offshore oil and gas industries. Today, FMEA is available in at least four (international standards. MIL-STD 1629A (1980), which is used in the united states military, IEC 60812 (IEC1985), BS EN 60812 (BSI 2006), SAE-J1739 (SAE 2002) standard (Braksmaa 2012) and DNV-RP-D102_2012.

An FMECA is a structured approach that examines potential failure modes and the impact of failures on product operation during field use or to identify and correct process problems prior to first execution (Wabnitz 2001, Mamman 2009). The technique is best applied during the planning and design stage for optimal results. It is an assessment tool that allows the user to methodically list system components or process steps, identifying their functions, failure modes, effects and failure causes to rank their criticality or risk. The approach can easily be modified and applied to a wide range of situations allowing adjusting the criteria for what constitutes “risk” to the respective purpose of the analysis.

FMECA is principally aimed at identifying failures, evaluating their probability of occurrence and establishing the criticality associated with the failure. The process starts out qualitatively progressing into quantitative evaluations as data becomes available with the identification of corrective actions for all associated failure modes as the end result. More details for FMECA is provided in chapter 5.

In Ammar, M. H. (2014) and Quintana, C (2014), FMECA is used for reliability and criticality assessment for systems by revealing failure modes, effects and the associated criticality.

2.6 Subsea Production System (SPS)

A subsea production system comprises a wellhead, valve tree ('x-mas tree') equipment, pipelines, structures and a piping system and, in many instances, a number of wellheads have to be controlled from a single location (Haritonov 2009) (see figure 23). Subsea systems deployments typically requires specialised and expensive vessels, which need to be equipped with diving systems for relatively shallow waters and robotic devices for deeper water depths (Sunde 2003). Figure 24 shows the deployment of a subsea umbilical termination assembly to the seabed.

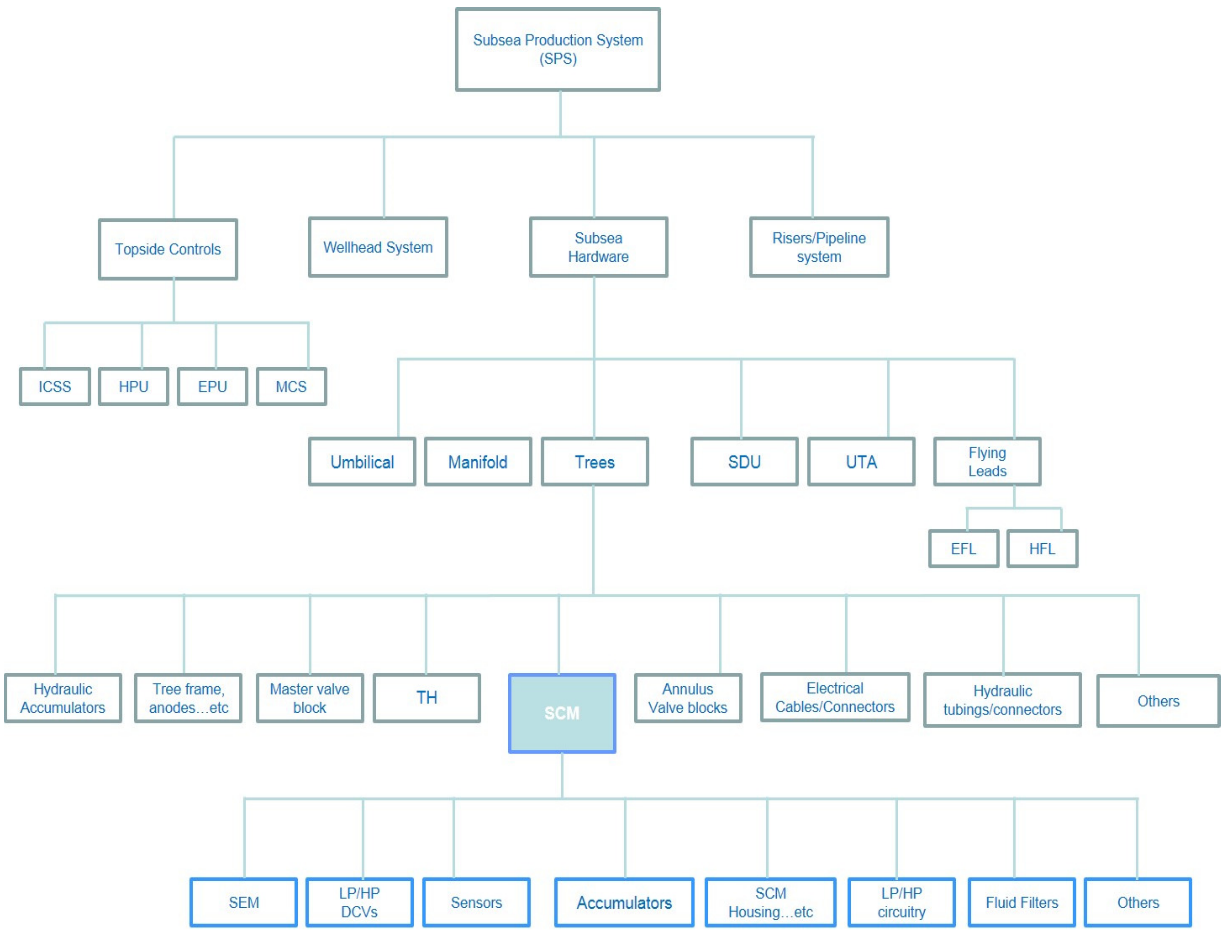


Figure 23 Subsea Production system (SPS) building blocks

Any requirement to intervene or repair with installed subsea system is thus normally very expensive and may result in economic failure of the development.

High equipment reliability is therefore required in order to safeguard the environment and make the exploitation of hydrocarbons with subsea technology economically feasible.

A key element of the subsea production system is the controls. The subsea control system (SCS) is responsible for the operation of valves and chokes on subsea manifolds, Xmas trees, completions, templates and pipelines. In addition to satisfactory operational characteristics, the design of the control system must also provide the means for a safe shutdown on failure of the equipment or on loss of hydraulic/electrical control from the topside (a platform or floating facility) and other safety features that automatically prevent dangerous occurrences.

Figure 24 Subsea equipment deployment

The interface between the subsea control system and its surroundings (boundary) as stated by OREDA is shown in figure 25. The boundary definition applies subsea production/injection control systems, controlling both satellite wells and more complex subsea production facilities such as multi-well manifold template systems.

There are four main subsea production system manufacturers in the world, namely:

- Cameron

- FMC
- Aker Solutions and
- GE (Oil and gas).

Cameron, now called Onesubsea have facilities in all major oil-producing regions including United Kingdom, Germany, Houston and Brazil. FMC's major facilities are located in United Kingdom, Norway and Houston. Aker Solutions is based in Houson and Norway, principally. GE's oil and gas hub is in USA, Italy and United Kingdom. These companies all have capacities for the manufacture of the key building blocks in a subsea production system with varying product range and track record. Other companies exist that manufacture subsea tie-in systems, subsea valves...etc. but are not considered to be subsea production system suppliers because of their limited product range.

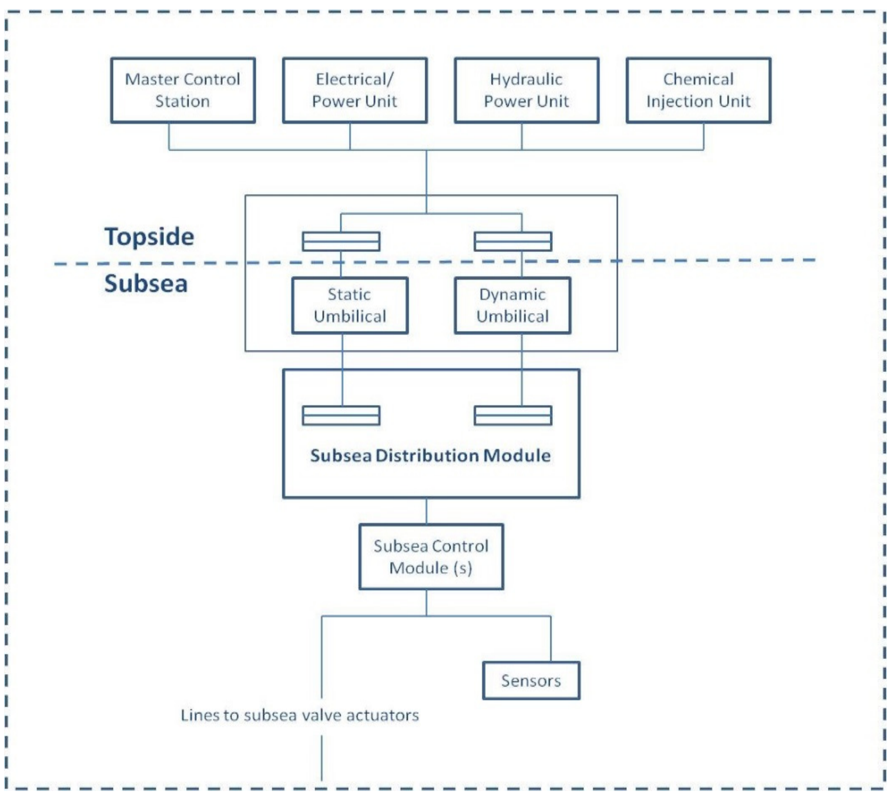


Figure 25 Subsea control system boundary, courtesy of OREDA 2009.

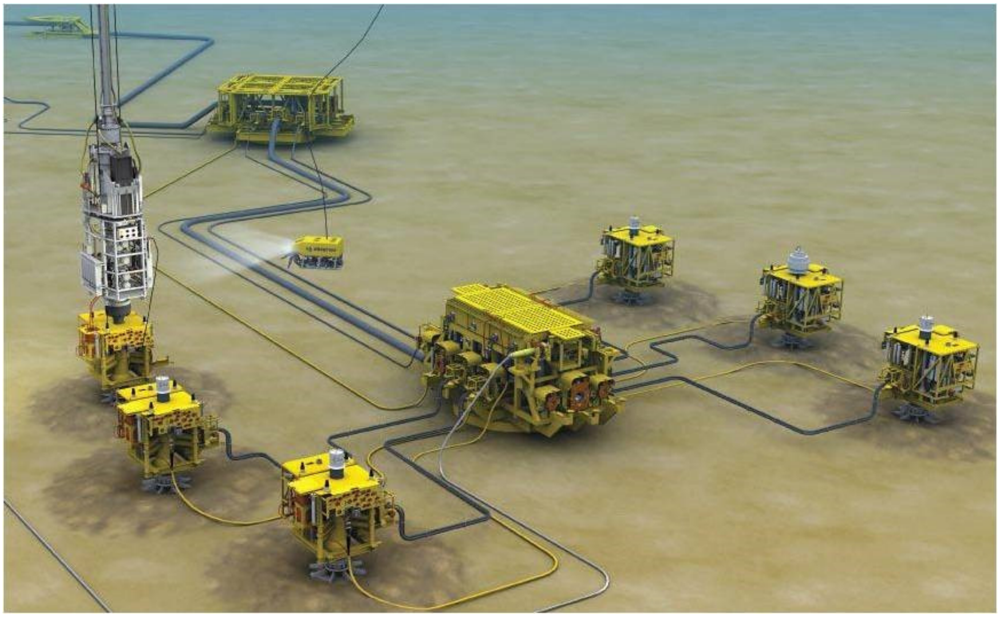


Figure 26 Subsea equipment in an SPS, courtesy of GE Vetco

2.6.1 Subsea Xmas Tree

A Christmas (Xmas) tree is an assembly of valves, spools, and fittings used for an oil well, gas well, water injection well, water disposal well, gas injection well, condensate well and other types of wells (Bai 2010). Christmas trees are used on both surface and subsea wells. Trees installed on the seabed are called subsea trees (see figure 27) while those on topside structures are called surface/dry trees.

DHXT	
Tree type	5" x 2" – DHXT
Pressure rating	10,000 PSI
Water depth	3000m
Treehead	Up to 10 functions: 8 off hydraulic, 2 off electric
Upper connection	18 ¾" Extended 52" H4 Mandrel, VX /VT metal seal
Lower connection	18 ¾" DW-HT-H4 (5.4MMft-lbs) with VX seal preparation
Header connection	Vetco Gray VCCS size 300 – HH trim (options for alternative tie-ins)
Trim	HH Production, EE Annulus
Temperatur e	U (0 to 250F) upstream choke L-U (-50 to 250F) downstream choke

Figure 27 A typical Subsea Xmas Tree System, coutesy of GE Vetco

There are lots of variations depending on the field requirements, features and functions. For this project, the focus is on subsea Xmas trees. Below are the functions of a subsea Xmas tree system:

- Control the production of hydrocarbons
- Provide a Safety barrier between the sea and the reservoir
- Safely stop produced or injected fluid
- Enables Injection of chemicals to well or flowline
- Provides control of downhole valves
- Deliver electrical signals to downhole gauges
- Excess pressure bleed off from the annulus
- Regulate of fluid flow through a choke (optional)
- Allow for well intervention

The subsea tree has a number of hydraulically operated remote operated valves, which can be used to open up or close hydrocarbon flow from the Well (Bradley 2006, Voss 2003). In a cluster configuration, the well fluids flow via the tree system to a pipe known as a Jumper to a Subsea Manifold before going to the topside processing unit. The tree valves provide safety barriers to the fluid flow, perform excess pressure bleed off, regulate fluid flow and also allow for intervention of the well system. The tree system also enables the injection of chemicals into the well stream and the flowline for flow assurance purposes.

The actuator, also referred to as cylinder, is the component in a subsea Xmas tree that drives the gate valves. It can produce linear or rotary motion. In subsea, they are principally hydraulic, though we now have electrically operated actuators. The hydraulic actuator (see figure 28) converts hydraulic power to mechanical power for the operation of subsea tree valves. During operations, fluid is injected at one side of a piston forcing the piston in the opposite direction. An actuator can be single or double acting, meaning that the pressure can be applied only from one side or from both directions.

Figure 28 Subsea hydraulic ball valve, courtesy of Weiku.

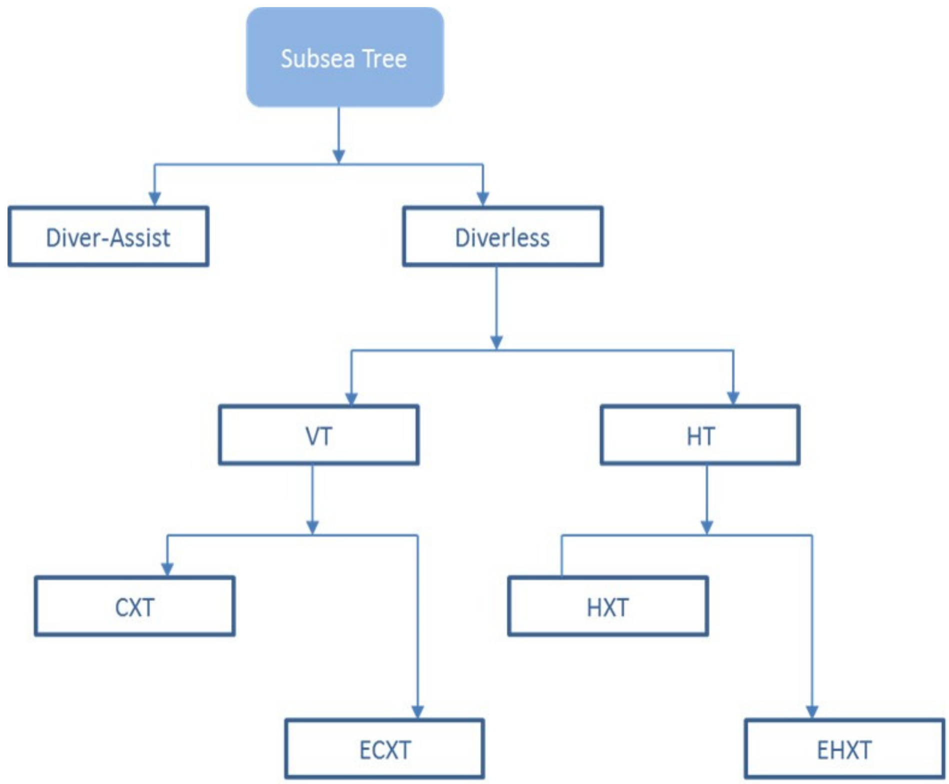


Figure 29 Types of Subsea Xmas tree, self-addition

There are basically two categories of subsea Xmas trees – Vertical trees (VT) and the horizontal trees (HT) (figure 29) (Matusek 2005, Wester 2001, Skeels 1993). The vertical trees are further broken down into basic conventional trees (CXT) and the enhanced conventional trees (ECXT) while the horizontal trees are divided into the basic horizontal trees (HXT) and the enhanced horizontal tree (EHXT).

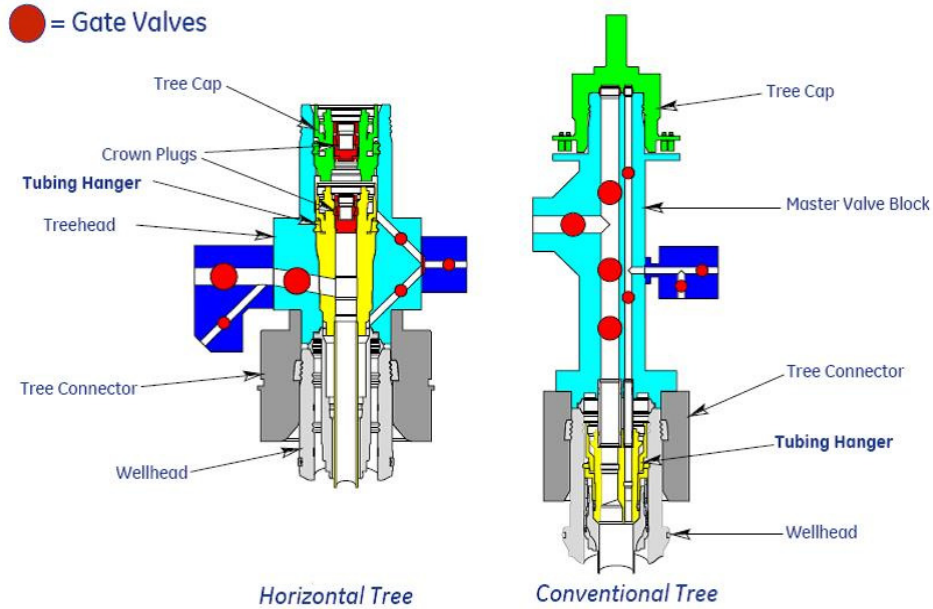


Figure 30 Horizontal and conventional subsea Xmas tree, courtesy GE

The main difference between the vertical and the horizontal trees are the configuration, size and weight. In consideration of water depth, trees could be driverless or have diver assist facilities (See figure 30)(Wester 2001). In the VT, the tubing hanger (TH) is installed on the wellhead and the well is completed before installing the tree. This differs from HT where the tree is installed before completions and the TH is installed in the tree body instead of the wellhead. This configuration requires the tree to be installed on the wellhead before the completion of the well. The pressure ratings for the subsea Xmas trees are 5000, 10,000 and 15,000psi in accordance to API 17D.

Subsea tree valves are operated directly from the topside using the subsea control system (SCS) or through a manual override with an ROV/diver. The main component of the tree mounted control system is the Subsea Control Module (SCM). The SCM contains electronics, instrumentation, and hydraulics for safe and efficient operation of subsea tree valves, chokes, and downhole valves. Other tree mounted equipment includes various sensors, electrical and hydraulic connectors. A typical horizontal subsea Xmas tree will contain the following valves as a minimum:

- Production wing valve, PWV
- Production master valve, PMV
- Annulus wing valve, AWV
- Crossover valve , XOV
- Methanol Injection valve, MIV (optional)
- Chemical Injection Valve, CIV

During a subsea tree operation, a typically a well start-up would be - Open PMV - Open MIV - Open AMV - Open AWV - Open SCSSV - Open CIV - Open PWV while a well shutdown would be - Close PWV - Close AWV - Close AMV - Close XOV - Close PMV - Close CIV - Close MIV - Close SCSSV.

These operations on an E-H SCS all pass through the subsea control module (SCM) for its execution, making the SCM one of the most critical components of a typical SPS.

2.6.2 Subsea Control System (SCS)

The subsea control system (SCS) comprises the surface installed master control station including hydraulic/electrical power units as well as the umbilical (s) and the control equipment installed subsea on the tree or the manifold/template (e.g. SDU and SCM). The umbilical is a conduit that connects the topside equipment's to the subsea, providing the hydraulic, signal, chemical injection and electrical power (Bai 2010). The SCS is considered the most critical part of any subsea installation with very high complexity in features and function (Fabbri 1988). Proper performance of the control system is required to ensure a reliable and safe operation. An SCS is basically divided into three main parts (see figure 31):

1. Topside equipment's
2. The Umbilical and
3. The subsea control equipment's

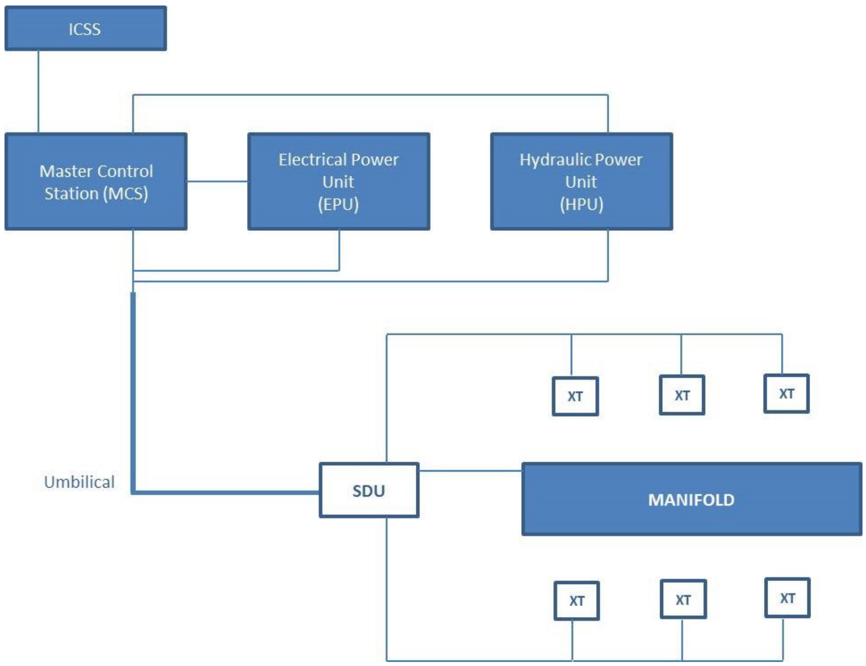


Figure 31 Schematic of an SCS showing the topside, umbilical and subsea controls equipment.

The topside is basically made up of the electronic power unit (EPU), hydraulic power unit (HPU) and the master control station (MCS) providing controls to the subsea equipment's. The HPU stores and deliver hydraulic fluids to the entire subsea system. Located topsides with redundant pumps, accumulators and hydraulic circuitry, the HPU supplies low pressure (LP) and high pressure (HP) control fluids through the topside umbilical termination unit (TUTU) into the subsea production system (SPS) umbilical.

The control umbilical is a critical link in the subsea production system and provides the connection between the topside and the subsea parts of the system. Not only do they provide hydraulic power and electrical signals to operate and control the production centers, they also convey fluids (production chemicals, gas lift, annulus bleed) to assist in the recovery process and to maintain the life and operability of the trees and flowlines (Stable 2010), see figure 33. According to Roberts (2002), most subsea failures come from the control system and summaries them as follows:

- Subsea Control Module: Water Ingress within directional valves &Internal subsea electronic architecture failure
- Subsea Monitoring: Pressure and temperature transducer housing weld failures
- Umbilical and Jumper Connections: Power and communication failures, Hydraulic Connection failures, Electrical connector failures

Figure 32 Subsea Umbilical, courtesy of Oceaneering**.**

There are principally six different types of subsea control systems (SCS), namely (Bai 2010):

- Direct hydraulic
- Piloted hydraulic
- Sequential hydraulic
- Electro-hydraulic (hard-wired
- Electro-hydraulic multiplexed and more recently
- The all-electric control system

The first control systems were basically direct hydraulic systems, with little or no telemetry. Figure 33 shows a typical block diagram for such a system. The system is simple, low cost, and reliable with a dedicated host for each of the control functions. It is typically used for subsea intervention/workover applications. However, its typically slow for long tie-back applications, requires a large number of hoses with no subsea monitoring information because of the absence of electrical signals.

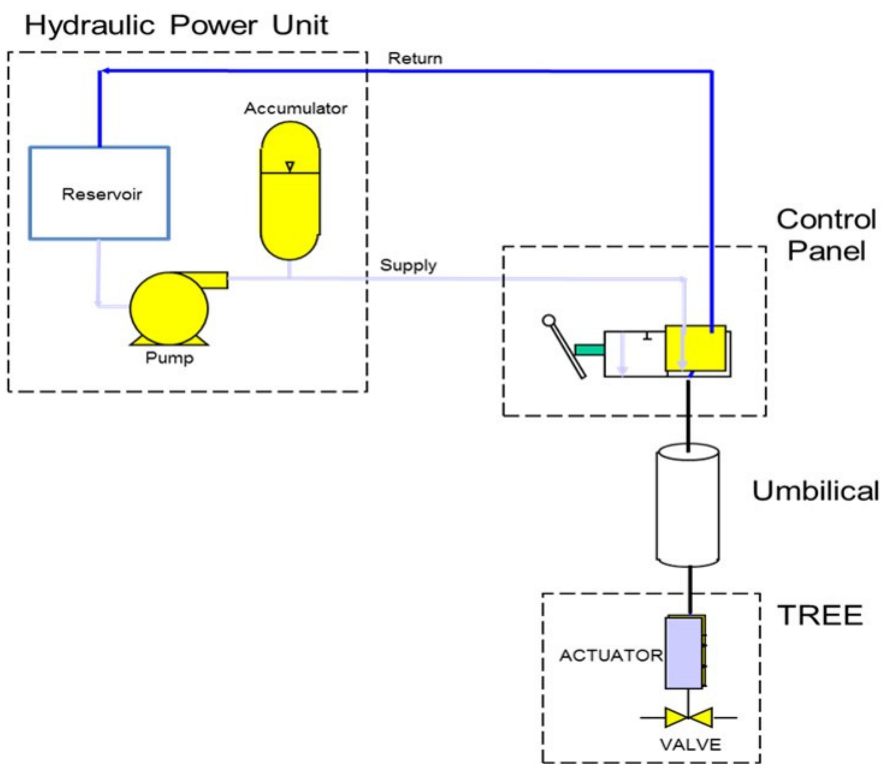


Figure 33 Direct hydraulic SCS

With the requirement for additional functions and the need for condition monitoring information, scaling hydraulic system became difficult giving rise to the multiplexed electro-hydraulic control systems, with the use of the subsea control module. The system initially started with analogue sensors adapted from land-based operations, but has progressed significantly into digital systems with higher bandwidths and standardised interfaces. Here a master control station, which is implemented using a computer unit communicating with a micro-processor installed subsea in an SCM while the electrical power unit (EPU) supplies a clean-noise-free power to the SEM unit. Coded signal is sent to the SEM for interpretation and direction to the appropriate solenoid valve, allowing the flow of hydraulics to the subsea tree valve. Sensor data is also communicated to the master control station (MCS) through the SEM. The Multiplexed Electro-Hydraulic system allows many Subsea Control Modules to be connected to the same communications, electrical and hydraulic supply lines. This allows many wells to be controlled through one simple umbilical (see figure 34 and 35). A summary of the different types of SCS is given in table 7.

The focus of this research will be on electro-hydraulic multiplexed controls.

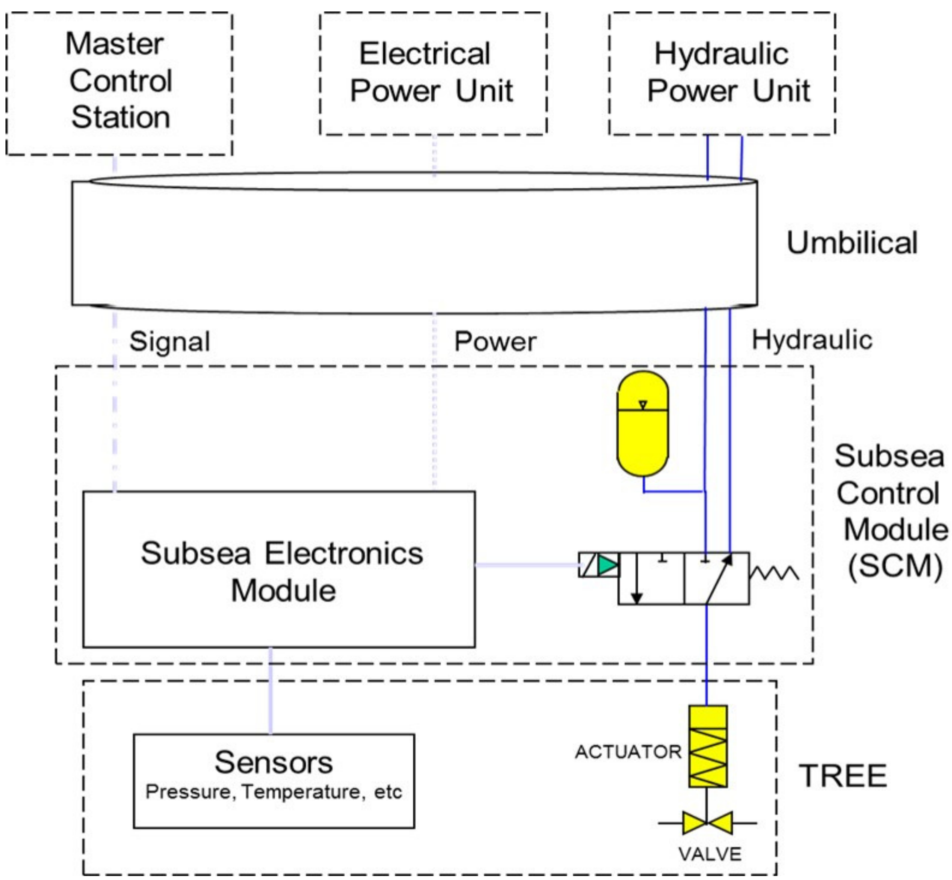


Figure 34 The E-H multiplexes subsea Control System, self-addition

Three key joint industry projects have been responsible for defining interfaces for subsea controls intelligent wells, sensor interfaces and the application of fibre optics

IWIS, defined in ISO13628-6 provides the intelligent wells interface standard for subsea controls integration for the operation of intelligent wells. It defines the interface requirements for physical size, communications, electric power and

Table 7 Types of Subsea Control Systems (SCS)

System type	Major components	Advantages	Disadvantages	Range	Typical Applications
Direct Hydraulic	-HPU -Control Panel -Umbilical	-Simple -No subsea pods -High reliability	-Slowest Response -Large Umbilical	0-3miles	-Single Satellite -Small fields -Short distances
Piloted hydraulic	-HPU -Control Panel -Umbilical -Subsea Pilot Valve	-Improved response -Reduced Umbilical -Proven Reliable	-Subsea Equipment -Large Umbilical -Costly>5 miles	2-5miles	-Medium distances -Satellite Trees
Electro-hydraulic Piloted (hard-wired)	-HPU -Control panel -Umbilical -Subsea mini pod	Quick response for selected tree valve	-Subsea Equipment -Large Umbilical -Costly>15 miles	2-15 Miles	-Long distance -Satellite Trees -Minimum feedback
Electro-hydraulic Multiplexed	-HPU -Control panel -Umbilical -Subsea control pod	-Fastest response -Subsea data feedback -Smallest umbilical Greatest flexibility	-Complex -Subsea equipment -Subsea Electrical connection -Costly Electronics	5 Miles+	-Long distance -Data feedback -Large templates -Remote manifold -Complex fields
All-electric	-DC power source -PRCM Control Panel Fibre optics Subsea control pod	-Instantaneous response -Subsea data feedback Fibre optics cable High reliability/flexibility	-Sea water ingress -Insulation issues Not enough reliability info	Unlimited distance	-Long distances -Data feedback/monitoring -Complex fields

testing to avoid incompatibility, multiple standards, extended project schedules, high engineering cost and reliability issues. Additionally, the Subsea Instrument Interface Standardisation (SIIS), setup in 2002, extends the IWIS to cover subsea control interfaces with sensor systems. SIIS is focussed mainly on 'simple' digital sensor interfaces. SEAFOM, a joint industry forum, covers the institution of a structured approach in the application of the fibre-optics to subsea systems

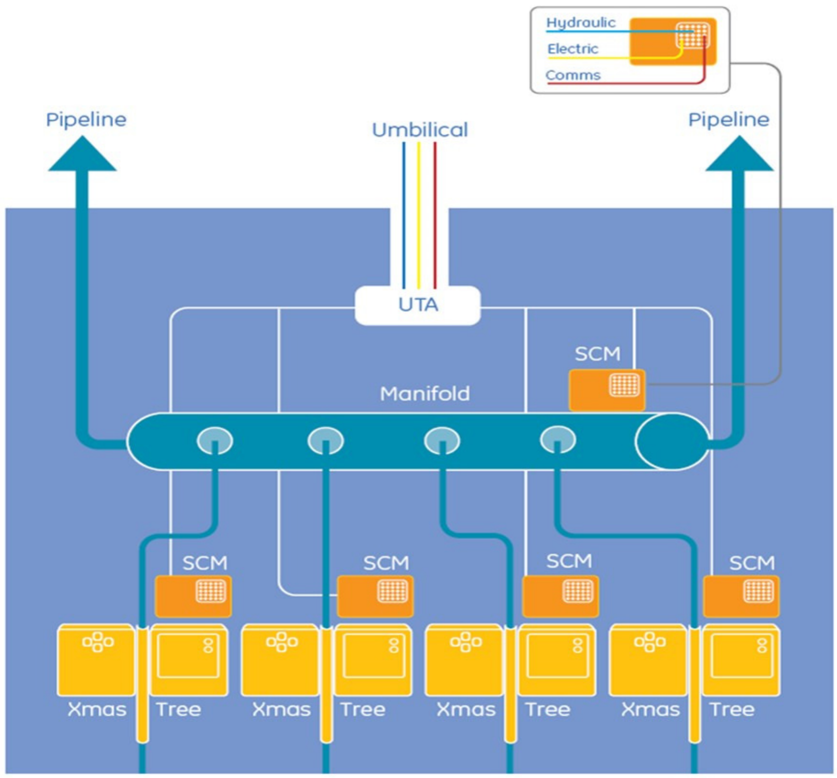


Figure 35 Subsea control Architecture, courtesy GE Vetco.

2.6.3 The All-Electric SCS

Today, the all-electric subsea systems are becoming an attractive supplement to the existing electro-hydraulic systems due to the following market trends and requirements (Mahler 2014):

- Deeper water/Longer offsets

- Pursuit of marginal fields
- Cost reductions
- Tie-in to existing subsea systems
- Subsea processing
- New operational requirements – fast response, better control
- Good reliability demonstrated with electrical cables and connectors
- Increased environmental focus

Generally, the system provides improved system reliability and uptime availability. Other benefits accrued include the ability to incorporate virtually unlimited step-out distances and water depth capabilities. The all-electric system eliminates hydraulics for power transmission, along with the need for fluid purchase, transportation, maintenance, interaction and disposal. An added environmental benefit is that the hydraulic fluid is no longer vented to sea during system operation. Despite the huge advantages of the all-electric systems, there are still unresolved issues with respect to hydrostatic effects in deeper water and limitations for long distance tieback. Management change is also a key issue in the bid to deploy this all new system because the conservativeness of the subsea industry. Figure 36 shows a picture of an all-electric subsea control module (SCM).

Figure 36 The all-electric SCM, courtesy of FMC

3 Risk Identification of Subsea Control Module (SCM)

3.1 Historical background

In the last 30years, the SCM has witnessed a huge leap in systems design and configuration. Much like the changes being experienced in the electronic industry, it took 25years to move from 1200bps to 9600bps (Morgan 2010). It is now 10Mbps in just five years. 1980 to 1990 witnessed the use of the diver-installed SCM (see figure 37a) used extensively in the UK North sea and shallow waters globally with little or no standardization and a slim bandwidth of 1200bps. The SCM has gone through evolutionary changes in design features, function and applications with focus now on modular and configurable products. Today, we have the monolock configurable style (figure 37g), with a higher speed function for downhole data retrieval and operations down to 3000m water depth. Table 8 shows a variation of the different types of SCM across the years, their features and application.

Table 8 A historical view of SCM development, self-summary

SCM Name	Year	Features	Application
DIVER type SCM	1980-1990	• Bandwidth 1200bps • Only one or two serial interfaces • Many variations, with few common parts • Little standardisation.	North Sea and Shallow waters globally
Forklock	1990-1995	• Similar to Diver type, 1200bps. • Similar designs, mainly common components used	Predominantly Norwegian North sea for Statoil and Hydro
Old Type twinlock	1990-2000	• Bandwidth of 1200bps with a data link to a downhole gauge • Many variations, with few common parts • Little standardisation, only one or two serial interfaces.	Used in shallow waters globally up to 600m
New style twinlock configurable	2005 - onwards	• Bandwidth up to 10Mbps. • Also backward compatible • Common core components, configurable, flexible design. Modbus, Canbus, Ethernet, IWIS, SIIS2 interfaces	For shallow and deepwaters up to 2000m
Old Style monolock/Old style IconSEM monolock	1990-2000	• Circular shape • Bandwidth of 1200bps • The IconSEM monolock communication speed was up to 9600bps with 12 serial interfaces	Used globally in deepwaters up to 2700m

		• Many variations, with few common parts, little standardisation. • Integrated baseplate and manifold application	
New style monolock configurable	2010 – onwards	• Communication speed of up to 10Mbps • Can be desiged off-project with extensive analysis and requirements for shallow and deep waters to to 3000m. • Common core components, highly configurable, flexible design. Modbus, Canbus, Ethernet, IWIS, SIIS2	Used globally

Figure 37 (a) Diver Scm (1980-90)

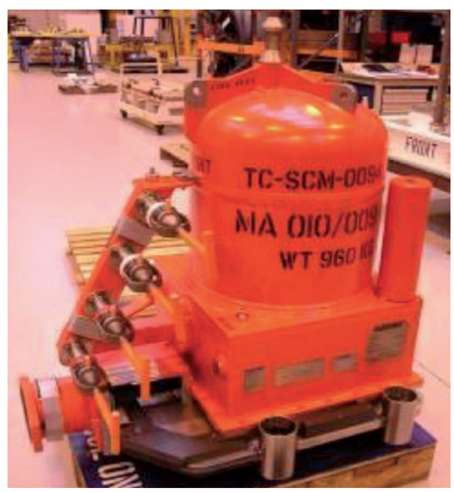


Figure 37 (b) Forklock Scm (1990-95)

Figure 37 (c) Old Style Twinlock 1990-2000

Figure 37 (d) Old Style

Monolock 1990-2000

Figure 37 (e) Old Style Iconsem Monolock

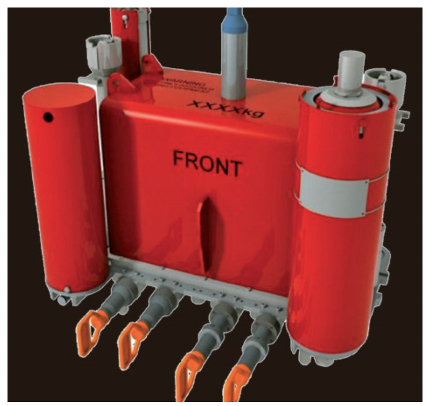


Figure 37 (f) New Style Twinlock Configurable

Figure 37 (g) New Style Monolock Configurable

Figure 37 Evolution of the subsea control module, courtesy of Aker solution

3.2 The SCM functional description

The SCM is the brain of a subsea control system. It is typically installed in a subsea Xmas tree, manifold or subsea distribution units (SDUs) and serves as the control centre responsible for the distribution of electrical and hydraulic power and the interpretation of all signals. A sealed, dielectric fluid-filled container at 1-atm pressure protects the internal components from seawater intrusion. Figure 38 is a picture of the subsea control module mounted in a subsea Xmas tree. There are basically three types of subsea control module (Broadbent 2010):

- The all-hydraulic SCM
- Electro-hydraulic SCM and
- The all-electric SCM

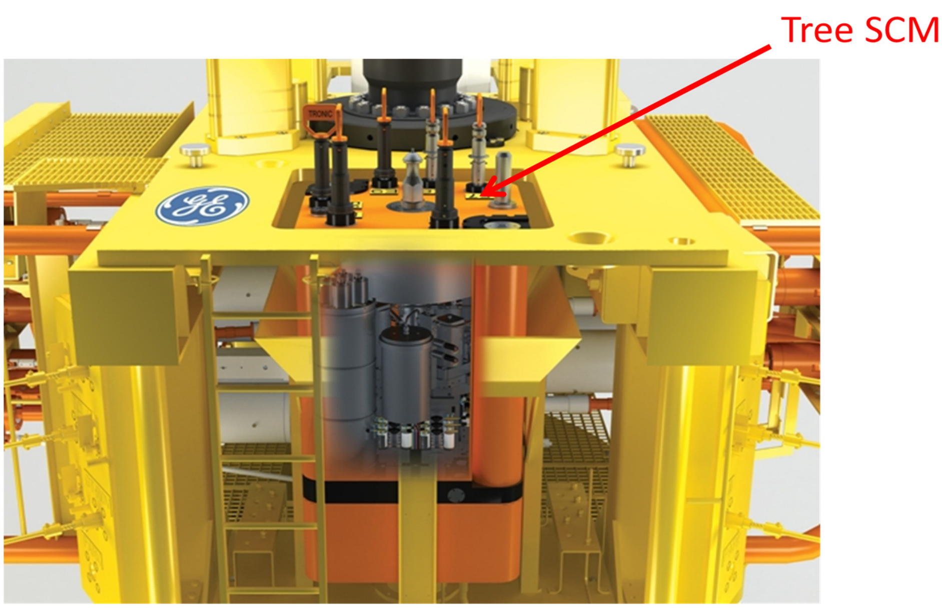


Figure 38 Subsea Xmas tree showing the tree SCM, courtesy of GE Oil and Gas

Current SCMs are primarily designed for subsea valve operations and downhole safety valve control and monitoring of temperature and pressure at the wellhead. Figure 39 shows the key functions of the SCM in an SPS.

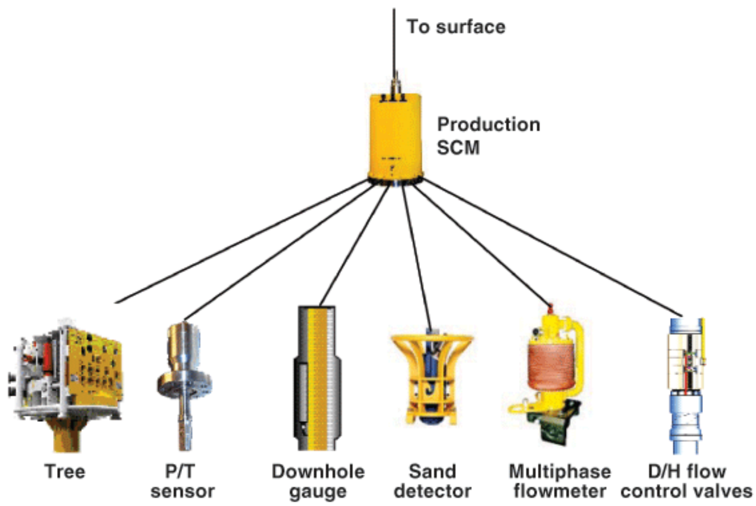


Figure 39 Functions of the SCM, courtesy of GE Vetco

The functions could be classified as:

- LP functions
- HP functions
- Remote sensing
- Internal sensing
- Control fluid accumulation and
- Down hole gauges control

The SCM contains two fully redundant subsea electronic modules (SEMs) for control of all subsea valve operations and communications with the topside. The two SEMS are completely independent of each other. If one SEM fails, the control link is switched to the next one for the provision of all control functions. Normally, the switching operation is performed manually by the topside control operator. See figure 40 for the picture of a subsea electronic module (SEM)

Figure 40 Subsea Electronic Module (SEM), courtesy of Weatherford

The SCM receives low pressure (LP), high pressure (HP) including multiplexed electrical power and signal from the surface via the umbilical. This operation triggers happens in such a way that a hydraulic signal is transmitted to the appropriate hydraulic valve in the subsea Xmas tree, manifold, downhole instrumentation or any other subsea equipment. Electrical signals decoded by the SEM operate solenoid directional control valves (DCVs), directing the fluid to the appropriate subsea system valves, safety valves or chemical injection functions. Signals from the subsea sensors are also encoded through the SEM in the SCM and sent back to the surface facility. The SCMMB provides the connecting point between the SCM and the subsea Xmas tree functions and monitoring equipment. Tubing and electrical cables connect the SCMMB to the tree.

