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Provision of Reliability Data for New Technology Equipment in Subsea Production Systems

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Reliability, Availability, Maintainability and Safety (RAMS)

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Norwegian University of Science and Technology
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for
stud. techn. Ishita Dash

**PROVISION OF RELIABILITY DATA FOR NEW TECHNOLOGY
EQUIPMENT IN SUBSEA PRODUCTION SYSTEMS
(Pålitelighetsdata for ny teknologi i undervanns produksjonssystemer)**

Increased water depths, the associated high cost of conventional topside installations, and hostile environmental conditions have paved the way for increased use of subsea production systems (SPSs) for oil and gas. During the last decade, several new technologies (e.g., subsea separation, pumping, and compression) have emerged to increase the production of an SPS. Many of these technologies are based on equipment that can be regarded as “marinization” of conventional topside equipment, but where the equipment needs to be more robust to withstand the hostile operational and environmental conditions.

To assess the reliability of the new technologies, equipment reliability estimates are required. Since these technologies are new, no relevant experience data is available and the required data must be “extrapolated” from data from similar equipment. The main objective of the current project assignment is to develop a procedure for how to carry out this “extrapolation” and to describe the associated methods and tools.

As part of this project thesis the candidate shall:

1. Give a survey of reliability data sources and evaluate these with respect to relevance and quality. Special focus should be put on FIDES and MechRel – and possible company-specific data sources.
2. Give a brief technical description of relevant new technologies.
3. Select relevant subsea equipment and carry out a failure modes and failure cause/mechanism analysis of these.
4. Compare the selected subsea equipment with similar topside equipment (for which data are available) to identify design changes, differences in stressors and maintenance and – based on this, compare the possible failure modes with respect to relevance and likelihood.
5. Identify the reliability influencing factors for both topside and subsea application and illustrate them by Bayesian networks.

6. Study the approach described by Brissaud, F. et al (2010) “Failure rate evaluation with influencing factors” and discuss whether or not this approach can be applicable in the current context – possibly in a modified version.
7. Discuss whether or not the assumption of constant failure rates will be realistic for subsea applications where the possibilities for preventive maintenance are limited.
8. Develop a new approach to determination of failure rate functions for new technology equipment in subsea applications.
9. Discuss the results, including ideas for further work related to the proposed approach.

Within three weeks after the date of the task handout, a pre-study report shall be prepared. The report shall cover the following:

- An analysis of the work task’s content with specific emphasis of the areas where new knowledge has to be gained.
- A description of the work packages that shall be performed. This description shall lead to a clear definition of the scope and extent of the total task to be performed.
- A time schedule for the project. The plan shall comprise a Gantt diagram with specification of the individual work packages, their scheduled start and end dates and a specification of project milestones.

The pre-study report is a part of the total task reporting. It shall be included in the final report. Progress reports made during the project period shall also be included in the final report.

The report should be edited as a research report with a summary, table of contents, conclusion, list of reference, list of literature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also important that exact references are given to any external source used in the text.

Equipment and software developed during the project is a part of the fulfilment of the task. Unless outside parties have exclusive property rights or the equipment is physically non-moveable, it should be handed in along with the final report. Suitable documentation for the correct use of such material is also required as part of the final report.

The student must cover travel expenses, telecommunication, and copying unless otherwise agreed.

If the candidate encounters unforeseen difficulties in the work, and if these difficulties warrant a reformation of the task, these problems should immediately be addressed to the Department.

The assignment text shall be enclosed and be placed immediately after the title page.

Deadline: June 11th 2012.

Two bound copies of the final report and one electronic (pdf-format) version are required.

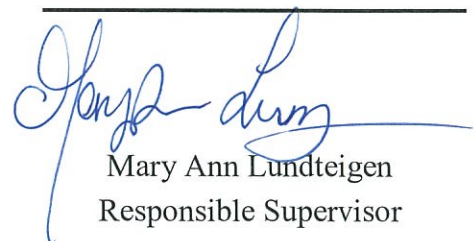
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STUDY REPORT

PROVISION OF RELIABILITY DATA FOR NEW TECHNOLOGY EQUIPMENT IN SUBSEA PRODUCTION SYSTEMS

MASTER THESIS

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Preface

This report documents the master thesis, at the Department of Production and Quality Engineering, Faculty of Engineering Science and Technology, NTNU. The thesis is part of the two year master degree program on Reliability, Availability, Maintainability and Safety (RAMS) at NTNU.