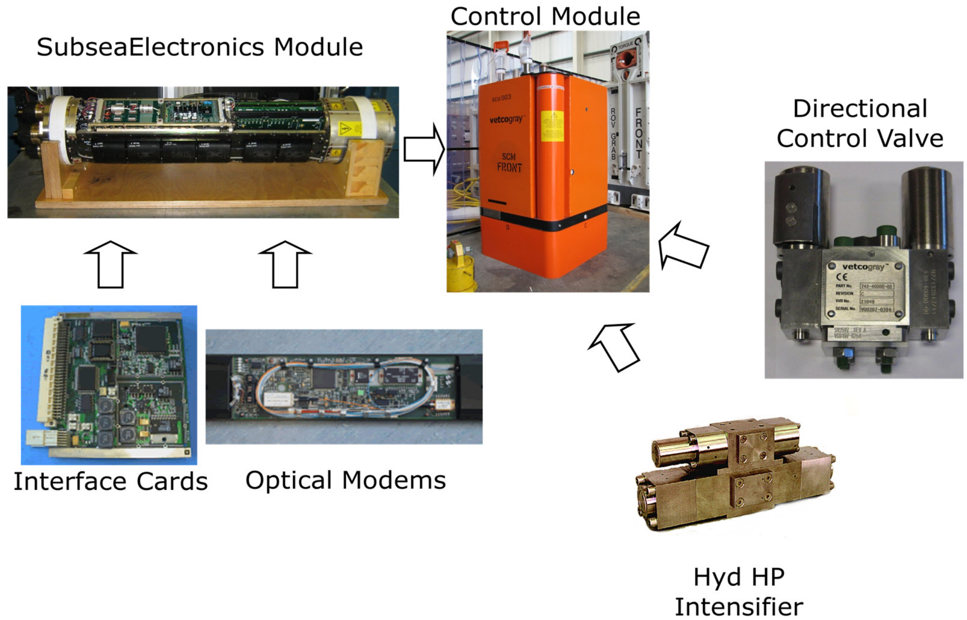


Figure 41 Key parts of the SCM, courtesy of GE Vetco

Figure 41 shows the key parts of the SCM. The SCM will typically contain the following parts (Broadbent 2010).

- A base plate
- A latching mechanism
- Hydraulic filters
- Selector valves
- Relief valves
- Needle valves
- Subsea electronic modules
- A compensation cover
- Electrical connectors
- Accumulators
- Hydraulic couplers
- Electrical connectors
- SCM housing/cover
- DHPT assemblies
- miscellaneous seals, fittings, fasteners and electrical components

A key component of the hydraulic system in the SCM is the directional control valve. DCVs are used in subsea control systems to provide hydraulic power to open and close hydraulically actuated process valves on subsea Christmas trees, manifolds and other similar subsea control equipment. Failure of a DCV is very critical to subsea control operations. Figure 42 below shows a dual solenoid, electro-hydraulic (E-H) directional control valve (DCV) with two stages – pilot and the main stage typically used in an SCM. The pilot stage, with small solenoid operated hydraulic valves; provide a hydraulic pilot to operate a main stage. The main stage is a larger hydraulic valve which diverts the hydraulic pressure to and from the process valve actuator, to open and close it.

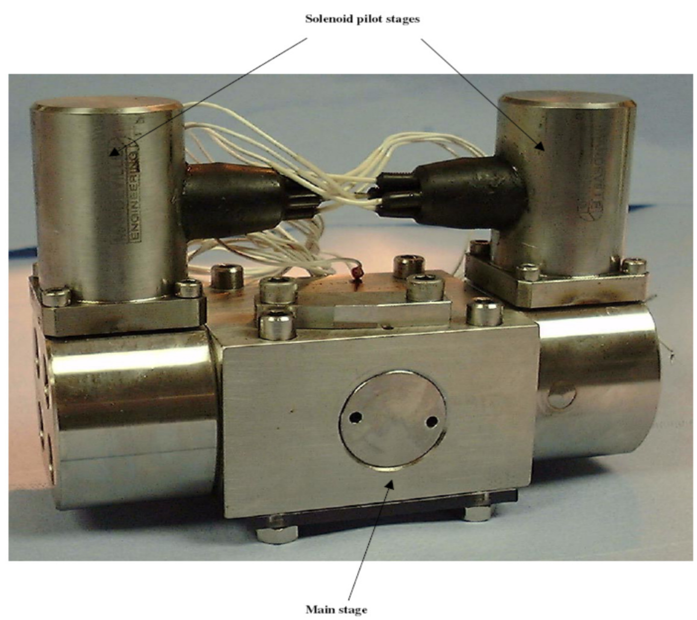


Figure 42 Directional control valve (DCV), courtesy OTC 13233

A pressure compensation system in the SCM provides compensation for pressure and temperature differentials as the SCM is lowered subsea during installation or retrieval. During installation, the SCM is lowered using a subsea control module running tool (SCMRT) onto the subsea control module mounting base (SCMMB) where the hydraulic couplers and electrical connectors on the SCM base plate mate with their associated couplings and connectors on the SCMMB. Figure 43 is a picture of an SCMMB, showing the couplers and tubings. A latch mechanism ensures an accurate mating of the SCM to the SCMMB. A typical subsea control module specification is shown in Appendix D.

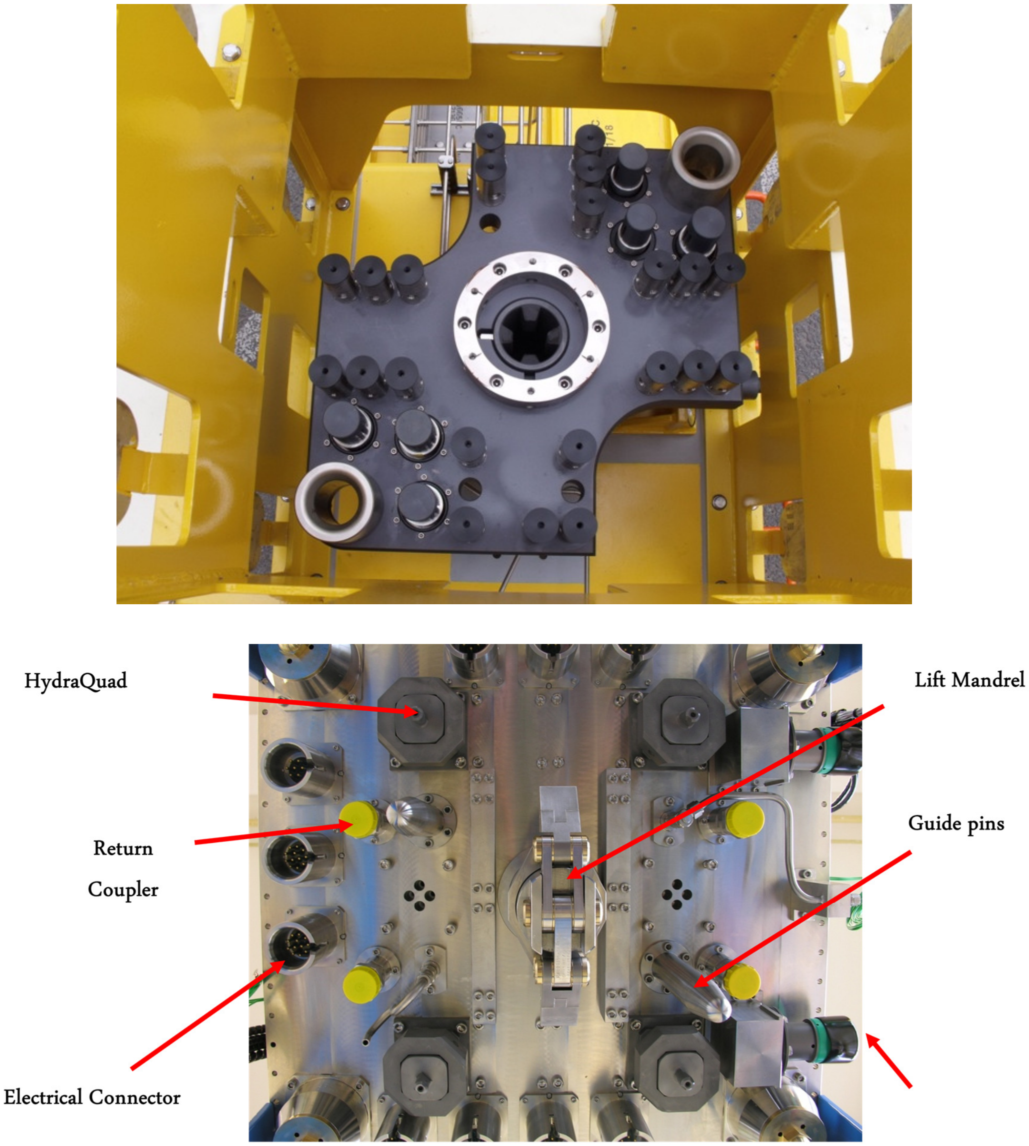


Figure 43 Subsea Control Module Mounting Bases (SCMMB), courtesy of GE Vetco

Typically, the SCM consists of four main parts as listed below:

- Electrical equipment subsystem
- Hydraulic equipment subsystem

- Mechanical Parts and
- The SCM housing

Figure 44 and 45 give a diagrammatic representation of the sections and parts of the SCM. To analyse the reliability of the SCM, the system should be broken down into its respective components or elements. According to Byrne (1994), the critical elements of the SCM includes the subsea electronic module (SEM), directional control valve (DCV), pin connectors, hydraulic couplings, hoses and cables while the non-critical parts are the pressure and temperature sensors.

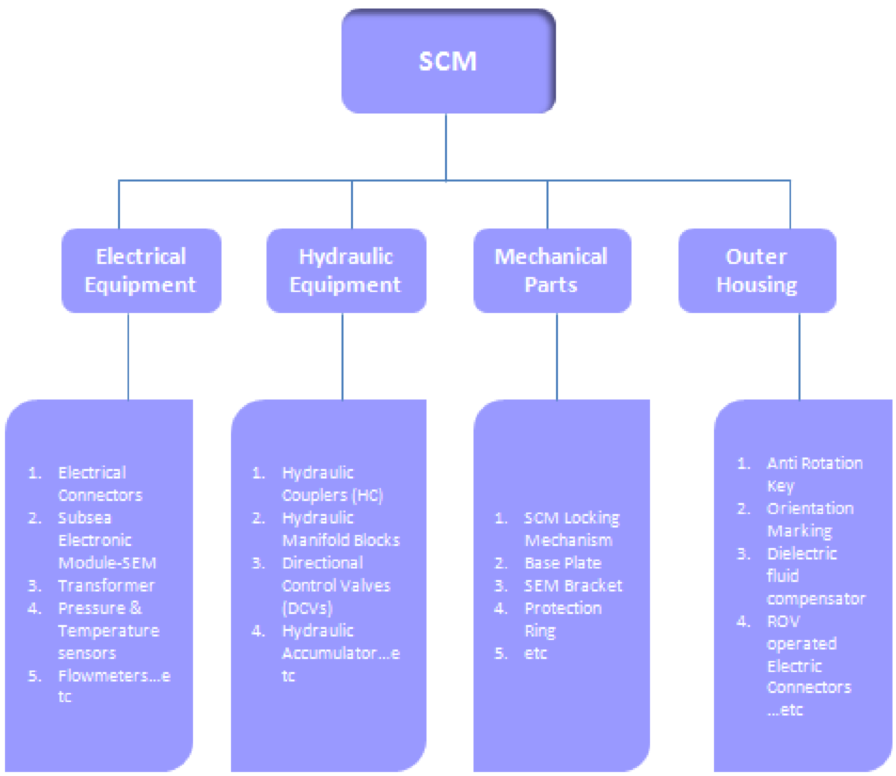


Figure 44 Schematic of the different sections of the SCM

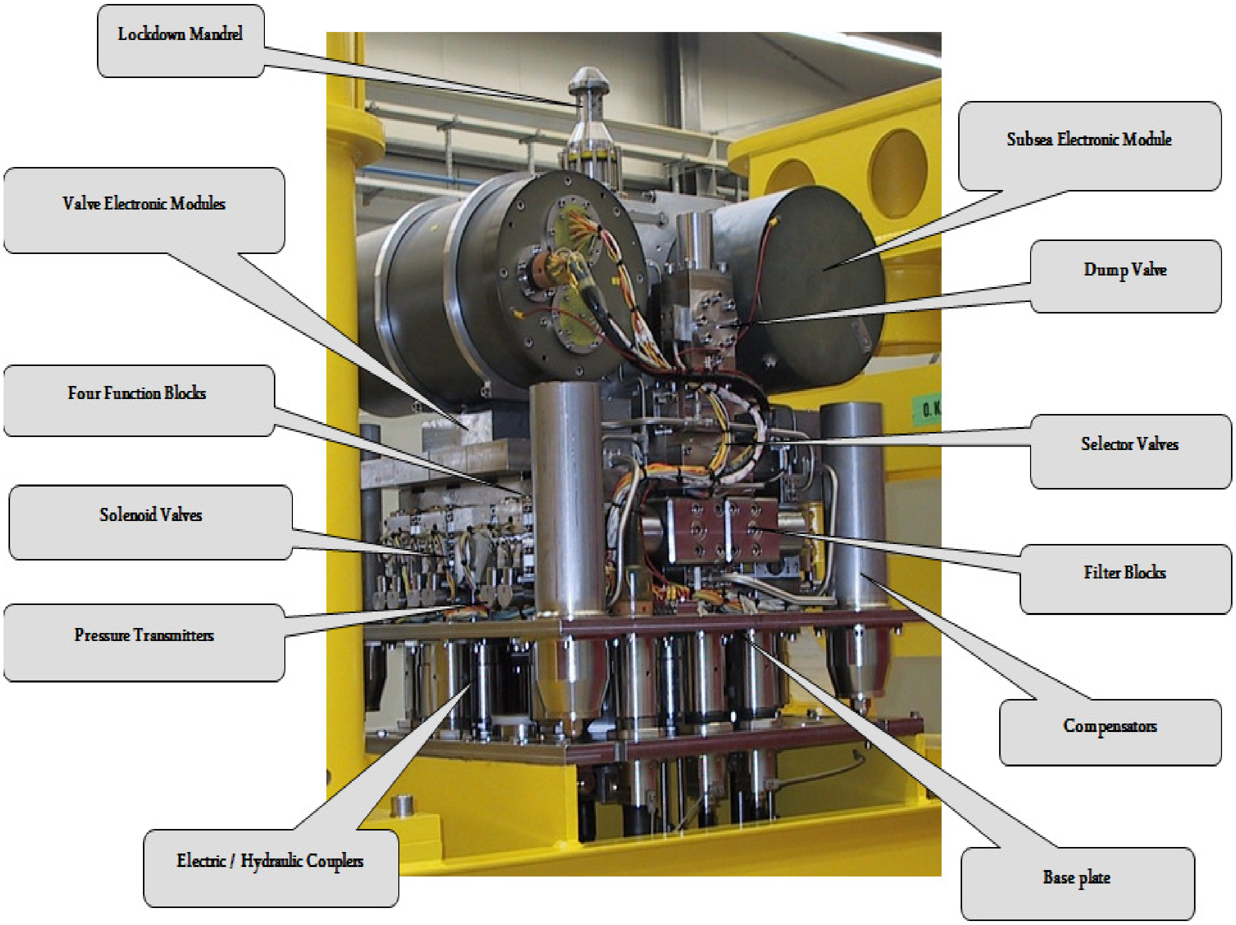


Figure 45 Parts a typical subsea control module (SCM), courtesy of Chevron.

Broadbent (2010) elaborates on the ten most common failure disciplines in the subsea control module as listed in table 9. He explains that SCMs must go through qualification testing, subsystem factory testing (FAT), system FAT test and environmental stress screening (ESS) before being sent offshore. All these tests are performed in accordance to ISO13628-6.

Table 9 Typical SCM Failure disciplines and the affected parts.

Top 10	Discipline	Main SCM Part Affected
1	Electrical	SEM
2	Electronic	SEM
3	Hydraulic	Directional control valves
4	Mechanical	SCM Housing
5	Mechanical	Directional Control Valve
6	Mechanical	Manifold
7	Mechanical	SEM
8	Hydraulic	Couplings
9	Electrical	Electrical Connector
10	Mechanical	External - Anode, Check valve ...etc

3.2.1 SCM hydraulic Equipment Subsystem

The SCM contains three separately rated circuits; an LP circuit, an HP circuit and a return circuit at pressure values typically lower than the LP and HP circuitries (See figure 46) Rowntree 2002, Cohan 2010, Beedie 2010, Bavidge 2013). The return circuit is common for spent fluid from both the LP and HP circuits.

Both the LP and HP circuits of the SCM are supplied via two separate supply lines termed ‘A’ and ‘B’, which enter the SCM via base mounted hydraulic couplers. Upon entering the SCM the fluid of each line is passed through filters and pressure transducers to remove contamination and enable individual line pressure measurement.

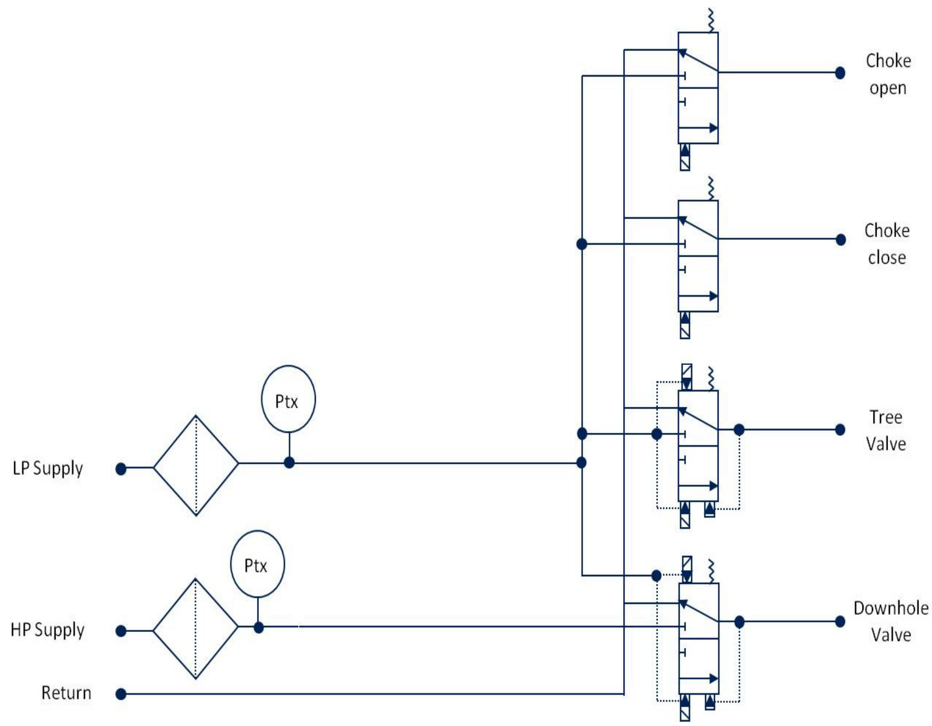


Figure 46 SCM Hydraulic schematic, self-addition

The dual supplies for each circuit are consolidated identically within the SCM, by the use of a selector and shuttle valve arrangement. The arrangement consists principally of a DCV, fitted to each of the incoming lines. The output lines from the DCV’s are routed to shuttle valves thus permitting a single supply to each of the SCM LP and HP distribution networks.

A selector valve arrangement presents several hydraulic supply options to the SCM namely (Cohan 2010, Bavidge 2013):

- Both selector DCV’s open (supply of fluid to the SCM distribution system controlled by the shuttle valve).
- Only selector DCV ‘A’ open, thus supply to the SCM via line ‘A’.

- Only selector DCV ‘B’ open, thus supply to the SCM via line ‘B’.
- Neither selector valve open, thus isolating the SCM from the system hydraulic distribution network.

Any of these options may be selected, depending on the agreed configuration. Following consolidation and selection of hydraulic supply line, both LP and HP fluid is fed via further pressure transducers and flowmeters, enabling pressure and flow measurement of the selected hydraulic supply. Fluid is then fed to each of the LP and HP function line DCVs.

The LP system passes through an accumulator system. The stored volume enables valve operation. Typically, an accumulator with a lower volume is fitted to the HP circuit. In the absence of an HP accumulator, an intensifier may be used in the LP circuitry to deliver HP functions.

The LP and HP DCVs are usually multiport, multi-way, bi-stable valves which require a pilot pressure and momentary electrical pulse to enable switching. The pilot pressure is derived from the main supply fluid within the DCV, through a pilot stage filtration screen. The electrical pulse is derived from the SEM, as and when it is required to open a valve. The DCV’s are set in a normally closed position; that is to say that the ‘function’ or ‘actuator’ line is normally connected to the return line. Upon switching, the valve connects the ‘supply’ and ‘function’ lines to permit supply of hydraulic pressure to tree valves via couplings in the SCM baseplate and the host structure mounting base. Pressure transducers are fitted to each of the LP and HP function lines to permit pressure read back in these lines and thus inference of the tree valve position.

The return line of the SCM vents to the sea in open loop system or returns to the surface for closed loop designs. Spent return fluid from the LP and HP DCV’s is co-mingled within the SCM and routed through the SCM baseplate for exhaust from the SCM.

A check valve separates the LP circuitry from the HP circuitry. The exhaust point from the SCM is also fitted with a dual redundant, metallic check valve to prevent pressure spikes from elsewhere in the system affecting the SCM.

Compensation accumulators on the return line provides system compensation against ambient pressure and also allows for a thermal expansion and contraction of control fluid in the system

The final components in the return line are the check valves fitted on the exhaust lines of the selector DCV's. These items protect the selector DCV's from pressure spikes and potentially contaminated fluid originating from elsewhere in the system.

3.2.2 SCM Electrical equipment Subsystem

The SCM is generally fitted with dual redundant electrical systems for reliability reasons (Bavidge 2013). Electrical power and communication between the SCM and topsides is achieved through the use of the comms on power (COPS) or comms and power system (CAPS) depending on the configuration. In the COPS, both power and communication signals are carried via the same wire pair. The wires are separate in the comms and power system (CAPS). Normally, two discrete channels are connected as separate supplies (termed channel A and channel B) to the SCM via two sets of electrical connectors located at the top of the SCM.

Within the SCM are dual Subsea Electronics Modules connected to the two redundant channels of the SCM. Within the SCM, each SEM is connected to all electrical components. The SEM is a computer-like electronic device responsible for the control of the hydraulic manifold system in the SCM using a selection of solenoid driven valves for the delivery of subsea hydraulic functions. It is also connected to internal and external sensors systems for production and subsea condition monitoring. Figure 47 is an electrical schematic showing the electrical distribution from the SEM to the SCM components.

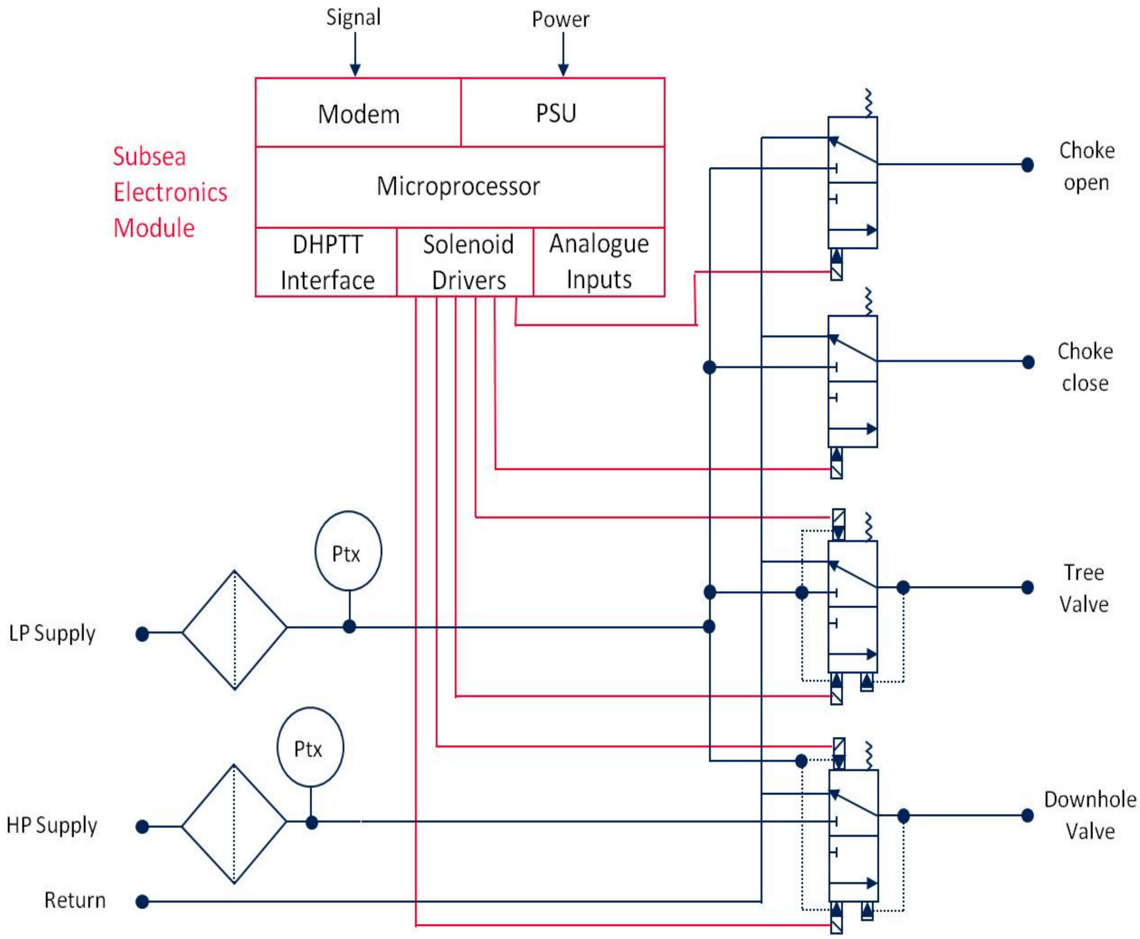


Figure 47 SCM electrical functional schematic, self-addition

A typical configuration will require pilot valves with two solenoids each to operate, one to open and the other to close. The solenoids are driven by the solenoid drivers in the SEM.

To open a tree valve, the appropriate solenoid is commanded from the MCS, the microprocessor in the SEM activates the solenoid driver which energises the open solenoid. This allows hydraulic fluid to flow into the function line to the tree valve actuator. The pressure in this line will rise very quickly to a value which allows the valve to latch open hydraulically. Thereafter, the valve will remain open as long as the hydraulic supply pressure remains above a prescribed value. To close a tree valve, the close solenoid is energised in a similar manner causing the spool in the valve to move, venting the hydraulic fluid from the tree valve actuator. The used fluid exits the SCM via the return line. It's worth mentioning here that most of the control valves in the SCM, when operated are latched open hydraulically. On electrical power failure to the SCM, these valves will stay as-is.

3.2.3 SCM Mechanical equipment subsystem

The SCM consists in principle of a pressure and temperature compensated, dielectric oil filled chamber, bound by a protective cover and baseplate. Within the dielectric chamber are housed all major hydraulic and electrical components Incoming electrical supplies are made via two electrical connectors located at the top of the unit. Hydraulic connections are made via couplers located in the baseplate of the SCM and hidden from view in normal operation by a protective skirt.

The SCM is designed to be locked to the mounting base through the use of a latch and lock mechanism. SCM podlock mechanism. During the lock down sequence the SCM is moved from an initial 'landed' position to a final fully 'locked' position, where all hydraulic and electrical connections are made and the SCM is torque tightened against a mechanical stop.

During subsea deployment, initial coarse positioning of the SCM on the mounting base is achieved by the RCRL in conjunction with host structure docking points. Intermediate positioning is achieved by the interface of the mounting base guidance funnel and SCM sides, final alignment being due to the engagement of the SCM guide pins and mounting base guide bushes.

3.2.4 SCM Housing subsystem

The SCM housing is a very critical part of the subsea control module as failure results in the ingress of water to the internals of the system (Bai 2010). This typically results in the corrosion of exposed metallic components and eventual failure of the entire system with time. The SCM is manufactured from either painted carbon steel, non-metallic materials or corrosion resistant alloys (primarily stainless steel). There are three separate corrosion cases relevant for the SCM when in its deployed state; these are the protection of the external surfaces of the SCM, the protection of the (shielded) under skirt area and the protection of the internal dielectric chamber.

The metallic external surfaces of the SCM rely on the cathodic protection system of the tree for corrosion protection. Physical connection between the SCM and host structure is achieved through the poppets of the SCM and SCMMB National couplers, which are clamped together by the podlock mechanism.

The area contained under the skirt of the SCM and above the mounting base top plate is shrouded from any host structure CP system and thus cannot be expected to derive any protection. Dedicated anodes are fitted to the SCM to protect components located in this shrouded area. The exposed surface area is minimised by the use of coatings (primarily Xylan), even on certain corrosion resistant materials to reduce the drain on the anodes.

Due to the long design life and the limited space in the under skirt area to fit anodes, it is recommended that the under skirt anodes are inspected and renewed on an opportunistic basis.

The internal structures of the SCM are primarily (uncoated) stainless steel and the painted metallic internal walls of the cover. The primary defence against corrosion in this area is the use of dielectric oil filling. The cover and any penetrations through it are sealed using O-rings and/or gaskets to prevent loss of dielectric fluid. The pressure balanced design of the SCM ensures no driving force exists to promote fluid loss. However, in the event of seawater ingress into this area, the SCM internals are fitted with anodes designed to provide at least 1 year cathodic protection. This is coupled to a seawater ingress detection system, designed to alert operators that ingress has occurred. The ingress detector has four levels of alarm, corresponding nominally to 25% increment seawater fill levels. Failure in the ingress detection system results in the loss of signal to the topside control system.

3.3 Failure Modes and Effect Criticality Analysis (FMECA)

In reliability engineering, there is a fundamental need of understanding the modes and mechanisms for which systems and components are likely to fail with the aim of eliminating them. In the words of Roberts (2002), achievement of reliability requires an understanding of what causes unreliability and how unreliability and its associated risks can be managed and prevented. This is particularly significant in the hydrocarbon industry due to the shift into deep/ultra-deep terrain of the ocean and the attendant safety, environmental and reliability concerns. The ability of FMEA/FMECA to provide the above information makes it one of the most applied reliability tools. Several definitions of FMEA exist, a few are mentioned below:

DNV 2003 defines FMEA as a structured review technique with the purpose to identify and analyze all significant failure modes and effects associated with the particular system under consideration. In Arierhe (2010), FMEA is defined as a structured qualitative analysis of a system, sub-system, components or function that highlights potential failure modes, their causes and the effects of a failure on system operations. The FMEA approach is an inductive approach which identifies the failure modes of the system and infers the likely consequences or impacts of these failures on the rest of the systems. Thus, the output is typically a listing of failure modes and the corresponding effects on the system (Ruede 2012).

The main objective of FMEA is to identify potential failure modes, evaluate the causes and effects of different component failure modes, and determine what could eliminate or reduce the chance of failure. The results of the analysis can help analysts to identify and correct the failure modes that have a detrimental effect on the system and improve its performance during the stages of design and production (Liu 2013). Fundamentally, there are five parts in a typical FMEA namely:

- Definition of objects or processes

- Identification of the potential failure modes
- Identification of the failure effects
- Establishment of the failure causes
- Risk assessment

The first step in conducting an FMEA is to define the scope of the exercise. This requires the breaking down of designs into sub-assemblies and components such that key failure modes and effects are not overlooked. Operational and environmental factors for each component are then evaluated for the corresponding failure modes and mechanisms. There are essentially four types of FMEA (Wardt 2011, Liu 2013), namely:

- System
- Design
- Process
- Service

System FMEA focuses on the global functions of a system, Design FMEA looks at the components and subsystems failures modes and mechanisms, process FMEA focuses on manufacturing and assembly processes while service FMEA focuses on service functions of the system in question. According to Don Shafer (2009), irrespective of the type, FMEA requires the identification of the following basic information: Item (s), Functions, Failure(s), Effect(s) of failure, Cause(s) of failure, Actions to be taken in case of failure, Remediation recommendations.

Typically, a failure mode and effect analysis would involve a method for evaluating the risk for each of the failures. When an FMEA involves analysing the criticality of the failures, this is called an FMECA (Hu-Chen Liu 2012).

Figure 48 Generic methodology for FMECA

The FMECA procedure is fundamentally made up of two procedures, the failure mode and effect analysis (FMEA) and the criticality analysis (CA). NASA (1966) defines FMECA as a reliability procedure which documents all possible failures in a system design within specified ground rules, determines by failure mode analysis the effect of each failure on system operation, identifies single failure points, i.e., those failures critical to mission success or crew safety, and ranks each failure according to criticality category of failure effect and probability of occurrence. In another definition, the FMECA is defined as a technique that permits evaluation of assets functions to predict critical failure modes and the resultant consequences in order to determine appropriate maintenance tasks for the assets (Mamman 2009). FMECA is conducted to identify, address and if possible, design out potential failure modes (Bai 2010). Figure 48 gives the general methodology for conducting an FMECA.

Criticality assessment (CA) could be qualitative or quantitative. In qualitative analysis, the severity and occurrence is being rated and used in the comparison which uses a criticality matrix. In quantitative analysis, the item reliability/unreliability is being evaluated at a time to deduce the corresponding failure mode/mechanism. For each mode, the probability of occurrence is then being evaluated and used in the criticality analysis. In practise, there are two key ways of performing failure modes criticality analysis (Braglia 2001 and Braglia 2003), namely:

- Calculating criticality number (CN)
- Developing a risk priority number (RPN)

Criticality number evaluation, as given in US MIL-STD-1629A (Todinov 2005), involves the evaluation of a failure effect probability (β), the mode ratio ($\propto$), the component failure rate (λ) and the operating time (t). With these values, the failure mode criticality number for each failure (i) is evaluated as follows:

$$CN_i = \propto_i * \beta_i * \lambda_p * t \tag{5.1}$$

A high level rigour is involved in this methodology, making it a relatively unpopular technique. In the RPN evaluations, linguistic terms are used in ranking the chance of failure mode occurrence O, chance of being undetected D and the severity S, usually on a numerical scale of 1 to 10. Mathematically, the RPN is calculated with a multiplication of these three values as:

$$\mathrm{RPN} = \mathrm{O} * \mathrm{S} * \mathrm{D} \tag{5.2}$$

This method has been found to be less expensive and quick compared to the CN technique. Key advantages of FMECA, according to Bai (2010) are listed below:

- Applicable at all project stages and can be used without data (Braaksma 2012),
- Versatile – applicable to high-level systems, components and processes
- Can prioritize areas of design weakness
- Systematic identification of all failure modes

Table 10 gives a simple comparison between the FMEA/FMECA and other common reliability techniques.

Table 10 A comparison of FMEA/FMECA with other engineering tools.

Tool	Purpose	Application	When to perform
FMEA/FMECA	• Bottom up approach to identify single failure points and their effects • To assist in the efficient systems design • To establish and rank critical failures • To identify interface problems	• More beneficial if performed on newly designed equipment • More applicable to equipment performing critical functions e.g. control systems.	• Early in design phase
Fault Tree Analysis (FTA)	Top down approach to identify effects of faults on system safety or reliability Address multiple failure	• Can be applied when FMECA is too expensive • To address effects of multiple failures	Early in design phase, in lieu of FMECA.
Reliability Block Diagram (RBD)	• This is equivalent to a success tree analysis. It is also known as dependence diagram. It is the logical inverse of a fault tree analysis. • It highlights a system using paths as against gates. • It is often drawn as a series of blocks connected in parallel or series configuration. Each block represents a component with failure rate.	• Can identify where redundancy is required • The diagrammatic procedure indicates how component reliability contributes to a system's success or failure.	• Trivial except for complex systems Cannot be used to identify hazards

Distribution Fitting	Fits distributions to data to find the type of distribution (normal, lognormal, gamma, beta, etc.)	• Presents forecasts for the future. • Checks the goodness-of-fit comparison. • Hypothesis testing because it quantifies the correlation between observed probabilities and predicted probabilities from a distribution.	• Subject to uncertainty • Change in environmental conditions can affect the probability of occurrence. • Resource intensive.
Fuzzy Set Theory	For forecasting uncertainties due to sparse or absence of data	• Very flexible and easy to apply. • Helps in reduction of maintenance and operational cost. • Used as a form of approximate reasoning • Applied when data are sparse and weak	• Time consuming. • Difficult to estimate membership function.

Common limitations of the FMEA process are:

- It requires a deep knowledge of the product or process being evaluated
- Scoping and organisational boundaries may be an issue
- Not able to report failure intervals
- A relatively questionable criticality and ranking process with RPN

3.4 Application of FMEA/FMECA in Offshore and subsea systems.

The most common methods of identifying and mitigating technical risks for deepwater completions are generally peer reviews, failure mode and effects analysis (FMEA), HAZOP and system integration testing (SIT) (Tomaso 2009, Schubert 2002, Duhon 2011, IEC 61882 2001). These methods are applicable across the equipment and project lifecycle, irrespective of the phase in question. However, the earlier they are applied for risk identification, the better the mitigation and corrective action plans. Again, Cuvex-Micholin (2012) posits that FMEA is a key approach used in analysing risks in both the upstream and downstream oil and gas industries other tools like HAZOP, preliminary hazard analysis, probabilistic risk assessment including hazard analysis and critical control point (HACCP).

In the words of (Brandt 2001) FMEA is always the first step in a system reliability study in the subsea industry. The author explains that FMEA/FMECA is highly effective during the concept selection stage of an offshore subsea project due to the availability of more detailed information for establishing reliability targets. In line with this, FMECA is applied in Harold (2004), for identifying technical risks in a high-technical subsea development offshores with high temperature-high pressure (HP/HT) risks. Binder (2009) mentions FMEA as a key tool for hazard analysis and offshore integrity management. Annamaria (2009) identifies FMEA as a key study for RAM and maintenance issues. Wael (2003) recommends that FMEA is a very effective tool for analysing complex systems. The tool is used here in the analysis of an integrated active heave hoisting system. Wardt (2011) evaluates the significance of using the FMECA in the commissioning phase of oil and gas projects in both the onshore and offshore sectors. The author posits that though FMECA tends to be used at the component level for drilling and commissioning operations, application of this tool at the system level is pertinent for reducing risks due to the complexity and cost involved in these operations. Finally, the paper concludes that application of FMECA significantly improves the reliability of automated drilling systems.

(Shaughnessy 1999) advocated that FMEA is key to design and manufacture of the BOP control system as it helps eliminate single point failures by implementing subsystems redundancy. According to Fenton (2002), the result of an FMEA directly impacts the CAPEX of a subsea facility. This comes in the form of alteration of a field design concept, changes in drilling locations and well end points, changes in well construction, alterations in pipeline routes and sizes, changes in manifold locations, inclusion of down-hole shut-off valves, all to minimize or completely eliminate failure in the subsea system.

In Riley (2001), FMEA is used in the documentation of failure and potential consequences in a well tieback system. This provides a direct feed to the system fault tree analysis including RISKEX and RAMEX calculations. In Rizzi (1998), FMEA/FMECA is used in the identification of hazards and the grouping of initiating events for deepwater field development alongside other tools like the HAZOP. FMEA offers design improvements by suggesting preventive and corrective measures early in the design phase of the project. Patel (2011) uses FMEA in the analysis of well control systems for mobile offshore drilling unit (MODU)/rig most especially when system modifications are performed that may affect the system classification. It is seen that FMEA/FMECA could also include human interfaces in operational evaluation and depending on the operational specifics and the phase of the project.

In Andrea (1998), FMEA/FMECA is used in the risk evaluation for floating oil production in deepwater environment along with other systems like the HAZOP and preliminary hazard assessment (PHA). Mamman (2009) looks at the criticality in the failure of subsea valves from both the technical and commercial perspective. The losses are evaluated looking into the loss production, environmental impact including subsea intervention and IMR costs. With the criticality analysis, a prevention and elimination strategy is then developed into the valve system to prevent early life failure. In (Langli 2001), FMECA is used for revealing design weaknesses in control systems covering topsides, umbilical, subsea distribution & control units, subsea and downhole instrumentation), workover control systems, subsea separation unit (including pump) and smart well equipment's.

API17N (2009) recommends three key activities for addressing reliability in subsea systems design, which are:

- Reliability, Availability and Maintainability (RAM)
- Failure mode assessment (FMEA and FMECA)
- External design review

This emphasizes the significance of FMEA/FMECA in the design of engineering systems including offshore and subsea control systems. According to API17N, FMEA helps to identify potential faults that could lead to components or system failure. With this, the failure will be detected, isolated and removed in order to maintain the component, subsystem and overall system integrity. Again, it is used in evaluating the failures across the functional hierarchy from component, subassembly down to the high-level system levels. The significance, probability, consequence of each failure type is also analysed. Again, the output from FMECA is used in FTA modelling for establishing reliability figures and in RCM analysis. A key concern in subsea systems deployments is the requirement for intervention; FMECA helps in the identification of subsea intervention task. Locheed (1979), emphasises that the application of FMEA to a subsea control module gives rise to improved reliability.

3.5 Subsea Control Module FMECA Evaluation

A key part of this research is that a very comprehensive FMECA analysis was being performed for a tree-mounted subsea control module (SCM) in an Offshore subsea production system. The evaluation was based on an assembly of subsea engineering experts. The results showing the failure modes ID are

Table 11 Criteria for FMECA Evaluation

Severity S		Occurrence O		Detectability D	
Hazardous	10	Exteremely high	10	Absolutely uncertain	10
Serious	9	Very High	9	Very remote	9
Extreme	8	Repeated failures	8	Remote	8
Major	7	High	7	Very low	7
Significant	6	Moderate high	6	Low	6
Moderate	5	Moderate	5	Moderate	5
Low	4	Relatively low	4	Moderately high	4
Minor	3	Low	3	High	3
Very Minor	2	Remote	2	Very high	2
None	1	Nearly impossible	1	Almost certain	1

shown in figure 49. In this analysis, the risk factors, occurrence (O), severity (S) and detectability (D) are evaluated and the associate risk priority number (RPN) generated for each of the failure modes. A total of one hundred failure modes were generated, derived from analysis typical loss of defined functions that could result from the SCM component. This involved a wide consultation of industry experts. Table 12 gives a comprehensive listing of the failures modes, causes, effects, risk factors and the RPN values for all the evaluated modes.

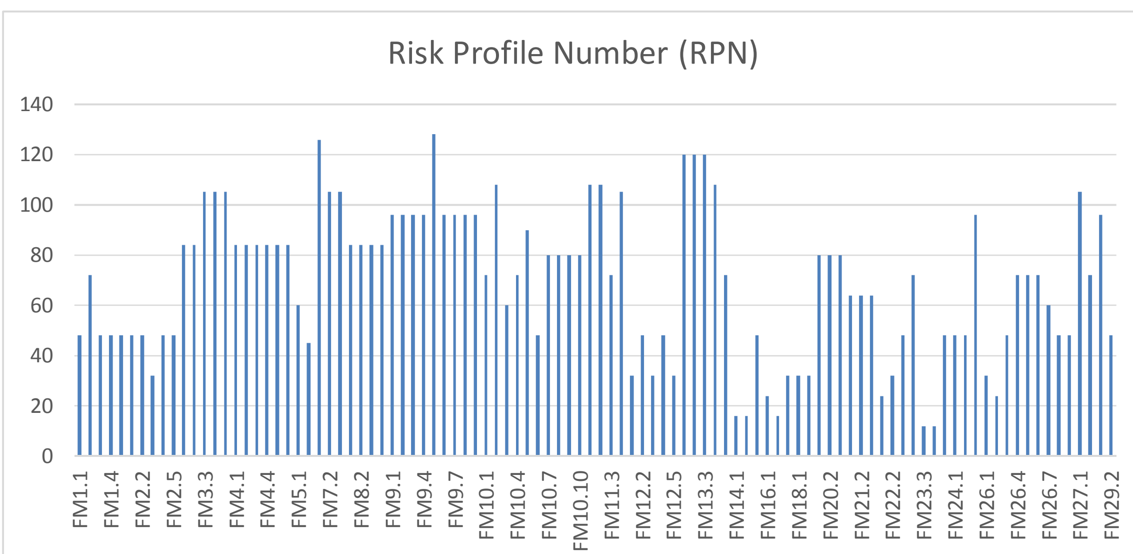


Figure 49 RPN for the SCM failure modes against FM ID

A further analysis was then performed with thirty (30) of the failure modes with the highest RPN values. The analysis was performed to determine the most critical failures modes in the SCM and the corresponding consequence.

FM ID	Subsystem or Component	Failure Mode	Failure Cause	Failure Effects	O	S	D	Risk Profile Number (RPN)
F1	LP Selector Valve	LP selector valve spuriously closes.	LP selector valve internal fault of the latching mechanism.	Selector Valve spuriously isolates and vent down an incoming supply Loss of a single LP hydraulic supply to the SCM. No Effect on normal operation Loss of hydraulic supply redundancy	4	6	2	**48**
F2		LP selector valve fails to open.	Failure of the valve solenoid system	Loss of a single LP hydraulic supply to the SCM. No Effect on normal operation Loss of hydraulic supply redundancy	6	6	2	**72**
F3			LP selector valve internal fault of the latching mechanism to latch.	Loss of a single LP hydraulic supply to the SCM. No direct Effect on normal operation Loss of hydraulic supply redundancy	4	6	2	**48**
F4		LP selector valve fails to close.	Complete failure of the selector valve solenoid system	Unable to select LP channel as required No direct Effect on normal operation Loss of hydraulic supply redundancy	4	6	2	**48**
F5			LP selector valve internal fault of the latching mechanism.	Unable to select LP channel as required No direct Effect on normal operation Loss of hydraulic supply redundancy	4	6	2	**48**
F6	HP Selector Valve	HP selector valve spuriously closes.	HP selector valve internal fault of the latching mechanism.	Selector Valve spuriously isolates and vent down an incoming supply Loss of a single HP hydraulic supply to the SCM. No Effect on normal operation Loss of HP hydraulic supply redundancy	4	6	2	**48**
F7		HP selector valve fails to open.	Failure of the valve solenoid system	Loss of a single HP hydraulic supply to the SCM. No Effect on normal operation Loss of hydraulic supply redundancy	6	4	2	**48**

F8			HP selector valve internal fault of the latching mechanism	Loss of a single HP hydraulic supply to the SCM. No direct Effect on normal operation Loss of hydraulic supply redundancy	4	4	2	**32**
F9		HP selector valve fails to close.	Failure of valve solenoid system	Unable to select HP channel as required No direct Effect on normal operation Loss of hydraulic supply redundancy	4	4	3	**48**
F10			HP selector valve internal fault of the latching mechanism.	Unable to select HP channel as required No direct Effect on normal operation Loss of hydraulic supply redundancy	4	4	3	**48**
F11	LP Shuttle Valve	Shuttle Valve fails to change over to the next LP supply line.	Shuttle valve internal fault.	Inability to select/change over to an LP supply on demand. No direct effect if 2nd line is serviceable	4	7	3	**84**
F12		Severe Leak in the Common LP Hydraulic Header.	Severe leak from the LP Shuttle valve.	Loss of common LP supply pressure All DCVs eventually unlatch Loss of Production	4	7	3	**84**
F13			Severe leak from a LP Accumulator.	Loss of common LP supply pressure All DCVs eventually unlatch Loss of Production	5	7	3	**105**
F14			Severe leak from the LP Common Header Pressure Transmitter.	Loss of common LP supply pressure All DCVs eventually unlatch Loss of Production	5	7	3	**105**
F15			Severe leak from the LP Common Header Flow Meter.	Loss of common LP supply pressure All DCVs eventually unlatch Loss of Production	5	7	3	**105**
F16	HP Shuttle Valve	Shuttle Valve fails to change over to the next HP supply line.	HP Shuttle valve internal fault.	Inability to select/change over to an HP supply on demand. No direct effect if both lines remain serviceable All DCVs unltach and Well shutin if 2nd line is not available Complete Loss of Production	6	7	2	**84**

F17		Severe Leak in the Common HP Hydraulic Header.	Severe leak from the HP Shuttle valve.	Loss of common HP supply pressure All DCVs eventually unltach Loss of Production	6	7	2	**84**
F18			Severe leak from the HP manifold (seals etc).	Loss of common HP supply pressure All DCVs eventually unlatch Loss of Production	6	7	2	**84**
F19			Severe leak from the HP Common Header Pressure Transmitter.	Loss of common HP supply pressure All DCVs eventually unlatch Loss of Production	6	7	2	**84**
F20			Severe leak from the HP Common Header Pressure Transmitter.	Loss of common HP supply pressure All DCVs eventually unlatch Loss of Production	6	7	2	**84**
F21			Severe leak from the HP Common Header Flow Meter.	Loss of common HP supply pressure All DCVs eventually unlatch Loss of Production	6	7	2	**84**
F22	LP Manifold System	Severe Leak in the LP Manifold	Faulty seals and other system malfunction	Loss of common LP supply pressure All LP DCVs eventually unltach and Well shutin. Complete Loss of Production	3	5	4	**60**
F23	HP Manifold System	Severe Leak in the HP Manifold (E.G. Seals etc)	Faulty seals and other system malfunction	Loss of common HP supply pressure All HP DCVs eventually unlatch and Well shutin. Loss of Production	3	5	3	**45**
F24	LP Accumulator System	Loss/reduction in LP Accumulation.	Loss all LP accumulator pre-charge.	Loss of common LP supply pressure All DCVs eventually unlatch Complete Loss of Production	6	7	3	**126**
F25			Severe leak from the LP Common Header Pressure Transmitter.	Reduction in LP accumulation Excessive drop in supply during valve operation All DCVs delatch/All tree valves close Complete Loss of Production	5	7	3	**105**
F26			Single LP bladder failure.	Reduction in LP accumulation Excessive drop in supply during valve operation All DCVs delatch/All tree valves close Complete Loss of Production	5	7	3	**105**

F27	HP Accumulation System	Reduction in HP Accumulation.	Single HP accumulator loss of pre-charge.	Reduction in HP accumulation Excessive drop in supply during valve operation All DCVs delatch/All tree valves close Loss of Production	4	7	3	**84**
F28			Single HP bladder failure.	Reduction in HP accumulation Excessive drop in supply during valve operation All DCVs delatch/All tree valves close Loss of Production	4	7	3	**84**
F29		Loss of HP Accumulation.	Loss all HP accumulator pre-charge.	Loss/reduction in HP accumulation All DCVs delatch Complete Loss of Production	4	7	3	**84**
F30		Loss/reduction of HP supply pressure.	HP supply line plugged with particulate.	Loss/reduction in HP accumulation Excessive drop in supply during valve operation All HP DCVs delatch Complete Loss of Production	4	7	3	**84**
F31	Subsea Electronic Module (SEM)	Complete Loss of Power supply from the SEM	Internal fault with the SEM power supply units Water ingress into the SCM unit	Loss of DHPT signal from the SEM channel Loss of control and communication to the topside Loss of power to all DCV valve solenoids Loss in SCM system redundancy Complete Loss of Production	6	8	2	**96**
F32		Loss of Controller board functionality	Controller board failure	Loss of single LP channel in the tree SCM. Loss of Tree Controls Loss of control and communication to the topside Loss of Production	6	8	2	**96**
F33		Loss of Signal from one SEM	I/O card failure in SEM, Corrupt software	Loss of single LP channel in the tree SCM. Loss of Tree Controls Complete Loss of Production	6	8	2	**96**
F34		Complete Loss of signal from both SEM	I/O card failure in SEM, Corrupt software	Loss of DCV Valve controls Loss of all associated subsea instrumentation. Loss of Xmas Tree controls Complete Loss of Production	6	8	2	**96**

F35		Loss of I/O Interface Board	I/O Board Internal fault.	Loss of the channel I/O Board. Inability to monitor one set of external instrumentation. All DCVs will remain latched to their current positions. Complete Loss of Production	8	8	2	**128**
F36		Loss of DHPT Board	DHPT Board Internal fault.	Loss of Communication to the Tree DHPT instruments from the Channel . All DCVs remain in their last positions. The redundant DHPT board provides the service Complete loss of monitoring	6	8	2	**96**
F37		Loss of Modem Functionality - Interface to topside	Modem Failure .	Loss of one communication channel to the topside Loss of control and communication to the topside The control function of the SCM is unaffected. Complete loss of monitoring	6	8	2	**96**
F38			Modem Freezes - produces steady output	Partial Loss of monitoring Loss of control and communication to the topside Complete loss of monitoring	6	8	2	**96**
F39		Critical Loss of Electronic Control	Combinational loss of power supply, modem and control board	Inability to monitor subsea instrumentation or command Inability to open or close any valve from the topside All hydraulically actuated valves remain in last positions Inability to shut in the tree in a controlled manner through the integrated system Complete loss of subsea monitoring Complete Loss of Production	6	8	2	**96**
F40	Hydraulic circuitry	Loss of single LP hydraulic supply	Solenoid valve spuriously operates	Loss of single LP channel in the tree SCM. Pressure drop in the shuttle valves Total loss of Tree controls Complete Loss of Production	4	6	3	**72**
F41			Leakage from LP hydraulic lines/connectors	Loss of single LP channel in the SCM. Leakage of hydraulic fluid into the sea. Loss of Production	6	6	3	**108**
F42			Single LP hydraulic line blocked	Loss of LP pressure in the affected channel. Loss of Xmas Tree controls Loss of Production	5	6	2	**60**

F43		Loss of single HP hydraulic supply	Loss in HP hydraulic line/connector in a single channel.	Loss of single HP channel to all the Xmas tree. Severe leakage of hydraulic fluid into the sea. Eventual drop of all the HP DCVs Loss of Production	6	6	2	**72**
F44			Leakage from HP hydraulic lines	Gradual loss of single HP channel to all the Xmas tree/Well. Leakage of hydraulic fluid into the sea. Loss of Production	6	5	3	**90**
F45			Single HP hydraulic line blocked	Loss of HP pressure in the affected channel. Loss in SCSSV and FCV Controls Loss of Production	4	6	2	**48**
F46		Loss of both LP hydraulic supplies	Line/connector Leakage in the LP supply Lines	Loss of hydraulic suplies to the LP DCVs Loss of Xmas Tree controls Complete Loss of Production	5	8	2	**80**
F47			Blocked LP hydraulic lines	Loss of hydraulic suplies to the LP DCVs Loss of Xmas Tree controls Complete Loss of Production	5	8	2	**80**
F48		Loss of both HP hydraulic supplies	Leakage in the HP supply lines	Loss of hydraulic suplies to the HP DCVs Loss of SCSSV and IWCV controls Complete Loss of Production	5	8	2	**80**
F49			Blocked HP hydraulic lines	Loss of hydraulic suplies to the HP DCVs Loss of SCSSV and IWCV controls Complete Loss of Production	5	8	2	**80**
F50	LP Directional Control Valves (DCV)	LP tree valves DCV fails to open on demand	Failure of the valve solenoid coils	Selected Xmas tree valve fails to open on demand DCV remains in the last latched and shut position. Well remains in the shutin position Complete Loss of Production	6	6	3	**108**
F51			Internal fault in the DCV latching mechanism	Selected Xmas tree valve fails to open on demand DCV remains in the last latched and shut position. Well remains in the shutin position Complete Loss of Production	6	6	3	**108**
F52		LP Tree valves DCV shuts spuriously from the open position.	Internal fault in the DCV latching mechanism	Associated tree valve spuriously closes Unscheduled Loss of production Complete Loss of Production	4	6	3	**72**

F53		LP Tree DCV fails to close on demand	Failure of the valve solenoid coils	Unable to shutoff production Partial Loss in well control	7	5	3	**105**
F54	Choke DCV valve	Choke DCV fails to open on demand.	Failure of the valve solenoid coils	Unable to set required choke valve position Reduction in flow of oil from the well. Partial Loss of Production	4	4	2	**32**
F55			DCV internal valve failure.	Unable to set required choke valve position Reduction in flow of oil from the well. Partial Loss of Production	6	4	2	**48**
F56		Choke DCV fails to shut on demand.	Solenoid valve sticks in energised position.	Production Choke Valve Close actuator (PCVC) fails to extend to required position. Reduction in flow of oil from the well. Partial Loss of Production	4	4	2	**32**
F57			DCV internal valve failure.	Production Choke Valve Close actuator (PCVC) fails to extend to required position. Reduction in flow of oil from the well. Partial Loss of Production	6	4	2	**48**
F58			Failure of the valve solenoid coils	Production Choke Valve Close actuator (PCVC) fails to extend to required position. Reduction in flow of oil from the well. Partial Loss of Production	4	4	2	**32**
F59	HP Directional Control Valves (DCVs)	SCSSV DCV fails to open on demand from the closed position.	Failure of the valve solenoid coils	SCSSV fails to open. Unable to start production from the well. Complete Loss in Production	5	6	4	**120**
F60			DCV internal fault of the latching mechanism	SCSSV fails to open. Unable to start production from the well. Complete Loss in Production	5	6	4	**120**
F61		SSCSV shuts spuriously from the open position.	DCV internal fault of the latching mechanism.	SCSSV spuriously closes. Unscheduled loss of production. Complete Loss in Production	5	6	4	**120**

F62		SCSSV fails to shut on demand from the open position.	Failure of the valve solenoid system	Loss of SCSSV protection Reduced well barrier for the SPS Partial Loss in Well Control	6	6	3	**108**
F63			DCV internal fault of the latching mechanism to latch.	Loss of SCSSV protection Reduced well barrier for the SPS Partial Loss in Well Control	6	6	2	**72**
F64	Baseplate mounted hydraulic couplings	Inability to connect the SCM to the Xmas tree	Worn couplings during SCM installation Corrosion and wear of the base couplings	Inability to makeup the SCM to the Xmas tree Complete Loss of Production	2	4	2	**16**
F65	LP Circuit Pressure Transducers + Return line	Loss of electronic monitoring of a single hydraquad function.	Loss of DCV Output Pressure Transducer.	All associated DCV's remain latched in their last position Loss of monitoring and positional status of a single DCV. No direct impact on a normally operating tree. Partial Loss in subsea monitoring	4	2	2	**16**
F66		Loss of electronic monitoring of the LP line Pressure.	Faulty LP Pressure Transducer.	All associated DCV's remain latched in their last position Loss of monitoring and positional status of a single DCV. No direct impact on a normally operating tree. Partial Loss in subsea monitoring	6	4	2	**48**
F67	HP circuit pressure transducers + Return Line	Loss of electronic monitoring of a single hydroquad function.	Loss of DCV Output Pressure Transducer.	All associated DCV's remain latched in their last position Loss of monitoring and positional status of a single DCV. No direct impact on a normally operating tree. Partial Loss in subsea monitoring	4	3	2	**24**
F68		Loss of electronic monitoring of the HP Supply Pressure.	Loss of HP Pressure Transducer.	All associated DCV's remain latched in their last position Loss of monitoring and positional status of a single DCV. No direct impact on a normally operating tree. Partial Loss in subsea monitoring	4	2	2	**16**

F69	LP supply flowmeter	Loss of electronic monitoring of the LP Supply flow.	Internal fault in the LP flowmeter	Loss of flow monitoring of the LP supply. No direct impact on a normally operating tree. Partial Loss in subsea monitoring	4	4	2	**32**
F70	HP supply flowmeter	Loss of electronic monitoring of the HP Supply flow.	Internal fault in the HP flowmeter	Loss of flow monitoring of the HP supply. No direct impact on a normally operating tree. Partial Loss in subsea monitoring	4	4	2	**32**
F71	Return line flowmeter	Loss of electronic monitoring of the Return line flow.	Internal fault in the Return line flowmeter	Loss of flow monitoring in the Return Line No direct impact on a normally operating tree. Partial Loss in subsea monitoring	4	4	2	**32**
F72	LP circuit hydraulic filters	Loss of LP hydraulic filtration	Filter element missing Rupture of filter element Wear filter element components Holed or filter by-pass spuriously operates.	Dormant failure in normal operation Clogging or binding of mobile parts of the DCV valves Unfiltered contaminated hydraulics - Blockage and Wearing of SCM components Stop or slow slowly moving of actuators. Malfunction of subsea components Complete Loss in well production	4	5	4	**80**
F73			Inadequate filter elements. Design error in the filter porosity	Clogging or binding of mobile parts of the DCV valves and other components, Wearing of SCM components Stop or slow slowly moving of actuators. Complete Loss in well production	4	5	4	**80**
F74			Clogging Blockage due to fluid contamination	Clogging or binding of mobile parts of the DCV valves and other components, Wearing of SCM components Stop or slow slowly moving of actuators. Complete Loss in well production	4	5	4	**80**
F75	HP circuit hydraulic filters	Loss of HP hydraulic fltration	Filter element missing Rupture of filter element Wear filter element components Holed or filter by-pass spuriously operates.	Dormant failure in normal operation Clogging or binding of mobile parts of the DCV valves Unfiltered contaminated hydraulics - Blockage and Wearing of SCM components Stop or slow slowly moving of actuators. Malfunction of subsea components Complete Loss in well production	4	4	4	**64**

F76			Inadequate filter elements. Design error in the filter porosity	Clogging or binding of mobile parts of the DCV valves and other components, Wearing of SCM components Stop or slow slowly moving of actuators. Complete Loss in well production	4	4	4	**64**
F77			Clogging Blockage due to fluid contamination	Clogging or binding of mobile parts of the DCV valves and other components, Wearing of SCM components Stop or slow slowly moving of actuators. Complete Loss in well production	4	4	4	**64**
F78	Return line check/dump valves	Reduction in LP hydraulic dump capability.	Blocked dump return lines.	Unable to completely "dump" LP hydraulic supply pressure to compensation circuit. All DCVs remain hydraulically latched with tree valves remaining in last position. Production flow is not shut in. No Loss in Production	4	3	2	**24**
F79		LP Dump Valve fails to operate on demand.	Internal fault in the dump valve system	Unable to completely "dump" LP hydraulic supply pressure to compensation circuit. All DCVs remain hydraulically latched with tree valves remaining in last position. No Loss in Production	4	4	2	**32**
F80	Electrical Connectors (External)	Loss of power from the SCM electrical connectors	Internal fault in the electrical connectors	Loss of power to one SEM channel in the SCM Loss of DHPT signal from the SEM channel Loss of control and communication to the topside Loss of power to all valve solenoids All DCVs remain in their last latched position Loss in SCM system redundancy Complete Loss in Well Production	6	4	2	**48**
F81			Leakage in the connector system	Loss of power to the SEM channels in the SCM Loss of DHPT signal from the SEM channels Loss in SCM system redundancy Loss of control and communication to the topside Loss of power to all valve solenoids All DCVs remain in their last latched position Complete Loss in Well Production	6	6	2	**72**

F82		Unable to disconnect EFL from SCM Assembly	Connector failure.	Unable to disconnect the Electrical Lead from the SCM Nil effect during normal operation If EFL fails, lead and umbilical repacement not possible Retrieval and replacement of the SCM Complete Loss in Well Production	1	6	2	**12**
F83		Unable to connect SCM assembly to tree.	Connector failure.	Complete Loss of subsea monitoring Complete Loss in Well Production	1	6	2	**12**
F84		Loss of electronic control from the terminals in the Connector.	Short circuit / open circuit.	Loss of power to the SEM channel in the SCM Loss of DHPT signal from the SEM channel Loss of control and communication to the topside Loss of power to all the DCVs All DCVs remain in their last position Complete Loss in production	4	6	2	**48**
F85	Electrical Connectors/Cabling (internal)	Loss of power from the SEM to the valve units	Short circuit / open circuit.	Loss of power to the associated valve solenoid DCV valve remains in its last latched position Loss of control and communication to the topside Loss of power to all the associated subsea/well instrument Partial Loss of subsea monitoring	4	6	2	**48**
F86			Faulty Electrical cable/connector	Loss of power to the associated valve solenoid DCV valve remains in its last latched position Loss of control and communication to the topside Loss of power to all the associated subsea/well instrument Partial Loss of subsea monitoring	4	6	2	**48**
F87	SCM Dielectric fluid chamber	Loss of dielectric protection to the electrical system	Leakage in the SCM housing system Wrong installation procedure	Seawater ingress into the SCM Contamination of the dielectric fluid Failure of the Electrical components of the SCM Total Complete Loss of production	2	6	8	**96**

F88	SCM Housing	Loss of communication from the Water ingress Sensor	Internal fault in the Water Sensor.	Loss of the internal house keeping water ingress monitoring. All DCVs remain in their current positions. Partial Loss of subsea monitoring Complete loss in production	2	8	2	**32**
F89		Loss of SCM pressure compensation.	Leakage of dielectric fluid from SCM via vent.	Dielectric fluid leaks from SCM whilst installed subsea Potential water ingress into SCM and damage to electronic components. Complete Loss in Well production	2	6	2	**24**
F90		Unable to disconnect SCM assembly from tree.	Hydraulic coupler failure.	Unable to disconnect the SCM from the tree. Nil effect under normal operation High Cost Tree retrieval and replacement Severe Loss in produdction + Pull Completion	2	4	6	**48**
F91		Unable to connect SCM assembly to tree.	Faulty Hydraulic couplers	Unable to connect the SCM to the tree. Possible replacement of the SCM assembly Loss in production	3	4	6	**72**
F92			Debris (sand, calcium carbonate)	Unable to connect the SCM to the tree. Possible replacement of the SCM assembly Loss in production	3	4	6	**72**
F93			Seal carrier misaligned/damaged	Unable to connect the SCM to the tree. Possible replacement of the SCM assembly Loss in production	3	4	6	**72**
F94			Damaged SCM baseplate	Unable to connect the SCM to the tree. Possible replacement of the SCM assembly SCM replacement Loss in production	3	4	5	**60**
F95		Loss off internal temperature sensor	Faulty temperature sensor	No Loss of normal systems operations Partial Loss of subsea monitoring	6	4	2	**48**
F96		Loss off internal pressure sensor	Faulty pressure sensor	No Loss of normal systems operations Partial Loss of subsea monitoring	6	4	2	**48**

F97	Seawater check valve	Seawater check Valve Leakage	Valve component embrittlement Installation damage Wear Dynamic instability	Seawater ingress into the SCM Contamination of the dielectric fluid Failure of the Electrical components of the SCM Total loss of electronic and hydraulic functions Complete Loss in well production	5	7	3	**105**
F98	Dieelectric chamber over pressure relief valve	Valve fails to operate on demand	Valve component embrittlement Worn valve components Dynamic instability	Overpressured SCM chamber Failure of the Electrical components of the SCM Failure in the hydraulic components Total loss of electronic and hydraulic functions Complete Loss in well production	3	6	4	**72**
F99	SCM Podlock	SCM not correctly locked to SCMMB	Insufficient number of turns	Unable to operate all LP and HP control functions	3	8	4	**96**
F100		Unable to unlock the SCM from the mounting base	Worn couplings during SCM installation Corrosion and wear of the base couplings Dead Hydraulic lockdown Live hydraulic lockdown Debris (sand, calcium carbonate)	Inability to disconnect the SCM from its SCMMB Inability to retrieve the SCM to the surface for repairs For VXT, Tree assembly retrieval to the surface For HXT, Tree and Well Completions retrieval Severe loss in production + Pull Completion	2	6	4	**48**

Table 12 Comprehensive Subsea control module failure modes and effect criticality analysis, FMECA

The FMECA was conducted using ten (10) experienced subsea experts in the industry. A characterisation of the experts used is briefly explained in section 4.3.1.1 of this report. The experts were given a listing of the failure modes and using the scale for the risk factors ticked the corresponding values of the risk factors to the associated failure mode. A statistical mode-based evaluation was used to determine the value of the risk to the associated failure mode and the results are as shown in figure 50.

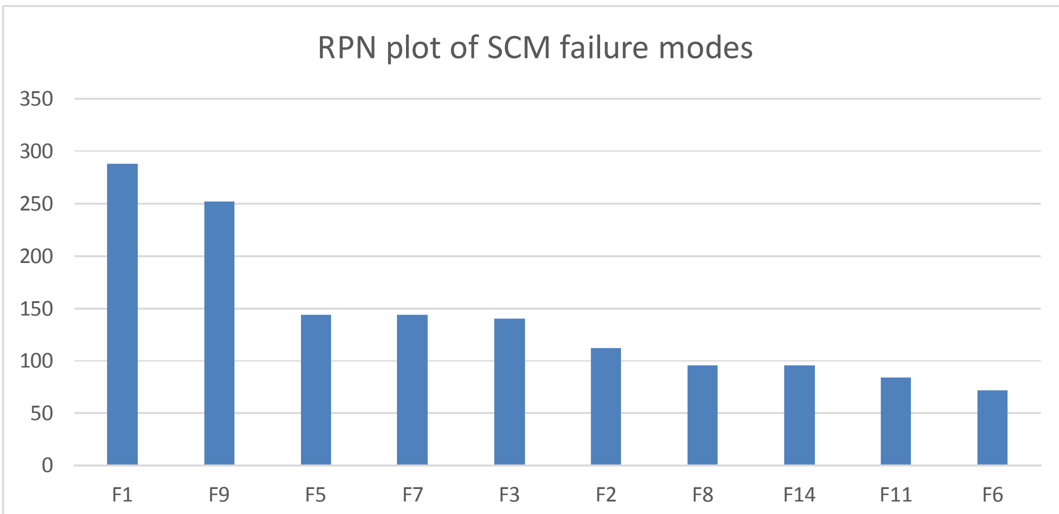


Figure 50 RPN plot of SCM Failure modes

At the end of the evaluation, all the failure modes were ranked considering the values of their RPN. Table 13 below shows the ten most critical failure modes and the failure mode ID, Its evaluated RPN and the ranking.

The result shows the SEM power failure as the most critical component in the SCM system with 'Loss of power supply' failure mode. In a typical communication on power (COPS) subsea control system, a loss in power invariably means a loss in the downhole signal to the topside and vice versa. Next to the SEM are the directional control valves.

Table 13 SCM Failure modes showing the RPNs and the failure mode ranking

Failure Modes	Failure ID	RPN	Failure Mode Ranking
Loss of power supply from the SEM Unit	F1	288	1
Severe leakage on the LP Shuttle valve	F9	252	2
Severe leakage from HP DCV	F5	144	3
Loss of HP Accumulation	F7	144	3
Total Loss of signal from the SEM module	F3	140	5
SCM housing check valve cracks open at lower pressure	F2	112	6
Severe leakage from LP DCV	F8	96	7
Shuttle valve fails to change over to the next LP supply line	F14	96	7
Loss of LP accumulation	F11	84	9
Loss of HP hydraulic filtration	F6	72	10
Shuttle valve fails to change over to the next HP supply line	F12	72	10
Severe leakage on the HP shuttle valve	F10	70	12
Loss of LP hydraulic filtration	F4	63	13
Severe leak in the LP common hydraulic header	F13	56	14
HP DCV shuts spuriously from the open position	F19	56	14
Loss of electronic monitoring of the HP supply pressure	F26	54	16
LP DCV fails to shut on demand from the open position	F21	48	17
LP selector valve fails to open	F15	48	17
Loss of SCM pressure compensation	F16	42	19
LP DCV shuts spuriously from the open position	F24	42	19
LP DCV fails to open on command	F18	42	19
Loss of electronic monitoring of the LP return flow	F27	42	19
HP DCV fails to open on command	F17	36	23
Loss of monitoring signal from the water ingress sensor	F22	30	24
HP DCV fails to shut on demand from the open position	F20	28	25
Loss of electronic monitoring of the HP return flow	F28	27	26
LP selector valve spuriously closes	F23	24	27
Loss of electronic monitoring of the LP supply pressure	F25	24	27
Loss of the SCM internal pressure monitoring	F29	18	29
Loss of the SCM internal temperature monitoring	F30	16	30

Leakages in LP and HP DCVs make up 33.33% of the top 20% failure modes in the evaluation. This is logical as DCV have been known to be a major contributor to frequent failures in the SCM system (Broadbent 2010, OREDA 2009) (see figure 51).

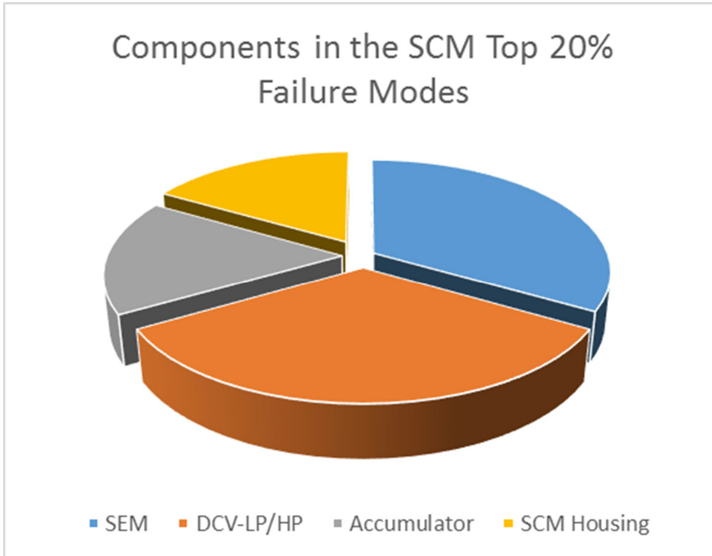


Figure 51 Components in the SCM top 20% most critical failure modes

Due to the gaps and limitations of the classical RPN evaluation as mentioned in section 3.6, a multi-criterion technique based on the fuzzy TOPSIS methodology was then used for further evaluation of the SCM failure modes, causes and effects. The results are shown in chapter 4.

3.6 Gaps/Limitations of FMEA/FMECA application

A key challenge in conducting an FMEA study is ensuring that the failure mechanisms are identified. The scope of the study has to be clearly defined in order to determine the level of detail to be covered in the exercise.

FMEA is best conducted in a group session, much like a HAZOP session. A group session will improve the identification of possible failure modes in the technology covered; it is however important that the right competence is made available including personnel with background and knowledge in several technological disciplines (Bradnt 2003). In Fougere (2006), we see that though FMEA has been the primary reliability tool for dynamic positioning systems, these vessels are known to experienced faults which were either not captured in the FMEA or were more severe than indicated by the FMEA. Key gaps identified by Fougere (2006) in conducting FMEA are as follows:

- Poor scoping leads to ineffective FMEA
- Normally requires specialists with in-depth knowledge of the system under examination.
- Multi-discipline team might be required for large and complex systems.

Scope is very important in conducting an FMEA as it defines the boundary around the system to be analysed. This is typically carried out by the team members involved in the evaluation. If not carefully performed, key parts of the system may be eliminated. An FMEA is as good as the member of the team and the failures highlighted are normally bordered around the experience of the team involved. If a team member has not experienced an issue, there is a tendency for that to be left out during the exercise. For complex systems, a requirement for a multi-disciplinary team makes the exercise a cumbersome one. Other weaknesses of the FMEA/FMECA according to Bai (2010) are listed below.

- Does not identify the real reason of the failure mode
- Highly a time-consuming task
- Extremely difficult for complex systems.
- High reliance on expert judgment with a probability for inaccuracy

Traditionally FMECA is performed by developing a risk priority number (RPN). RPN helps to compare and prioritize issues for necessary correction. For RPN to be used, the severity (S) of the risk has to be rated, the occurrence (O) rated and the likelihood of detection also known (Xu Bai 2012, Tomaso Ceccarelli 2009) and RPN is a multiplication of these three factors

RPN = Severity (S) x Occurrence (O) x Detection (D) (3.1)

These three factors are evaluated in a scale of 1-10 each. For each failure mode, the values for S, O and D are being evaluated and multiplied to obtain an

RPN number, which is then priotised and ranked. Focus is then given to the high RPN failure modes for the possibility of corrective actions. Though this technique has proven to be a vital and useful tool for preventing failures in system design, process and services, the methodology has been extensively criticised (Sutrisno 2011, Liu 2013, Braglia 2003) in many literatures for the following reasons.

- Lack of consideration to the relative importance of O, S and D
- Different combinations of O, S and D produces equal values with differing implications
- Difficulty in precision on the prediction of the values for O, S and D
- Varying methods for converting the scores of the risk factors
- The RPN is not capable of measuring the effective of the corrective actions
- The values of the RPN are not continuous with many holes
- The interdependencies across the failure modes are not considered.
- The RPN is highly sensitive to variations in the risk factors
- Many duplicate RPN numbers in the evaluations
- The RPN considers just three factors principally on safety terms

An extensive study of FMEA methodologies all aimed at bridging these gaps, according to Hu-Chen Liu 2012, shows that they are grouped into five key categories namely:

- Multi-criteria decision making (MCDM)
- Artificial Intelligence (AI)
- Mathematical programming (MP)
- Hybrid approaches
- Others

Fundamentally, each of these techniques have varying approaches of implementation. Prominent among all these according to the author is the fuzzy approach.

In this research, a multi-criteria decision making methodology called technique of order preference by similarity to ideal solution (TOPSIS) is being implemented for prioritising the associated criticality in subsea control module failure modes. This is principally to overcome the obvious limitations with the conventional FMECA. A fuzzy approach is adopted as it eliminates the intrinsic difficulty of handling crisp values during the conventional FMECA RPN evaluation. Again, considering the vague nature of the three conventional FMECA risk factors – occurrence (O), severity (S) and detectability (D), they are being expanded into ten parameters.

4 A framework for Multi-criteria Risk assessment of SCM with unconventional parameters

In this chapter, a multi-criteria fuzzy TOPSIS analysis of a subsea control module (SCM) failure modes is conducted using unconventional parameters. A set of thirty (30) failure modes produced from a comprehensive failure mode and effect analysis (FMECA) of the system is used in the analysis. At the end of the evaluation, a risk ranking is presented in order to prioritise the risk for each of the failure modes. This innovative risk-based reliability analysis approach serves as a key part of the PhD and a novel contribution to knowledge. The methodology is demonstrated, the worksheets presented and the results explained. Finally, a sensitivity analysis is also performed.

Key objectives of this evaluation are:

- Identify critical components of the SCM responsible for the failure of the SCM
- Perform a comprehensive fuzzy TOPSIS risk analysis of the SCM using unconventional parameters
- Identify the most probable failure mode in the operation of the SCM
- Perform a comparative analysis between results obtained using the conventional FMECA technique and the fuzzy TOPSIS methodology
- Perform a sensitivity analysis of the TOPSIS evaluation accessing the effect of each risk factor on the failure modes ranking
- Identify the criticality of the SCM failure modes by using the fuzzy TOPSIS ranking methodology

4.1 Multi-criteria decision Analysis

Multi-criteria decision analysis (MCDA) sometimes called multi-criteria decision making (MCDM) or multi-attribute decision analysis (MADA) is one of the fastest growing areas in the last decades a popular topic in decision making and refers to the process of making selection from a number of actions in the face of multiple and often conflicting attributes (Virine 2007, Bejari 2010, Jahanshahloo

2006). Computer systems have significantly enhanced the application of MCDM in complex systems and decision analysis. According to Jahashahloo (2006), the primary concerns in discrete decision analysis are listed below:

1. The choosing of the a most preferred alternative
2. The ranking of the alternatives in the order of importance or
3. Screening of the alternatives with the aim of a final decision

MCDM does not necessarily produce an optimised solution of all the objective functions, but introduces an efficient solution other called the Pareto optimal solution (Jahashahloo 2006). This is normally a set of solutions that aid in the choice of final decision. This final choice remains an issue. Below is a concise representation of MCDM problem.

Table 14 A representation of MCDM problem

	C_1	C_1	……………	C_n
A_1	x_{11}	x_{12}	……………	x_{1n}
A_2	x_{21}	x_{12}	……………	x_{1n}
A_m	x_{m1}	x_{m2}	……………	x_{mn}

$$W = [w_1, w_2, \ldots\ldots, w_n], \tag{4.1}$$

Where A_1, A_2, ……….A_m are possible alternatives by which decision makers have to measure performance and choose based on the criterion C_1, C_2, ……C_n . X_{ij} represents the rating of the alternatives A_i based on the criterion C_j while w_j refers to the weight of the criterion C_j. Below are the man steps in MCDM:

- Establish the system evaluation criteria
- Develop alternatives
- Evaluate alternatives based on set criteria
- Apply normative multicriteria analysis method
- Accept and optimal/preferred alternative
- Re-perform an iteration of the with additional information

The weights in MCDM do not have clear significance to the process, though they help in modeling the preference analysis in the classical MCDM analysis. TOPSIS, known as the technique for order performance by similarity to ideal solution gives performance ratings including the weights of the criteria in clear exact values and has been used extensively in the analysis of MCDA issues as exemplified by Kolios (2010), Braglia (2003), Ahmet Can (2012), Jahanshahloo (2006), Anish (2009) , Liu (2013) and Wang (2009). In (Kolios 2010), MCDA is used in the analysis and comparison of support structures for offshore wind turbines. (Braglia 2003 and Ahmet 2012) give practical applications of MCDA for failure modes and effects criticality analysis based on the fuzzy version of the technique for order preference by similarity to ideal solution (TOPSIS). The papers also highlight the limitations associated with the conventional FMECA methodology. In Jahanshahloo 2006 Anish (2009), Liu (2013) and Wang (2009, the MCDA TOPSIS method is used for decision making based on data for feasible alternatives.

In MCDA, the first step is to define the criteria for the analysis (Cheng 2003, Sodhi 2012). For the subsea control module the evaluation matrices includes the hydraulic performance, electrical performance, ultra-deepwater suitability, cost, familiarity with operators & engineers, qualification/proven, complexity…etc.

4.2 MCDM methods and their application in engineering applications

Decision making is one of the most important and popular aspect of application of mathematical methods. MCDM techniques have been used in many performance measurements as they are useful in the identification and evaluation of compatible alternatives (or solutions) in decision support tools. According to Medineckiene (2014), there are five steps in multi-criteria decision making. These are:

1. Identification of the problem
2. Structuring of the issue
3. Model building
4. Use of the model as as assessment tool
5. Development of an action plan.

Jato-Espino (2014) and Liu (2013) enumerate several MCDM methods and their application in the engineering construction industry. The summary is as shown below:

AHP - Analytic hierarchy process structured technique for analysing MCDM problems according to a pairwise comparison scale.

ANP- Analytic network process Generalization of the AHP method which enables the existence of interdependences among criteria.

COPRAS Complex proportional assessment - Stepwise method aimed to rank a set of alternatives according to their significance and utility degree.

DEA - Data envelopment analysis non-parametric system for measuring the efficiency of a set of multiple decision making units.

Delphi Iterative method - designed to obtain the most reliable consensus from a group of experts responding to a series of questionnaires.

DRSA - Dominance-based rough set approach Derivation of rough set theory which allows defining a MCDM problem through a series of inference rules of the type

"if… then".

ELECTRE - Elimination et choix traduisant la realité Group of techniques addressed to outrank a set of alternatives by determining their concordance and discordance indexes.

FSs - Fuzzy sets Extension of the traditional concept of crisp sets which states that the belongingness of an element to a set may vary within the interval [0, 1].

GST-Grey system theory Philosophy of handling data according to the information contained in them, from black (no information) to white (complete information).

GT - Game theory Area of applied mathematics that studies the interaction of formalized structures to make strategic decisions.

HOQ - House of quality House-shaped diagram that transforms user demands into quality design criteria through a relationship matrix and a correlation matrix.

IFSs - Intuitionistic fuzzy sets In addition to the belongingness grade of an element to a set proposed by FSs, IFSs also considers its non-belongingness grade (hesitancy).

MAUT - Multi-attribute utility theory Methodology employed to make decisions by comparing the utility values of a series of attributes in terms of risk and uncertainty.

MAVT - Multi-attribute value theory Compensatory technique that converts the attributes forming a MCDM problem into one single value through the called value functions.

MCS Monte Carlo simulations- Non-deterministic methods used to find approximate solutions to complex problems by experimenting with random numbers.

MEW - Multiplicative exponential weighting Aggregative scoring system in which alternatives are evaluated by the weighted product of their attributes.

MIVES - Modelo integrado de valor para evaluaciones sostenibles: Nested methodology which combines two concepts as MCDA and Value Engineering to synthesize any type of criteria in a value index.

PROMETHEE- Preference ranking organization method for enrichment of evaluations. Family of outranking methods based on the selection of a preference function for each criterion forming a MCDM problem.

SAW - Simple additive weighting Technique aimed to determine a weighted score for each alternative by adding the contributions of each attribute multiplied by their weights.

SIR - Superiority and inferiority raking Method that uses six generalized criteria to establish the preferences of a decision maker by determining the superiority and inferiority flows.

SMAA -Stochastic multi-objective acceptability analysis. Methodology that determines the acceptability index of an alternative as the variety of measurements making it the preferred one.

TOPSIS - Technique for order of preference by similarity to ideal solution. Technique based on the concept that the best alternative to a MCDM problem is that which is closest to its ideal solution.

UT - Utility theory Method for measuring the degree of desirability provided by tangible and/or intangible criteria through their utility functions.

UTA - Utilities additives Methodology that uses linear programming to optimize the use of utility functions to properly reflect the preferences of decision makers.

VIKOR - Visekriterijumska Optimizacija Ikompromisno resenje. Method for determining the compromise ranking - list of a set of alternatives according to the measure of closeness to the ideal solution.

Jato-Espino (2014) clearly reveals the TOPSIS as one of the most popular multi-criteria techniques with a very wide application. TOPSIS is seen in both isolated application and in hybrid use with other techniques such as AHP, FSs, IFS, GST, ANP and VIKOR. The TOPSIS method is easy to compute and algorithmically structured, which considerably automates its implementation procedure. Similarly, the VIKOR method searches for the closest solution to the overall ideal, but unlike TOPSIS, its normalization process is made linearly, instead of vectorially. In any case, the greater difference resides in their diffusion grade; VIKOR's spread is far from that of TOPSIS, presumably because the first became known to the public several years after the second.

4.3 TOPSIS method, theory, advantages and limitations

TOPSIS is a multi-criteria decision making linear weighing technique initially proposed by Hwang (1981). TOPSIS starts with creating a decision matrix:

$$\mathrm{X} = [\, \mathrm{x_{ij}} \,] \qquad (4.2)$$

Where the i^{th}alternative (*i* = 1, 2........,*n*) is evaluated with respect to j^{th} criteria (*j* = 1, 2........,*m*). The next step is the normalisation of the judgement matrix $\mathrm{X} = [\, \mathrm{x_{ij}} \,]$. Many approaches are used for this. From Deng at al 2000, to transform each element $[\, \mathrm{x_{ij}} \,]$, the equation below is used:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \qquad i = 1, 2, \ldots, n \qquad (4.3)$$

Next to this is the weight computation for each of the comparison criterion. This is done by first evaluating the entropy e_j of each criterion C_1, C_2, ..., C_n

Let e_j represent the entropy of the j^{th} criterion.

$$e_j = \frac{1}{\ln n} \sum_{i=1}^{n} r_{ij} \ln r_{ij} \qquad \text{j = 1,2..........m} \qquad (4.4)$$

Here, 1/ln m is a constant term and keeps the value of e_j among 0 and 1.

The weights of each criterion given by:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \qquad (4.5)$$

The positive and negative ideal solution is then determined. This gives the performance indicator for each of the criterion of comparison.

$$v^+ = (\underset{i}{max}(r_{i1}), \underset{i}{max}(r_{i2}), \dots\dots\dots \underset{i}{max}(r_{in})) \qquad (4.6)$$

$$v^+ = (v_1^+, v_2^+, \dots\dots\dots\dots\dots\dots\dots v_n^+) \qquad (4.7)$$

and

$$v^- = (\underset{i}{max}(r_{i1}), \underset{i}{max}(r_{i2}), \dots\dots\dots \underset{i}{max}(r_{in})) \qquad (4.8)$$

$$v^- = (v_1^-, v_2^-, \dots\dots\dots\dots\dots\dots\dots v_n^-) \qquad (4.9)$$

The distance of the criterion between the positive ideal and negative solutions is then computed. The following equation is used in the calculation of the Euclidean distance of each alternative to v_1^+ and v_1^-:

$$d_i^+ = \sqrt{\sum_{j=1}^{m} w_j (v_j^+ - r_{ij})^2} \qquad (4.10)$$

$$d_i^- = \sqrt{\sum_{j=1}^{m} w_j (r_{ij} - v_j^-)^2} \qquad (4.11)$$

The d_i^+gives the distance of the i^{th}criterion relative to the positive ideal solution while d_i^- represents the distance of the i^{th}criterion measured from the negative ideal solution. Finally, the preference order is then ranked.

In principle, TOPSIS method is performed in such a way that the alternative chosen would have the "shortest distance" from the positive ideal solution and the longest distance from the negative ideal solution. Though a very popular technique, some limitations of the method exists. These are listed below:

1. It uses the Euclidean distance algorithm in principle, but the algorithm doesn't consider the correlation of attributes.
2. The weight coefficients are fixed using an expert method or AHP, which all have some elements of subjectivity

4.4 The Fuzzy Concept to FMECA

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise (Mesut Kumru 2013). The variables in a fuzzy logic have membership values between 0 and 1. Here the degree of truth is not constraint to the truth values of (1) and (0) but can range in values of anything between 0 and 1. Hence, it provides a basis for approximate reasoning giving values that is not exact or say very exact. It offers a relatively more realistic framework or human reasoning rather than the traditional two-valued logic. Below is steps for the fuzzy logic algorithm:

- Definition of linguistic variable and terms
- Construction of membership function (MF)
- Construction of the rule base
- Fuzzification – Conversion of crisp values into their fuzzy values using MF
- Evaluation of the rules in the rule base
- Combination of the results in each rule base
- De-fussification – conversion of the fussified values into crisp values

Linguistic variables are basically inputs or output variables of systems whose values are words or sentences instead of numerical values. Generally, it is usually decomposed into a set of linguistic terms (Wang 2009, Chen 2000). Membership functions in fuzzy logic systems (FLS) are used in the fuzzification and de-fuzzification in mapping non-fuzzy values to fuzzy linguistic terms and vice versa. It basically quantifies the value of a linguistic term. Different forms of membership functions exists – trapezoidal, piecewise linear, triangular, Gaussian or singleton (Chen 2000, Wang 2009).

The triangular membership function is the most popular among all (Ahmet Can 2012) and is represented with three points as A = (a_1, a_2, a_3), see figure 52. The membership function $\mu_A(x)$ can be represented as follows:

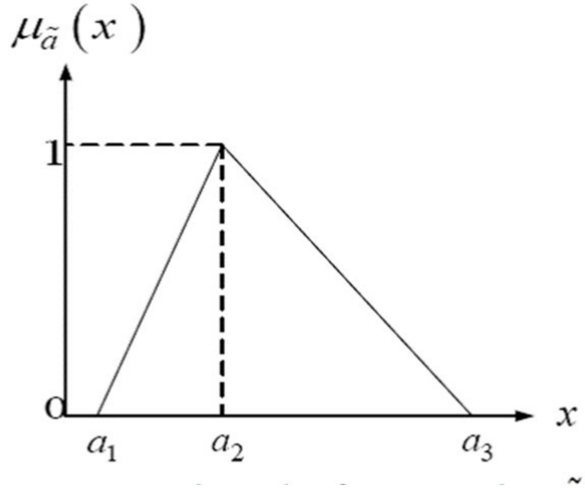


Figure 52 The triangular fuzzy

Key merits of using the triangular fuzzy numbering are as follow (Braglia 2003):

- Its relatively less complex in handling
- It provides an easier and better raking result
- It more effective in representing the judgement distribution of multiple experts

Let X be a nonempty set. A fuzzy set A in X is characterised by its membership function $\mu_A: X \rightarrow [0,1]$ and $\mu_A(x)$ expresses the degree of membership of element x in fuzzy set A for each $x \in X$.

$$\mu_A(x) = \begin{cases} \frac{x-a_1}{a_2-a_1} \quad if\ a_1 \leq x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}\ if\ a_2 \leq x \leq a_3 \\ 0\ \ if\ x < a_1\ or\ x > a_3 \end{cases} \tag{4.12}$$

Where a_1, a_2, a_3 are real numbers. Assuming that A and B are defined as

$$A = (a_1, a_2, a_3) \text{ and } B = (b_1, b_2, b_3).$$

Then the addition of these variables, C will be represented as

$$C = (a_1 + b_1, a_2 + b_2, a_3 + b_3),$$

The subtraction D as

$$D = (a_1 - b_1, a_2 - b_2, a_3 - b_3),$$

And the multiplication

$$E = (a_1.b_1, a_2.b_2, a_3.b_3).$$

Fuzzy FMECA allows the use of quantitative data and qualitative linguistic information to be analysed in a consistent way making it possible for the risk factors – severity, occurrence and detectability to be combined in a more flexible structure. However, Braglia (2000) and Braglia 2003 argue that ranking and priotising failure modes with the fuzzy if-then rules was faulty as the relative importance of the risk factors is not captured in the analysis. The author developed a geometric methodology for bridging this gap using linear programming. In Braglia et al 2003, a fuzzy TOPSIS methodology is developed which allows for the relative evaluation of the conventional FMECA risk factors (O, D and S) capturing the importance of their weights using the triangular fuzzy numbers. The fuzzy TOPSIS methodology is explained in the following sections.