The title of this thesis is “Provision of Reliability Data for New Technology Equipment in Subsea Production Systems”.

It is assumed that the reader is familiar with, or has similar knowledge to, the contents of the book “System Reliability Theory; Models, Statistical Methods, and Applications” (Rausand 2004).

I wish to thank my supervisors Marvin Rausand, Mary Ann Lundteigen and my co-supervisor Yiliu Liu for their contributions and comments during the project period.

Trondheim, 2012-06-27

Dash, Ishita

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I.D.

Abstract

For certain new technologies such as subsea processing systems reliability, compactness and easy maintainability are the most important factors to be considered while designing. This is because installation and retrieval costs increase with the increase in the size of the equipment. Failure of such equipments will cause huge production losses leading to enormous financial losses.

However to have a better understanding of how reliable a component is, it is most appropriate to express it quantitatively. Methods to predict the reliability of equipment have been suggested however they all require historical data to be fed as input to conduct the analysis. When dealing with new technologies these historical datas are nearly absent.

The objective of this thesis is to propose a method for estimating the failure rate of such new technologies with special focus on subsea processing systems.

A literature study was carried out on the various reliability datas such as OREDA, MIL-HDBK-217, FIDES and NSWC. The key features of each of the reliability data handbooks were identified. Also the various methods used for estimating the failure rates were discussed especially for FIDES and NSWC. A literature review of the various subsea processing systems was also carried out and a final focus was made on subsea multiphase helico-axial pump.

A bayesian approach was chosen for the new proposed approach. The suggested approach consists of six steps where the analysis starts with a failure mode and effect analysis of the chosen new technology, helico-axial subsea pump in our case. Using the results from the failure mode and effect analysis and literature reviews an influence diagram is developed for the helico-axial pump. The probabilities of the priors and the conditional probabilities are assigned based reliability data handbooks and literature reviews. The importance of each of the failure modes is identified. Finally the failure of the pump is calculated by multiplying the failure rate of each of the failure modes with its calculated importance. The total failure rate of the pump is obtained by adding the modified failure rates.

Using this method it was seen that the failure rate of the helico-axial pump with the given current design has a failure rate which is less than that of a centrifugal pump which is required to operate for a period of six years with one failure. Finally recommendations for further work have also been included at the final part of this report.

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1. Introduction

1.1 Background

To produce, process and transport the offshore oil & gas in deep waters subsea production systems prove to be an answer where traditional facilities like offshore installations might be either technically unfeasible or uneconomical due the great water depth. It should be however noted that the development of subsea oil and gas fields requires specialized equipment. These equipments require a high availability, that is it must be reliable enough to safe guard the environment, and make the exploitation of the subsea hydrocarbons economically feasible. Also attention needs to be paid to maintenance of these subsea equipments as it would add to the operational cost. Any repair or a requirement to intervene with installed subsea equipment is normally very expensive. With most of the new oil fields located in deeper waters, subsea technology is a highly specialized field of application with high demands on engineering and simulation. Strict requirements are set for verification of the various system functions and their compliance with current requirements and specifications (DNV-RP-0401 1985). In addition when the equipment is under operation it undergoes degradation, especially mechanical equipment, such as friction between moving parts in a severe operating environment. In the oil industry modern data technology has been adopted as a tool for virtual testing of deepwater systems that enables detection of costly faults at an early phase of the project, which is the design phase^a. A reliability prediction is performed in the early stages of a development program to support the design process which highlights the reliability requirements in the early development phase and an awareness of potential degradation of the equipment during its life cycle. By using modern simulation tool models deepwater systems are set up and used to verify the system functions and dynamic properties, against various requirements and/or specifications^b. As a result of performing a reliability prediction, equipment designs can be improved, costly over-designs prevented and development testing time optimize (NSWC-06/LE10 2006).