4.5 The Fuzzy TOPSIS methodology

The fuzzy multi-criteria decision methodology is a preferred approach for bridging the gaps and limitations in the conventional FMEA approaches (Ahmet 2012, Liu 2013). Sodhi 2012 confirms that the fuzzy TOPSIS method is an objective, systematic and efficient strategy of evaluating alternatives on multiple criteria analysis based on a selected set of criteria. In the fuzzy TOPSIS analysis, the alternative closest to the fuzzy positive ideal solution (FPIS) and farthest from the fuzzy negative ideal solution (FNIS) is selected as the optimal alternative. FPIS is indicative of a higher performance compared to that of the FNIS, which is being attributed to a worse performance. According to Lee (2013), the use of FUZZY TOPSIS has the following advantages:

- A sound logic that represents the rationale of human choice;
- A scalar value that accounts for both the best and worst alternatives simultaneously
- A simple computation process that can be easily programmable.
- the performance measures for all alternatives can be visualised

In Summary, there is no fool-proof map of how to manage risks in deepwater completion projects (Tomaso 2009). The FMEA is a qualitative analysis outlines all the possible failures that may be encountered during equipment's operational lifecycle. It is implemented early during the system's design phase and often the first step in the evaluation of subsea systems reliability. During the exercise, as many components, sub-assemblies, assemblies, sub-systems and systems as possible is being reviewed with the purpose of identifying failure modes, causes and their respective effects. Though often finalized during the detailed engineering stage of a project, the list of the failure modes is often not exhaustive as more failure modes could be generated during the equipment lifecycle.

It is therefore recommended that instead of finalizing the FMEA/FMECA documentation at the detailed design stage, documentations indicating an FMEA/FMECA conducted before and after the detailed design stage should be maintained for future referencing for system maintenance and design improvements of future projects. For a subsea control module (SCM), the FMECA serves a particularly useful tool for generating all possible failures that could be encountered by the system. For this report, the fuzzy TOPSIS FMEA method is being proposed. Figure 53 gives a general overview on the fuzzy TOPSIS methodology:

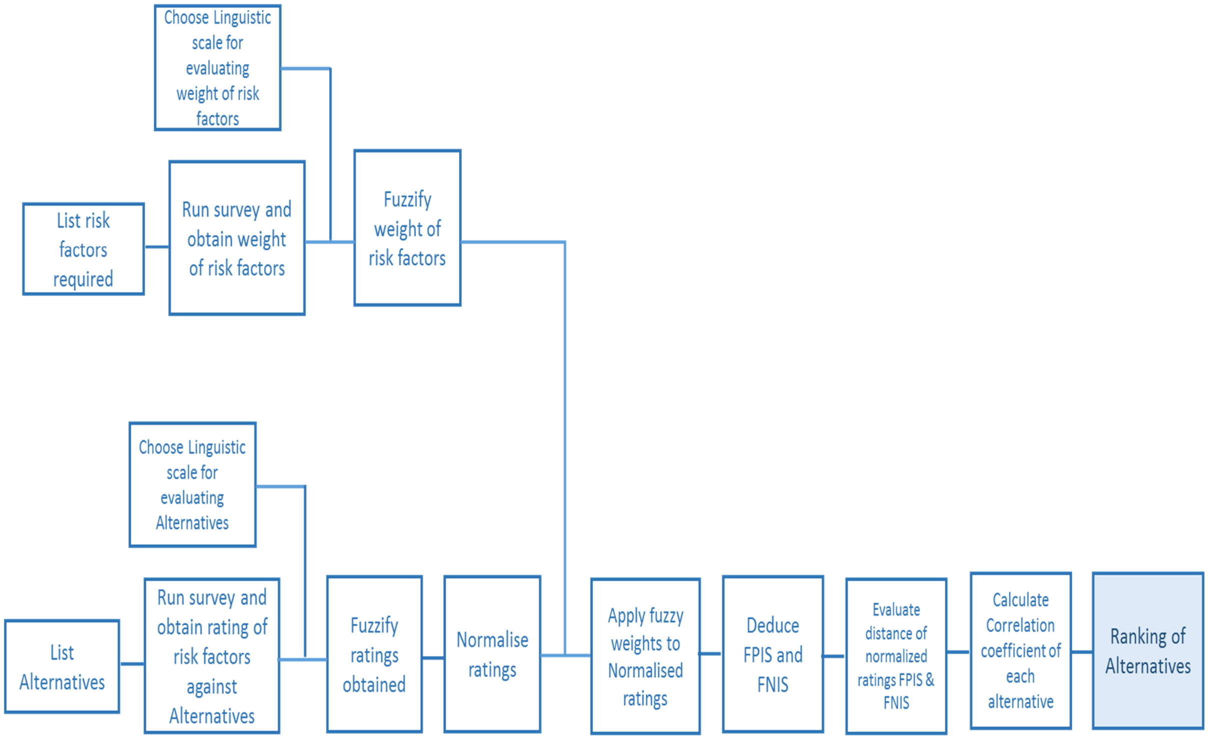


Figure 53 Fuzzy TOPSIS Methodology

In fuzzy TOPSIS application, the importance (weight) of each evaluation criterion is expressed in linguistic terms as shown in table 15 (Chen 2000, Braglia 2000).

Table 15 Linguistic scale for importance weight of each criterion (R_i)

Linguistic variable	Corresponding triangular fuzzy number (TFN)		
Very Low (VL)	0.0	0.0	0.1
Low (L)	0.0	0.1	0.3
Medium (M)	0.3	0.5	0.7
High (H)	0.7	0.9	1.0
Very High (VH)	0.9	1.0	1.0

Similarly, the linguistic scale for evaluating the SCM failure modes to the corresponding risk factors is depicted in table 16 (Chen 2000, Braglia 2000).

Table 16 Linguistic scale for rating the SCM failure modes against the risk factors

Linguistic variable	Fuzzy Score		
Very Low (VL)	0	0	1
Low (L)	0	1	3
Medium Low (ML)	1	3	5
Medium (M)	3	5	7
Medium High (MH)	5	7	9
High (H)	7	9	10
Very High (VH)	9	10	10

Consider that we have K number of experts or decision makers making use of the linguistic variables shown in table 15 and 16 to evaluate the weight of each criterion and the rating of these criterions to the corresponding alternatives, the fuzzy rating and importance weight of a k_{th} decision maker about an i_{th} alternatives based on j_{th} criterion are:

$$x_{ij}^{k} = (a_{ij}^{k}, b_{ij}^{k}, c_{ij}^{k},) \text{ and } w_{j1}^{k}, w_{j2}^{k}, w_{j3}^{k}) \text{ respectively} \qquad (4.13)$$

where *i=1,2,…,m, and j=1,2,…,n.* Then the aggregated rating, x_{ij} of the alternatives (*i)* in correspondence to the respective criterion (*j*) is given by: $x_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where:

$$a_{ij} = \min_{k}\{a_{ij}^{k}\},\ b_{ij} = \frac{1}{K}\sum_{ij}^{k} b_{ij}^{k}, \text{ and } c_{ij} = \max_{k}\{c_{ij}^{k}\}, \qquad (4.14)$$

Similarly, the aggregated weights w_{ij} of each criterion is $w_{ij} = (w_{j1}, w_{j2}, w_{j3})$, where

$$w_{j1} = \min_{k}\{w_{jk1}\},\ w_{j2} = \frac{1}{K}\sum w_{jk2},\ \text{, and } w_{j3} = \max_{k}\{w_{jk3}\} \tag{4.15}$$

Accordingly, a fuzzy decision matrix of the alternatives can then be represented in the format below:

$$D = \begin{matrix} & c_1 \quad c_2 \dots\dots c_n \\ \begin{matrix} A_1 \\ A_2 \\ \\ A_m \end{matrix} & \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & x_{ij} & \cdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{pmatrix} \end{matrix}$$

$W = w_1, w_{2,\dots\dots\dots}w_n$ denoting the weight of the criterion.

Here x_{ij} are built by failure modes $A_i(i = 1, \dots\dots m)$, which are evaluated against criterion $C_j = 1, \dots\dots\dots n)$. To avoid complication, a linear scale transformation is used for the normalisation process of the criteria scale. The fuzzy normalised decision matrix,

$$\widetilde{\mathbf{R}} = [\tilde{r}_{ij}]_{mn} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{11} & \dots & r_{11} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & & r_{mn} \end{bmatrix} \tag{4.16}$$

Where *i=1, 2, …m, j=1,2….,n.* The normalised values for benefit and cost related criteria are as shown below:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \text{and } c_j^* = \max_i c_{ij}; (j \in B, benefit\ criteria) \tag{4.17}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{c_{ij}}\right), \text{and } a_j^- = \min_i a_{ij}; (j \in C, cost\ criteria) \tag{4.18}$$

The normalisation process here preserves and maintains the triangular fuzzy numbers within the range [0, 1]. Considering the weight of each criterion, the weighted normalised fuzzy matrix is computed as:

$$\tilde{V} = [v_{ij}]_{mn},\ i=1, 2 \dots m; j=1,2 \dots n \tag{4.19}$$

Where $v_{ij} = \tilde{r}_{ij}(.)\tilde{w}_j$

The fuzzy positive ideal solution (FPIS) and fuzzy ideal negative solution (FNIS) of the failure modes (A*i)* are then defined as follows:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots \dots, \tilde{v}_n^*) \qquad (4.20)$$

$$where, v_j^* = \max_i \{v_{ij3}\}, \; i = 1,2, \dots \dots, m; j = 1,2, \dots \dots \dots, n$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots \dots, \tilde{v}_n^-) \qquad (4.21)$$

$$where, v_j^- = \min_i \{v_{ij1}\}, \; i = 1,2, \dots \dots, m; j = 1,2, \dots \dots \dots, n$$

The distances (d_i^* and d_i^-) of the failure modes (A*i, i=1,2….m), from the FPIS (A*) and FNIS (A-*) respectively is computed as follows:

$$d_i^* = \sum_{j=1}^{n} d_v \left(\tilde{v}_{ij}, \tilde{v}_j^*\right), i = 1,2, \dots, m. \qquad (4.22)$$

$$d_i^- = \sum_{j=1}^{n} d_v \left(\tilde{v}_{ij}, \tilde{v}_j^-\right), i = 1,2, \dots, m \qquad (4.23)$$

Where $d_v(\tilde{a}, \tilde{b})$ denotes the Euclidean distance between two fuzzy numbers $\tilde{a}$ and $\tilde{b}$.

The closeness coefficient CC_i is then calculated to determine the ranking of each alternative (A*i, i=1,2,…..m).* The closeness coefficient,

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}, where \; i = 1,2, \dots \dots \dots \dots m. \qquad (4.24)$$

With respect to the SCM failure modes evaluation using the fuzzy TOPSIS methodology, the failure mode with the highest closeness coefficient CC_i represents the concept with the highest risk and is closest to the FPIS and farthest from the FNIS. The sheer implication of this is that the component with this failure mode would require a closer attention and focus for subsea control module (SCM) design evaluation, close attention during manufacturing and would demand a good attention during installation and operations.

4.5.1 The Survey and Data gathering

Risk analysis requires a lot of data for the system under examination. Obtaining a representative set of data for the system or component is a very challenging task. In offshore oil and gas, this is complicated due to the move into deep and ultra-deepwaters with the application of new and often unproven technologies application in the environment.

Common sources for obtaining data are:

- Industry data banks (OREDA, Wellmaster, WOAD, E&P Forum)
- Vendor Data
- Expert judgements
- Synthesized Data
- Combination of the above methods

Industry data represents data obtained from operators, OEMs and similar companies typically from a defined joint industry project and are often limited to the experience and environment for which they were obtained.

Prominent in the offshore industry is the OREDA database. The OREDA Joint Industry Project (JIP) consists ten (10) major oil companies and acts as the hub for managing and coordinating reliability data collection. The OREDA subsea software covers subsea equipment such as umbilical, Xmas trees, control systems, template, manifolds, and subsea pumps, including critical components such as valves, connectors and sensors. More information on OREDA is provided in section 7.2. Use of this data for system evaluation requires a certain level of understanding for proper application. If available and where applicable vendor data could be very useful. Vendor data are typically obtained from an OEM across the equipment life-cycle from design through testing, manufacturing and even decommissioning. They are often combined along with expert judgment when required. Expert judgments are very useful for system reliability analysis where historical data is either sparse or totally unavailable.

Synthesised data applies when no explicit historical data is available for a system reliability analysis. Closely related to expert judgement, it is based on a ranking technique which produces a numerical encoding of results about the probability of failure. New technologies and environments typically involve innovative features that cannot be addressed by the existing scenario or normative standards. This is particularly peculiar in the subsea industry as developments shift into deeper waters and harsher unpredictable environments. Expert opinion plays a key role in evaluating the risk and reliability of systems in this terrain. The data used in this analysis were obtained through expert elicitation (EE). To ensure credibility, a systematic process is applied for obtaining and processing of the data. Below are some steps that were taken during the survey in order to ensure a more objective and accurate results:

- Each of the experts were engaged in a structured interview. Twenty five experts were contacted, but ten of them responded. This added to the project cost as the experts were spread across different continents of the world. The approach was adopted in order to add value to the whole research, but was time consuming.
- Experts were interviewed across different operating units and across continents from Europe, Africa through to Americas. This ensured the decisions were not skewed
- The list of experts came from the major oil and gas operators, subsea equipment manufacturers down to the engineering consultancy firms.
- The experts were given an opportunity to revise their assessments before sending in the final results
- During the engagement, the experts were asked to state the rationale behind their evaluations.

The key limitation with the use of data databases is that the information is skewed to the function specification of the system under study including the specific environment being examined. Results may be different with varying system specification, usage and environmental parameters. For expert judgement, the limitation is that the results obtained is relatively subjective and in congruent with the exposure, knowledge and know-how of the experts involved in the analysis.

A survey was designed for evaluating the weight of the SCM risk factors including the rating of these risk factors to the corresponding failure modes. Ten (10) reputable experts in the offshore subsea industry cutting across Oil and Gas operators, original equipment manufacturers (OEM) to subsea systems industry design consultants were used for the exercise. The survey had two sections. The first section focused on the importance of the risk factors. This is called weight evaluation and represents the significance of the respective risk factors in the SCM system reliability. In the second section, the risk factors were then used in establishing a rating with the respective failure modes.

4.5.1.1 Characterisation of Experts

The SCM survey was conducted using very experienced offshore engineering professionals with proven practice in the subsea industry. Below are brief profiles of the experts that were used for this analysis:

Decision Expert-1:

This expert has over fifteen years of experience in the offshore subsea industry. He has worked across the entire system lifecycle from field concept evaluation studies, concept selection, concept definition down to equipment construction, installation, pre-commissioning and commissioning. The expert is specialised in subsea controls and currently works for an operator group. He has been involved in several subsea failure and root cause analysis for field controls failure.

Decision Expert-2:

Decision expert is a subsea controls expert working for a top subsea equipment original equipment manufacturer. He has been involved for over ten years in the manufacturing, testing, installation and retrieval of subsea control module.

Expert currently works for a controls equipment manufacturer in the United Kingdom.

Decision Expert-3:

This is a subsea controls reliability expert currently working for a subsea engineering organization as a controls expert. With about twenty years' experience in the oil and gas industry, the expert has worked for several years as a client representative on subsea engineering controls projects. His experience span delivery in the North-Sea and the West African waters.

Decision Expert-4:

Expert works for an operator as a subsea site representative on subsea hardware covering subsea control module, subsea distribution units (SDUs), Umbilical termination units (UTAs) including Electrical and hydraulic flying leads. He has about ten years' experience in the subsea industry. Expert has been involved in extensive subsea equipment testing in manufacturing yards cutting across, Norway, Houston, United Kingdom and several other locations in the world.

Decision Expert-5

Decision expert 5 works for a major international IOC in West Africa. Expert also has a practical subsea equipment manufacturing experience for several years working as a project engineer responsible for the delivery of subsea controls equipment. Expert has a huge experience in subsea tree systems from vertical right through to the horizontal enhanced deepwater tree systems.

Decision Expert-6

This specialist expert works with subsea equipment manufacturer and has twenty years' experience of subsea equipment's manufacturing, testing including offshore installations in shallow, deep and ultra-Deepwater. Expert is also a specialist in hydraulic systems with several years of hydraulic systems design engineer.

Decision Expert-7

Decision Expert with a top oil and gas operator. He has worked on several offshore projects with cognate experience in Deepwater controls. Expert has been involves in the operation of several subsea assets in the West-African waters. Expert works as a subsea operations engineer with eight years of experience supporting shallow and deepwater subsea operations.

Decision Expert-8

Expert works for an operator group as a Senior Subsea Engineer responsible for delivery of deepwater projects. He is directly responsible for testing of subsea control equipment and the subsea intervention portfolio. He has been involved in several subsea systems qualification from tree systems to the tie-ins. Expert has been involved in systems failure analysis for subsea systems.

Decision Expert-9

Decision expert here is a controls technician with a top equipment manufacturer that has been involved in the manufacturing, testing, running and retrieval of subsea control modules for over twenty years. Technician has experience across three of the four major subsea equipment manufacturing companies. His experience spans the North sea and the West-african waters. Expert also has experience working as a systems reliability engineer in a consulting portfolio.

Decision Expert-10

This expert is a consultant in subsea controls technology with twenty five (25) years of experience. Trusted with several years of practical experience on subsea production systems. His experience cuts across Gulf of Mexico, North-sea and the West African waters.

4.5.2 The Risk Factors – Expanding conventional factors

A lot of risk factors affect the reliability of the subsea control module (SCM) operation. This ranges from the subsea field architecture, tie-back distance, water depth, safety requirements and other environmental requirements.

Conventionally, three parameters have been used for the failure modes effect criticality analysis (FMECA) and the criticality ranking of the failure modes. These are occurrence (O), Severity (S) and detectability. These three factors do not present the true picture of the associated risks in the system. For this reason, they have been broken down into more appreciable units for better comprehension. Figure 54, shows the breakdown of the conventional risk factors into ten risk factors.

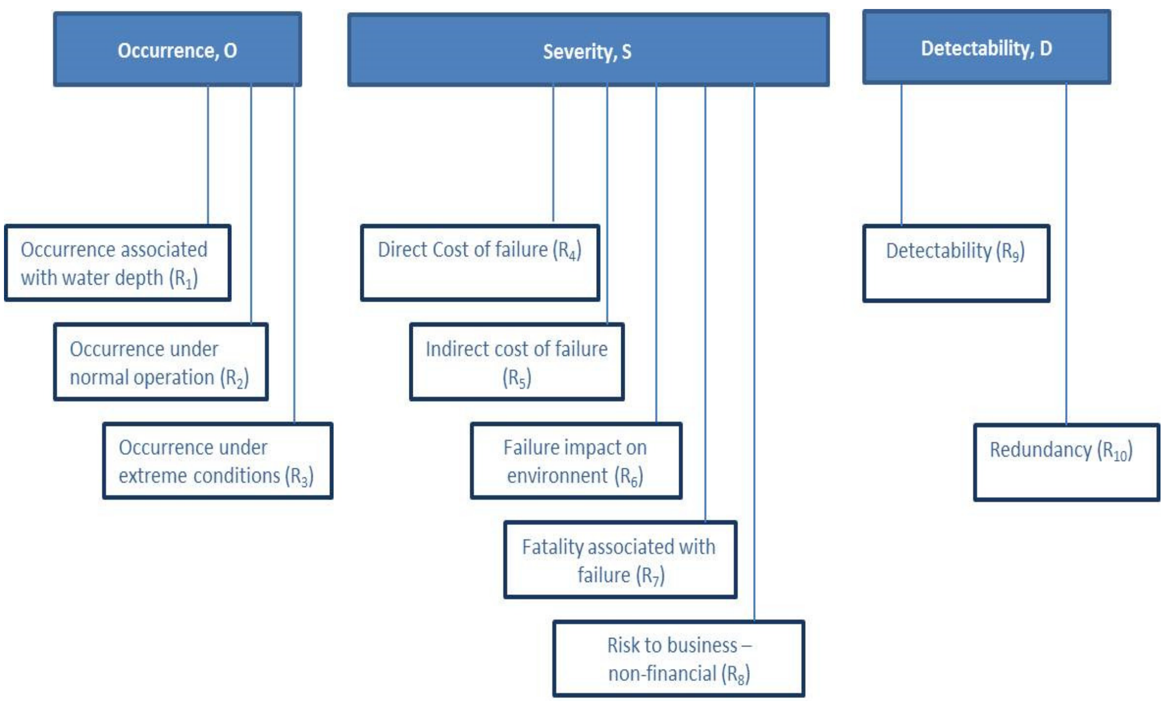


Figure 54 Breakdown of the conventional FMECA risk factors

Occurrence here, presents the probability of the respective failure modes to occur. It, however, does not in any way define the environment or functional boundary for which the probability is being predicted. This makes the value a bit vague and unrepresentative of the true setting for the evaluation of the failure probability. In order to make this more explicit and paint the picture of the true scenario, the occurrence parameter as a risk has been split into three different factors namely:

- Occurrence associated with water depth (R_1)
- Occurrence under normal operation (R_2)
- Occurrence under extreme conditions (R_3)

R_1 here represents the risk of failures in relation to increase in water depth. In the ocean environment, every 10m increase in water depth represents a proportional hydrostatic pressure increase of 1bar with attendant effect on subsea systems. The change in pressure, temperature, salinity and other depth-varying sea parameters constitute potential sources of failure to the SCM. The R_1 evaluates these in correspondence to each of the failure modes.

R_2 evaluates the probability of the system failure under a defined set of functional design parameters. SCMs designed within a known operational boundary are still known to fail even with correctly defined functional parameters. This parameter is used in rating such failures.

Sometimes the SCM is found operate in unpredictable conditions that are outside their standard design specifications like higher pressure ratings, temperature range, salinity…etc. The R_3 factor evaluates the probability of failure occurring if the system is operated outside its defined design specification. For example, what is the probability that an SCM designed to operate with a maximum LP working pressure of 3000psi will fail if the actual flow pressure in the LP circuitry increases to 4500psi.

In the same way as occurrence, the severity parameter in FMECA analysis is an assessment of the seriousness of a failure mode on the user or customer if the corresponding failure occurs. The parameter is a bit vague as it does give in quantitative terms the value of the severity in terms of cost, impact to the environment or associated personnel. In this evaluation, the parameter is split into the following risk factors:

- Direct Cost of failure (R_4)
- Indirect cost of failure (R_5)
- Failure impact on environnent (R_6)
- Fatality associated with failure (R_7)
- Risk to business – non-financial (R_8)

SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright replacement. The R_4 risk factor rates the failure modes in terms of the market cost of the corresponding component that failed. This factor is attributed to the direct cost associated with repair or outright replacement of the faulty component (e.g. cost of SCM filter, cost of LP sensor, unit cost of DCV…etc.

Indirect cost of failure (R_5) evaluates the level of secondary cost associated with restoring the component function back to service. A typical failure in the offshore environment requires the hiring of a maintenance vessel in order to have access to the component or system for repair or replacement. These vessels come at very high and prohibitive values. The SCM under evaluation is electro-hydraulic with the application of electrical as well as hydraulic power for control. Principally, two types of hydraulic fluids are in use – water-based and oil-based. These all come at their respective level of contamination if discharged to sea during operation whether by design or by accident. The R_6 factor evaluates the impact of each of the failure modes to the offshore environment. This measure considers parameters like discharge to sea and failure impact on aquatic life.

R_7 assesses the severity of the failure modes in terms on the number of lives that may be lost as a result of such a failure mode. For SCMs that operate in deep and ultra-deep waters, this would be unlikely as the operation is typically performed using the remote operated vehicle (ROV). However, this may not be completely ruled out in shallow waters where divers are sometimes used. Loss of live may occur from failures associated with the high pressure systems and even with failures associated with the power units.

Not all effects associated with failures could actually be quantified in terms of cost, impact to environment or fatality. Some failures may have effect in the business on a global perspective. This value is being assessed using R_8 - Risk to business – non-financial. For example, a failure in the HP circuitry that leads to a shutdown of the well means a reduction in production to the offshore field operator. Due to the huge risks involved, most oil and gas fields are run in a joint venture (JV) arrangement with other firms and sometimes even the government of the country of operation. Incessant shutdown of a well (s) due to the failure of the surface controlled subsurface safety valve (SCSSV), for example, may lead to a poor reputation of the firm in the face of its partners because of the associated loss in production. In the same way, frequent contamination of seawater due to failure of the SCM might lead to litigation with the environmental agencies and other regulation authorities. Cumulatively, the company may lose public respect, business partnership and may be disallowed into subsequent biddings for new oil blocks in the country of operation.

Other risk factors used in this evaluation are:

- Detectability (R_9) **and**
- Redundancy (R_{10})

These factors are principally safeguards, which are introduced into the system to enhance system availability. The R_9 factor evaluates the ease for which a failure mode occurrence could be detected. Sensors are the primary means of failure detection in subsea systems. They provide process data and parameters for assessing the condition of the equipment. Examples of sensors in the subsea environment are combined pressure and temperature sensors, flow sensors, level sensors, pressure sensors, sand detectors/fluid cleanliness, temperature sensor, valve position sensor...etc. Not all failure modes could be detected using sensors. This factor evaluates the risk involved in the inability to detect the respective failure mode.

Due to the huge risk associated with failure of systems in the subsea environment, most systems are operated in redundancy. Though, not a direct function of detectability, redundancy also helps to detect if a subsystem or component is operational or faulty. The R_{10} factor assesses the risk associated with the requirement and loss of redundancy in relation to the corresponding failure mode. For example, in a typical SCM, there are two subsea electronic modules (SEMs) operated in redundancy. If one fails, the system switches to the next for continued operations. Loss of this redundant SEM means a loss of power to all the LP and DCVs and a total loss of communications from the downhole well system as well as a loss in signal to the topside operator. The impact here is severe as it leads to a total shutdown of the well and required a support vessel for the retrieval of the SCM in order to fix the failure.

The R_9 and R_{10} risk factors bother on the system safeguards to failure. Redundancy prevents a complete failure of the entire system due to the failure of a component or subsystem. Detectability allows for quick and easy detection of potent failure in the system allowing for time for mitigation measures to be taken.

In summary, the risk factors being considered in the evaluation are listed below:

Table 17 Risk Factors - Expanded conventional risk factors

Risk ID	The risk Factors
R_1	Occurrence associated with water depth
R_2	Occurrence under normal operation
R_3	Occurrence under extreme conditions
R_4	Direct Cost of failure
R_5	Indirect cost of failure
R_6	Failure impact on environment
R_7	Fatality associated with failure
R_8	Risk to business – non-financial
R_9	Detectability

R_{10}	Redundancy

4.5.3 The SCM failure modes under Evaluation

The failure modes (*FM*ᵢ) under consideration are the thirty (30) drawn from a comprehensive evaluation of SCM failure modes considering each of the key components and subsystems in the subsea control module and the corresponding possible causes of their failures.

- Loss of power supply from the SEM Unit (F_1)
- SCM housing check valve cracks open at lower pressure (F_2)
- Total Loss of signal from the SEM module (F_3)
- Loss of LP hydraulic filtration (F_4)
- Severe leakage from HP DCV (F_5)
- Loss of HP hydraulic filtration (F_6)
- Loss of HP Accumulation (F_7)
- Severe leakage from LP DCV (F_8)
- Severe leakage on the LP Shuttle valve (F_9)
- Severe leakage on the HP shuttle valve (F_{10})
- Loss of LP accumulation (F_{11})
- Shuttle valve fails to change over to the next HP supply line (F_{12})
- Severe leak in the LP common hydraulic header (F_{13})
- Shuttle valve fails to change over to the next LP supply line (F_{14})
- LP selector valve fails to open (F_{15})
- Loss of SCM pressure compensation (F_{16})
- HP DCV fails to open on command (F_{17})
- LP DCV fails to open on command (F_{18})
- HP DCV shuts spuriously from the open position (F_{19})
- HP DCV fails to shut on demand from the open position (F_{20})
- LP DCV fails to shut on demand from the open position (F_{21})
- Loss of monitoring signal from the water ingress sensor (F_{22})
- LP selector valve spuriously closes (F_{23})
- LP DCV shuts spuriously from the open position (F_{24})

- Loss of electronic monitoring of the LP supply pressure (F_{25})
- Loss of electronic monitoring of the HP supply pressure (F_{26})
- Loss of electronic monitoring of the LP return flow (F_{27})
- Loss of electronic monitoring of the HP return flow (F_{28})
- Loss of the SCM internal pressure monitoring (F_{29})
- Loss of the SCM internal temperature monitoring (F_{30})

The SEM is responsible for the supply of power to the various components of the SCM. A loss of power from the SEM unit (F_1) means a total failure of the system. The SCM is equipped with a check valve, principally responsible for preventing seawater ingress into the SCM and as safety release of overpressure in the SCM chamber. Failure of this (F_2) leads to a water ingress into the SCM. The SEM also coordinates all condition monitoring signals in the SCM and downhole instrumentations relaying same to the topside units. Loss of this (F_3), leads to total loss of subsea control. Clean fluid is quite key in the delivery of subsea controls. A loss of filtration (F_4 and F_6) leads to blockage in the control tubings and loss of controls. Leakage of DCVs in the SCM (F_5, $F_{8,}$ $F_{9,}$ $F_{10,}$ and F13) leads to loss of hydraulic power in the SCM. This is particularly important in the electro-hydraulic (EH) SCM where the valves are hydraulically powered. A loss in in accumulation (F_7 and F_{11}) occurs as a result of the inability of the subsea accumulator in the SCM to hold hydraulic power. This failure mode leads to the entire system shutdown and loss of production. Sometimes, spurious signals trigger the shutdown of SCM valves F_{19} and F_{24}). This failure mode could lead to a loss in production. The failure of either an LP or HP shuttle valve to change over from its initial position is critical to SCM operations. This is because the valve is mostly implemented as a single unit, so this failure mode (F_{12} and F_{14}) leads to a loss total loss in hydraulic control for either LP or HP. Valves sometimes get stuck to their last position of operation either in the open, close or midway for several reasons ranging from loss in power, wears and tear, debris, unclean fluids and other mechanical failures. These failure modes ($F_{15,}$ $F_{17,}$ $F_{18,}$ and F20) lead to loss in hydraulic control of the valve under operation. Condition monitoring data from the SCM is very key to the evaluation and control of subsea systems. Loss of these signals lead to loss in critical information and control of the SCM. The consequence is sometimes as high as a total loss in production as the system may shutdown with a clear reason of known logic. Failure modes associated with this are F_{25}, F_{26}, F_{27}, F_{28}, F_{29}, and F30.

4.5.4 The SCM Fuzzy TOPSIS Evaluation

Ten experts, D_1 to D_{10}, from the subsea industry used the weighing variables shown in table 15 to assess the importance of the risk factors (see section 4.3.1.1 above). The rating of these risk factors against the failure modes was also evaluated by each of them. The evaluation is such that, for example, if increase in water depth increases the probability of occurrence of that failure mode, the rating value is expected to have a high value and vice versa. A high value for all the risk factors imply a big risk for the respective failure mode being evaluated.

The experts used the weighing variables shown in table 15 to assess the importance of the risk factors listed in section 4.3.1.1. The results are presented in table 18. Clearly, from the table, the experts believe that increase in water depth is a key factor that would affect the reliability of water depth. Nine of the experts give the risk factor (R1) a VH, with only one ticking an H. The next highest is the indirect cost of failure (R_2) factor. This is not strange because a typical failure in the subsea control module would require hiring an expensive offshore support vessel (OSV) equipped with a remote operated vessel (ROV) for effecting the repair subsea and most times a retrieval, repairs and re-installation of the module. Typical cost for such operations run into millions of dollars. This is further amplified by the cost of deferred production as the well may have to remain shut down for such operations, a huge loss to the operating company.

Table 18 Importance weight of the risk factors.

	Importance weight Evaluation									
	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
Occurrence associated with water depth, R_1	VH	VH	VH	H	VH	VH	VH	VH	VH	VH
Occurrence under normal operation, R_2	VH	H	H	VH	VH	VH	VH	VH	H	H
Occurrence under extreme conditions, R_3	H	H	H	H	M	H	H	H	M	M
Direct Cost of failure, R_4	M	M	M	M	H	H	H	H	H	VH
Indirect cost of failure, R_5	VH	VH	VH	H	VH	VH	VH	VH	H	H
Failure impact on environment, R_6	M	M	H	H	M	M	M	H	H	H
Fatality associated with failure, R_7	L	L	M	L	M	M	L	M	H	M
Risk to business – non-financial, R8	H	H	M	H	M	M	M	M	M	M
Detectability, R_9	VH	H	H	VH	H	M	H	H	VH	VH
Redundancy, R_{10}	H	H	VH	H	VH	VH	VH	H	VH	H

At the bottom of the weight scale are the direct cost of failure factor (R_4) and fatality related with the failure modes (R_7). The direct cost of failure refers to the flat cost of the failed component if an outright replacement is considered without looking at lost production, cost of a repair vessel or any other cost required to fix the failure. This value is normally quite small in comparison to those that would be incurred indirectly as a result of a component failure. The SCM is typically placed thousands of kilometres on a subsea hardware unit and remotely operated through an umbilical system from a topside facility. For deep and ultra-Deepwater operations, divers are not allowed at this depth, hence the chance of fatality (R_7) is virtually eliminated. Again, the tree valves in the production bore controlled by the SCM are usually of fail-safe-close configuration. The means a complete loss of hydraulic control from the SCM to the tree system will lead to a closure of all the valves in the production tubing. Hence, no direct effect on the topside system and personnel. For shallow water intervention, however, divers come in very handy and fatality cannot be totally ruled out.

Next, the experts use the linguistic variables shown in table 16 to evaluate the rating of the risk factors to the corresponding failure modes. Result is shown in Appendic C. The fuzzy Decision matrix and fuzzy weights of the failure modes applying tables 15 and 16 to tables 17 and Appendix C respectively is as shown in table 19. Though experts were accessed across the globe, he results showed a very high level of consistency with very minor deviations in the values provided.

Table 19 Fuzzy decision matrix for the failure modes (F_i) and the respective weights of the risk factors (R_i)

Failure Modes		R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
		W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}
	Failure Mode ID	(0.7, 0.99, 1.0)	(0.7, 0.96, 1.0)	(0.3, 0.78, 1.0)	(0.3, 075, 1.0)	(0.7, 0.97, 1.0)	(0.3, 0.7, 1.0)	(0.0, 3.9, 1.0)	(0.3, 0.6, 1.0)	(0.3, 0.9, 1.0)	(0.7, 0.95, 1.0)
Loss of power supply from the SEM Unit	F_1	(0, 0.8, 3)	(5, 7.8, 10)	(7, 9.9, 10)	(7, 9.4, 10)	(9, 10, 10)	(0, 0.3, 3)	(0, 0.1, 3)	(0, 2.1, 7)	(0, 0.9, 3)	(9, 10, 10)
SCM housing check valve cracks open at lower pressure	F_2	(5, 9.3, 10)	(0, 0.9, 5)	(7, 9.6, 10)	(3, 5.0, 7)	(7, 9.9, 10)	(0, 3, 10)	(0, 0, 1)	(0, 0.7, 7)	(7, 9, 10)	(1, 4.8, 5)
Total Loss of signal from the SEM module	F_3	(0, 1.8, 7)	(1, 5.2, 9)	(7, 9.4, 10)	(7, 9.3, 10)	(9, 10, 10)	(0, 0.7, 7)	(0, 0, 1)	(0, 1.7, 7)	(0, 0.2, 3)	(7, 9.8, 10)
Loss of LP hydraulic filtration	F_4	(0, 0.4, 3)	(0, 0.9, 5)	(7, 9.5, 10)	(, 7.2, 10)	(5, 7.2, 10)	(0, 0.2, 3)	(0, 0, 1)	(0, 2.8, 5)	(7, 9.8, 10)	(7, 9.2, 10)
Severe leakage from HP DCV	F_5	(0, 1.4, 5)	(0, 4.2, 7)	(7, 9.3, 10)	(3, 7.8, 9)	(7, 0.1, 3)	(7, 9.2, 10)	(0, 0.1, 3)	(5, 7 9)	(0, 2.0, 7)	(5, 8.2, 10)
Loss of HP hydraulic filtration	F_6	(0, 0.1, 3)	(0, 2.8, 7)	(5, 8.7, 10)	(0, 1.0, 3)	(7, 9.6, 10)	(0, 1.2,10)	(0, 0.1, 3)	(0, 1.0, 5)	(7, 9.4, 10)	(5, 8.0, 10)
Loss of HP Accumulation	F_7	(3, 5.6, 9)	(0, 0.7, 5)	(5, 8.9, 10)	(3, 6.4, 9)	(5, 7.2, 10)	(0, 0.4, 3)	(0, 0.1, 3)	(1, 3.8, 7)	(0, 2.8, 7)	(5, 7.4, 10)
Severe leakage from LP DCV	F_8	(0, 1.5, 5)	(0, 1.3, 7)	(7, 9.5, 10)	(3, 5.4, 9)	(7, 9, 10)	(3, 5, 7)	(0, 0.1, 3)	(3, 3.6, 9)	(0, 0.4, 3)	(3, 7.8, 10)
Severe leakage on the LP Shuttle valve	F_9	(0, 1.6, 5)	(0, 1.4, 7)	(7, 9.9, 10)	(3, 5.8, 9)	(7, 9.9, 10)	(1, 5, 7)	(0, 0.1, 3)	(3, 5.4, 9)	(0, 2.0, 5)	(5, 8.2, 10)
Severe leakage on the HP shuttle valve	F_{10}	(0, 2.0, 5)	(0, 1.0, 5)	(7, 9.6, 10)	(3, 6.2, 9)	(7, 9.9, 10)	(0, 1.6, 5)	(0, 0.1, 3)	(3, 5, 7)	(0, 1.2, 5)	(3, 8,2, 10)
Loss of LP accumulation	F_{11}	(3, 6.4, 10)	(0, 0.7, 5)	(7, 9.6, 10)	(1, 6.4, 9)	(7, 9.6, 10)	(0, 0, 1)	(0, 0.1, 3)	(0, 2.8, 5)	(0, 2.2, 5)	(5, 7.8, 10)
Shuttle valve fails to change over to the next HP supply line	F_{12}	(0, 1.0, 5)	(0, 0.5, 3)	(7, 9.6, 10)	(3, 6.2, 9)	(7, 9.1, 10)	(0, 0, 1)	(0, 0.1, 3)	(0, 1.2, 5)	(0, 0.7, 3)	(3, 7.4, 10)
Severe leak in the LP common hydraulic header	F_{13}	(0, 0.8, 5)	(0, 0.4, 5)	(7, 9.7, 10)	(1, 6.4, 9)	(7, 9.9, 10)	(0, 0, 1)	(0, 0.1, 3)	(5, 7.6, 10)	(0, 0.8, 3)	(5, 7.6, 10)
Shuttle valve fails to change over to the next LP supply line	F_{14}	(0, 1.7, 5)	(0, 0.6, 3)	(7, 9.7, 10)	(1, 6.0, 9)	(7, 9, 10)	(0, 0.1, 3)	(0, 0.1, 3)	(0, 1.6, 7)	(0, 0.1, 3)	(5, 8.4, 10)
LP selector valve fails to open	F_{15}	(0, 1.3, 5)	(0, 1.3, 5)	(5, 9.2, 10)	(3, 6.4, 9)	(5, 8.8, 10)	(0, 0, 1)	(0, 0.1, 3)	(0, 1, 3)	(0, 1.1, 5)	(3, 5.6, 9)
Loss of SCM pressure compensation	F_{16}	(7, 9.6, 10)	(7, 8.6, 10)	(7, 9.6, 10)	(3, 6.0, 9)	(7, 9.9, 10)	(0, 0, 1)	(0, 0, 1)	(3, 5, 7)	(0, 2.6, 5)	(3, 6.2, 9)
HP DCV fails to open on command	F_{17}	(0, 1.2, 5)	(0, 1.5, 5)	(5, 9.2, 10)	(1, 6.4, 9)	(5, 8.6, 10)	(0, 0.1, 3)	(0, 0, 1)	(0, 0.8, 3)	(0, 1.3, 5)	(5, 8.6, 10)
LP DCV fails to open on command	F_{18}	(1, 1.8, 7)	(0, 1.2, 5)	(5, 8.6, 10)	(0, 5.6, 9)	(5, 8.6, 10)	(0, 0.1, 3)	(0, 0, 1)	(0, 0.5, 3)	(0, 0.9, 5)	(3, 6.0, 10)
HP DCV shuts spuriously from the open position	F_{19}	(0, 2.2, 5)	(0, 1.3, 5)	(5, 7.7, 10)	(0, 5.8, 9)	(5, 7.8, 10)	(0, 0.8, 3)	(0, 0.1, 3)	(0, 0.3, 3)	(0, 1.6, 7)	(3, 5.6, 9)
HP DCV fails to shut on demand from the open position	F_{20}	(0, 0.5, 3)	(0, 1.2, 5)	(7, 9.6, 10)	(0, 6.0, 9)	(5, 8.0, 10)	(0, 0.8, 3)	(0, 0.1, 3)	(0, 0.4, 3)	(0, 0, 1)	(3, 5.8, 9)
LP DCV fails to shut on demand from the open position	F_{21}	(0, 1.1, 5)	(0, 1.4, 5)	(5, 9.4, 10)	(1, 6.2, 9)	(5, 8.4, 10)	(0, 0.7, 3)	(0, 0.1, 3)	(0, 0.6, 3)	(0, 1.4, 5)	(3, 5.2, 9)
Loss of monitoring signal from the water ingress sensor	F_{22}	(0, 0.1, 3)	(0, 0.5, 3)	(7, 9.3, 10)	(0, 1.6, 5)	(5, 7.8, 10)	(1, 3, 5)	(0, 0.1, 3)	(0, 1, 7)	(0, 0.3, 3)	(3, 5.8, 10)
LP selector valve spuriously closes	F_{23}	(0, 0, 1)	(0, 0.1, 3)	(5, 8.7, 10)	(0, 5.4, 9)	(5, 8.6, 10)	(0, 0, 1)	(0, 0.1, 3)	(0, 0.7, 3)	(0, 0.5, 7)	(3, 5.6, 10)
LP DCV shuts spuriously from the open position	F_{24}	(0, 0.1, 3)	(0, 0, 1)	(5, 9.1, 10)	(1, 5.6, 9)	(5, 8.6, 10)	(0, 0.1, 3)	(0, 0.1, 3)	(1, 5.2, 9)	(0, 1.3, 7)	(1, 4.4, 10)
Loss of electronic monitoring of the LP supply pressure	F_{25}	(0, 0.2, 3)	(0, 0.8, 5)	(5, 9.3, 10)	(0, 3.2, 7)	(7, 9, 10)	(0, 0.1, 3)	(0, 0.1, 3)	(0, 0.2, 3)	(0, 0.7, 5)	(1, 4.0, 7)
Loss of electronic monitoring of the HP supply pressure	F_{26}	(0, 0.3, 3)	(0, 0.6, 5)	(7, 9.7, 10)	(0, 3.2, 7)	(5, 7.6, 10)	(0, 0.1, 3)	(0, 0.1, 3)	(0, 1.0, 5)	(0, 0.4, 5)	(1, 4.2, 10)
Loss of electronic monitoring of the LP return flow	F_{27}	(0, 0.3, 3)	(0, 0.6, 5)	(5, 9.2, 10)	(0, 2.2, 7)	(0, 6.4, 9)	(0, 0.1, 3)	(0, 0.1, 3)	(0, 0.9, 5)	(0, 0.5, 5)	(1, 4.8, 10)
Loss of electronic monitoring of the HP return flow	F_{28}	(0, 0.2, 3)	(0, 0.8, 5)	(7, 9.7, 10)	(0, 2.8, 7)	(3, 6.8, 9)	(0, 0.1, 3)	(0, 0.1, 3)	(0, 1.3, 5)	(0, 0.7, 5)	(1, 3.8, 7)
Loss of the SCM internal pressure monitoring	F_{29}	(0, 0.3, 3)	(0, 1.3, 5)	(7, 9.8, 10)	(0, 2.4, 7)	(3, 5.6, 9)	(0, 1, 3)	(0, 0.1, 3)	(0, 1.4, 5)	(0, 0.6, 5)	(1, 4.2, 7)
Loss of the SCM internal temperature monitoring	F_{30}	(0, 0.3, 3)	(0, 0.8, 5)	(5, 8.9, 10)	(0, 2.6, 7)	(3, 5.2, 9)	(0, 0, 1)	(0, 0.1, 3)	(0, 0.9, 3)	(0, 1.0, 5)	(1, 3.2, 7)

Applying equation 4.17 and 4.18, the fuzzy decision matrix is normalised and the weight applied. This leads to a normalised weighed fuzzy matrix. Next, the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS) is obtained as shown below:

FPIS:	$F^* =$	[(1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1)]
FNIS:	F^-	[(0, 0, 0), (0, 0, 0), (0.15, 0.15, 0.15), (0, 0, 0), (0, 0, 0), (0, 0, 0), (0, 0, 0), (0, 0, 0), (0, 0, 0), (0.07, 0.07, 0.07)]

The distance of the failure modes to the FPIS and FNIS is then evaluated using the vertex method (equation 16 and 17). A correlation coefficient for each failure mode is evaluated and ranked (see table 20 and figure 55).

Table 20 Summary of the failure modes evaluation using Fuzzy TOPSIS methodology with Unconventional parameters

Failure Modes		R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	d^+		R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	d^-	CC_i	Fuzzy TOPSIS RANKING
Loss of power supply from the SEM Unit	$d(F_1, F^*)$	0.88	0.57	0.47	0.49	0.21	0.90	0.77	0.79	0.88	0.22	6.18	$d(F_1, F^-)$	0.18	0.75	0.61	0.72	0.88	0.17	0.58	0.41	0.18	0.81	5.29	**6.15**	3
SCM housing check valve cracks open at lower pressure	$d(F_2, F^*)$	0.38	0.78	0.48	0.66	0.30	0.74	0.90	0.82	0.59	0.69	6.32	$d(F_2, F^-)$	0.81	0.29	0.60	0.46	0.85	0.59	0.19	0.40	0.74	0.33	5.28	**6.11**	4
Total Loss of signal from the SEM module	$d(F_3, F^*)$	0.77	0.63	0.48	0.49	0.21	0.82	0.90	0.80	0.90	0.30	6.30	$d(F_3, F^-)$	0.42	0.60	0.60	0.71	0.88	0.41	0.19	0.41	0.17	0.77	5.16	**5.97**	6
Loss of LP hydraulic filtration	$d(F_4, F^*)$	0.90	0.88	0.48	0.59	0.41	0.91	0.90	0.80	0.46	0.30	6.64	$d(F_4, F^-)$	0.17	0.29	0.60	0.66	0.73	0.17	0.19	0.30	0.78	0.75	4.66	**5.36**	13
Severe leakage from HP DCV	$d(F_5, F^*)$	0.81	0.73	0.48	0.58	0.30	0.50	0.77	0.60	0.77	0.40	5.93	$d(F_5, F^-)$	0.30	0.47	0.59	0.62	0.84	0.70	0.58	0.58	0.42	0.69	5.79	**6.77**	1
Loss of HP hydraulic filtration	$d(F_6, F^*)$	0.91	0.82	0.52	0.88	0.41	0.78	0.77	0.84	0.46	0.40	6.81	$d(F_6, F^-)$	0.17	0.43	0.58	0.18	0.73	0.58	0.58	0.29	0.77	0.69	5.00	**5.74**	8
Loss of HP Accumulation	$d(F_7, F^*)$	0.53	0.79	0.52	0.61	0.30	0.90	0.77	0.74	0.74	0.41	6.30	$d(F_7, F^-)$	0.62	0.29	0.58	0.59	0.83	0.17	0.58	0.43	0.43	0.67	5.20	**6.02**	5
Severe leakage from LP DCV	$d(F_8, F^*)$	0.81	0.82	0.48	0.63	0.30	0.67	0.77	0.71	0.90	0.48	6.57	$d(F_8, F^-)$	0.30	0.41	0.60	0.57	0.82	0.45	0.58	0.54	0.17	0.67	5.11	**5.89**	7
Severe leakage on the LP Shuttle valve	$d(F_9, F^*)$	0.81	0.82	0.47	0.62	0.30	0.70	0.77	0.67	0.80	0.40	6.34	$d(F_9, F^-)$	0.30	0.41	0.61	0.58	0.85	0.45	0.58	0.55	0.31	0.69	5.34	**6.18**	2
Severe leakage on the HP shuttle valve	$d(F_{10}, F^*)$	0.79	0.83	0.48	0.61	0.30	0.82	0.77	0.70	0.83	0.47	6.60	$d(F_{10}, F^-)$	0.31	0.29	0.60	0.59	0.85	0.30	0.58	0.44	0.30	0.68	4.94	**5.68**	10
Loss of LP accumulation	$d(F_{11}, F^*)$	0.50	0.79	0.48	0.64	0.30	0.97	0.77	0.80	0.79	0.40	6.44	$d(F_{11}, F^-)$	0.69	0.29	0.60	0.59	0.84	0.06	0.58	0.30	0.31	0.68	4.95	**5.72**	9
Shuttle valve fails to change over to the next HP supply line	$d(F_{12}, F^*)$	0.83	0.85	0.48	0.61	0.30	0.97	0.77	0.84	0.89	0.49	7.02	$d(F_{12}\ F^-)$	0.29	0.18	0.60	0.59	0.82	0.06	0.58	0.29	0.18	0.65	4.24	**4.85**	18
Severe leak in the LP common hydraulic header	$d(F_{13}, F^*)$	0.84	0.85	0.48	0.64	0.30	0.97	0.77	0.58	0.89	0.41	6.71	$d(F_{13}, F^-)$	0.29	0.29	0.60	0.59	0.85	0.06	0.58	0.64	0.18	0.68	4.76	**5.47**	12
Shuttle valve fails to change over to the next LP supply line	$d(F_{14}, F^*)$	0.80	0.84	0.48	0.65	0.30	0.91	0.77	0.80	0.91	0.39	6.85	$d(F_{14}, F^-)$	0.30	0.18	0.60	0.58	0.82	0.17	0.58	0.41	0.17	0.70	4.52	**5.18**	14
LP selector valve fails to open	$d(F_{15}, F^*)$	0.82	0.82	0.48	0.61	0.38	0.97	0.77	0.89	0.83	0.53	7.10	$d(F_{15}, F^-)$	0.30	0.30	0.59	0.59	0.79	0.06	0.58	0.18	0.29	0.55	4.23	**4.82**	19
Loss of SCM pressure compensation	$d(F_{16}, F^*)$	0.69	0.36	0.48	0.62	0.30	0.97	0.90	0.69	0.78	0.52	6.29	$d(F_{16}, F^-)$	0.45	0.80	0.60	0.58	0.85	0.06	0.19	0.44	0.32	0.57	4.86	**5.63**	11
HP DCV fails to open on command	$d(F_{17}, F^*)$	0.82	0.81	0.48	0.64	0.39	0.91	0.90	0.89	0.82	0.39	7.06	$d(F_{17}, F^-)$	0.30	0.30	0.59	0.59	0.78	0.17	0.19	0.18	0.30	0.71	4.10	**4.68**	21
LP DCV fails to open on command	$d(F_{18}, F^*)$	0.74	0.79	0.49	0.67	0.39	0.91	0.90	0.90	0.84	0.52	7.14	$d(F_{18}, F^-)$	0.42	0.30	0.58	0.57	0.78	0.17	0.19	0.17	0.29	0.61	4.09	**4.66**	22
HP DCV shuts spuriously from the open position	$d(F_{19}, F^*)$	0.79	0.82	0.51	0.67	0.40	0.89	0.77	0.90	0.78	0.53	7.06	$d(F_{19}, F^-)$	0.31	0.30	0.56	0.58	0.75	0.18	0.58	0.17	0.41	0.55	4.40	**5.02**	16
HP DCV fails to shut on demand from the open position	$d(F_{20}, F^*)$	0.89	0.87	0.48	0.66	0.40	0.89	0.77	0.90	0.97	0.53	7.35	$d(F_{20}, F^-)$	0.18	0.30	0.60	0.58	0.76	0.18	0.58	0.17	0.06	0.56	3.96	**4.50**	26
LP DCV fails to shut on demand from the open position	$d(F_{21}, F^*)$	0.83	0.82	0.48	0.64	0.39	0.89	0.77	0.90	0.86	0.54	7.12	$d(F_{21}, F^-)$	0.30	0.30	0.60	0.59	0.77	0.18	0.58	0.17	0.29	0.54	4.31	**4.92**	17
Loss of monitoring signal from the water ingress sensor	$d(F_{22}, F^*)$	0.91	0.89	0.48	0.82	0.40	0.78	0.77	0.81	0.90	0.52	7.29	$d(F_{22}, F^-)$	0.17	0.18	0.59	0.30	0.75	0.31	0.58	0.41	0.17	0.61	4.08	**4.64**	23
LP selector valve spuriously closes	$d(F_{23}, F^*)$	0.97	0.96	0.49	0.67	0.39	0.97	0.77	0.90	0.82	0.53	7.46	$d(F_{23}, F^-)$	0.06	0.17	0.58	0.57	0.78	0.06	0.58	0.17	0.40	0.60	3.98	**4.52**	25
LP DCV shuts spuriously from the open position	$d(F_{24}, F^*)$	0.91	0.91	0.49	0.66	0.39	0.91	0.77	0.69	0.79	0.63	7.13	$d(F_{24}, F^-)$	0.17	0.06	0.59	0.57	0.78	0.17	0.58	0.55	0.41	0.57	4.46	**5.09**	15
Loss of electronic monitoring of the LP supply pressure	$d(F_{25}, F^*)$	0.90	0.88	0.48	0.75	0.30	0.91	0.77	0.91	0.84	0.67	7.41	$d(F_{25}, F^-)$	0.17	0.29	0.59	0.43	0.82	0.17	0.58	0.17	0.29	0.41	3.93	**4.46**	27
Loss of electronic monitoring of the HP supply pressure	$d(F_{26}, F^*)$	0.90	0.89	0.48	0.75	0.40	0.91	0.77	0.84	0.85	0.64	7.43	$d(F_{26}, F^-)$	0.17	0.29	0.60	0.43	0.75	0.17	0.58	0.29	0.29	0.57	4.15	**4.70**	20
Loss of electronic monitoring of the LP return flow	$d(F_{27}, F^*)$	0.90	0.89	0.48	0.77	0.62	0.91	0.77	0.85	0.85	0.62	7.66	$d(F_{27}, F^-)$	0.17	0.29	0.59	0.42	0.63	0.17	0.58	0.29	0.29	0.58	4.02	**4.54**	24
Loss of electronic monitoring of the HP return flow	$d(F_{28}, F^*)$	0.90	0.88	0.48	0.76	0.50	0.91	0.77	0.84	0.84	0.67	7.55	$d(F_{28}, F^-)$	0.17	0.29	0.60	0.42	0.66	0.17	0.58	0.29	0.29	0.40	3.89	**4.40**	28
Loss of the SCM internal pressure monitoring	$d(F_{29}, F^*)$	0.90	0.87	0.48	0.77	0.53	0.89	0.77	0.86	0.85	0.66	7.56	$d(F_{29}, F^-)$	0.17	0.30	0.61	0.42	0.62	0.18	0.58	0.29	0.29	0.41	3.86	**4.38**	29
Loss of the SCM internal temperature monitoring	$d(F_{30}, F^*)$	0.90	0.88	0.49	0.76	0.54	0.97	0.77	0.89	0.83	0.69	7.73	$d(F_{30}, F^-)$	0.17	0.29	0.58	0.42	0.61	0.06	0.58	0.18	0.29	0.39	3.57	**4.04**	30

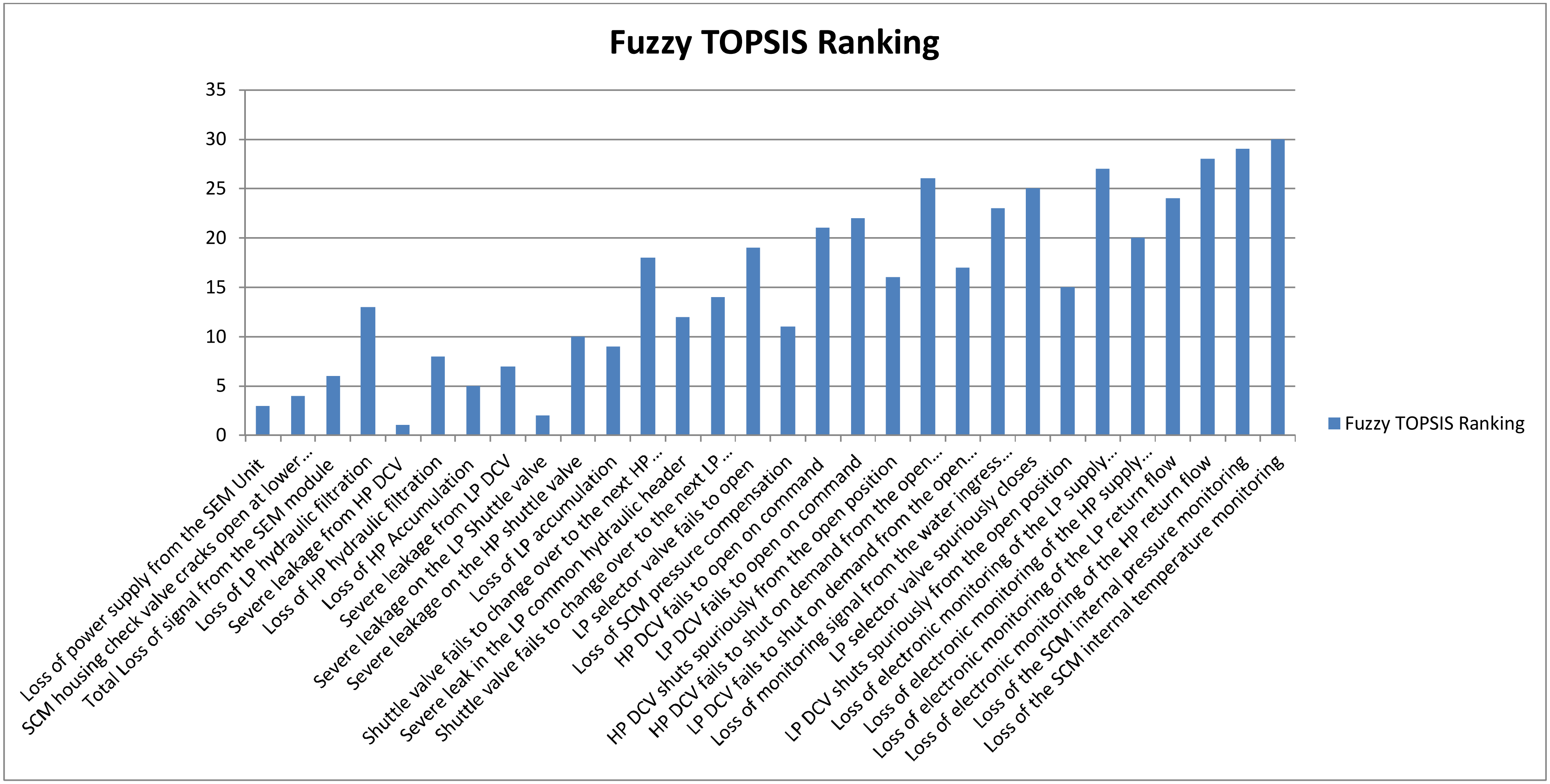


Figure 55 Fuzzy TOPSIS ranking for SCM failure modes.

In summary, the analysis presents the following failure modes as the top 10% failure modes:

- Severe leakage from HP DCV
- Severe leakage on the LP Shuttle valve
- Loss of power supply from the SEM Unit

Clearly, the evaluation shows that severe leakage in the HP DCV (F_1) has the highest risk among the failure modes. The HP DCV is responsible for the control of the all-important and sensitive surface controlled sub-surface safety valve which is a key safety barrier in a typical subsea completion well. It is also responsible for the control of the well intelligent flow control valves (IFCVs).

Severe leakage in this valve would lead to a loss in pressurization of the SCSSV and eventual closure of the valve. This automatically means a loss in production from the well. This failure modes requires the SCM to be pulled, DCV fixed before the SCM is re-installed subsea. An offshore support vessel is required for this along with the retrieval and installation tools. Support vessels come at a high cost which is further amplified in the form of deferred production if a vessel is not readily available in the field and there is no spare compatible SCM which is immediately available for a replacement operation.

Next in ranking is severe leakage in the LP shuttle valve (F_9). The clearly demonstrate that DCV leakage is a major problem in the subsea industry.

Hydraulic control in subsea production system is such that two low pressure supplies come in from the topside HPU to the SCM for redundancy purposes. The LP shuttle valve is responsible for the selection of which of the lines (typically named LP-A and LP-B) is selected to for supply for functioning of the LP circuitry in the SCM. Shuttle valve failure is a common point failure with serious implications. Such failure will lead to the closure of all DCVs and eventual closure of key LP valves in the tree like the production wing valve (PWV), production master valve (PMV) …etc.

Loss of power from the subsea electronic module (SEM) (is the third in the ranking. This is not surprising as the SEM serves as the central power and signal processing unit in the SCM. A loss of power in the SEM automatically means a total loss in the operation of the SEM. This required a retrieval and replacement of the SCM unit.

Again, the top 25% in the criticality ranking of key contributors to SCM's potential functional failure reveals the following:

- Severe leakage from HP DCV
- Severe leakage on the LP Shuttle valve
- Loss of power supply from the SEM Unit
- SCM housing check valve cracks open at lower pressure
- Loss of HP Accumulation
- Total Loss of signal from the SEM module
- Severe leakage from LP DCV
- Loss of HP hydraulic filtration

The next one in the ranking is F_2- SCM check valve cracks open at a lower pressure. Typically, a check valve is installed in the SCM housing for pressure compensation and prevent the ingress of seawater into the module chamber. As water depth increases, the probability of failure of this component increases. Failure of this component is critical to the operation of the SCM as an unwanted ingress of water into the increases would cause a loss of insulation to the electrical system, contamination of the hydraulic system and eventual failure of the entire system.

Another failure mode in this band is the Loss in HP accumulation. This is potentially caused by a loss in the HP-accumulator pre-charge. It could also be caused by a blocked line in the system due to contaminated fluid or a related cause. Next to this is the loss of signal from the subsea electronic module (SEM). The SEM is responsible for gathering all SCM internal parameters including those of the well downhole instrumentation and relaying same to the topside console. Loss of this signal could have severe impact in the short or long term operation of the system.

Still in the 25% range is severe leakage in LP DCV. This happens to be a common failure in the LP system of the SCM and are known to cause issues like the accidental delatching and closure of the corresponding valves in the tree system under control.

Very salient but critical failure in this band is loss I filtration of the HP system. Fluid cleanliness is very important in subsea control systems. The SCM, for example is required to be flushed clean and operated with hydraulic fluid that has been cleaned to NAS 1638 class or better. HP and LP Hydraulic headers in the SCM are mounted with filters to ensure the required level of cleanliness.

Filters are installed in systems to ensure the flow of clean fluids for smooth control operations. In subsea, filters may have a bypass path. The bypass is normally a secondary path past the filter in case of a blockage. This would normally have a higher cracking pressure than the filter side implemented using a check valve. This configuration directs the flow of fluid to the filter side. If the filter is blocked, this leads to a pressure build-up and a re-direction of the fluid to the by-pass.

The last 10% in the ranking among the thirty failure modes are:

- Loss of electronic monitoring of the HP return flow
- Loss of the SCM internal pressure monitoring
- Loss of the SCM internal temperature monitoring

This does not necessarily mean that the risk associated with these ones are trivial. It is just that in the ranking among all the thirty, these ones are slightly lower I terms of the probability of occurrence and immediate consequence.

At the lowest end of the raking is the Loss in monitoring of the SCM internal temperature. Though this parameter is important, the loss in monitoring of the parameter is not that critical to the operation of the SCM. All tree DCVs will remain in their original position at the loss of this signal. This is similar to the F29-Loss in the monitoring of the SCM internal pressure. Though, this signal is very important in prescribing the state of the SCM unit, a loss monitoring of this may not require an immediate retrieval and repair as production is not distorted.

4.5.4.1 Sensitivity Analysis:

A sensitivity analysis of the SCM failure modes is conducted below by eliminating one risk factor at a time. The effect of the risk factors elimination is evaluated by assessing the ranking of the failure modes. The elimination reveals the most significant and the least significant risk factors in the evaluation. The ranking results from the risk elimination are shown in table 21 while the sensitivity results are shown in table 22.

Table 21 Fuzzy TOPSIS SCM Failure modes sensitivity analysis

Failure Modes	Full Ranking	Ranking Without R_1	Ranking Without R_2	Ranking Without R_3	Ranking Without R_4	Ranking Without R_5	Ranking Without R_6	Ranking Without R_7	Ranking Without R_8	Ranking Without R_9	Ranking Without R_{10}
Loss of power supply from the SEM Unit	3	2	9	3	6	4	1	5	2	2	5
SCM housing check valve cracks open at lower pressure	4	11	2	4	2	3	8	2	3	11	2
Total Loss of signal from the SEM module	6	6	8	6	8	7	7	3	6	4	7
Loss of LP hydraulic filtration	13	9	12	13	13	12	12	9	12	21	13
Severe leakage from HP DCV	1	1	1	1	1	1	2	1	1	1	1
Loss of HP hydraulic filtration	8	5	10	8	3	8	13	10	7	13	9
Loss of HP Accumulation	5	8	4	5	5	5	3	7	5	6	4
Severe leakage from LP DCV	7	4	5	7	7	6	10	8	9	5	6
Severe leakage on the LP Shuttle valve	2	3	3	2	4	2	5	4	4	3	3
Severe leakage on the HP shuttle valve	10	7	7	10	10	10	11	12	10	8	11
Loss of LP accumulation	9	14	6	9	9	9	4	11	8	7	10
Shuttle valve fails to change over to the next HP supply line	18	18	17	18	20	19	17	20	18	14	19
Severe leak in the LP common hydraulic header	12	10	11	12	12	13	9	13	16	10	12
Shuttle valve fails to change over to the next LP supply line	14	15	14	14	14	14	14	14	15	12	16
LP selector valve fails to open	19	20	19	19	21	18	18	21	17	18	18
Loss of SCM pressure compensation	11	12	16	11	11	11	6	6	11	9	8
HP DCV fails to open on command	21	24	22	21	24	22	21	15	19	23	27
LP DCV fails to open on command	22	28	24	22	23	24	22	16	20	24	22
HP DCV shuts spuriously from the open position	16	16	15	16	16	16	16	18	13	17	15
HP DCV fails to shut on demand from the open position	26	25	26	26	29	27	25	26	24	19	28
LP DCV fails to shut on demand from the open position	17	17	18	17	18	17	19	19	14	16	17
Loss of monitoring signal from the water ingress sensor	23	22	20	23	17	23	26	23	27	20	24
LP selector valve spuriously closes	25	21	23	25	28	28	23	25	23	28	29
LP DCV shuts spuriously from the open position	15	13	13	15	15	15	15	17	21	15	14
Loss of electronic monitoring of the LP supply pressure	27	26	27	27	25	29	27	27	25	26	21
Loss of electronic monitoring of the HP supply pressure	20	19	21	20	19	20	20	22	22	22	20
Loss of electronic monitoring of the LP return flow	24	23	25	24	22	21	24	24	26	25	26
Loss of electronic monitoring of the HP return flow	28	27	28	28	26	26	28	28	28	27	23
Loss of the SCM internal pressure monitoring	29	29	29	29	27	25	29	29	29	29	25
Loss of the SCM internal temperature monitoring	30	30	30	30	30	30	30	30	30	30	30

Table 22 – Sensitivity analysis results for the Fuzzy TOPSIS evaluation

Correlation Performed	Value of correlation
Correlation between ranking without R_1 and ranking without R_2	0.931034
Correlation between ranking without R_2 and ranking without R_3	0.971969
Correlation between ranking without R_3 and ranking without R_4	0.969744
Correlation between ranking without R_{10} and ranking without R_1	0.912792
Correlation between ranking without R_5 and ranking without R_8	0.949722
Correlation between ranking without R_9 and ranking without R_2	0.911902
Correlation between ranking without R_3 and ranking without R_8	0.970634
Correlation between ranking without R_2 and ranking without R_{10}	0.935039
Correlation between ranking without R_2 and ranking without R_7	0.913237

The above sensitivity result confirms that severe leakage in the HP is the most critical failure in the SCM across the respective risk factors. Its worthy of note that SCM HP system is responsible for wells chemical injection, control of the surface controlled subsurface safety valve (SCSSV) including flow control valves (FCVs)/inflow control valves (ICVs) for multiple level completions. It is not uncommon for the control HP system to be dependent on the LP system for fluid supply. This means that if the LP supply, accumulation or filtration system fails, the entire control system fails and leads to a total loss in production.

It is also important to note that in an E-H SCM, the process of opening and closing of valves is controlled by the multiplexing activity occurring in the subsea electronic module (SEM). The SEM is also responsible for the retrieval and transmittal of wells condition monitoring data to the topside controls interface. Hence, a failure in this unit means a complete failure in the directing and control of the SCM valves/fluid as well as a loss in data retrieval and transmission. Though the ranking doesn't show the SEM failure as an overriding failure mode with the highest ranking, it is worthy of mention that the SEM failure is quite critical to the functioning of the entire system.

A complete failure of the SEM requires a retrieval and replacement of the subsea control module (SCM), which comes with a huge due to the requirement for a diver intervention for shallow waters, ROV in deep waters, cost of intervention vessel, cost of the replacement SCM, personnel and other miscellaneous logistics and associated cost.

5 SCM Failure mode evaluation using stochastic inputs

The process of selecting the most critical failures in a subsea control module (SCM) introduces less confidence in the results due to the probability of subjectivity in the data obtained.

This chapter introduces an extension of the popular technique of order preference by similarity to ideal solution (TOPSIS) for SCM failure modes evaluation that requires both technical and non-technical info. The unavailability of data demands the use of expert opinions in the evaluations. The methodology considers stochastic inputs (statistical distributions). The technique has been implemented in a numerical tool and a case study performed successfully applied in offshore wind turbine evaluations (Kolios 2014). This illustrates the applicability of the simulation method allowing for a sensitivity analysis of the methodology, selection of statistical distributions and the weighing of the experts opinion based on their perceived experience or knowledge of the subject. (Mateo 2012) identifies a number of MCDM processes which are suitable for the use in the renewable energy industry, including the Analytical Hierarchy Process (AHP) (Saaty 1980), Weighted Sum and Weighted Product Method (WSM & WPM), Technique for Order or Preference by Similarity to Ideal Solution (TOPSIS) (Hwang 1981), Preference Raking Organization Method for Enrichment Evaluation (PROMETHEE) (Brans 1985 and Brans 1992) and Elimination Et Choix Traduisant la Realite Method (ELECTRE) (Benayoun 1966). These methods have been in use over the years in operational research and lately in application for engineering systems as a result of their robustness and transparency.

The analysis takes stochastic rather than deterministic inputs for the decision matrices as well as the weight factor with results obtained from experts' survey.

5.1 Deterministic TOPSIS Algorithm

Technique for order preference by similarity to ideal solution (TOPSIS) methodology as shown in section 4.3 is based on a strategy that the solution should be closest to a positive ideal solution and farthest to the negative ideal solution (Yoon 1995).

In the deterministic TOPSIS, the rating and weight values considered are crisp values. However, for most real life situations, real values are not enough to model the situations since human judgements are vague and difficult to estimate with exact numerical figures. To resolve the ambiguity that normally arises from human judgements, fuzzy concepts have been applied in a lot of cases to enhance the results obtained from the analysis.

To resolve the ambiguity frequently arising in information from human judgments, fuzzy set theory has been incorporated in many MCDM methods including TOPSIS. In fuzzy TOPSIS all the ratings and weights are defined by means of linguistic variables. Although it is a non-complex method of multi criteria decision making TOPSIS still has its deficiencies, i.e. despite using the Euclidean distance algorithm it doesn't consider the correlation of attributes. The method generally fixes weight coefficients using expert investigation and it is more difficult to determine weights when using larger matrices.

A key disadvantage of most variations of TOPSIS, as well as MCDM methods in general, that have been so far suggested is the fact that qualitative or semi-quantitative data that are collected through surveys and questionnaires should be represented through one or a limited number of values that will serve as inputs to the calculations. For example, a case of making observations for two variables with results (1, 2, 3, 6, 9) and (5,5,5,5,5), a representation of the observations with a mean value is misleading as it would reduce both data sets to be represented by the value 5 with no further information regarding the spread of the values been taken into account.

The methodology developed in this paper is an extension of TOPSIS in the way that input variables are considered stochastically as statistical distributions that are derived by best fit of the data collected for each value in the decision matrix and weight vector. Stochastic input data will allow Monte Carlo simulations to perform numerous iterations of analysis in order to quantify results and identify the number of cases where the optimum solution will prevail, i.e. there is a *pi* probability that option *Xi* will rank first. Figure 56 illustrates the methodology that is proposed, which has been modelled in a numerical tool and validated numerically in MathWorks Matlab and Visual Basic.

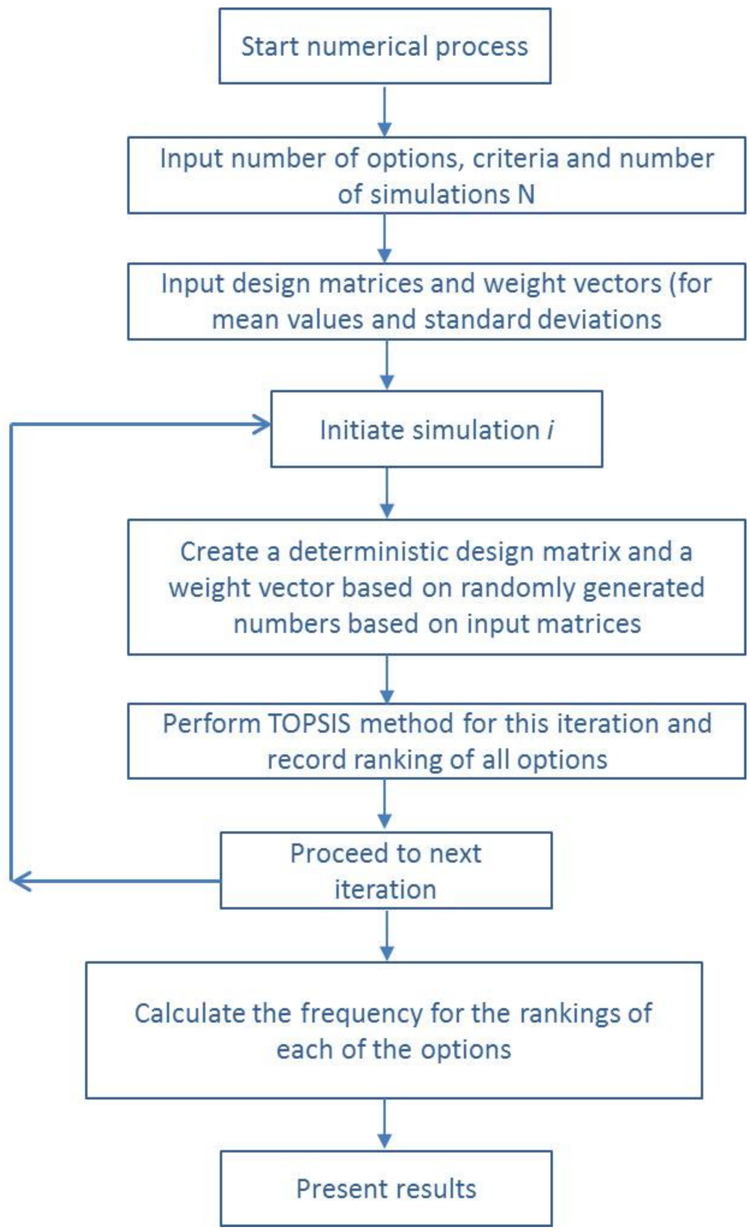


Figure 56 - Steps for stochastic input analysis

Multi criteria decision making methods can become as advanced and complicated as the resources that are allocated allow so, but without sufficient thought being put into the collection and processing of input data, especially when considering qualitative attributes, the results of the analysis can become of no much use. In order to capture the correct data for the study in question, two main aspects must be included; the weight vector assigned to the importance of each risk criterion and the decision matrix marking alternatives against the specified criteria. In order to make all input data uniform and easy to process the questionnaire may employ a Likert scale for marking the relevant values. With this technique, the responder specifies a level of agreement or disagreement to the concept under study, using one of a number of positions on a Likert scale (often specifying as highest being most critical). A 1 to 10 scale is used to rank the failure modes against risks criteria. Depending on the nature of the criterion it can be either positive (10 representing the most risky). Weights influence significantly the ranking results and are based on the practical engineering expertise of the decision makers; consequently, the more experienced the decision makers are, the more objective the result. Relevant generic studies from (Bonner 2002 and Baumann 2013) have shown the effect of considering level of expertise of participants towards successful prediction of survey outcomes. Further, results from previous studies of the authors have shown that expertise weighting is significantly important to the derived results and hence its effect should be investigated based on perceived levels of the survey participants (Kolios 2013).

5.2 Case Study – Evaluation of SCM critical failure modes

The failure modes considered in this evaluation were those obtained from the conventional FMECA and the fuzzy TOPSIS evaluation conducted in chapters 3 and 4 in this report. The top 30 failure modes used in the analysis are listed in section 4.5.3. Data for this evaluation were obtained from a systematic survey obtained using questionnaires with twenty five (25) participants. At the end of the painstaking process, ten (10) complete results were obtained from the experts representing a 40% participation from the total of questionnaires sent out.

On a scale of 1 to 5 or the weight evaluation for VL, L, M, H and VH respectively, the weight evaluation for the risk factors of the processed questionnaires is as shown in figure 57.

	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	mean	std	min	max	mode
Occurrence associated with water depth, R_1	5	5	5	4	5	5	5	5	5	5	4.9	0.316	4	5	5
Occurrence under normal operation, R_2	5	4	4	5	5	5	5	5	4	4	4.6	0.516	4	5	5
Occurrence under extreme conditions, R_3	4	4	4	4	3	4	4	4	3	3	3.7	0.483	3	4	4
Direct Cost of failure, R_4	3	3	3	3	4	4	4	4	4	5	3.7	0.675	3	5	4
Indirect cost of failure, R_5	5	5	5	4	5	5	5	5	4	4	4.7	0.483	4	5	5
Failure impact on environment, R_6	3	3	4	4	3	3	3	4	4	4	3.5	0.527	3	4	3
Fatality associated with failure, R_7	2	2	3	2	3	3	2	3	4	3	2.7	0.675	2	4	3
Risk to business – non-financial, R8	4	4	3	4	3	3	3	3	3	3	3.3	0.483	3	4	3
Detectability, R_9	5	4	4	5	4	3	4	4	5	5	4.3	0.675	3	5	4
Redundancy, R_{10}	4	4	5	4	5	5	5	4	5	4	4.5	0.527	4	5	4

Figure 57 Importance weight evaluation for Stochastic Analysis

Tables 23 present the mean values while table 24 gives the standard deviations of the data for the failure modes of the processed questionnaire.

Table 23 Mean values of ratings from the processed questionnaire

	mean values									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
ID										
F_1	1.8	5.4	6.9	6.4	7	1.3	1.1	2.5	1.9	7
F_2	6.4	1.7	6.6	4	6.9	3	1	1.5	6	3.9
F_3	2.4	4.1	6.4	6.3	7	1.5	1	2.3	1.2	6.8
F_4	1.4	3.2	6.5	5.1	5.1	1.2	1	2.9	6.8	6.2
F_5	2	3.6	6.3	5.4	6.6	6.2	1.1	5	2.5	5.6
F_6	1.1	2.9	6	2	5.1	1.8	1.1	1.9	6.4	5.6
F_7	4.3	1.6	6.1	4.7	6.3	1.4	1.1	3.4	2.9	5.2
F_8	2.1	1.9	6.5	4.2	6	4	1.1	4.7	2.4	5.5
F_9	2.4	2	6.9	4.4	6.9	3.9	1.1	4.2	2.5	5.6
F_{10}	2.4	1.8	6.6	4.6	6.9	2.3	1.1	4	2.1	5.6
F_{11}	4.7	1.6	6.6	4.7	6.6	1	1.1	2.9	2.6	5.4
F_{12}	1.9	1.5	6.6	4.6	6.1	1	1.1	2.1	1.7	5.2
F_{13}	1.7	1.3	6.7	4.7	6.9	1	1.1	5.4	1.8	5.3
F_{14}	2.2	1.6	6.7	4.5	6	1.1	1.1	2.3	1.1	5.7
F_{15}	2.1	2.1	6.3	4.7	5.9	1	1.1	2	2	4.3
F_{16}	3.1	5.8	6.6	4.5	6.9	1	1	4	2.8	4.6
F_{17}	2	2	6.3	4.7	5.8	1.1	1	1.8	2.1	5.3
F_{18}	2.4	1.9	5.8	4.3	5.8	1.1	1	1.5	1.9	5
F_{19}	2.3	2	5.4	4.4	5.4	1.8	1.1	1.3	2.3	4.3
F_{20}	1.5	2	6.6	4.5	5.5	1.8	1.1	1.4	1	4.4
F_{21}	1.8	2	6.5	4.6	5.7	1.7	1.1	1.6	2.1	4.1
F_{22}	1.1	1.5	6.3	2.3	5.4	3	1.1	2.1	1.2	4.4
F_{23}	1	1.1	6	4.2	5.8	1	1.1	1.7	1.3	4.3
F_{24}	1.1	1	6.3	4.3	5.8	1.1	1.1	4.1	1.9	3.6
F_{25}	1.2	1.6	6.4	3.1	6	1.1	1.1	1.2	1.5	3.5
F_{26}	1.3	1.5	6.7	3.1	5.3	1.1	1.1	1.9	1.3	3.6
F_{27}	1.3	1.5	6.4	2.6	4.7	1.1	1.1	1.8	1.4	3.9
F_{28}	1.2	1.6	6.7	2.9	4.9	1.1	1.1	2.1	1.6	3.4
F_{29}	1.3	2	6.8	2.7	4.3	2	1.1	2.2	1.5	3.6
F_{30}	1.3	1.6	6.2	2.8	4.1	1	1.1	1.9	1.7	3.1

Table 24 Standard deviation values of ratings from the processed questionnaire

Standard Deviation Values									
R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
0.421637	0.516398	0.316228	0.516398	0	0.483046	0.316228	1.080123	0.316228	0
0.699206	0.823273	0.516398	0	0.316228	1.699673	0	0.971825	0	0.316228
0.843274	0.994429	0.516398	0.483046	0	0.971825	0	0.948683	0.421637	0.421637
0.516398	0.788811	0.527046	0.737865	0.316228	0.421637	0	0.316228	0.421637	0.421637
0.942809	0.843274	0.483046	0.699206	0.516398	0.421637	0.316228	0	0.707107	0.516398
0.316228	0.994429	0.816497	0	0.316228	1.549193	0.316228	0.875595	0.516398	0.843274
0.483046	0.699206	0.737865	0.483046	0.483046	0.516398	0.316228	0.516398	0.737865	0.421637
0.875595	1.197219	0.527046	0.421637	0	0	0.316228	0.483046	0.516398	0.971825
1.074968	1.154701	0.316228	0.516398	0.316228	0.316228	0.316228	0.421637	0.527046	0.699206
0.843274	0.788811	0.516398	0.516398	0.316228	0.483046	0.316228	0	0.316228	0.699206
0.674949	0.699206	0.516398	0.674949	0.516398	0	0.316228	0.316228	0.516398	0.516398
0.567646	0.527046	0.516398	0.516398	0.316228	0	0.316228	0.316228	0.483046	0.788811
0.674949	0.674949	0.483046	0.674949	0.316228	0	0.316228	0.843274	0.421637	0.483046
0.918937	0.516398	0.483046	0.707107	0	0.316228	0.316228	0.674949	0.316228	0.483046
0.567646	0.567646	0.674949	0.483046	0.316228	0	0.316228	0	0.471405	0.483046
0.316228	0.421637	0.516398	0.527046	0.316228	0	0	0	0.421637	0.843274
0.666667	0.942809	0.674949	0.674949	0.421637	0.316228	0	0.421637	0.567646	0.483046
0.699206	0.875595	0.421637	1.05935	0.421637	0.316228	0	0.527046	0.875595	0.816497
0.483046	0.816497	0.699206	0.843274	0.516398	0.421637	0.316228	0.483046	0.674949	0.483046
0.527046	0.666667	0.516398	1.080123	0.527046	0.421637	0.316228	0.516398	0	0.516398
0.918937	0.942809	0.707107	0.843274	0.483046	0.483046	0.316228	0.516398	0.737865	0.316228
0.316228	0.527046	0.483046	0.483046	0.516398	0	0.316228	1.100505	0.632456	0.699206
0	0.316228	0.816497	0.918937	0.421637	0	0.316228	0.483046	0.948683	0.674949
0.316228	0	0.823273	0.823273	0.421637	0.316228	0.316228	0.737865	1.286684	0.966092
0.421637	0.843274	0.699206	0.737865	0	0.316228	0.316228	0.421637	0.849837	0.527046
0.483046	0.707107	0.483046	0.737865	0.483046	0.316228	0.316228	0.567646	0.674949	0.966092
0.483046	0.707107	0.843274	0.699206	0.948683	0.316228	0.316228	0.632456	0.699206	1.197219
0.421637	0.843274	0.483046	0.875595	0.316228	0.316228	0.316228	0.567646	0.699206	0.516398
0.483046	0.816497	0.421637	0.823273	0.483046	0	0.316228	0.421637	0.707107	0.516398
0.483046	0.843274	0.918937	0.788811	0.316228	0	0.316228	0.316228	0.948683	0.316228

Table 25 shows the results and ranking of the SCM failure modes based on arithmetic mean and standard deviation evaluation. The table is such that ranking 1 represents the most critical failure, followed by 2 in that order.

Table 25 - Top10 most critical SCM failure modes based on stochastic evaluation ranking

Failure Modes	Ranking
SCM housing check valve cracks open at lower pressure	1
Severe leakage from HP DCV	2
Loss of SCM pressure compensation	3
Severe leakage on the LP Shuttle valve	4
Loss of LP hydraulic filtration	5
Severe leakage from LP DCV	6
Loss of HP hydraulic filtration	7
Total Loss of signal from the SEM module	8
Loss of power supply from the SEM Unit	9
Loss of LP accumulation	9

The above ranking here provides a correlation coefficient of 73.5% to the results obtained from the SCM failure modes fuzzy TOPSIS analysis. Table 26 provides a comparison between the results of the critical failures obtained from the fuzzy TOPSIS analysis and that of input evaluation.

Table 26 – Top10 most critical failure modes based on Fuzzy TOPSIS ranking

Failure Modes	Fuzzy TOPSIS ranking
Severe leakage from HP DCV	1
Severe leakage on the LP Shuttle valve	2
Loss of power supply from the SEM Unit	3
SCM housing check valve cracks open at lower pressure	4
Loss of HP Accumulation	5
Total Loss of signal from the SEM module	6
Severe leakage from LP DCV	7
Loss of HP hydraulic filtration	8
Loss of LP accumulation	9
Severe leakage on the HP shuttle valve	10

The analysis reveals that nine (9) out of the top ten (10) most critical failures modes obtained from the fuzzy TOPSIS analysis are also obtained from the stochastic evaluation. These critical failure modes are listed below:

- Severe leakage from HP DCV
- Severe leakage on the LP Shuttle valve
- Loss of power supply from the SEM Unit
- SCM housing check valve cracks open at lower pressure
- Loss of HP Accumulation
- Total Loss of signal from the SEM module
- Severe leakage from LP DCV
- Loss of HP hydraulic filtration
- Severe leakage on the HP shuttle valve

The result also further confirms that directional control valves (DCVs) and the subsea electronic modules (SEM) are two of the most critical components in the subsea control module (SCM). In summary, the stochastic simulation provides a very strong additional validation to the conventional FMECA and fuzzy TOPSIS evaluation performed on the subsea control module (SCM) most critical failure modes as shown in chapters 3 and 4 of this report.

6 Comparative Analysis between All-Electric and the Electro-hydraulic SCM

6.1 Background of study

Subsea control systems fundamentally open and close valves in a typical subsea production system. They are also responsible for choke control, intelligent valves control and delivery of condition monitoring data to the topside control units. From the 1960s, the control system has evolved from the direct control systems to the electro-hydraulic systems and recently the all-electric systems all in a bit for a faster response time and efficient control for longer tie-back distances.

The offshore oil and gas industry currently uses the electro-hydraulic (EH) control subsea system as the main system for the control of hydrocarbon and other fluids in subsea field developments (Theobald 2005). However, there has been a lot of interest in all-electric controls concept. This led to a project study in Cranfield University in 2004 that compared the Cameron all-electric system with the conventional electro-hydraulic subsea control system (Theobald 2005). This study was assembled by key players in the oil and gas industry – BP and Cameron. This study modelled a 4-well cluster.

The evolution of the all-electric control system eliminates the requirement of the topside hydraulic power unit (HPU), reduces the size of the control umbilical with huge merits in CAPEX, OPEX and the environment. The all-electric controls is principally built around three key components, namely:

1. The power regulation and communication module (PRCM)
2. The electric subsea control module (eSCM)
3. The electric actuator (EA)

In this chapter, a comparative analysis comparing the risk performance EH SCM and the all-electric SCM is being performed.