^a <http://www.tekna.no/ikbViewer/Content/783313/13%20-%20%D8ylvstad%20-%20..>

^b [http://en.wikipedia.org/wiki/Subsea_\(technology\)](http://en.wikipedia.org/wiki/Subsea_(technology))

Statistical analysis forms the basis for reliability prediction. Reliability is defined as “the probability that equipment will perform a specified function under stated conditions for a given period of time”(Rausand 2004). This is a probabilistic approach where the probability is calculated to be within certain statistical confidence limits. To perform such calculation the fundamental requirement is reliability data. For a qualitative risk analysis the key reliability parameters to be taken into consideration from the reliability data sources is the failure rate or the mean time to failure (MTTF) or the probability of failure on demand.

1.2 Objective

To assess the reliability of new technologies, such as subsea production systems, reliability estimates are required. However as no relevant experience data is available, the required data is required to be ‘extrapolated’ from the data of similar equipments. The main objective of this project is to develop a procedure to ‘extrapolate’ and describe the associated methods and tools.

The main objective is further divided into the following more specific sub-objectives:

1. Give a survey of the reliability data sources and evaluate these with respect to relevance and quality. Special focus should be put on FIDES and MechRel – and possible company-specific data sources.
2. Give a brief technical description of relevant new technologies.
3. Select relevant subsea equipment and carry out a failure modes and failure cause/mechanism analysis of these.
4. Compare the selected subsea equipment with similar topside equipment (for which data is available) to identify design changes, differences in stressors and maintenance and – based on this compare the possible failure modes with respect to relevance and likelihood.
5. Identify the reliability influencing factors for both topside and subsea application and illustrate them by Bayesian networks.

6. Study the approach described by Brissaud, F. Et al (2010) ‘Failure rate evaluation with influencing factors’ and discuss whether or not this approach can be applicable in the current context – possibly in a modified version.
7. Discuss whether or not the assumption of constant failure rates will be realistic for subsea applications where the possibilities for preventive maintenance are limited.
8. Develop a new approach to determination of failure rate functions for new technology equipment in subsea applications.
9. Discuss the results, including ideas for further work related to the proposed approach.

1.3 Limitation

The main focus of this master thesis is to estimate the reliability of new technologies such as subsea production systems. In this report we have chosen to focus on single subsea equipment, helico-axial multiphase pump to limit the scope of the report. The most relevant reliability analysis tool used in this report is the Bayesian belief network (BBN).

Most attention is being paid to the sub-objectives 7 and 8 above, as these are the parts that are considered to be the most challenging of the sub-objectives. The thesis is related to subsea processing systems and is carried out at NTNU, Trondheim. As a result there has been a limitation on the subsea equipment / system description and the reliability datas.

An in-depth understanding and use of the Bayesian method has proved to be quite a time-consuming task. A detailed review and understanding of the various reliability datas such as FIDES and NSWC was also required to be carried out which required several days.

As mentioned in the preface to the report, it is assumed that the reader has some prior knowledge of basic statistics and reliability studies. This is done to be able to go straight to the core of the problem without spending unnecessary time on the explanation of all otherwise well-known theories and models. It is assumed that the reader is familiar with concepts like failure rates, failure modes, Weibull distribution, exponential distribution, and confidence intervals.

1.4 Approach

A brief description of the new technologies within subsea production systems is carried out. Reliability procedure in FIDES^c and MechRel^d is reviewed and discussed. In both procedures a new reliability assessment method has been developed which provides an engineering process and tools to improve reliability in the development of new systems / equipments. The approach by Brissaud has also been discussed briefly where he takes the influencing factors into consideration while estimating the failure rate.

The main focus of this thesis is to develop a procedure to carry out the ‘extrapolation’ of data from equipment which are similar to the new technology equipments in subsea production systems. A detailed approach for this extrapolation has been explained in chapter 7 of this report. In short the new methodology uses the bayesian method to combine the available historical data of similar topside equipment and expert judgement. The worst contributor is calculated which is the limiting factor for the failure rate of the equipment.