6.2 The All-electric control system

The all-electric subsea control system comes in various variants. Some are battery-operated while others are powered directly from a topside supply. Typical components of the all-electric system are (Lopez 2005):

- Surface units
  - Electrical power Unit (EPU)
  - Surface power line modem
  - Communication controller
- Subsea Controls
  - Power regulator
  - Subsea power line modem
  - Electric Subsea Control Module (eSCM)
- Surface to Subsea Elements
  - Power and signal cable (coaxial)
  - Subsea power connector (wet mateable)

Figure 58 shows the Cameron 1st generation all-electric subsea controls architecture. The system has no batteries, no hydraulics and no subsea accumulators. High voltage DC power in the range of 6Kv DC is being delivered subsea and consumption in typically in kilowatts. DC power has been preferred to AC for economic reasons, as AC power is uneconomical for long offset distances. The system uses seawater as the return path. This reduces the diameter of the power cable and increases the available power to the system. This is a common application typically applied in the power industry.

A key part of the all-electric subsea system is the electric tree system. The system uses a fail-safe-close electrical actuator system. The actuator is made up of a drive motor and a clutch motor. The drive motor is responsible for forcing a valve open against a closing spring. Once the valve is open, the motor stops and the clutch motor ensures that the valve remains in the open position using a friction-based mechanism. The architecture is such that in the open position, the drive motor is fully unloaded. Only a small amount of power (<100w) is required to hold the valve in position of normal operations. An interruption in the electrical supply causes the valve to move to a safe closed position, with the closing of the spring. The principle of –fail-safe-close at the loss of power provides the safety requirements for well applications. The electrical choke, on the other hand, is a fail as-is system. It remains at its last know position if power is lost from the system.

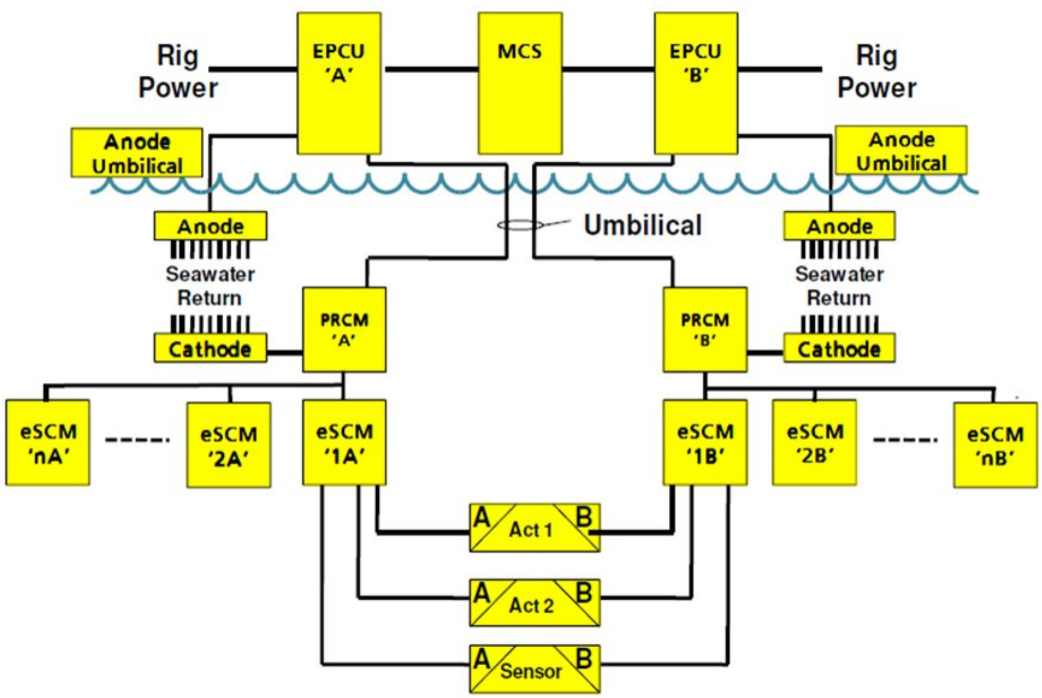


Figure 58 First generation all-electric technology concept

The system high bandwidth allows for the transfer of large of condition monitoring data to and from the topside units even for complex subsea architecture. Depending on design requirements, the eSCM can control up to 32 electrical actuators. For increased reliability and availability, all key components of the system like the PSU, modems and motor controllers are designed for self-protection against short-circuiting. The eSCM also provides interface for tree interface and other 3rd part control units.

The use of fibre optics for communication in the all-electric system enables communication to very long distances. However, a repeater system is sometimes required when very long distances. Repeater systems covering up to 13km or more are commercially available. These systems are very reliable and offer speeds far above those required by the subsea systems.

Similar to the EH system, valve and choke operation for this system is initiated at the topside MCS. The signal is transmitted through the fibre optics link and delivered to the specified PRCM. The PRCM on receipt of the command, requests sufficient power from the topside, regulates it and transmits same to the eSCM after a few seconds of stabilisation. The eSCM then drives the actuator until the sensor indicator shows that the valve is open to its maximum aperture. The drive power then reduces and the actuator is held open with a minimal held power typically 1% of the drive power. In the idle mode (without operation of valve or choke), the eSCM only needs sufficient power to keep the actuator open and to for running of diagnostics and delivery of system readings. Higher power is only required for actuator open sequences.

6.3 The advantages of the All-electric system.

The all-electric system also addresses some health, safety and environmental (HSE) concerns. Hydraulic fluids and associated equipment's are eliminated. Similarly, equipment's required for the storage, pumping, pressurisation, filtering and disposal of the fluids are also eliminated with a significant benefit. Personnel contact with the fluid, slippage, deck spillage during handling or leakage are also eliminated. The absence of high pressure accumulator bottles and lines on the topside lso brings a huge HSE advantage.

In summary, key merits of the all-electric system over the conventional electro-hydraulic system are listed below:

- Enhanced HSE. The elimination of the HPU system and the associated fluid including their storage systems leads to improved HSE.
- Higher reliability - The all-electric system brings about faster response time and reduced failure points.
- Reduced cost. Umbilical geometry is simplified and size reduced. Hydraulic infrastructure and consumption is eliminated for both subsea and topside units.
- Technology merits: The all-electric system is less sensitive to water depth and tie-back distances, offers faster and better choke operations and lower consumption

6.4 The All-electric SCM

The electrical Subsea Control Module (eSCM) provides all the required power for the opening and closing of valves on the associated subsea equipment (figure 59). It is also responsible for receiving and delivery of data to the topside system and vice versa. Interfaces with the entire subsea production system for actuator control, emergency shutdown/production shutdown control including all subsea data/housekeeping management.

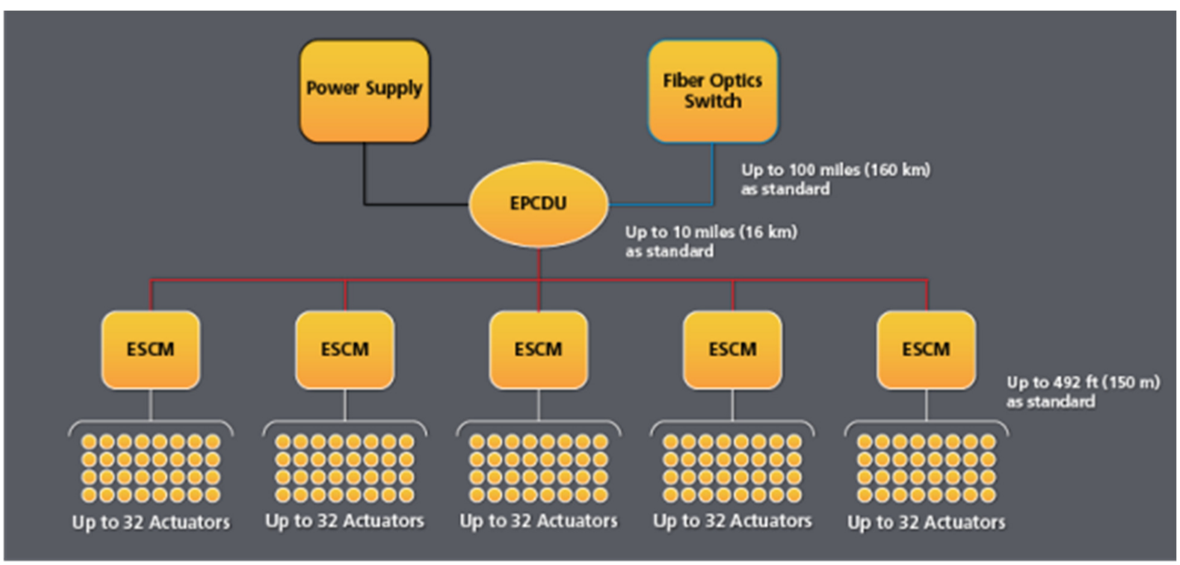


Figure 59 All-electric subsea controls showing the eSCM, courtesy Cameron

Valve actuation from the eSCM does not require control fluids as in the EH Mux systems, providing environmental friendliness. The e-SCM is supplied with a stabilised direct current (DC) coming from the power and regulation control module (PRCM). One PRCM serves up to eight e-SCMs. Each PRCM power is delivered using a dedicated coaxial cable tied directly from the topside. The system allows for simultaneous actuators operation of several valves so far it is within the power limits of the system.

Latest standards such as IWIS and ISIS are in use for the eSCM system.

The eSCM typically contains the following components:

- Ethernet switch/router
- Power supply
- Central processing Unit/controller
- Current monitor – Low/High
- Power switch controller
- Switches
- Process shutdown controller

6.5 The EH and all-electric SCM Risk assessment Comparative Analysis

The risk factors being considered in this evaluation are listed below. These criteria are based on industry concern on the need to improve the delivery of subsea controls from the electro-hydraulic (EH) system (Thebald 2005, Bouquier 2007, Akker 2009).

1. Occurrence (O)
2. CAPEX (C)
3. OPEX (P)
4. Environment (E)
5. Technology (T)
6. Schedule (S)

The occurrence (O) factor evaluates the probability of failure in the two systems system. System failure in subsea developments are highly undesirable as the smallest intervention typically runs into millions of dollars. The cost factors evaluate the expenditure associated with implementing the electro-hydraulic system in comparison to the all-electric SCM option. This is split into the CAPEX (C) and OPEX (P) components, CAPEX being cost associated with the development and implementation of the system while OPEX are those required for the running of the system.

Environment (E) evaluates the associated risk to the environment and environmental regulations relating to the implementation of the system. The technology (T) factor looks at the ease of implementation of the system, its robustness, efficiency and acceptability including access to competent resources for its deployment. The schedule (S) factor looks into the risk in terms with the associated time line required to plan, design, construct and deploy the system for a typical subsea projects. Some projects are heavily schedule-dependent. This factor looks at the challenges associated with meeting a typical subsea development schedule.

6.5.1 Characterisation of Experts

The all-electric subsea controls is relatively new in the offshore oil and gas industry with few data recorded on its operations. Five industry experts were used for this evaluation. Three of these industry experts came from the OEM firms for these systems while two were from the operator's side. The average experience of these experts is ten years in the industry. This represents a substantial experience in the profession to be assessed as being credible to provide an expert info that could be used for the evaluation.

The evaluation was also carried out through a face-to-face evaluation. This was to ensure that every answer provided had a credible and objective reasons behind the evaluation. It however added to the project cost as these experts were located in various continents of the world. The approach was again adopted so that the associated results is not skewed to a non-objective reasoning.

6.5.2 The comparison evaluation between EH SCM and eSCM

A TOPSIS methodology is applied in the comparative analysis between the EH SCM and the eSCM. The steps shown in chapter four is being adopted for this evaluation. The alternatives being evaluated are:

- A_1 - The Electro-hydraulic SCM and
- A_2 - The all-electric SCM

The risk factors being considered for the evaluation are:

R_1 – Occurrence (O)

R_2 - Capex (C)

R_3 – Opex (P)

R_4 - Environment (E)

R_5 – Technology (T)

R_6 – Schedule (S)

The linguistic scale used for the weight evaluation is shown below:

Table 27 Linguistic scale for the importance of each risk factor

Linguistic variable	Corresponding triangular fuzzy number
Very Low (VL)	(0.0, 0.0, 0.1)
Low (L)	(0.0, 0.1, 0.3)
Medium (M)	(0.3, 0.5, 0.7)
High (H)	(0.7, 0.9, 1.0)
Very High (VH)	0.9, 1.0, 1.0)

The linguistic scale used in rating the alternatives against the risk factors is as shown below:

Table 28 Linguistic variables for the rating of the alternatives against the risk factors

Linguistic Variable	Corresponding TFN
Very Low (VL)	(0, 0, 1)
Low (L)	(0, 1, 3)
Medium Low (ML)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium High (MH)	(5, 7, 9)
High (H)	(7, 9, 10)
Very High (VH)	(9, 10, 10)

The experts used the scale in table 27 to evaluate the importance of each risk factor and the result is as shown table 29.

Table 29 Importance weight of the risk factors

	D_1	D_2	D_3	D_4	D_5
Occurrence (O)	VH	H	VH	VH	VH
CAPEX (C)	M	H	M	H	VH
OPEX (P)	H	H	H	M	H
Environment (E)	H	H	VH	H	VH
Technology (T)	H	H	VH	H	H
Schedule (S)	M	H	H	M	M

The experts also used the scale shown in table 28 to rate the alternatives against each of the risk factors and the result is as shown in table 30 below.

Table 30 Rating of the alternatives using the linguistic scale

		D_1	D_2	D_3	D_4	D_5
OCCURRENCE (O)	A_1	MH	H	H	H	VH
	A_2	M	H	H	MH	H
CAPEX (C)	A_1	H	MH	H	H	H
	A_2	M	H	M	MH	M
OPEX (P)	A_1	VH	MH	H	VH	H
	A_2	L	ML	M	ML	L
ENVIRONMENT (E)	A_3	M	H	MH	M	M
	A_4	L	ML	L	M	L
Technology (T)	A_1	MH	M	H	H	M
	A_2	L	M	H	M	ML
Schedule (S)	A_1	ML	M	L	ML	L
	A_2	L	H	ML	M	L

Applying the tables 27 and 28 to tables 29 and 30, the fuzzy decision matrix and fuzzy weights of the alternatives are as shown in table 31:

Table 31 Fuzzy decision matrix of the SCMs showing weights of the risk factors

Alternatives	OCCURRENCE (O)	CAPEX (C)	OPEX (P)	Environment (E)	Technology (T)	Schedule (S)
	Weight W_O	Weight W_C	Weight W_p	Weight W_E	Weight W_T	Weight W_S
	(0.9, 0.98, 1.0)	*(0.3, 0.76, 1.0)*	*(0.3, 0.82, 1.0)*	*(0.7, 0.94, 1.0)*	*(0.7, 0.92, 1.0)*	*(0.3, 0.66, 1.0)*
A_1	(5.0, 8.8, 10)	(5, 8.6, 10)	(5.0, 9.0, 10))	(3, 6.2, 10)	(3.0, 7.0, 10)	(0.0, 2.6, 7.0)
A_2	(3.0, 7.8, 10)	(3.0, 6.2, 10)	(0.0, 2.6, 7.0)	(0.0, 2.2, 7.0)	(0.0, 6.6, 10)	(0.0, 3.8, 10)

Next, the normalised fuzzy decision matrix for the SCM alternatives is shown in table 32:

Table 32 Normalised Fuzzy decision matrix of the SCMs showing weights of the risk factors.

Alternatives	OCCURRENCE (O)	CAPEX (C)	OPEX (P)	Environment (E)	Technology (T)	Schedule (S)
	Weight W_O	Weight W_C	Weight W_p	Weight W_E	Weight W_T	Weight W_S
	(0.9, 0.98, 1.0)	*(0.3, 0.76, 1.0)*	*(0.3, 0.82, 1.0)*	*(0.7, 0.94, 1.0)*	*(0.7, 0.92, 1.0)*	*(0.3, 0.66, 1.0)*
A_1	(0.5, 0.88, 1.0)	(0.5, 0.86, 1.0)	(0.5, 0.9, 1.0)	**(0.3, 0.62, 1.0)**	(0.3, 0.7, 1.0)	(0.0, 0.26, 0.7)
A_2	**(0.3, 0.78, 1.0)**	(0.3, 0.62, 1.0)	(0.0, 0.26, 0.7)	(0.0, 0.22, 0.7)	(0.0, 0.66, 1.0)	(0.0, 0.38, 1.0)

Applying the weights, the weighted normalised fuzzy decision matrix of the SCM alternatives are shown in table 33:

Table 33 Weighted normalised Fuzzy decision matrix of the SCM alternatives.

Alternatives	OCCURRENCE (O)	CAPEX (C)	OPEX (P)	Environment (E)	Technology (T)	Schedule (S)
A_1	(0.45, 0.86, 1.0)	(0.15, 0.65, 1.0)	(0.15, 0.74, 1.0)	**(0.21, 0.58, 1.0)**	(0.21, 0.64, 1.0)	(0.0, 0.17, 0.70)
A_2	**(0.27, 0.76, 1.0)**	(0.09, 0.47, 1.0)	(0.0, 0.21, 0.70)	(0.0, 0.21, 0.70)	(0.0, 0.61, 1.0)	(0.0, 0.25, 1.0)

The fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solutions (FNIS) are obtained as shown below:

$A^* = [(1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1)]$

$A^- = [(0.27, 0.27, 0.27), (0.09, 0.09, 0.09), (0.0, 0.0, 0.0), (0.0, 0.0, 0.0), (0.0, 0.0, 0.0), (0.0, 0.0, 0.0)]$

The distance of the alternatives to the FPIS and FNIS is then evaluated using the vertex method. The distance to the positive ideal solution is shown in table 34:

Table 34 Distance from the positive ideal solution.

	O*	C*	P*	E*	T*	S*	d^+
d (A_1, A*)	0.33	0.53	0.51	0.52	0.50	0.77	1.89
d (A_2, A*)	0.44	0.61	0.75	0.76	0.62	0.72	2.56

Similarly, the distance to the negative ideal solution is also evaluated as shown in table 35:

Table 35 Distance from the negative ideal solution

	O-	C-	P-	E-	T-	S-	d-
d (A_1, A^-)	0.55	0.62	0.72	0.68	0.70	0.42	2.02
d (A_2, A^-)	0.51	0.57	0.42	0.42	0.68	0.60	2.09

Finally, a correlation coefficient of the alternatives and ranking is then evaluated and the result is shown in table 36

Table 36 SCM Correlation coefficient and ranking

	CCi	Ranking
Electro-hydraulic SCM (A_1)	0.52	1
All-Electric SCM (A_2)	0.45	2

Tables 34 and 35 demonstrate the closeness of the two alternatives to the associated risks. In table 34, the distance on the probability of failure occurrence (O) for the electro-hydraulic system (EH) is 0.33 compared to 0.44 for the all-electric system showing that the occurrence (O) for the electro-hydraulic system is perceived to be higher. In the same way, the CAPEX (C), OPEX (P), Environmental risk (E) and Technology risk (T) are all closer to the FPIS. These values eventually lead to a higher value of correlation coefficient for the electro-hydraulic (EH) SCM.

The above result shows that EH SCM, with a correlation coefficient of 0.52 has a comparatively higher risk than the all-electric SCM (eSCM). This demonstrates that the eSCM is a less risky technology and would probably be the technology of the future. This is particularly due to its huge CAPEX savings, efficiency, OPEX and performance.

6.6 Summary of Evaluation

The requirement for extraction of hydrocarbon from harsh and unconventional offshore terrain prescribes the need for innovative techniques for efficiency as well as capital benefits. The all-electric system proves to be a potential candidate for this replacement and solution.

The all-electric system demonstrates enormous potential for replacing the EH system as it offers improvements in system availability, reliability and operability which leads to a significant CAPEX and OPEX savings while addressing key HSE issues in the offshore oil and gas production.

In this analysis, the conventional EH SCM was compared to the all-electric SCM (eSCM). The analysis was based on six key criterion, Failure occurrence (O), Capex (C), Opex (P), Environment (E), Technology (T) and schedule (S) for delivery. The above evaluation shows that the eSCM deployment is less risky than the conventional SCM. Undoubtedly, the eSCM offers a significant merits in performance for deep, ultra-deep waters and long step-out distance as execution commands are delivered in seconds and condition monitoring data are delivered in much less time that time to the topside control systems than those of the EH system. The elimination of hydraulics and entire circuitry from the eSCM system brings in improved reliability and a significant HSE advantage. The all-electric choke concept powered by eSCM offers the operator an ability to return to any desired position within seconds in the choke system during operations. This is not practical with the current EH choke system as it takes minutes if not hours to do this.

As the oil and gas business pushes its limits to the deep and ultra-Deepwater domain, the incremental advantages of the eSCM becomes a big factor. The tougher environmental regulations coming in from the governments' local authorities also make the eSCM an attractive option over the conventional EH SCM considering the HSE and reliability merits involved.

In summary, though the above analysis demonstrates a huge benefit to the electro-hydraulic option, there still room for more analysis to be performed using more criteria. One of the key limitations in this analysis is that quite a few engineers worldwide have worked on the all-electric system, so it was quite difficult sourcing for the right experts to respond to the survey.

7 Discussions

7.1 OREDA SCM Data evaluation and validation

OREDA is the oil and gas industry reliability baseline database. Its main purpose is to collect and exchange reliability data among the participating companies and act as 'The Forum' for co-ordination and management of reliability data collection within the oil and gas industry. The OREDA JIP has established a comprehensive database with reliability and maintenance data for exploration and production equipment from a wide variety of geographic areas, installations, equipment types and operating conditions.

Offshore subsea and topside equipment are primarily covered, but onshore equipment is also included. The data are stored in a database, and specialised OREDA software and guidelines have been developed to collect, retrieve and analyse the information. This enables participating companies to comply with the ISO 14224 standard.

It provides the Vehicle to meet the need for subsea reliability performance for oil & gas industry, and is managed through the OREDA project organisation sponsored by the following 10 oil companies with worldwide operations namely (Ostebo 2001):

- BP
- Chevron
- ENI/Agip
- TotalFinaEl
- ExxonMobil
- Norsk Hydro
- PPCON
- Shell
- Statoil and
- Texaco

OREDA's main purpose is to collect and exchange reliability data among the participating companies and act as 'The Forum' for co-ordination and management of reliability data collection within the oil and gas industry.Data collection is done by:

- Collection and sharing of OREDA®-type data into the joint OREDA-industry database in accordance with annual data collection plans in the JIP
- Secondly, performing additional OREDA®-type data collection as required within each company, which later can be fed into an updated industry database.

The following equipment's are covered in the OREDA reliability database – Control systems (including topside controls, subsea control module, umbilicals), flowlines, manifolds, production risers, running tools, wellhead and Xmas trees, templates and subsea pumps. OREDA makes it possible to extract and analyse failures with some defined similarities, calculate variables like failure rates, downtime, trends and perform benchmarking. The subsea database is used by the participating companies to record their real life data on their subsea experience. This provides a sound platform for the exchange of subsea info among participating companies and the users.

The analysis was conducted based on data obtained from OREDA based on subsea installations located in water depths ranging from shallow water 22m to deepwater 1300m in a combination of satellite, manifold templates and clustered well developments. A total of 7,480 subsea control modules were used in the analysis in fields covering the North Sea, Gulf of Mexico (GoM), the West African waters, Guinean gulf, Adriatic Sea and West of Shetland. Again, a combination of driverless and diver-assist systems were analysed. Below is a summary:

- No of SCM – 69
- Number of components analysed - 7480
- Water depth: 22 – 1300m

- Location: North Sea. GoM, Gulf of Guinea, West of Shetland and West Africa

Table 37 shows a count of the various components that were used in the analysis. This included the SCM accumulator system, the chemical injection couplings, filters, power/signal couplers, power supply units (PSU), module base plates, hydraulic couplings, solenoid control valves, subsea electronic module (SEM) including other miscellaneous valve and components.

Table 37 Total number for the SCM components analysed

SCM Components	No of Components	No of Failures	No of Critical Failures
Accumulator - subsea	464	2	0
Chemical injection coupling	130	0	0
Filter	586	1	0
Hydraulic coupling	1218	6	2
Module base plate	457	4	4
Other	453	16	10
Power supply unit	304	0	0
Power/signal coupler	1262	5	1
Solenoid control valve	1629	66	35
Subsea electronic module	605	258	100
Unknown	13	0	0
Valve, check	138	2	1
Valve, other	221	7	1
Total	**7480**	**367**	**154**

The analysis showed that the subsea electronic module has the highest number of failures as 42.7% of the component failed representing a whopping 70.30% of the entire number of failures recorded during the period of the failure survey. This is closely followed by the SCM solenoid valves in which a total of 66 failed representing a total of 17.98% failure during the same period. A summary of the number of SCM component failures as analysed from the OREDA database is shown in figure 60.

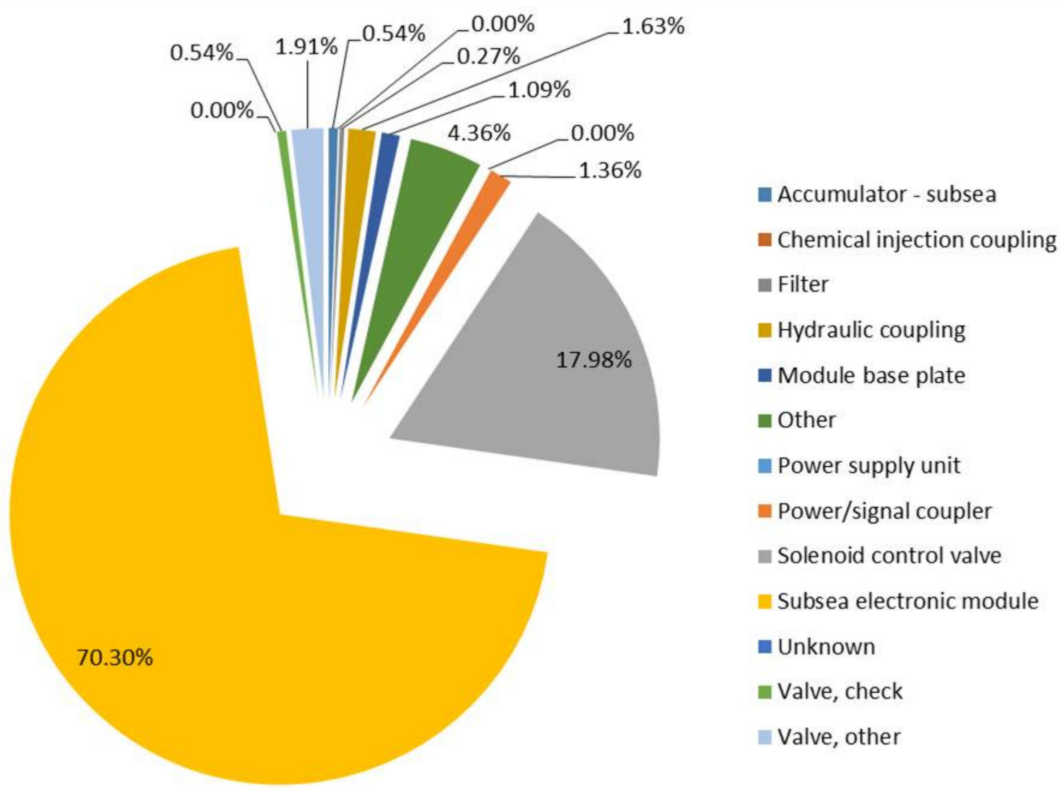


Figure 60 SCM Components failure.

The analysis also revealed the subsea electronic module (SEM) as the primary culprit for critical failures in the SCM. As shown in figure 61, the SEM had a total of 64.94% of the SCM critical failures. Critical failures in the SCM are failures that lead to loss in production from that well. Normally, this will involve a retrieval, repair and replacement or an outright replacement of the faulty SCM.

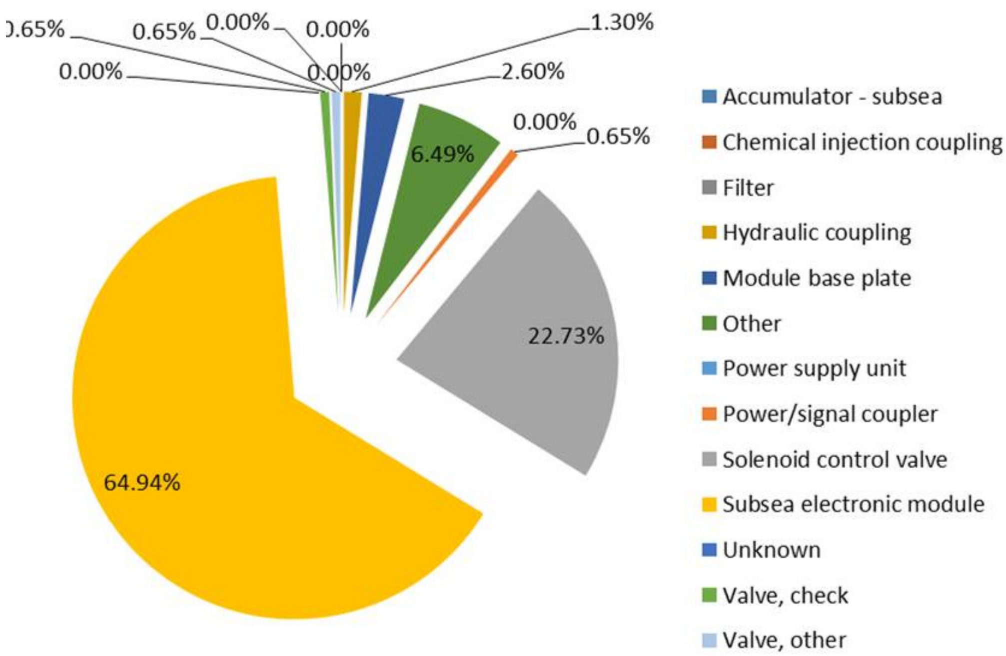


Figure 61 SCM critical failures.

The analysis also shows that the solenoid control valves as having the second highest critical failures in the SCM. These are the LP and HP directional control valves (DCVs) responsible for the control of the production tree valves including the surface controlled subsurface safety valve (SCSSV), the intelligent control and chemical injection valves.

The above analysis from OREDA validates the fuzzy TOPSIS analysis results shown in section 7.1 including those obtained from the stochastic inputs in chapter five (5). The fuzzy TOPSIS analysis showed that the three most critical failure modes in the SCM are:

- Severe leakage in HP DCV
- Severe leakage in LP shuttle valve and
- Loss of power from the SEM unit

The HP DCV controls the surface controlled subsurface safety valve (SCSSV), a primary well control barrier. It also controls the downhole intelligent control valves. These two functions are very critical to the operation of any production well as failure leads to shutdown and eventual loss in production. This confirms that the SEM and the solenoid control valves (HP and LP) are the most critical failures in the subsea control module (SCM).

7.2 SCM FMECA and Fuzzy TOPSIS analysis

In Chapters 3 and 4, a reliability analysis of the SCM was made using FMECA and the multi-criteria Fuzzy TOPSIS methodology. These evaluations were based on thirty (30) most critical failure modes deducted from a comprehensive and detailed failure modes and effect criticality analysis (FMECA) conducted for the subsea control module (SCM). The study was based on a tree-mounted SCM for control of hydrocarbon fluids from a production well. A summary of the results is as shown in tables 38.

Table 38 SCM failure modes showing ranking from FMECA and Fuzzy TOPSIS evaluation.

Failure Modes	Failure ID	FMECA Ranking	Fuzzy TOPSIS Ranking
Severe leakage from HP DCV	F5	3	1
Severe leakage on the LP Shuttle valve	F9	2	2
Loss of power supply from the SEM Unit	F1	1	3
SCM housing check valve cracks open at lower pressure	F2	6	4
Loss of HP Accumulation	F7	3	5
Total Loss of signal from the SEM module	F3	5	6
Severe leakage from LP DCV	F8	7	7
Loss of HP hydraulic filtration	F6	10	8
Loss of LP accumulation	F11	9	9
Severe leakage on the HP shuttle valve	F10	12	10
Loss of SCM pressure compensation	F16	19	11
Severe leak in the LP common hydraulic header	F13	14	12
Loss of LP hydraulic filtration	F4	13	13
Shuttle valve fails to change over to the next LP supply line	F14	7	14
LP DCV shuts spuriously from the open position	F24	19	15
HP DCV shuts spuriously from the open position	F19	14	16
LP DCV fails to shut on demand from the open position	F21	17	17
Shuttle valve fails to change over to the next HP supply line	F12	10	18
LP selector valve fails to open	F15	17	19
Loss of electronic monitoring of the HP supply pressure	F26	16	20
HP DCV fails to open on command	F17	23	21
LP DCV fails to open on command	F18	19	22
Loss of monitoring signal from the water ingress sensor	F22	24	23
Loss of electronic monitoring of the LP return flow	F27	19	24
LP selector valve spuriously closes	F23	27	25
HP DCV fails to shut on demand from the open position	F20	25	26
Loss of electronic monitoring of the LP supply pressure	F25	27	27
Loss of electronic monitoring of the HP return flow	F28	26	28
Loss of the SCM internal pressure monitoring	F29	29	29
Loss of the SCM internal temperature monitoring	F30	30	30

Based on table 38, a correlation between the FMECA criticality rankings and those obtained from fuzzy TOPSIS analysis is shown in figure 62.

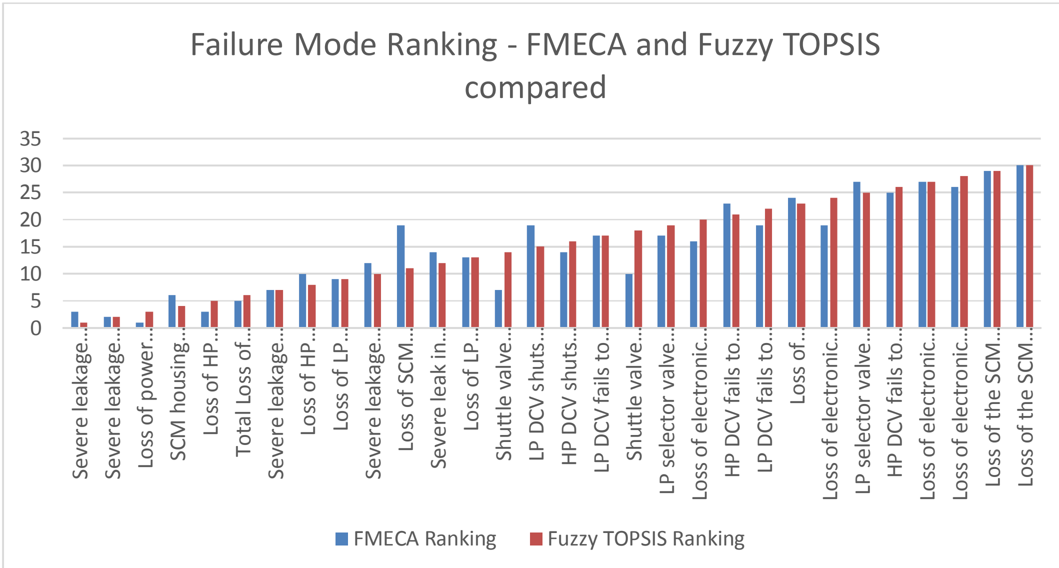


Figure 62 Correlation between the SCM FMECA and the fuzzy TOPSIS evaluation

A correlation coefficient of 93.5% is obtained between the two methods. From both evaluations, we see that the top 10% most critical failure modes are:

- Severe leakage in HP DCV
- Severe leakage in LP shuttle valve and
- Loss of power from the SEM unit

The HP DCV is responsible for the control of the well SCSSV, a primary safety barrier in the well production tubing. The HP DCV is also responsible for the control of the intelligent well control valves (ICVs) which are responsible for production isolation in multi-zone intelligent well completions, reduction in unwanted water and gas production, minimisation of well intervention and enhancement of well productivity. The HP DCV is also responsible for methanol and other flow assurance chemical injections to the well stream. These functions in a typical production tree system, makes the HP DCV a very critical part of the SCM.

The LP shuttle valve is the entry point for the two redundant LP lines coming from the control umbilical. Most tree valves are LP-driven. A severe leakage at the LP shuttle valve means a loss in all LP control functions in the production tree system and invariable a loss in well control.

Very critical and with virtually an overriding function is the SEM unit. The SCM DCV valves are solenoid-driven with electrical power coming from the SEM unit. This implies that a loss in power from the SEM unit leads to a loss in both LP and HP functions including a total loss in signal delivery to and from the topside unit.

Similarly, the bottom 10% of the evaluation shows the following the failure modes listed below with a ranking correlation of 96%.

- Loss of electronic monitoring of the HP return flow
- Loss of the SCM internal pressure monitoring
- Loss of the SCM internal temperature monitoring

A loss in the internal temperature of the subsea control module, much like any other failure mode is important. However, a loss in this signal does not automatically lead to a loss in production or a requirement for the retrieval and re-installation of the SCM. In the loss of this signal, other parameters could be deductively used to determine the status of the internals of the SCM. This also applies to some extent to loss in the internal pressure monitoring of the SCM. The SCM may continue operations until such a time that a retrieval and re-installation is properly planned. The monitoring in the HP return flow is very important during the operation of the SCM. This gives an indication of the extent to which the valve is opened or closed. A significant process change as a result of a loss in this signal will require a retrieval and re-installation of a new or replacement SCM.

7.3 Subsea Control Module Reliability – A case Study

This study is based on an FPSO development with subsea completion wells installed in a remote Deepwater in West-Africa. The field control philosophy is electro-hydraulic (E-H). The tree system is installed on a well producing approximately ten thousand barrels of oil per day (10,000 bopd). The SCM was installed in an enhanced horizontal tree system (EHXT) for well control on a satellite configuration with a direct tie-back to the processing facility. The field layout had five wells, XT_P1, XT_P2, XT_P3, XT_G1 and XT_W1, the first three being producer wells while the fourth and fifth were gas injection and water injection wells respectively.

The SCM mounted on XT_P1 was recovered to a well intervention vessel as a result of a subsea control failure after some months of production from the well. Water ingress was noticed from the topside control unit. Without replacement, the SCM subsea electronic module (SEM) failed after a while. Being a dual-redundant sub-system, the controls operation was switched to the second channel utilising the second SEM, which eventually failed leading to a complete loss of communication to the topside units, well shut-in and total loss in production from the well. The case study illustrates the importance of SCM and how the failure of a subsea control module (SCM) component affects the reliability of the entire subsea production system. It also reveals the sensitivity and interconnectivity in relative dependence on how the failure of one component affects the failure of the next sub-system or component and its overall significance to the SCM system reliability. Details of the operator has been masked for confidentiality reasons.

7.3.1 The Field concept and architecture

The field concept was such that five subsea wells were on a tie-back to spread-moored FPSO in about 800metres water depth (see figure 63). FPSO concepts are particularly preferred options for remote and deep water developments as they eliminate the need for laying long expensive pipes to onshore facilities. Again, they are relative quicker to mobilise and less demanding for decommissioning purposes. The ability to move and reuse the FPSO in a new location at the end of a field life also offers a huge CAPEX advantage.

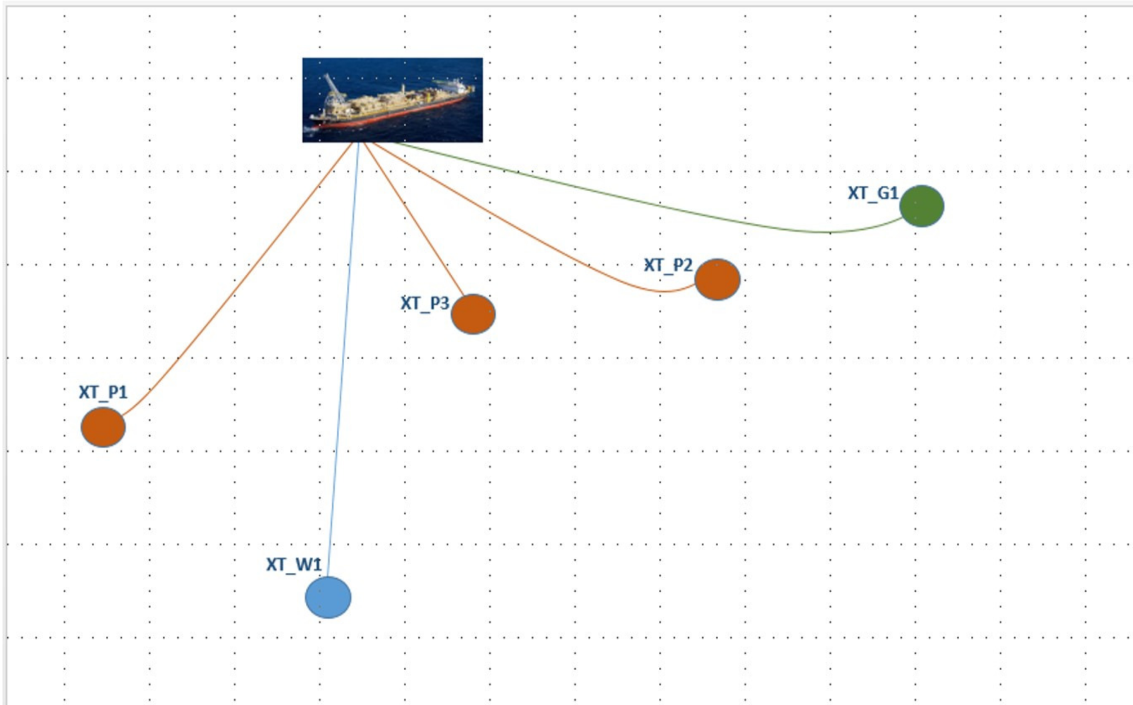


Figure 63 Field Layout under case study

There were three producer wells in the field XT_P1, XT_P2 and XT_P3, one water injection well XT_W1 and one gas injection well XT_G1. The field has an optimum daily production of 24,000barrels of oil per day tied back to an FPSO with a storage capacity of 500,000barrels, located at average step-out distance of 2000m from the wells.

The tree system in the field was of Enhanced horizontal (EHXT) type designed in accordance with API 6A and API 17D and had a design life of 15years based on the field production profile. Based on a production bore of 5.1/8'' and an annulus bore of 2.1/16'', the 5,000psi horizontal tree provides the primary control of produced fluids from the subsea well and monitoring of temperature and pressure. It also allows for a safe execution of well workover and intervention of the well as it connects to the wellhead with a HT-H4 hydraulic connector. The tree was modular built, comprising of the choke valve block, wing valve block, spool body, isolation sleeve, wellhead connector, process pipe work and the tree frame. The tree 18 ¾ 10,000psi HT-H4 connector provides the pressure containment and structural strength for connection to the subsea wellhead. The tree to wellhead interface is sealed with a VX gasket which is retained hydraulically.

The tree master valve block (MVB) had a concentric stepped internal profile for the tubing hanger, integral production and annulus master valves and annulus access valve. A wing block that houses the rest of the valves is bolted to the treehead. The tree upper connection was a standard 18 ¾ outer diameter H4 mandrel profile, which allows for the landing of a BOP stack on top of the tree. The tree has a front-mounted ROV panel with class4 rotary valve overrides based on ISO13628-8. Due to flow assurance considerations like hydrate, wax, emulsion…etc., and considering the low seabed temperature, the tree is also insulated. Control of the tree is achieved with an SCMMB-mounted subsea control module.

7.3.2 The Field SCS philosophy

Starting from the topside, the subsea control system (SCS) is made up of the electrical power unit (EPU), hydraulic power unit (HPU) and the master control station (MCS). An uninterruptible power supply (UPS) provides and maintains power for the complete SCS units in redundant configuration (see figure 64). Each UPS unit is equipped with inverter, rectifier and a standard sized battery bank. The SCS provides a comprehensive power, control and monitoring starting from the surface interface to all the subsea installed equipment. Acquired data is displayed in the topside HMI, allowing for proper monitoring of the entire system. The MCS, located topside had a dual redundant operating system operating. The system is equipped with dual redundant programmable logic controllers to allow for the monitoring and control of the EPU functions including the ESD system

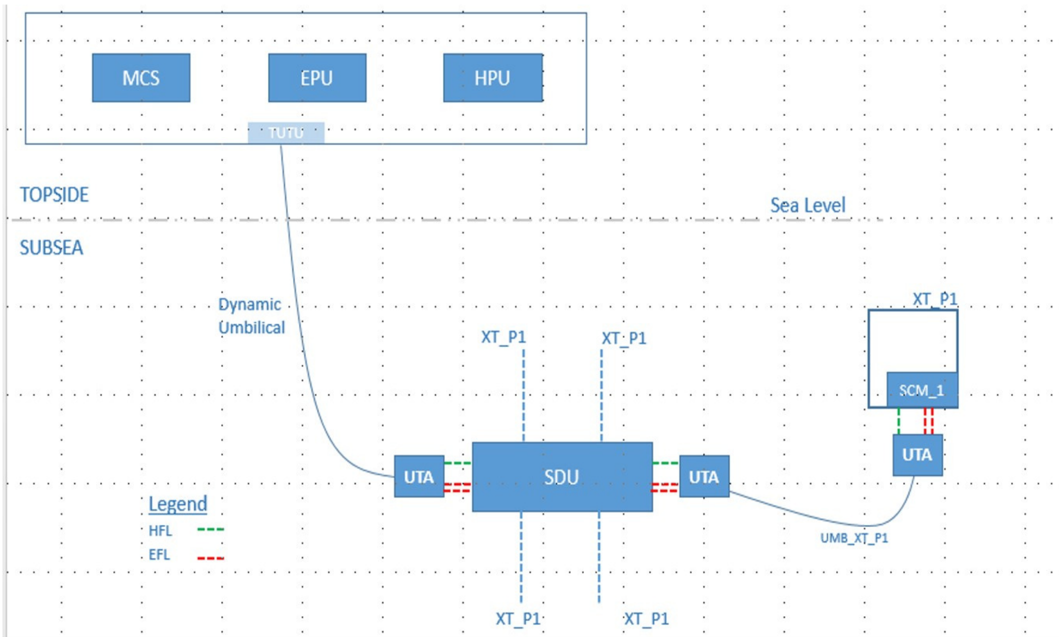


Figure 64 The Field SCS architecture

The HPU provides the hydraulic supply to the field routed through a topside umbilical termination unity (TUTU) to a dynamic umbilical. The control fluid from the HPU is maintained at a cleanliness level of SAE AS 4059C Class 6B-F or better. The HPU supply is regulated and monitored from the operator's workstation in the control room.

A common dynamic umbilical delivers power, control and chemical injection functions from the topside umbilical termination assembly (TUTU) and electrical junction boxes to a 6-port subsea distribution unit (SDU) on the seabed. The umbilical contains 2-off LP lines plus a spare, 2-off HP lines plus a spare, methanol injection and other chemical injection lines for flow assurance purposes. The topside tie-in is such that the dynamic umbilical runs down to an umbilical termination assembly (UTA) located at the seabed while hydraulic and electrical flying leads tie-in the UTA to the SDU.

On the other end also, a hydraulic flying lead (HFL) in combination with a pair of EFLs in redundancy connects the SDU to each of the out-going infield static umbilicals to the trees. Finally, the HFL at the end of the infield umbilical UTA is connected to the tree MQC while the EFLs are directly connected to the SCM.

The control philosophy in the field is Communication on Power (COP), closed loop electro-hydraulic (E-H) with the control fluid returning to the topside HPU during depressurisation. This means that the same cable carries a combination of power and communication signals. The signal for control execution is multiplexed at the SCM SEM. The SEM is also responsible for power regulation and for energising of the solenoid-based DCVs responsible for the control of the LP/HP tree valves, downhole intelligent control including condition monitoring downhole pressure and temperature (DHPT) values.

7.3.3 The SCM

The subsea control module (SCM) is a part of the subsea tree system, normally mounted on a SCMMB (see figure 65) and responsible for the control and monitoring of subsea mounted equipment in a subsea production system (SPS).

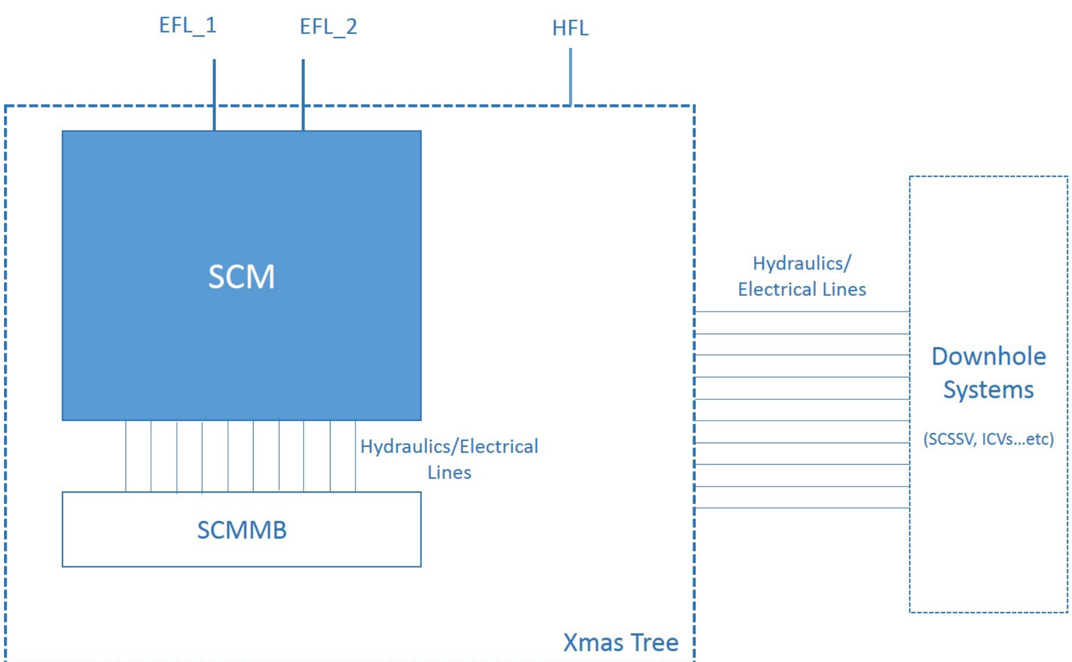


Figure 65 SCM mounted on the SCMMB showing interconnections in the SPS

Figure 65 also shows the SCM interconnections with the tree system and other SPS components. The SCM is retrievable and re-installable with the aid a multi-purpose tool in conjunction with a work-type remote operated vehicle (ROV). The installation operation is guidelineless and requires the latch of the SCM to the SCMMB during the operation using the ROV.

The SCM contains two redundant SEM, all purged and filled with inert nitrogen at 1bar (14.5psi) pressure. The SCM serves two key functions. First is the delivery of all LP/HP control functions while the second is the acquisition of subsea data and delivery of same to the topside units. Filters are provided in the SCM LP and HP headers to ensure that only clean fluids get into the control circuitry.

The SCM had thirty two function valves delivering LP, choke and HP functions. Self-sealing male hydraquad couplers provided at the baseplate of the SCM mated automatically with their female halves mounted in the SCMMB. Each hydraulic output function has a separate DCV. The DCVs were 2-way, 3 position types operated by integral solenoid valves in the DCV valve module. The solenoid valves all had low power consumption (<10watts). The functional valves were electrically pulsed, but hydraulically latched open such that the piloted DCVs remain in their current position when the electrical signal is eliminated. As shown in figure 66, the hydraulic latch comes from the LP pilot supply used for opening of the functional valves. In the event of loss in power and communication to the SCM, the LP functions remain as-is. In the event of loss in LP supply from the umbilical, all LP function valves in the tree will fail to their safe position. This way all actuators move to their fail safe positions. In the same way, the LP choke remains as-is for loss of power and communication to the choke DCV in the SCM. The operation of the HP functional valves is quite similar to that of the LP functions. However, its hydraulic supply comes from dual redundant HP lines.

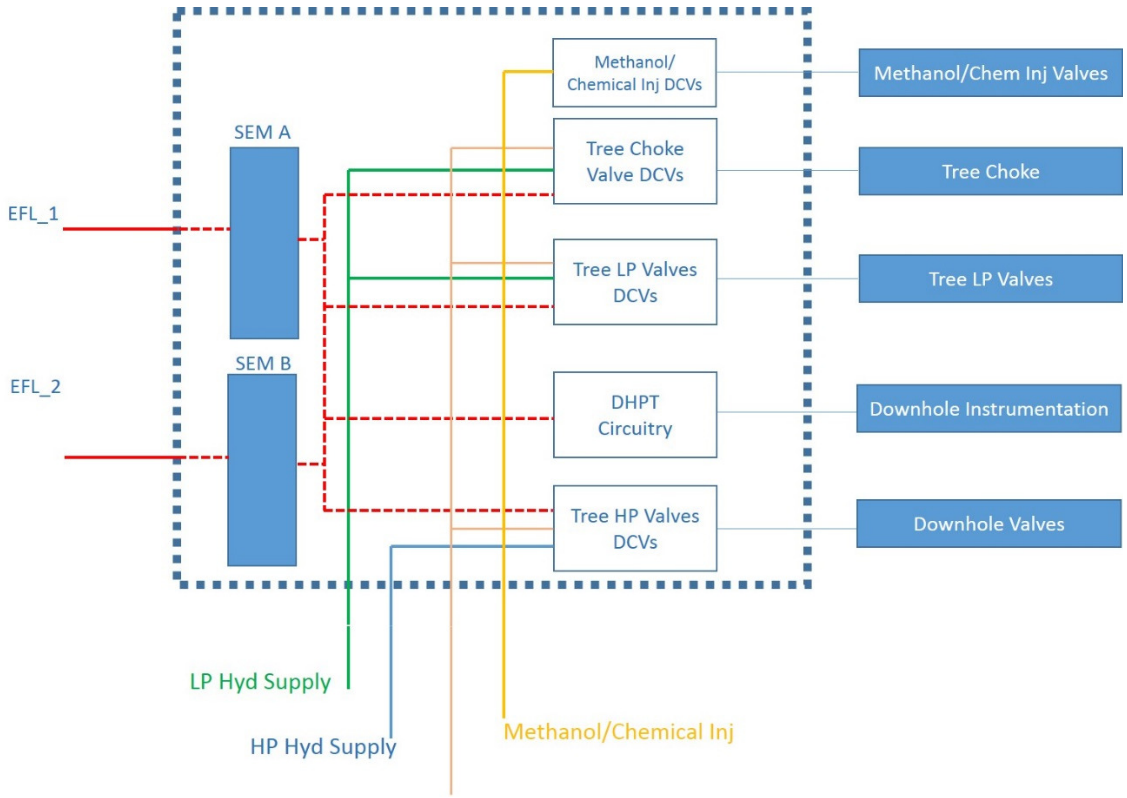


Figure 66 The SCM Architecture

7.3.4 The failure mode analysis

This case study is meant to illustrate how the interconnectivity between failure modes, the associated severity, the importance of detection in subsea control module reliability and a requirement for good IMR practise in the offshore subsea industry. This is depicted in figure 67.

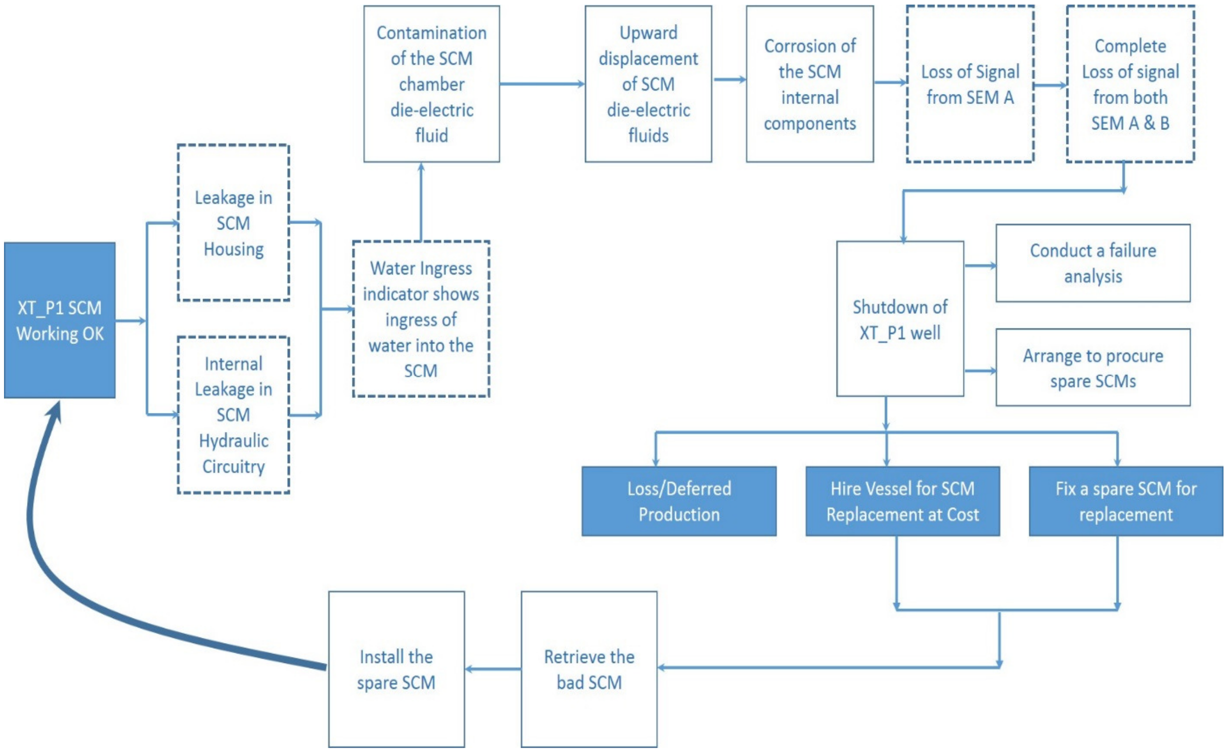


Figure 67 Case study – The failure mode analysis

The SCM on the XT_P1 well was working fine for about three years before the observation of a water ingress in the operator controls console.

The control fluid used in the operation was water-based transaqua fluid. The SCM die-electric fluid is immiscible with seawater and transaqua. Ingress introduces a different conductivity in the SCM chamber and being of higher density, displaces the die-electric fluid. Monitoring of the ingress is performed with the aid of electrodes pairs mounted at calibrated points within the SCM housing. The change in conductivity in the chamber closes the electrical circuit of the electrode at that level, which is connected to an amplification system that corresponds to the level of ingress. This introduces an analogue signal which is converted to a digital signal and transmitted to the topside through the SCM-mounted SEM unit.

The ingress of water into an SCM contaminated the chamber die-electric fluid, caused an upward displacement of the SCM fluid and initiated corrosion on the exposed hydraulic and electrical couplers. The ingress grew steadily. Two years after, the tree subsea electronic module (SEM-A) signal was lost and reported as faulty in the operators console. Based on designed, the system automatically switched to channel B, making use of SEM-B for powering the tree system for control of hydrocarbon flow from the well. The ingress rose to 95% percentage and in twenty eight (28) days, a failure in SEM-B was observed. This led to a completed loss of well control and the whole system packed up leading to a shutdown of the well.

The two suspects for the water ingress into the SCM were:

- Seawater ingress through the SCM housing and
- Internal leakage through the hydraulic system

The SCM housing is equipped with a check valve system. This is a directional valve that only allows flow in only one direction. Based on this, flow is only allowed from the SCM to the seawater and not the reverse. On retrieval of the SCM to the workshop, the check valves were taken off the SCM housing for inspection and testing. The check valve had no indication of damage for the time spent subsea, but had signs of contamination. They were then tested and one was found to be mal-functional.

The SCM housing was taken off for inspection of the system internal components. The components were found to be in a rusty state, a clear indication of water ingress as against the oil-based die-electric chamber fluids. Marine growths were also found around the couplers. Logically, it was concluded that a failure in one of the check valves may have caused a gradual ingress of seawater into the SCM chamber. An ingress of seawater causes a gradual upward displacement of the die-electric fluid initiating corrosion in the internals. It is also believed that the failure was partial as it took about two years for the two SEMs in the SCM to fail.

Interestingly, the spare SCM available had some components that needed replacement. The parts had to be air-freighted to the country for the replacement of the faulty units. The spare system was quickly was tested and loaded out to a standby well support vessel for the retrieval of the faulty one and installation of the spare SCM. The whole exercise took approximately 12days for the well to be restored back to normalcy, leading to a huge loss in terms of deferred production, cost of hiring a well support vessel and additional cost for the fixing of the spare SCM.

7.3.5 Loss Associated with the SCM failure

The SCM is the heart of a subsea production system; hence its failure normally results in very significant losses. The water ingress into the SCM led to the following losses:

Associated Loss	Cost
Direct Cost of replacement SCM	$900,000.00
Cost of hiring a Well support vessel	$2,400,000.00
Cost of deferred production for two weeks	$12,000,000.00
Personnel, tools and associated Logistics Cost	$290,000.00
Total	***$15,590,000.00***

In total, the failure led to an estimated total loss of over $15m. Quite a huge sum considering the expected production from the well and other associated operation losses.

7.3.6 Lessons Learnt:

A water ingress into the subsea control module (SCM) led to a corrosion in the internals of the SCM. This led to a failure of the two SEM units and eventually a total failure of the SCM and loss in production. Below are the lessons from the analysis:

1. Failure modes in a subsea control module are inter-related. A failure in one component may lead to a failure in another component or sub-system. Failure in the check valve here led to a failure in the SEM units.
2. The check valve is a very important component of the SCM as its failure leads to a direct ingress of seawater into the SCM system.
3. The SEM plays an overriding role in the operation of the SCM. A loss in power or signal from the SEM, means a total failure or collapse of the entire system.
4. Good spare philosophy is very important in subsea projects. A timely change of the SCM would have saved the huge associated cost/losses.
5. A robust field IMR policy is key in running an offshore oil and gas field.

8 Conclusion, Recommendation and Further Work

8.1 Conclusion

Deepwater oil and gas development is both challenging and risky with a huge demand for reliability, safety and positive economic matrix. Today, subsea is the preferred technology for deepwater oil and gas discoveries due to its huge technical and economic merits. Subsea control module (SCM) plays a very crucial role for this delivery but highly challenged due to the demand for its reliability.

This research was focussed on the reliability analysis of the tree-mounted electro-hydraulic (E-H) subsea control module (SCM) for oil and gas production.

Tools for evaluating systems/components reliability were analysed. The analysis revealed that understanding failure mode and mechanisms is very fundamental for achieving optimum system reliability and FMECA filled this gap due to its ability to not only identify the failure, but also map the failure modes to the causes, effects, associated components and provides a mitigation strategy.

A comprehensive component-based FMECA of the SCM was conducted and narrowed down to the 30 most critical failure modes in the SCM. A criticality assessment and ranking was also performed using the conventional RPN technique.

As part of this research, a comprehensive review was performed on the use of FMECA including its application to the offshore subsea industry. Its gaps and limitations were also explored. This revealed that the major gap in FMECA is its risk priority modelling as reflected in the unscientific crisp results that emanate from conventional RPN evaluations. To close the identified gaps in the FMECA, various tools were analysed and the multi-criteria fuzzy TOPSIS methodology was applied in evaluating the reliability of the SCM due to its robustness and huge associated merits.

The FMECA result revealed the failures modes listed in table 39 as the top 20% most critical failure modes in the SCM.

Table 39 Top 20% most critical failure modes in the SCM

SCM Critical Failure Modes	Ranking
• Severe leakage in HP DCV	1
• Severe leakage in LP shuttle valve and	2
• Loss of power from the SEM unit	3
• Loss of HP Accumulation	4
• Total Loss of signal from the SEM module	5
• SCM housing check valve cracks open at lower pressure	6

A similar evaluation conducted using the fuzzy TOPSIS and the stochastic input strategy revealed that the above failure modes were also the top 20% most critical failure modes in the SCM with an overall correlation coefficient of 93.5% from an analysis which was conducted on the 30 most critical failure modes of the SCM.

In further validation of these analyses, the industry de-facto reliability database, OREDA, was also used in analysing the reliability of the SCM. The result showed that the SEM and the solenoid controlled valves are the most critical components in the SCM as they contribute to over 80% of the critical failures in the SCM.

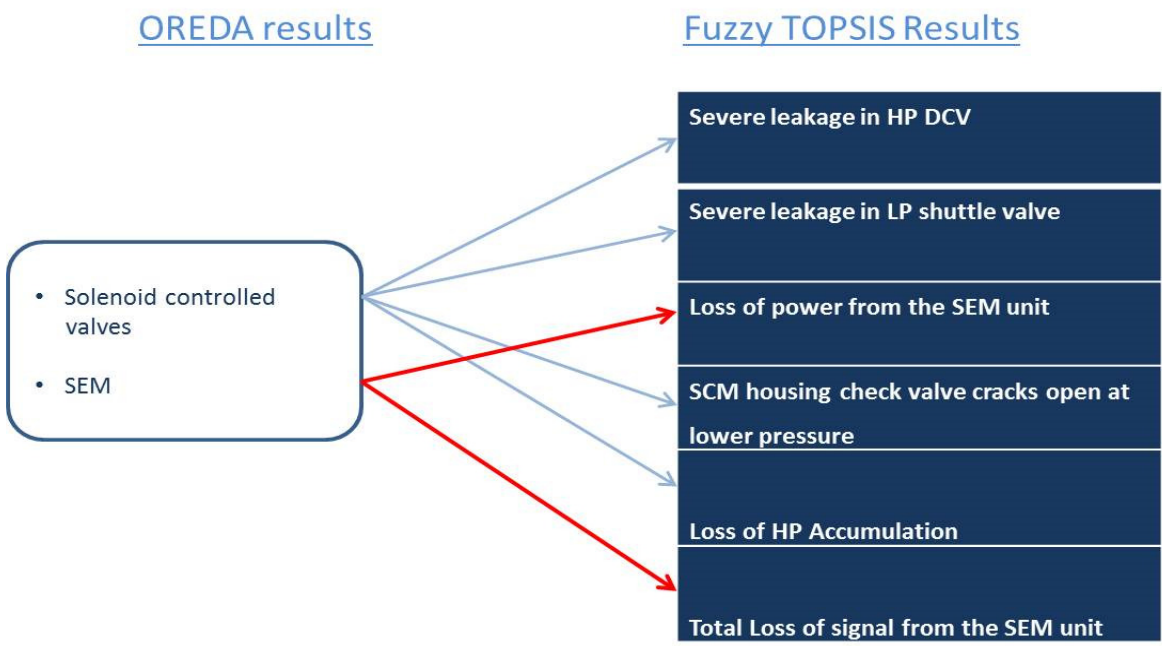


Figure 68 A validation of the fuzzy TOPSIS results with OREDA analysis

The OREDA results validate the results obtained from the FMECA evaluation, fuzzy TOPSIS analysis and the stochastic modelling as the results also produced the most critical failure modes which were all directly associated with two components of the SCM (see figure 68).

8.2 Novelty/Contribution of the PhD Study

Below is a list of novelty/contribution to knowledge developed during this research project:

1. Development of a multi-criteria TOPSIS framework for the reliability assessment of the SCM using unconventional parameters. A novel technique and first ever performed.
2. Development and implementation of a novel stochastic model for assessing the criticality of the subsea control module (SCM) failure modes.

3. Component-based analysis of SCM failure modes including criticality assessment using the fuzzy TOPSIS methodology, stochastic modelling and validation using the OREDA database.
4. Fuzzy TOPSIS assessment of the SCM reliability using weighted criteria obtained using expert opinion. A productive, but time consuming exercise.
5. An exhaustive failure modes identification of the subsea control module and evaluation using unconventional parameters such as water depth, fatality, environment, direct cost, indirect cost…etc.
6. An innovative comparative analysis of the all-electric and E-H multiplexed subsea control modules (SCMs) using the multi-criteria fuzzy TOPSIS methodology.

8.3 Recommendation and further work/plan

A lot of work has gone into this research study on the underlying reasons for the failure of the subsea control module (SCM). However, it is believed that more work in this area has the potential to reveal a lot more on the reliability of the SCM. The following are recommended as further work to this research:

1. The fuzzy TOPSIS evaluation in this research revealed how unconventional parameters closely affect the reliability assessment of the SCM in a more realistic manner. It also offered an insight into the underlying causes of failure in the SCM. There is a need for a more expanded analysis of these risk factors in evaluating the reliability of the system.
2. This research revealed that the subsea electronic module (SEM) and the solenoid controlled valves are the two most critical components that require attention for a reliable SCM during oil and gas production. A deeper study in the operability and system mechanisms of these two systems will reveal a lot more on improving the SCM system reliability.

3. As at today, the all-electric SCM system remains the potential replacement to the commonly used electro-hydraulic SCM. Though the oil and gas industry is relatively conservative, further work on the comparative analysis would convince the operators to move in this direction. It is recommended that the parameters for the evaluation be expanded to include other variables that may be useful for operators assessment before choice

4. The framework developed in this study could be extended for the evaluation of other complex systems like the blowout preventer (BOP) used in hydrocarbon drilling and completion operations. This will further validate the usefulness of the model.

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APPENDICES

Appendix A: Possible RPN Values for O, S and D on a 10-point scale

Detection	Occurrence	Severity									
		S=1	S=2	S=3	S=4	S=5	S=6	S=7	S=8	S=9	S=10
D=1	O=1	1	2	3	4	5	6	7	8	9	10
	O=2	2	4	6	8	10	12	14	16	18	20
	O=3	3	6	9	12	15	18	21	24	27	30
	O=4	4	8	12	16	20	24	28	32	36	40
	O=5	5	10	15	20	25	30	35	40	45	50
	O=6	6	12	18	24	30	36	42	48	54	60
	O=7	7	14	21	28	35	42	49	56	63	70
	O=8	8	16	24	32	40	48	56	64	72	80
	O=9	9	18	27	36	45	54	63	72	81	90
	O=10	10	20	30	40	50	60	70	80	90	100
D=2	O=1	2	4	6	8	10	12	14	16	18	20
	O=2	4	8	12	16	20	24	28	32	36	40
	O=3	6	12	18	24	30	36	42	48	54	60
	O=4	8	16	24	32	40	48	56	64	72	80
	O=5	10	20	30	40	50	60	70	80	90	100
	O=6	12	24	36	48	60	72	84	96	108	120
	O=7	14	28	42	56	70	84	98	112	126	140
	O=8	16	32	48	64	80	96	112	128	144	160
	O=9	18	36	54	72	90	108	126	144	162	180
	O=10	20	40	60	80	100	120	140	160	180	200
D=3	O=1	3	6	9	12	15	18	21	24	27	30
	O=2	6	12	18	24	30	36	42	48	54	60
	O=3	9	18	27	36	45	54	63	72	81	90
	O=4	12	24	36	48	60	72	84	96	108	120
	O=5	15	30	45	60	75	90	105	120	135	150
	O=6	18	36	54	72	90	108	126	144	162	180
	O=7	21	42	63	84	105	126	147	168	189	210
	O=8	24	48	72	96	120	144	168	192	216	240
	O=9	27	54	81	108	135	162	189	216	243	270
	O=10	30	60	90	120	150	180	210	240	270	300
D=4	O=1	4	8	12	16	20	24	28	32	36	40
	O=2	8	16	24	32	40	48	56	64	72	80
	O=3	12	24	36	48	60	72	84	96	108	120
	O=4	16	32	48	64	80	96	112	128	144	160
	O=5	20	40	60	80	100	120	140	160	180	200
	O=6	24	48	72	96	120	144	168	192	216	240
	O=7	28	56	84	112	140	168	196	224	252	280
	O=8	32	64	96	128	160	192	224	256	288	320
	O=9	36	72	108	144	180	216	252	288	324	360
	O=10	40	80	120	160	200	240	280	320	360	400

Severity											Detection
O=1	5	10	15	20	25	30	35	40	45	50	
O=2	10	20	30	40	50	60	70	80	90	100	
O=3	15	30	45	60	75	90	105	120	135	150	
O=4	20	40	60	80	100	120	140	160	180	200	
O=5	25	50	75	100	125	150	175	200	225	250	D=5
O=6	30	60	90	120	150	180	210	240	270	300	
O=7	35	70	105	140	175	210	245	280	315	350	
O=8	40	80	120	160	200	240	280	320	360	400	
O=9	45	90	135	180	225	270	315	360	405	450	
O=10	50	100	150	200	250	300	350	400	450	500	
O=1	6	12	18	24	30	36	42	48	54	60	
O=2	12	24	36	48	60	72	84	96	108	120	
O=3	18	36	54	72	90	108	126	144	162	180	
O=4	24	48	72	96	120	144	168	192	216	240	
O=5	30	60	90	120	150	180	210	240	270	300	D=6
O=6	36	72	108	144	180	216	252	288	324	360	
O=7	42	84	126	168	210	252	294	336	378	420	
O=8	48	96	144	192	240	288	336	384	432	480	
O=9	54	108	162	216	270	324	378	432	486	540	
O=10	60	120	180	240	300	360	420	480	540	600	
O=1	7	14	21	28	35	42	49	56	63	70	
O=2	14	28	42	56	70	84	98	112	126	140	
O=3	21	42	63	84	105	126	147	168	189	210	
O=4	28	56	84	112	140	168	196	224	252	280	
O=5	35	70	105	140	175	210	245	280	315	350	D=7
O=6	42	84	126	168	210	252	294	336	378	420	
O=7	49	98	147	196	245	294	343	392	441	490	
O=8	56	112	168	224	280	336	392	448	504	560	
O=9	63	126	189	252	315	378	441	504	567	630	
O=10	70	140	210	280	350	420	490	560	630	700	
O=1	8	16	24	32	40	48	56	64	72	80	
O=2	16	32	48	64	80	96	112	128	144	160	
O=3	24	48	72	96	120	144	168	192	216	240	
O=4	32	64	96	128	160	192	224	256	288	320	
O=5	40	80	120	160	200	240	280	320	360	400	D=8
O=6	48	96	144	192	240	288	336	384	432	480	
O=7	56	112	168	224	280	336	392	448	504	560	
O=8	64	128	192	256	320	384	448	512	576	640	
O=9	72	144	216	288	360	432	504	576	648	720	
O=10	80	160	240	320	400	480	560	640	720	800	
O=1	9	18	27	36	45	54	63	72	81	90	
O=2	18	36	54	72	90	108	126	144	162	180	
O=3	27	54	81	108	135	162	189	216	243	270	
O=4	36	72	108	144	180	216	252	288	324	360	
O=5	45	90	135	180	225	270	315	360	405	450	D=9
O=6	54	108	162	216	270	324	378	432	486	540	
O=7	63	126	189	252	315	378	441	504	567	630	
O=8	72	144	216	288	360	432	504	576	648	720	
O=9	81	162	243	324	405	486	567	648	729	810	
O=10	90	180	270	360	450	540	630	720	810	900	
O=1	10	20	30	40	50	60	70	80	90	100	
O=2	20	40	60	80	100	120	140	160	180	200	
O=3	30	60	90	120	150	180	210	240	270	300	
O=4	40	80	120	160	200	240	280	320	360	400	
O=5	50	100	150	200	250	300	350	400	450	500	D=10
O=6	60	120	180	240	300	360	420	480	540	600	
O=7	70	140	210	280	350	420	490	560	630	700	
O=8	80	160	240	320	400	480	560	640	720	800	
O=9	90	180	270	360	450	540	630	720	810	900	
O=10	100	200	300	400	500	600	700	800	900	1000	

Appendix B – Key Definitions

- **Availability** is defined as the probability that a system is in an operational state (i.e. percentage of time a system will be operational relative to the overall time period under consideration).

  Availability = $\frac{MTBF}{MTBF+MTTR}$

- A **control system** is a device or set of devices to manage, command, direct or regulate the behaviour of other devices or systems.
- **Failure** is an event in which any part of an equipment or machine does not perform according to its operational specification. Failures are classified into several categories: dependent failure, non-critical failures, critical failure, random failure, etc

  Failure Mechanism is the basic material behavior that resulted in the failure.
- **Failure Mode** is defined as the way an item of equipment fails to function as intended.
- **Failure rate** is the average rate at which failure occurs, and may be constant or vary with time.
- **Maintainability** is defined as the probability that a particular repair is performed within a given time.
- **Redundancy** is the duplication of critical components or functions of a system with the intention of increasing the system availability.
- **Reliability** the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

- **Subsea** is a term used to refer to equipment, technology, and methods employed to explore, drill, and develop oil and gas fields that exist below the sea bed.
- **Umbilical** – An assembly of hydraulic hoses, electrical cables or optic optics cables used in controlling subsea systems from an offshore platform or floating vessel.

Appendix C – Rating of the ten experts for all the risk factors

		Occurrence associated with water depth R_1									
Failure Modes	**ID**	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
Loss of power supply from the SEM Unit	F_1	L	L	L	VL	VL	L	L	L	L	L
SCM housing check valve cracks open at lower pressure	F_2	VH	VH	H	VH	VH	H	MH	VH	H	H
Total Loss of signal from the SEM module	F_3	L	L	L	L	L	M	L	L	L	M
Loss of LP hydraulic filtration	F_4	VL	L	VL	L	VL	L	VL	VL	L	VL
Severe leakage from HP DCV	F_5	VL	ML	ML	ML	ML	VL	VL	L	VL	L
Loss of HP hydraulic filtration	F_6	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
Loss of HP Accumulation	F_7	M	M	MH	MH	M	M	M	M	M	MH
Severe leakage from LP DCV	F_8	L	L	L	ML	ML	ML	ML	VL	VL	VL
Severe leakage on the LP Shuttle valve	F_9	VL	L	M	ML	ML	ML	ML	VL	ML	VL
Severe leakage on the HP shuttle valve	F_{10}	VL	L	ML	ML	ML	ML	ML	VL	L	ML
Loss of LP accumulation	F_{11}	M	MH	MH	MH	M	MH	H	MH	M	M
Shuttle valve fails to change over to the next HP supply line	F_{12}	VL	VL	L	L	L	L	L	ML	L	L
Severe leak in the LP common hydraulic header	F_{13}	VL	VL	VL	VL	ML	L	L	L	L	L
Shuttle valve fails to change over to the next LP supply line	F_{14}	VL	VL	ML	ML	ML	ML	ML	L	VL	L
LP selector valve fails to open	F_{15}	ML	ML	VL	L	L	L	L	L	L	L
Loss of SCM pressure compensation	F_{16}	M	ML	ML	ML	ML	ML	ML	ML	ML	ML
HP DCV fails to open on command	F_{17}	VL	L	VL	L	L	ML	ML	L	L	L
LP DCV fails to open on command	F_{18}	M	L	L	L	L	ML	ML	L	L	L
HP DCV shuts spuriously from the open position	F_{19}	ML	ML	L	L	L	L	ML	L	L	L
HP DCV fails to shut on demand from the open position	F_{20}	VL	L	L	VL	VL	VL	VL	L	L	L
LP DCV fails to shut on demand from the open position	F_{21}	VL	VL	ML	ML	ML	L	VL	VL	VL	L
Loss of monitoring signal from the water ingress sensor	F_{22}	VL	VL	VL	VL	L	VL	VL	VL	VL	VL
LP selector valve spuriously closes	F_{23}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
LP DCV shuts spuriously from the open position	F_{24}	VL	VL	VL	VL	L	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP supply pressure	F_{25}	VL	VL	L	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP supply pressure	F_{26}	VL	L	L	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP return flow	F_{27}	VL	L	L	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP return flow	F_{28}	VL	VL	L	L	VL	VL	VL	VL	VL	VL
Loss of the SCM internal pressure monitoring	F_{29}	VL	L	L	L	VL	VL	VL	VL	VL	VL
Loss of the SCM internal temperature monitoring	F_{30}	VL	L	L	L	VL	VL	VL	VL	VL	VL

		R_2									
Failure Modes	**ID**	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
Loss of power supply from the SEM Unit	F_1	MH	H	MH	H	H	H	MH	MH	MH	MH
SCM housing check valve cracks open at lower pressure	F_2	VL	VL	VL	VL	L	ML	ML	L	L	VL
Total Loss of signal from the SEM module	F_3	ML	M	MH	MH	MH	MH	ML	ML	ML	MH
Loss of LP hydraulic filtration	F_4	M	M	M	ML	ML	ML	ML	L	L	M
Severe leakage from HP DCV	F_5	M	L	L	M	M	M	M	M	M	M
Loss of HP hydraulic filtration	F_6	M	L	M	L	M	L	ML	L	L	M
Loss of HP Accumulation	F_7	VL	L	VL	L	VL	L	VL	ML	VL	L
Severe leakage from LP DCV	F_8	M	L	M	VL	L	L	VL	VL	VL	VL
Severe leakage on the LP Shuttle valve	F_9	M	L	M	VL	VL	L	VL	L	VL	L
Severe leakage on the HP shuttle valve	F_{10}	VL	L	VL	ML	ML	L	VL	L	VL	L
Loss of LP accumulation	F_{11}	VL	L	VL	L	VL	L	VL	ML	VL	L
Shuttle valve fails to change over to the next HP supply line	F_{12}	VL	L	VL	L	VL	L	VL	L	VL	L
Severe leak in the LP common hydraulic header	F_{13}	VL	VL	VL	VL	VL	VL	VL	ML	L	VL
Shuttle valve fails to change over to the next LP supply line	F_{14}	VL	L	VL	L	VL	L	VL	L	L	L
LP selector valve fails to open	F_{15}	L	VL	ML	ML	L	L	L	L	L	L
Loss of SCM pressure compensation	F_{16}	H	H	H	H	H	H	MH	MH	H	H
HP DCV fails to open on command	F_{17}	VL	VL	ML	ML	ML	ML	VL	VL	L	L
LP DCV fails to open on command	F_{18}	VL	VL	ML	ML	L	ML	VL	VL	L	L
HP DCV shuts spuriously from the open position	F_{19}	VL	L	ML	ML	L	ML	VL	VL	L	L
HP DCV fails to shut on demand from the open position	F_{20}	VL	L	ML	ML	L	L	VL	L	L	L
LP DCV fails to shut on demand from the open position	F_{21}	VL	VL	ML	ML	ML	ML	VL	VL	L	L
Loss of monitoring signal from the water ingress sensor	F_{22}	VL	VL	L	L	L	L	L	VL	VL	VL
LP selector valve spuriously closes	F_{23}	VL	VL	VL	VL	VL	VL	L	VL	VL	VL
LP DCV shuts spuriously from the open position	F_{24}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP supply pressure	F_{25}	VL	ML	L	ML	L	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP supply pressure	F_{26}	VL	ML	L	L	L	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP return flow	F_{27}	VL	ML	L	L	L	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP return flow	F_{28}	VL	ML	L	L	ML	VL	VL	VL	VL	VL
Loss of the SCM internal pressure monitoring	F_{29}	VL	ML	L	ML	ML	L	VL	L	VL	L
Loss of the SCM internal temperature monitoring	F_{30}	VL	L	L	ML	ML	VL	VL	VL	VL	VL

Failure Modes	ID	R_3									
Loss of power supply from the SEM Unit	F_{1}	VH	VH	VH	VH	VH	VH	VH	H	VH	VH
SCM housing check valve cracks open at lower pressure	F_{2}	VH	H	H	H	VH	VH	VH	H	VH	VH
Total Loss of signal from the SEM module	F_{3}	VH	H	VH	H	VH	H	VH	H	H	H
Loss of LP hydraulic filtration	F_{4}	VH	H	VH	H	VH	H	VH	H	VH	H
Severe leakage from HP DCV	F_{5}	VH	H	H	H	VH	H	H	H	VH	H
Loss of HP hydraulic filtration	F_{6}	VH	H	MH	MH	VH	H	MH	H	VH	H
Loss of HP Accumulation	F_{7}	VH	H	MH	H	VH	H	MH	H	VH	H
Severe leakage from LP DCV	F_{8}	VH	H	H	H	VH	H	VH	VH	VH	H
Severe leakage on the LP Shuttle valve	F_{9}	VH	VH	VH	H	VH	VH	VH	VH	VH	VH
Severe leakage on the HP shuttle valve	F_{10}	VH	VH	H	H	VH	VH	H	H	VH	VH
Loss of LP accumulation	F_{11}	VH	VH	H	H	VH	VH	H	H	VH	VH
Shuttle valve fails to change over to the next HP supply line	F_{12}	VH	VH	H	H	VH	VH	H	H	VH	VH
Severe leak in the LP common hydraulic header	F_{13}	VH	VH	H	H	VH	VH	VH	H	VH	VH
Shuttle valve fails to change over to the next LP supply line	F_{14}	VH	VH	H	H	VH	VH	VH	H	VH	VH
LP selector valve fails to open	F_{15}	H	VH	MH	H	H	VH	VH	H	H	VH
Loss of SCM pressure compensation	F_{16}	VH	VH	H	H	H	VH	VH	H	VH	VH
HP DCV fails to open on command	F_{17}	H	VH	H	H	MH	VH	VH	H	H	VH
LP DCV fails to open on command	F_{18}	H	H	MH	H	MH	H	H	H	H	H
HP DCV shuts spuriously from the open position	F_{19}	VH	H	MH	MH	MH	MH	MH	MH	MH	H
HP DCV fails to shut on demand from the open position	F_{20}	VH	VH	H	H	VH	VH	H	H	VH	VH
LP DCV fails to shut on demand from the open position	F_{21}	VH	VH	MH	H	VH	VH	H	H	VH	VH
Loss of monitoring signal from the water ingress sensor	F_{22}	VH	H	H	H	VH	H	H	H	VH	H
LP selector valve spuriously closes	F_{23}	VH	MH	H	H	VH	MH	H	H	VH	MH
LP DCV shuts spuriously from the open position	F_{24}	VH	MH	MH	H	VH	VH	H	H	VH	VH
Loss of electronic monitoring of the LP supply pressure	F_{25}	VH	VH	MH	H	VH	VH	VH	H	H	H
Loss of electronic monitoring of the HP supply pressure	F_{26}	VH	VH	VH	H	VH	VH	VH	H	VH	H
Loss of electronic monitoring of the LP return flow	F_{27}	VH	VH	VH	H	VH	VH	VH	H	MH	MH
Loss of electronic monitoring of the HP return flow	F_{28}	VH	VH	VH	H	VH	VH	VH	H	VH	H
Loss of the SCM internal pressure monitoring	F_{29}	VH	VH	VH	H	VH	VH	VH	H	VH	VH
Loss of the SCM internal temperature monitoring	F_{30}	VH	VH	VH	H	VH	VH	MH	H	MH	MH

Failure Modes	ID	R_4									
Loss of power supply from the SEM Unit	F_1	VH	VH	H	VH	VH	H	H	H	H	H
SCM housing check valve cracks open at lower pressure	F_2	M	M	M	M	M	M	M	M	M	M
Total Loss of signal from the SEM module	F_3	VH	H	H	VH	H	H	H	VH	H	H
Loss of LP hydraulic filtration	F_4	M	H	H	H	MH	MH	MH	M	MH	MH
Severe leakage from HP DCV	F_5	M	MH	MH	MH	H	H	H	MH	H	H
Loss of HP hydraulic filtration	F_6	L	L	L	L	L	L	L	L	L	L
Loss of HP Accumulation	F_7	MH	M	M	MH	MH	M	MH	MH	MH	MH
Severe leakage from LP DCV	F_8	MH	M	M	M	M	M	M	M	MH	M
Severe leakage on the LP Shuttle valve	F_9	MH	M	M	M	M	M	M	MH	MH	MH
Severe leakage on the HP shuttle valve	F_{10}	MH	M	M	MH	M	MH	M	MH	MH	MH
Loss of LP accumulation	F_{11}	MH	MH	MH	ML	MH	MH	MH	M	MH	MH
Shuttle valve fails to change over to the next HP supply line	F_{12}	MH	MH	M	M	MH	M	MH	M	MH	MH
Severe leak in the LP common hydraulic header	F_{13}	MH	MH	MH	MH	MH	M	MH	ML	MH	MH
Shuttle valve fails to change over to the next LP supply line	F_{14}	MH	MH	M	MH	M	M	MH	ML	MH	MH
LP selector valve fails to open	F_{15}	MH	MH	MH	M	MH	M	MH	M	MH	MH
Loss of SCM pressure compensation	F_{16}	MH	MH	M	M	M	M	MH	M	MH	MH
HP DCV fails to open on command	F_{17}	MH	MH	MH	M	MH	MH	MH	ML	MH	MH
LP DCV fails to open on command	F_{18}	MH	MH	L	M	MH	M	MH	ML	MH	MH
HP DCV shuts spuriously from the open position	F_{19}	MH	MH	M	ML	MH	M	MH	ML	MH	MH
HP DCV fails to shut on demand from the open position	F_{20}	MH	MH	MH	L	MH	MH	MH	ML	MH	MH
LP DCV fails to shut on demand from the open position	F_{21}	MH	MH	MH	ML	MH	MH	MH	ML	MH	MH
Loss of monitoring signal from the water ingress sensor	F_{22}	L	L	L	L	L	ML	L	ML	ML	L
LP selector valve spuriously closes	F_{23}	MH	MH	M	L	MH	M	MH	M	M	M
LP DCV shuts spuriously from the open position	F_{24}	MH	MH	MH	ML	MH	M	MH	ML	M	M
Loss of electronic monitoring of the LP supply pressure	F_{25}	L	M	ML	L	M	M	ML	ML	ML	ML
Loss of electronic monitoring of the HP supply pressure	F_{26}	L	M	ML	L	M	M	ML	ML	ML	ML
Loss of electronic monitoring of the LP return flow	F_{27}	L	M	L	L	L	L	ML	ML	ML	ML
Loss of electronic monitoring of the HP return flow	F_{28}	L	M	ML	L	M	M	L	L	ML	ML
Loss of the SCM internal pressure monitoring	F_{29}	L	M	L	L	M	L	L	ML	ML	ML
Loss of the SCM internal temperature monitoring	F_{30}	L	M	ML	L	L	M	ML	L	ML	ML