1.5 Structure of the report

Chapter 1 gives a brief background, objective, limitation and approach. Chapter 2 gives a brief description of the failure rates. Various reliability datas such as OREDA, MIL-HDBK-217, FIDES and NSWC has been discussed in chapter 3. An introduction to new technology and its qualification is reflected in chapter 4. As part of new technology, we focus on subsea equipments especially multiphase pumps (helico-axial pump) in chapter 5 and 6 respectively. In chapter 6 a comparison between subsea equipment and topside equipment with respect to design, failure rate and maintenance has also been discussed. Chapter 7 details out a methodology to estimate the failure rate of such new technology. Summary and conclusion and recommendations for further work are shown in chapter 8. Appendix A - explains the FMEA methodology and a FMEA of chosen subsea equipment (helico-axial multiphase pump) is performed. Appendix B – shows the calculation for the proposed methodology.

^c <http://fides1.imdr.eu/>

^d <http://www.mechrel.com/>

Appendix C - gives a brief technical description of other new technologies in subsea processing systems (subsea separator, subsea compressor and subsea powergrid).

2. Failure rate

According to IEC 61511-1 failure is “*termination of the ability of a functional unit to perform a required function.*” Failure can be further divided into safe and dangerous failures where safe failure is “*failures which does not have the potential to put the SIS in a hazardous or fail-to-function state*”^e. The PDS method handbook tries to clarify and define safe failures further but introducing the term non-critical failure and spurious trip which is also shown in figure 4. The former refers to failures which do not affect the main safety function, whereas the latter focuses on the safety function unavailability due to a spurious trip. PDS is the Norwegian abbreviation for “reliability of computer-based safety systems”. PDS Method Handbook is developed by Sintef which describes the approach to quantify the safety unavailability and loss of production for SIS. The PDS method is in line with the main principles in the IEC 61508 and IEC 61511. Dangerous failure as defined by IEC 61511-1 is “*failure which has the potential to put the SIS in a hazardous or fail-to-function state*”. In figure 1 one may notice that dangerous and safe failures are further classified as detected and undetected. The most critical type of failures is the dangerous undetected failures as this governs the unavailability. The dangerous undetected failures include hardware failures as well as systematic failures (SINTEF 2010).

^e http://en.wikipedia.org/wiki/Safety_instrumented_system

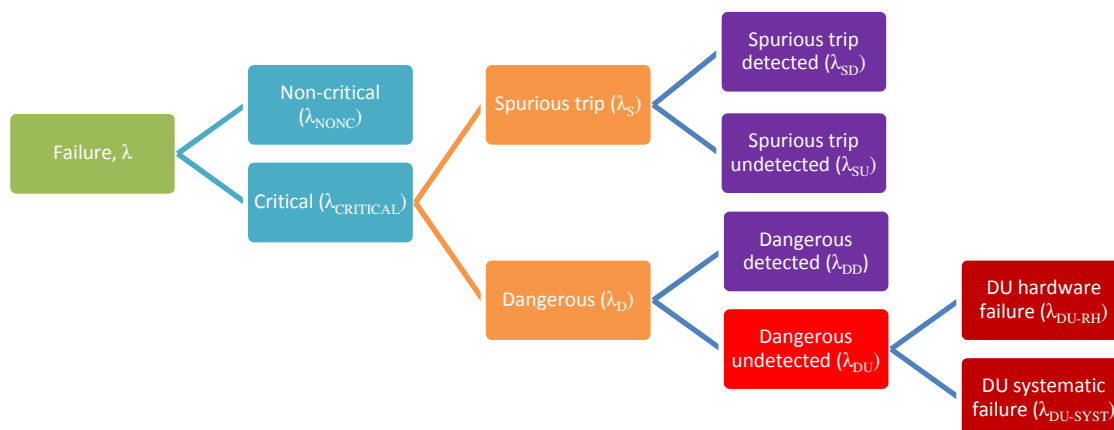


Figure 1: Failure mode classification, adapted from IEC 61508 & PDS method handbook

The failure rate (λ) for a component is the ratio of the total number of failures (k) to the cumulative operational time (T), such that

$$\lambda = k/T \quad 1$$

The pattern of failure of a component across time can be understood with a bathtub curve. The life of an item/component is split into three phases namely the infant mortality phase, useful (constant) phase and the wear out phase. The failure rate function is different in all the three phases and is illustrated in figure 2 and this curve is called the ‘bath-tub’ curve due to its shape.