Failure Modes	ID	R_5									
Loss of power supply from the SEM Unit	F_1	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
SCM housing check valve cracks open at lower pressure	F_2	VH	VH	H	VH	VH	VH	VH	VH	VH	VH
Total Loss of signal from the SEM module	F_3	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Loss of LP hydraulic filtration	F_4	MH	MH	H	MH	MH	MH	MH	MH	MH	MH
Severe leakage from HP DCV	F_5	H	H	H	VH	VH	VH	VH	H	VH	VH
Loss of HP hydraulic filtration	F_6	MH	MH	H	MH	MH	MH	MH	MH	MH	MH
Loss of HP Accumulation	F_7	VH	VH	H	H	VH	H	H	H	H	H
Severe leakage from LP DCV	F_8	H	H	H	H	H	H	H	H	H	H
Severe leakage on the LP Shuttle valve	F_9	VH	VH	VH	VH	VH	VH	VH	VH	VH	H
Severe leakage on the HP shuttle valve	F_{10}	VH	VH	VH	VH	VH	VH	VH	VH	VH	H
Loss of LP accumulation	F_{11}	H	H	H	VH	VH	H	VH	VH	VH	VH
Shuttle valve fails to change over to the next HP supply line	F_{12}	H	H	H	H	H	H	H	H	VH	H
Severe leak in the LP common hydraulic header	F_{13}	VH	H	VH	VH	VH	VH	VH	VH	VH	VH
Shuttle valve fails to change over to the next LP supply line	F_{14}	H	H	H	H	H	H	H	H	H	H
LP selector valve fails to open	F_{15}	H	H	H	H	MH	H	H	H	H	H
Loss of SCM pressure compensation	F_{16}	VH	VH	H	VH	VH	VH	VH	VH	VH	VH
HP DCV fails to open on command	F_{17}	H	H	H	MH	MH	H	H	H	H	H
LP DCV fails to open on command	F_{18}	H	H	H	H	MH	MH	H	H	H	H
HP DCV shuts spuriously from the open position	F_{19}	H	MH	H	H	MH	MH	MH	MH	MH	H
HP DCV fails to shut on demand from the open position	F_{20}	MH	MH	H	H	MH	MH	MH	H	H	H
LP DCV fails to shut on demand from the open position	F_{21}	MH	H	H	H	MH	H	MH	H	H	H
Loss of monitoring signal from the water ingress sensor	F_{22}	MH	MH	MH	H	H	H	H	MH	MH	MH
LP selector valve spuriously closes	F_{23}	H	H	MH	MH	H	H	H	H	H	H
LP DCV shuts spuriously from the open position	F_{24}	H	H	MH	MH	H	H	H	H	H	H
Loss of electronic monitoring of the LP supply pressure	F_{25}	H	H	H	H	H	H	H	H	H	H
Loss of electronic monitoring of the HP supply pressure	F_{26}	MH	MH	MH	H	H	H	MH	MH	MH	MH
Loss of electronic monitoring of the LP return flow	F_{27}	MH	MH	MH	MH	MH	MH	MH	MH	MH	L
Loss of electronic monitoring of the HP return flow	F_{28}	MH	M	MH	MH	MH	MH	MH	MH	MH	MH
Loss of the SCM internal pressure monitoring	F_{29}	M	M	M	MH	MH	MH	M	M	M	M
Loss of the SCM internal temperature monitoring	F_{30}	M	M	M	MH	M	M	M	M	M	M

Failure Modes	ID	R_6									
Loss of power supply from the SEM Unit	F_1	VL	L	L	L	VL	VL	VL	VL	VL	VL
SCM housing check valve cracks open at lower pressure	F_2	H	H	M	L	L	L	L	L	L	L
Total Loss of signal from the SEM module	F_3	VL	L	M	L	VL	VL	VL	VL	VL	VL
Loss of LP hydraulic filtration	F_4	VL	VL	L	L	VL	VL	VL	VL	VL	VL
Severe leakage from HP DCV	F_5	H	H	VH	H	H	H	H	VH	H	H
Loss of HP hydraulic filtration	F_6	L	L	H	L	VL	VL	VL	VL	VL	VL
Loss of HP Accumulation	F_7	L	L	L	L	VL	VL	VL	VL	VL	VL
Severe leakage from LP DCV	F_8	M	M	M	M	M	M	M	M	M	M
Severe leakage on the LP Shuttle valve	F_9	M	M	M	M	M	M	M	M	M	ML
Severe leakage on the HP shuttle valve	F_{10}	L	L	L	L	ML	ML	ML	L	L	L
Loss of LP accumulation	F_{11}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle valve fails to change over to the next HP supply line	F_{12}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Severe leak in the LP common hydraulic header	F_{13}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Shuttle valve fails to change over to the next LP supply line	F_{14}	L	VL	VL	VL	VL	VL	VL	VL	VL	VL
LP selector valve fails to open	F_{15}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Loss of SCM pressure compensation	F_{16}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
HP DCV fails to open on command	F_{17}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
LP DCV fails to open on command	F_{18}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
HP DCV shuts spuriously from the open position	F_{19}	VL	VL	L	L	L	L	L	L	L	L
HP DCV fails to shut on demand from the open position	F_{20}	VL	VL	L	L	L	L	L	L	L	L
LP DCV fails to shut on demand from the open position	F_{21}	VL	VL	L	L	L	L	L	L	L	VL
Loss of monitoring signal from the water ingress sensor	F_{22}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
LP selector valve spuriously closes	F_{23}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
LP DCV shuts spuriously from the open position	F_{24}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP supply pressure	F_{25}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP supply pressure	F_{26}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP return flow	F_{27}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP return flow	F_{28}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
Loss of the SCM internal pressure monitoring	F_{29}	L	L	L	L	L	L	L	L	L	L
Loss of the SCM internal temperature monitoring	F_{30}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL

Failure Modes	ID	R_7									
Loss of power supply from the SEM Unit	F_1	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
SCM housing check valve cracks open at lower pressure	F_2	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Total Loss of signal from the SEM module	F_3	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Loss of LP hydraulic filtration	F_4	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
Severe leakage from HP DCV	F_5	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of HP hydraulic filtration	F_6	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of HP Accumulation	F_7	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Severe leakage from LP DCV	F_8	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Severe leakage on the LP Shuttle valve	F_9	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Severe leakage on the HP shuttle valve	F_{10}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of LP accumulation	F_{11}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Shuttle valve fails to change over to the next HP supply line	F_{12}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Severe leak in the LP common hydraulic header	F_{13}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Shuttle valve fails to change over to the next LP supply line	F_{14}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
LP selector valve fails to open	F_{15}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of SCM pressure compensation	F_{16}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
HP DCV fails to open on command	F_{17}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
LP DCV fails to open on command	F_{18}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
HP DCV shuts spuriously from the open position	F_{19}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
HP DCV fails to shut on demand from the open position	F_{20}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
LP DCV fails to shut on demand from the open position	F_{21}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of monitoring signal from the water ingress sensor	F_{22}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
LP selector valve spuriously closes	F_{23}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
LP DCV shuts spuriously from the open position	F_{24}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP supply pressure	F_{25}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP supply pressure	F_{26}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the LP return flow	F_{27}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP return flow	F_{28}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of the SCM internal pressure monitoring	F_{29}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
Loss of the SCM internal temperature monitoring	F_{30}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL

Failure Modes	ID	R_8									
Loss of power supply from the SEM Unit	F_1	L	VL	M	L	M	M	L	L	L	L
SCM housing check valve cracks open at lower pressure	F_2	VL	M	L	L	VL	VL	VL	VL	VL	VL
Total Loss of signal from the SEM module	F_3	L	L	VL	L	M	M	L	L	L	L
Loss of LP hydraulic filtration	F_4	ML	ML	L	ML	ML	ML	ML	ML	ML	ML
Severe leakage from HP DCV	F_5	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
Loss of HP hydraulic filtration	F_6	VL	VL	VL	VL	L	ML	ML	ML	L	L
Loss of HP Accumulation	F_7	M	M	M	M	ML	ML	ML	ML	ML	ML
Severe leakage from LP DCV	F_8	M	M	MH	M	MH	MH	MH	MH	MH	MH
Severe leakage on the LP Shuttle valve	F_9	M	M	M	M	MH	MH	M	M	M	M
Severe leakage on the HP shuttle valve	F_{10}	M	M	M	M	M	M	M	M	M	M
Loss of LP accumulation	F_{11}	ML	L	ML	ML	ML	ML	ML	ML	ML	ML
Shuttle valve fails to change over to the next HP supply line	F_{12}	L	L	L	L	L	L	L	L	ML	L
Severe leak in the LP common hydraulic header	F_{13}	MH	MH	VH	MH	MH	MH	VH	MH	MH	MH
Shuttle valve fails to change over to the next LP supply line	F_{14}	L	L	M	L	L	L	ML	L	L	L
LP selector valve fails to open	F_{15}	L	L	L	L	L	L	L	L	L	L
Loss of SCM pressure compensation	F_{16}	M	M	M	M	M	M	M	M	M	M
HP DCV fails to open on command	F_{17}	L	L	L	VL	VL	L	L	L	L	L
LP DCV fails to open on command	F_{18}	L	VL	L	L	L	VL	L	VL	VL	VL
HP DCV shuts spuriously from the open position	F_{19}	L	VL	VL	L	L	VL	VL	VL	VL	VL
HP DCV fails to shut on demand from the open position	F_{20}	L	VL	VL	L	L	VL	L	VL	VL	VL
LP DCV fails to shut on demand from the open position	F_{21}	L	VL	L	L	L	L	L	VL	VL	VL
Loss of monitoring signal from the water ingress sensor	F_{22}	L	L	L	M	VL	L	M	L	VL	VL
LP selector valve spuriously closes	F_{23}	L	VL	L	L	L	VL	L	L	L	VL
LP DCV shuts spuriously from the open position	F_{24}	MH	M	MH	M	M	M	ML	ML	M	MH
Loss of electronic monitoring of the LP supply pressure	F_{25}	VL	VL	L	L	VL	VL	VL	VL	VL	VL
Loss of electronic monitoring of the HP supply pressure	F_{26}	ML	VL	L	L	L	L	L	L	L	VL
Loss of electronic monitoring of the LP return flow	F_{27}	L	L	VL	L	L	VL	ML	L	L	VL
Loss of electronic monitoring of the HP return flow	F_{28}	L	ML	L	L	L	VL	ML	L	L	L
Loss of the SCM internal pressure monitoring	F_{29}	L	L	ML	L	L	L	ML	L	L	L
Loss of the SCM internal temperature monitoring	F_{30}	L	L	VL	L	L	L	L	L	L	L

Failure Modes	ID	R_9									
Loss of power supply from the SEM Unit	F_1	L	L	L	L	L	VL	L	L	L	L
SCM housing check valve cracks open at lower pressure	F_2	H	H	H	H	H	H	H	H	H	H
Total Loss of signal from the SEM module	F_3	VL	VL	VL	VL	L	L	VL	VL	VL	VL
Loss of LP hydraulic filtration	F_4	H	VH	VH	VH	H	VH	VH	VH	VH	VH
Severe leakage from HP DCV	F_5	ML	M	L	L	L	L	ML	ML	L	L
Loss of HP hydraulic filtration	F_6	H	VH	VH	VH	H	H	H	H	H	VH
Loss of HP Accumulation	F_7	ML	M	ML	ML	L	L	ML	L	M	ML
Severe leakage from LP DCV	F_8	L	L	L	L	L	ML	ML	ML	L	ML
Severe leakage on the LP Shuttle valve	F_9	ML	ML	ML	ML	L	L	L	L	ML	L
Severe leakage on the HP shuttle valve	F_{10}	L	L	L	L	L	L	L	L	L	ML
Loss of LP accumulation	F_{11}	ML	L	ML	ML	ML	ML	ML	L	L	L
Shuttle valve fails to change over to the next HP supply line	F_{12}	L	L	VL	VL	VL	L	L	L	L	L
Severe leak in the LP common hydraulic header	F_{13}	VL	VL	L	L	L	L	L	L	L	L
Shuttle valve fails to change over to the next LP supply line	F_{14}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
LP selector valve fails to open	F_{15}	VL	ML	L	L	L	L	L	L	L	L
Loss of SCM pressure compensation	F_{16}	ML	ML	ML	L	ML	ML	ML	ML	ML	L
HP DCV fails to open on command	F_{17}	L	L	L	L	L	L	L	ML	ML	VL
LP DCV fails to open on command	F_{18}	L	M	L	L	L	L	L	VL	VL	VL
HP DCV shuts spuriously from the open position	F_{19}	L	M	L	L	L	ML	L	L	L	L
HP DCV fails to shut on demand from the open position	F_{20}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
LP DCV fails to shut on demand from the open position	F_{21}	L	ML	VL	L	L	L	ML	ML	VL	L
Loss of monitoring signal from the water ingress sensor	F_{22}	VL	ML	VL	VL	VL	VL	VL	VL	VL	VL
LP selector valve spuriously closes	F_{23}	VL	M	VL	VL	VL	VL	VL	VL	VL	VL
LP DCV shuts spuriously from the open position	F_{24}	L	M	VL	VL	VL	VL	VL	ML	M	VL
Loss of electronic monitoring of the LP supply pressure	F_{25}	L	VL	VL	VL	VL	VL	ML	ML	VL	VL
Loss of electronic monitoring of the HP supply pressure	F_{26}	VL	L	VL	VL	VL	VL	VL	VL	VL	ML
Loss of electronic monitoring of the LP return flow	F_{27}	VL	VL	VL	L	L	VL	VL	VL	VL	ML
Loss of electronic monitoring of the HP return flow	F_{28}	VL	L	VL	ML	L	L	L	VL	VL	VL
Loss of the SCM internal pressure monitoring	F_{29}	VL	L	VL	VL	VL	VL	VL	ML	L	L
Loss of the SCM internal temperature monitoring	F_{30}	ML	VL	ML	ML	VL	VL	VL	VL	VL	L

Failure Modes	ID	R_{10}									
Loss of power supply from the SEM Unit	F_1	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
SCM housing check valve cracks open at lower pressure	F_2	M	M	M	M	ML	M	M	M	M	M
Total Loss of signal from the SEM module	F_3	VH	VH	VH	VH	H	VH	VH	VH	VH	H
Loss of LP hydraulic filtration	F_4	H	VH	H	H	H	H	H	VH	H	H
Severe leakage from HP DCV	F_5	H	H	MH	H	MH	MH	H	H	H	MH
Loss of HP hydraulic filtration	F_6	VH	H	VH	H	MH	MH	MH	MH	MH	MH
Loss of HP Accumulation	F_7	MH	MH	H	H	MH	MH	MH	MH	MH	MH
Severe leakage from LP DCV	F_8	H	VH	VH	H	M	MH	MH	MH	MH	MH
Severe leakage on the LP Shuttle valve	F_9	H	H	H	H	M	MH	MH	H	H	H
Severe leakage on the HP shuttle valve	F_{10}	H	M	H	H	MH	MH	H	H	H	H
Loss of LP accumulation	F_{11}	H	H	MH	H	MH	MH	MH	H	MH	MH
Shuttle valve fails to change over to the next HP supply line	F_{12}	H	H	MH	H	MH	M	MH	H	MH	M
Severe leak in the LP common hydraulic header	F_{13}	MH	MH	H	H	H	MH	MH	MH	MH	MH
Shuttle valve fails to change over to the next LP supply line	F_{14}	MH	MH	MH	H	H	H	H	H	H	H
LP selector valve fails to open	F_{15}	M	M	M	M	MH	M	MH	MH	M	M
Loss of SCM pressure compensation	F_{16}	M	M	H	H	MH	M	MH	M	M	M
HP DCV fails to open on command	F_{17}	MH	MH	H	H	MH	MH	MH	MH	H	MH
LP DCV fails to open on command	F_{18}	H	H	M	M	MH	MH	MH	MH	H	M
HP DCV shuts spuriously from the open position	F_{19}	M	M	M	M	M	M	M	MH	MH	MH
HP DCV fails to shut on demand from the open position	F_{20}	M	M	M	M	MH	MH	MH	MH	M	M
LP DCV fails to shut on demand from the open position	F_{21}	M	M	M	M	M	M	MH	M	M	M
Loss of monitoring signal from the water ingress sensor	F_{22}	MH	M	M	MH	H	M	M	M	M	M
LP selector valve spuriously closes	F_{23}	M	M	M	M	M	M	M	M	H	MH
LP DCV shuts spuriously from the open position	F_{24}	ML	ML	M	M	ML	ML	ML	ML	M	H
Loss of electronic monitoring of the LP supply pressure	F_{25}	M	ML	M	M	ML	ML	ML	ML	M	M
Loss of electronic monitoring of the HP supply pressure	F_{26}	ML	ML	M	M	ML	ML	ML	ML	M	H
Loss of electronic monitoring of the LP return flow	F_{27}	ML	M	H	M	M	ML	ML	ML	ML	H
Loss of electronic monitoring of the HP return flow	F_{28}	ML	ML	ML	M	M	M	M	ML	ML	ML
Loss of the SCM internal pressure monitoring	F_{29}	ML	M	ML	ML	M	ML	M	M	M	M
Loss of the SCM internal temperature monitoring	F_{30}	ML	ML	ML	ML	ML	ML	M	ML	ML	ML

Appendix D – Results of the SCM Failure modes survey:

Subsea Control Module (SCM) – FMECA and Fuzzy TOPSIS evaluation

PhD RESEARCH Questionnaire

School: SOE**,** Cranfield University, United Kingdom 2013/14
Student: C105147

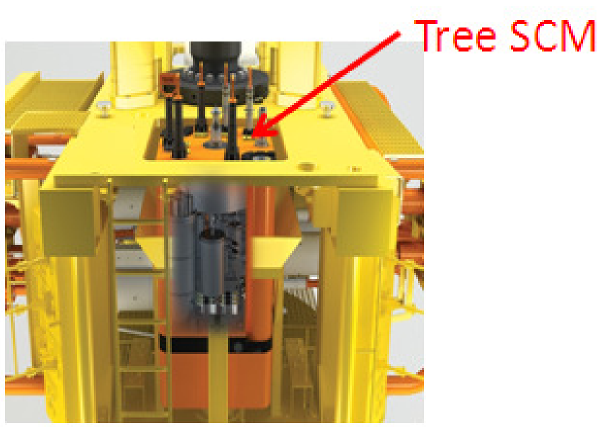
Results – Expert1

Foreword:

With increasing move into deeper waters, access to evaluation data becomes more difficult. This necessitates the use of experts operational knowledge in assessment of SCM reliability.

You have been chosen to participate in this survey because you are identified as an expert in the Subsea oil and gas industry. It will take about 20**minutes** to complete. Your professional answers will be quite useful in this evaluation.

Information obtained here is strictly for research purposes. No propriety information is being solicited. At the end, you will have access to the outcome of this research. Thank you.



Introduction:

Failure of subsea control module (SCM) is a big issue in the offshore oil and gas industry. This survey is being conducted as part of a research to understand the failure modes, failure mechanisms, causes and effects of the SCM in its application to deep and ultra-deepwater oil and gas production.

The SCM being considered here are those mounted on a subsea Xmas tree with the main aim of controlling the tree valves, chemical injection system, downhole functions control and delivery of condition monitoring data from the tree and downhole instrumentations to the topside units.

This is a fallout from a comprehensive analysis performed on the SCM subsystems and components failure modes, causes and effects.

There are two sections in the questionnaire:

In section one, the importance or weight of each risk factor (criterion) on SCM reliability will be assessed. **In second two**, the impact of each risk factor (criterion) is rated against a corresponding SCM failure mode.

Section 1

Risk factors to be considered in the analysis are listed below:

Risk Factors

R_1 - Occurrence associated with water depth

R_2 - Occurrence under normal operation

R_3 - Occurrence under extreme conditions

R_4 - Direct Cost of failure

R_5 - Indirect cost of failure

R_6 - Failure impact on environment

R_7 - Fatality associated with failure

R_8 - Risk to business – non-financial

R_9 - Detectability

R_{10} - Redundancy

The weighting Legend:

VL – Very Low   L – Low   M – Medium   H – High   VH – Very High

Each of the questions below reflect the **importance weight** of the risk factors above in evaluating the reliability of a tree-mounted subsea control module (SCM) for its role in the production of oil and gas. Please tick **'x'** against the corresponding value for each of the questions.

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☐ VH ☒

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
VL ☐ L ☐ M ☒ H ☐ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
VL ☐ L ☐ M ☒ H ☐ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
VL ☐ L ☒ M ☐ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
VL ☐ L ☐ M ☐ H ☐ VH ☒

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

Section 2

In this section of the questionnaire, the rating/influence of the risk factors against the respective SCM failure modes is being evaluated. Below is a list of the risk factors to be evaluated against the failure modes.

Risk Factors

R_1 - Occurrence associated with water depth

R_2 - Occurrence under normal operation

R_3 - Occurrence outside design boundaries

R_4 - Direct Cost of failure

R_5 - Indirect cost of failure

R_6 - Failure impact on environment

R_7 - Fatality associated with failure

R_8 - Risk to business – non-financial

R_9 - Detectability

R_{10} - Redundancy

The rating legend is also shown below:

The rating Legend:

VL – Very Low L – Low ML – Medium Low M – Medium

MH – Medium High H – High VH – Very High

Failure Modes, F_i

F_1 - Loss of power supply from the SEM Unit

F_2 - SCM housing check valve cracks open at lower pressure

F_3 - Total Loss of signal from the SEM module

F_4 - Loss of LP hydraulic filtration

F_5 - Severe leakage from HP DCV

F_6 - Loss of HP hydraulic filtration

F_7 - Loss of HP Accumulation

F_8 - Severe leakage from LP DCV

F_9 - Severe leakage on the LP Shuttle valve

F_{10} - Severe leakage on the HP shuttle valve

F_{11} - Loss of LP accumulation

F_{12} - Shuttle valve fails to change over to the next HP supply line

F_{13} - Severe leak in the LP common hydraulic header

F_{14} - Shuttle valve fails to change over to the next LP supply line

F_{15} - LP selector valve fails to open

F_{16} - Loss of SCM pressure compensation

F_{17} - HP DCV fails to open on command

F_{18} - LP DCV fails to open on command

F_{19} - HP DCV shuts spuriously from the open position

F_{20} - HP DCV fails to shut on demand from the open position

F_{21} - LP DCV fails to shut on demand from the open position

F_{22} - Loss of monitoring signal from the water ingress sensor

F_{23} - LP selector valve spuriously closes

F_{24} - LP DCV shuts spuriously from the open position

F_{25} - Loss of electronic monitoring of the LP supply pressure

F_{26} - Loss of electronic monitoring of the HP supply pressure

F_{27} - Loss of electronic monitoring of the LP return flow

F_{28} - Loss of electronic monitoring of the HP return flow

F_{29} - Loss of the SCM internal pressure monitoring

F_{30} - Loss of the SCM internal temperature monitoring

This section evaluates how each failure mode is affected by the risk factors. Experts are expected to fill the boxes in the table below with the relevant values **(VL, L, ML, M, MH, H, VH)**.

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}

F_1	L	L	L	VL	VL	L	L	L	L	L
F_2	VH	VH	H	VH	VH	H	MH	VH	H	H
F_3	L	L	L	L	L	M	L	L	L	M
F_4	VL	L	VL	L	VL	L	VL	VL	L	VL
F_5	VL	ML	ML	ML	ML	VL	VL	L	VL	L
F_6	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_7	M	M	MH	MH	M	M	M	M	M	MH
F_8	L	L	L	ML	ML	ML	ML	VL	VL	VL
F_9	VL	L	M	ML	ML	ML	ML	VL	ML	LV
F_{10}	VL	L	ML	ML	ML	ML	ML	VL	L	ML
F_{11}	M	MH	MH	MH	M	MH	H	MH	M	M
F_{12}	VL	VL	L	L	L	L	L	ML	L	L
F_{13}	VL	VL	VL	VL	ML	L	L	L	L	L
F_{14}	VL	VL	ML	ML	ML	ML	ML	L	VL	L
F_{15}	ML	ML	VL	L	L	L	L	L	L	L
F_{16}	M	ML	ML	ML	ML	ML	ML	ML	ML	ML
F_{17}	VL	L	VL	L	L	ML	ML	L	L	L
F_{18}	M	L	L	L	L	ML	ML	L	L	L
F_{19}	ML	ML	L	L	L	L	ML	L	L	L
F_{20}	VL	L	L	VL	VL	VL	VL	L	L	L
F_{21}	VL	VL	ML	ML	ML	L	VL	VL	VL	L
F_{22}	VL	VL	VL	VL	L	VL	VL	VL	VL	VL
F_{23}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{24}	VL	VL	VL	VL	L	VL	VL	VL	VL	VL
F_{25}	VL	VL	L	L	VL	VL	VL	VL	VL	VL

F_{26}	VL	L	L	L	VL	VL	VL	VL	VL	VL
F_{27}	VL	L	L	L	VL	VL	VL	VL	VL	VL
F_{28}	VL	VL	L	L	VL	VL	VL	VL	VL	VL
F_{29}	VL	L	L	L	VL	VL	VL	VL	VL	VL
F_{30}	VL	L	L	L	VL	VL	VL	VL	VL	VL

Expert 2 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☒ H ☐ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☒ M ☐ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☒ VH ☐

Expert2 – Section2

	Risk Factors									
Failure Modes	**R_1**	**R_2**	**R_3**	**R_4**	**R_5**	**R_6**	**R_7**	**R_8**	**R_9**	**R_{10}**
F_1	MH	H	MH	H	H	H	MH	MH	MH	MH
F_2	VL	VL	VL	VL	L	ML	ML	L	L	VL
F_3	ML	M	MH	MH	MH	MH	ML	ML	ML	MH
F_4	M	M	M	ML	ML	ML	ML	L	L	M
F_5	M	L	L	M	M	M	M	M	M	M
F_6	M	L	M	L	M	L	ML	L	L	M
F_7	VL	L	VL	L	VL	L	VL	ML	VL	L
F_8	M	L	M	VL	L	L	VL	VL	VL	VL
F_9	M	L	M	VL	VL	L	VL	L	VL	L
F_{10}	VL	L	VL	ML	ML	L	VL	L	VL	L
F_{11}	VL	L	VL	L	VL	L	VL	ML	VL	L
F_{12}	VL	L	VL	L	VL	L	VL	L	VL	L
F_{13}	VL	VL	VL	VL	VL	VL	VL	ML	L	VL
F_{14}	VL	L	VL	L	VL	L	VL	L	L	L
F_{15}	L	VL	ML	ML	L	L	L	L	L	L
F_{16}	H	H	H	H	H	H	MH	MH	H	H
F_{17}	VL	VL	ML	ML	ML	ML	VL	VL	L	L
F_{18}	VL	VL	ML	ML	L	ML	VL	VL	L	L
F_{19}	VL	L	ML	ML	L	ML	VL	VL	L	L
F_{20}	VL	L	ML	ML	L	L	VL	L	L	L
F_{21}	VL	VL	ML	ML	ML	ML	VL	VL	L	L

F_{22}	VL	VL	L	L	L	L	L	VL	VL	VL
F_{23}	VL	VL	VL	VL	VL	VL	L	VL	VL	VL
F_{24}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{25}	VL	ML	L	ML	L	VL	VL	VL	VL	VL
F_{26}	VL	ML	L	L	L	VL	VL	VL	VL	VL
F_{27}	VL	ML	L	L	L	VL	VL	VL	VL	VL
F_{28}	VL	ML	L	L	ML	VL	VL	VL	VL	VL
F_{29}	VL	ML	L	ML	ML	L	VL	L	VL	L
F_{30}	VL	L	L	ML	ML	VL	VL	VL	VL	VL

Expert3 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
VL ☐ L ☐ M ☒ H ☐ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
VL ☐ L ☐ M ☒ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
VL ☐ L ☐ M ☐ H ☒ VH ☒

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
VL ☐ L ☐ M ☐ H ☐ VH ☒

Expert3 – Section2

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}

F_{1}	VH	VH	VH	VH	VH	VH	VH	H	VH	VH
F_{2}	VH	H	H	H	VH	VH	VH	H	VH	VH
F_{3}	VH	H	VH	H	VH	H	VH	H	H	H
F_{4}	VH	H	VH	H	VH	H	VH	H	VH	H
F_{5}	VH	H	H	H	VH	H	H	H	VH	H
F_{6}	VH	H	MH	MH	H	VH	H	MH	VH	H
F_{7}	VH	H	MH	H	VH	H	MH	H	VH	H
F_{8}	VH	H	H	H	VH	H	VH	VH	VH	H
F_{9}	VH	VH	VH	H	VH	VH	VH	VH	VH	VH
F_{10}	VH	VH	H	H	VH	VH	H	H	VH	VH
F_{11}	VH	VH	H	H	VH	VH	H	H	VH	VH
F_{12}	VH	VH	H	H	VH	VH	H	H	VH	VH
F_{13}	VH	VH	H	H	VH	VH	VH	H	VH	VH
F_{14}	VH	VH	H	H	VH	VH	VH	H	VH	VH
F_{15}	H	VH	MH	H	H	VH	VH	H	H	VH
F_{16}	VH	VH	H	H	H	VH	VH	H	VH	VH
F_{17}	H	VH	H	H	MH	VH	VH	H	H	VH
F_{18}	H	H	MH	H	MH	H	H	H	H	H
F_{19}	VH	H	MH	MH	MH	MH	MH	MH	MH	H
F_{20}	VH	VH	H	H	VH	VH	H	H	VH	VH
F_{21}	VH	VH	MH	H	VH	VH	H	H	VH	VH
F_{22}	VH	H	H	H	VH	H	H	H	VH	H
F_{23}	VH	MH	H	H	VH	MH	H	H	VH	MH
F_{24}	VH	MH	MH	H	VH	VH	H	H	VH	VH
F_{25}	VH	VH	MH	H	VH	VH	VH	H	H	H

F_{26}	VH	VH	VH	H	VH	VH	VH	H	VH	H
F_{27}	VH	VH	VH	H	VH	VH	VH	H	MH	MH
F_{28}	VH	VH	VH	H	VH	VH	VH	H	VH	H
F_{29}	VH	VH	VH	H	VH	VH	VH	H	VH	VH
F_{30}	VH	VH	VH	H	VH	VH	MH	H	MH	MH

Expert4 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☒ H ☐ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☒ M ☐ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☒ VH ☐

Expert4 – Section2

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
F_1	VH	VH	H	VH	VH	H	H	H	H	H
F_2	M	M	M	M	M	M	M	M	M	M
F_3	VH	H	H	VH	H	H	H	VH	H	H
F_4	M	H	H	H	MH	MH	MH	M	MH	MH
F_5	M	MH	MH	MH	H	H	H	MH	H	H
F_6	L	L	L	L	L	L	L	L	L	L
F_7	MH	M	M	MH	MH	M	MH	MH	MH	MH
F_8	MH	M	M	M	M	M	M	M	MH	M
F_9	MH	M	M	M	M	M	M	MH	MH	MH
F_{10}	MH	M	M	MH	M	MH	M	MH	MH	MH
F_{11}	MH	MH	MH	ML	MH	MH	MH	M	MH	MH
F_{12}	MH	MH	M	M	MH	M	MH	M	MH	MH
F_{13}	MH	MH	MH	MH	MH	M	MH	ML	MH	MH
F_{14}	MH	MH	M	MH	M	M	MH	ML	MH	MH
F_{15}	MH	MH	MH	M	MH	M	MH	M	MH	MH
F_{16}	MH	MH	M	M	M	M	MH	M	MH	MH
F_{17}	MH	MH	MH	M	MH	MH	MH	ML	MH	MH
F_{18}	MH	MH	L	M	MH	M	MH	ML	MH	MH
F_{19}	MH	MH	M	ML	MH	M	MH	ML	MH	MH
F_{20}	MH	MH	MH	L	MH	MH	MH	ML	MH	MH

F_{21}	MH	MH	MH	ML	MH	MH	MH	ML	MH	MH
F_{22}	L	L	L	L	L	ML	L	ML	ML	L
F_{23}	MH	MH	M	L	MH	M	MH	M	M	M
F_{24}	MH	MH	MH	ML	MH	M	MH	ML	M	M
F_{25}	L	M	ML	L	M	M	ML	ML	ML	ML
F_{26}	L	M	ML	L	M	M	ML	ML	ML	ML
F_{27}	L	M	L	L	L	L	ML	ML	ML	ML
F_{28}	L	M	ML	L	M	M	L	L	ML	ML
F_{29}	L	M	L	L	M	L	L	ML	ML	ML
F_{30}	L	M	ML	L	L	M	ML	L	ML	ML

Expert5 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☐ VH ☒

Expert5 – Section2

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
F_1	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
F_2	VH	VH	H	VH	VH	VH	VH	VH	VH	VH
F_3	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
F_4	MH	MH	H	MH	MH	MH	MH	MH	MH	MH
F_5	H	H	H	VH	VH	VH	VH	H	VH	VH
F_6	MH	MH	H	MH	MH	MH	MH	MH	MH	MH
F_7	VH	VH	H	H	VH	H	H	H	H	H
F_8	H	H	H	H	H	H	H	H	H	H
F_9	VH	VH	VH	VH	VH	VH	VH	VH	VH	H
F_{10}	VH	VH	VH	VH	VH	VH	VH	VH	VH	H
F_{11}	H	H	H	VH	VH	H	VH	VH	VH	VH
F_{12}	H	H	H	H	H	H	H	H	VH	H
F_{13}	VH	H	VH	VH	VH	VH	VH	VH	VH	VH
F_{14}	H	H	H	H	H	H	H	H	H	H
F_{15}	H	H	H	H	MH	H	H	H	H	H
F_{16}	VH	VH	H	VH	VH	VH	VH	VH	VH	VH
F_{17}	H	H	H	MH	MH	H	H	H	H	H
F_{18}	H	H	H	H	MH	MH	H	H	H	H
F_{19}	H	MH	H	H	MH	MH	MH	MH	MH	H
F_{20}	MH	MH	H	H	MH	MH	MH	H	H	H

F_{21}	MH	H	H	H	MH	H	MH	H	H	H
F_{22}	MH	MH	MH	H	H	H	H	MH	MH	MH
F_{23}	H	H	MH	MH	H	H	H	H	H	H
F_{24}	H	H	MH	MH	H	H	H	H	H	H
F_{25}	H	H	H	H	H	H	H	H	H	H
F_{26}	MH	MH	MH	H	H	H	MH	MH	MH	MH
F_{27}	MH	MH	MH	MH	MH	MH	MH	MH	MH	L
F_{28}	MH	M	MH	MH	MH	MH	MH	MH	MH	MH
F_{29}	M	M	M	MH	MH	MH	M	M	M	M
F_{30}	M	M	M	MH	M	M	M	M	M	M

Expert6 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☐ VH ☒

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
VL ☐ L ☐ M ☐ H ☒ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
VL ☐ L ☐ M ☒ H ☐ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
VL ☐ L ☐ M ☒ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
VL ☐ L ☐ M ☒ H ☐ VH ☒

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
VL ☐ L ☐ M ☐ H ☐ VH ☒

Expert6 – Section2

	Risk Factors									
Failure Modes	**R_1**	**R_2**	**R_3**	**R_4**	**R_5**	**R_6**	**R_7**	**R_8**	**R_9**	**R_{10}**
F_1	VL	L	L	L	VL	VL	VL	VL	VL	VL
F_2	H	H	M	L	L	L	L	L	L	L
F_3	VL	L	M	L	VL	VL	VL	VL	VL	VL
F_4	VL	VL	L	L	VL	VL	VL	VL	VL	V
F_5	H	H	VH	H	H	H	H	VH	H	H
F_6	L	L	H	L	VL	VL	VL	VL	VL	VL
F_7	L	L	L	L	VL	VL	VL	VL	VL	VL
F_8	M	M	M	M	M	M	M	M	M	M
F_9	M	M	M	M	M	M	M	M	M	ML
F_{10}	L	L	L	L	ML	ML	ML	L	L	L
F_{11}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{12}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{13}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{14}	L	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{15}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{16}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{17}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{18}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{19}	VL	VL	L	L	L	L	L	L	L	L
F_{20}	VL	VL	L	L	L	L	L	L	L	L

F_{21}	VL	VL	L	L	L	L	L	L	L	VL
F_{22}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
F_{23}	ML	ML	ML	ML	ML	ML	ML	ML	ML	ML
F_{24}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_{25}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_{26}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_{27}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_{28}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_{29}	L	L	L	L	L	L	L	L	L	L
F_{30}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL

Expert7 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☒ M ☐ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☐ VH ☒

Expert7 – Section2

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
F_1	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_2	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_3	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_4	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_5	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_6	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_7	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_8	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_9	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{10}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{11}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{12}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{13}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{14}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{15}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{16}		VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{17}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{18}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
F_{19}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{20}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL

F_{21}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{22}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{23}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{24}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{25}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{26}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{27}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{28}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{29}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL
F_{30}	VL	VL	L	VL	VL	VL	VL	VL	VL	VL

Expert8 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☐ VH ☒

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☒ VH ☐

Expert8 – Section2

	Risk Factors									
Failure Modes	**R_1**	**R_2**	**R_3**	**R_4**	**R_5**	**R_6**	**R_7**	**R_8**	**R_9**	**R_{10}**
F_1	L	VL	M	L	M	M	L	L	L	L
F_2	VL	M	L	L	VL	VL	VL	VL	VL	VL
F_3	L	L	VL	L	M	M	L	L	L	L
F_4	ML	ML	L	ML	ML	ML	ML	ML	ML	ML
F_5	MH	MH	MH	MH	MH	MH	MH	MH	MH	MH
F_6	VL	VL	VL	VL	L	ML	ML	ML	L	L
F_7	M	M	M	M	ML	ML	ML	ML	ML	ML
F_8	M	M	MH	M	MH	MH	MH	MH	MH	MH
F_9	M	M	M	M	MH	MH	M	M	M	M
F_{10}	M	M	M	M	M	M	M	M	M	M
F_{11}	ML	L	ML	ML	ML	ML	ML	ML	ML	ML
F_{12}	L	L	L	L	L	L	L	L	ML	L
F_{13}	MH	MH	VH	MH	MH	MH	VH	MH	MH	MH
F_{14}	L	L	M	L	L	L	ML	L	L	L
F_{15}	L	L	L	L	L	L	L	L	L	L
F_{16}	M	M	M	M	M	M	M	M	M	M
F_{17}	L	L	L	VL	VL	L	L	L	L	L
F_{18}	L	VL	L	L	L	VL	L	VL	VL	VL
F_{19}	L	VL	VL	L	L	VL	VL	VL	VL	VL
F_{20}	L	VL	VL	L	L	VL	L	VL	VL	VL

F_{21}	L	VL	L	L	L	L	L	VL	VL	VL
F_{22}	L	L	L	M	VL	L	M	L	VL	VL
F_{23}	L	VL	L	L	L	VL	L	L	L	VL
F_{24}	MH	M	MH	M	M	M	ML	ML	M	MH
F_{25}	VL	VL	L	L	VL	VL	VL	VL	VL	VL
F_{26}	ML	VL	L	L	L	L	L	L	L	VL
F_{27}	L	L	VL	L	L	VL	ML	L	L	VL
F_{28}	L	ML	L	L	L	VL	ML	L	L	L
F_{29}	L	L	ML	L	L	L	ML	L	L	L
F_{30}	L	L	VL	L	L	L	L	L	L	L

Expert9 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☐ H ☒ VH ☐

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☐ VH ☒

Expert9 – Section2

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
F_1	L	L	L	L	L	VL	L	L	L	L
F_2	H	H	H	H	H	H	H	H	H	H
F_3	VL	VL	VL	VL	L	L	VL	VL	VL	VL
F_4	H	VH	VH	VH	H	VH	VH	VH	VH	VH
F_5	ML	M	L	L	L	L	ML	ML	L	L
F_6	H	VH	VH	VH	H	H	H	H	H	VH
F_7	ML	M	ML	ML	L	L	ML	L	M	ML
F_8	L	L	L	L	L	ML	ML	ML	L	ML
F_9	ML	ML	ML	ML	L	L	L	L	ML	L
F_{10}	L	L	L	L	L	L	L	L	L	ML
F_{11}	ML	L	ML	ML	ML	ML	ML	L	L	L
F_{12}	L	L	VL	VL	VL	L	L	L	L	L
F_{13}	VL	VL	L	L	L	L	L	L	L	L
F_{14}	VL	VL	VL	L	VL	VL	VL	VL	VL	VL
F_{15}	VL	ML	L	L	L	L	L	L	L	L
F_{16}	ML	ML	ML	L	ML	ML	ML	ML	ML	L
F_{17}	L	L	L	L	L	L	L	ML	ML	VL
F_{18}	L	M	L	L	L	L	L	VL	VL	VL
F_{19}	L	M	L	L	L	ML	L	L	L	L
F_{20}	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL

F_{21}	L	ML	VL	L	L	L	ML	ML	VL	L
F_{22}	VL	ML	VL	VL	VL	VL	VL	VL	VL	VL
F_{23}	VL	M	VL	VL	VL	VL	VL	VL	VL	VL
F_{24}	L	M	VL	VL	VL	VL	VL	ML	M	VL
F_{25}	L	VL	VL	VL	VL	VL	ML	ML	VL	VL
F_{26}	VL	L	VL	VL	VL	VL	VL	VL	VL	ML
F_{27}	VL	VL	VL	L	L	VL	VL	VL	VL	ML
F_{28}	VL	L	VL	ML	L	L	L	VL	VL	VL
F_{29}	VL	L	VL	VL	VL	VL	VL	ML	L	L
F_{30}	ML	VL	ML	ML	VL	VL	VL	VL	VL	L

Expert10 – Section1

1. SCM installed subsea is exposed to several hydrostatic and hydrodynamic forces. How significant is SCM failure occurrence associated with water depth (**R_1**)?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

2. SCM subjected to normal design operating conditions (**R_2**) still fail and sometimes in their early life. How important is SCM failure under normal operations (**R_2**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

3. Sometimes SCM sometimes operate in conditions that are outside their design operational boundaries. How important is SCM failure under these **extreme operations** (**R_3**) to evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

4. SCM component failure leads to loss in revenue as the part/subsystem system may require repair or outright changeout. What is the importance of this **direct cost** (**R_4**) of this component/subsystem in assessing SCM reliability?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

5. SCM failures leads to **indirect cost** (**R_5**) in terms deferred production, cost for offshore repair vessel rental…etc. How significant is this to making SCM more reliable.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

6. Failure in SCM functionality may have some impact on the environment in terms of control fluid leakage to the sea, oil spillage…etc. How important is this **environmental impact** (**R_6**) in assessing SCM reliability.
   VL ☐ L ☐ M ☐ H ☒ VH ☐

7. Loss in SCM functionality might lead to loss of life. How significant is **fatality** (**R_7**) consideration in designing SCM for reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

8. Some SCM failures lead to non-financial business impact (**R_8**) to the business owner/operator, like loss in reputation…etc. How important is this in evaluating SCM reliability.
   VL ☐ L ☐ M ☒ H ☐ VH ☐

9. Some SCM failures are easy to detect while others are not. How important is the ability to detect failure (**R_9**) on SCM reliability?
   VL ☐ L ☐ M ☐ H ☐ VH ☒

10. Some components in the SCM are duplicated in redundancy (**R_{10}**) as safeguard in case of failure. How important is redundancy in SCM reliability.
    VL ☐ L ☐ M ☐ H ☒ VH ☐

Expert10 – Section2

	Risk Factors									
Failure Modes	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
F_1	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
F_2	M	M	M	M	ML	M	M	M	M	M
F_3	VH	VH	VH	VH	H	VH	VH	VH	VH	VH
F_4	H	VH	H	H	H	H	H	VH	H	H
F_5	H	H	MH	H	MH	MH	H	H	H	MH
F_6	VH	H	VH	H	MH	MH	MH	MH	MH	MH
F_7	MH	MH	H	H	MH	MH	MH	MH	MH	MH
F_8	H	VH	VH	H	M	MH	MH	MH	MH	MH
F_9	H	H	H	H	M	MH	MH	H	H	H
F_{10}	H	M	H	H	MH	MH	H	H	H	H
F_{11}	H	H	MH	H	MH	MH	MH	H	MH	MH
F_{12}	H	H	MH	H	MH	M	MH	H	MH	M
F_{13}	MH	MH	H	H	H	MH	MH	MH	MH	MH
F_{14}	MH	MH	MH	H	H	H	H	H	H	H
F_{15}	M	M	M	M	MH	M	MH	MH	M	M
F_{16}	M	M	H	H	MH	M	MH	M	M	M
F_{17}	MH	MH	H	H	MH	MH	MH	MH	H	MH
F_{18}	H	H	M	M	MH	MH	MH	MH	H	M
F_{19}	M	M	M	M	M	M	M	MH	MH	MH
F_{20}	M	M	M	M	MH	MH	MH	MH	M	M

F_{21}	M	M	M	M	M	M	MH	M	M	M
F_{22}	MH	M	M	MH	H	M	M	M	M	M
F_{23}	M	M	M	M	M	M	M	M	H	MH
F_{24}	ML	ML	M	M	ML	ML	ML	ML	M	H
F_{25}	M	ML	M	M	ML	ML	ML	ML	M	M
F_{26}	ML	ML	M	M	ML	ML	ML	ML	M	H
F_{27}	ML	M	H	M	M	ML	ML	ML	ML	H
F_{28}	ML	ML	ML	M	M	M	M	ML	ML	ML
F_{29}	ML	M	ML	ML	M	ML	M	M	M	M
F_{30}	ML	ML	ML	ML	ML	ML	M	ML	ML	ML

Appendix E: Subsea Control Module (SCM) Specification

Environmental Data	
Water Depth	3000 meters LAT
Operating temperature range (°F/°C)	Surface unit = 23 to 104 *(-5 to 40)* Subsea unit = 23 to 104 *(-5 to 40)*
Shock	iaw ISO 13628-6
Vibration	iaw ISO 13628-6
EMC	iaw ISO 13628-6
Subsea Equipment Design	
Design life	25 years
Intervention	ROV or diver deployment and intervention
SCM size (in./*mm*)	33.5 x 33.5 x 3 high *(850 x 850 x 75 high)*, excluding mounting base
SCM weight (lb./*kg*)	In air, 1874 *(850)* In water, 1323 *(600)* approximately
SCM housing	Pressure compensated, dielectric fluid filled
Mounting	Subsea tree or manifold structure (ROV to API 17 H or diver)
System Pressures and Fluid	
High pressure (psig/*barG*)	15k (1034) MWP
Low pressure (psig/*barG*)	5k (345) MWP
Control fluid	Water based biodegradable, open loop or petroleum based synthetic mineral oil (standard)
Control fluid cleanliness	NAS 1638 Class 6
Supply filtration	Integral single B3–200 rating elements (3 micron)
Electrical	
Analog	4 to 20 mA (standard) 12-bit, other configurations available
Discrete	24 VDC, 0.5 to 8 A (maximum) output configurable 24 VDC input configuration available
Power supply	110, 230 or 480, 50/60 Hz single phase (nominal), 24 VDC (option)
Communications	Comms-on-power, comms-and-power and/or fiber optic