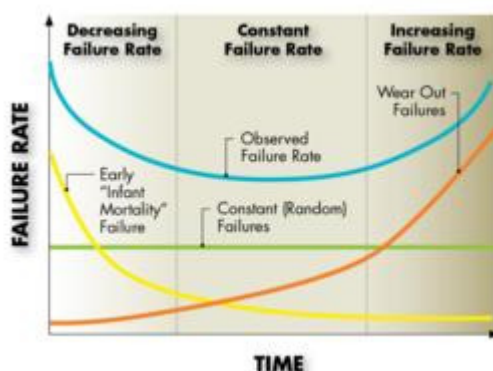


Figure 2: Bath-tub curve, source http://www.exponent.com/electronic_component_reliability/

In order to perform analysis of failure patterns outside of the constant failure rate period a level of detailed information is required that is typically not available from the recorded data (e.g. actual age of equipment of failure, homogeneous samples).

Therefore an assumption is made that all failures recorded are experienced during the useful life phase, and the pattern of these failures may be described by a random, exponential distribution. This can, at least to a certain extent, be justified on the following grounds:

- Early life failures resulting from commissioning problems may not be recorded as equipment failures
- Early life failures resulting from manufacturing defects can be largely eliminated by testing prior to installation
- Wear out failures largely eliminated by preventative maintenance and planned renewals.

Note that this assumption may be less valid for wear out of subsea equipment where no planned maintenance will be performed.

The most common way to estimate failure rate (λ) is to divide the total number of failures to the total time in service. However this is only applicable when the samples are homogeneous, that is items operate under similar conditions. A multi sample estimation can be used when dealing with non-homogeneous samples (Rausand 2004; OREDA 2009). In reality products do not exhibit constant failure rates. This is quite true for a mechanical part where wear-out is the primary failure mode. And all kinds of parts, mechanical and electronic, are subject to infant mortality failures from intrinsic defects. But there are common situations where a true random failure potential exists. There are other cases, especially in electronic products, where a "constant" failure rate may be appropriate (although approximate). This is the basis for MIL-STD-217 and other methods to estimate system failure rates from consideration of the types and quantities of components used. For many electronic components, wear-out is not a practical failure mode. The time that the product is in use is significantly shorter than the time it takes to reach wear-out modes. That leaves infant mortality and normal life failure modes as the causes of all significant failures.

3. Reliability Data

To perform reliability predictions one would require several types of data, such as technical, operational and environmental, maintenance and reliability data. We can define 'reliability data' as information about failure/error modes and time to failure distribution for hardware, software and human (Rausand 2004). Our focus would be on the hardware component

reliability databases (Rausand 2004) which provide estimates of failure rates for single components. The failure rate estimates are based on recorded failure events or expert judgement or laboratory testing or a combination of all three. Two methods have been widely used to predict the reliability which is statistical failure models and physics of failure. Statistical failure models use set of mathematical equations along with reliability data of similar equipments in operation. Formulas to quantify the reliability have been provided such as in PDS method handbook (SINTEF 2010) and System reliability theory (Rausand 2004). When using statistical models, reliability datas are taken from historical data or from failure rate data handbooks (MIL-HDBK-217F 1991; OREDA 2009) or from data obtained from test samples. Physics of Failure is a technique under the practice of Design for Reliability that leverages the knowledge and understanding of the processes and mechanisms that induce failure to predict reliability and improve product performance. The concept of Physics of Failure involves the use of degradation algorithms that describe how physical, chemical, mechanical, thermal, or electrical mechanisms evolve over time and eventually induce failure. It is interesting to note that physics of failure is typically designed to predict wear out. There are some limitations with the use of physics of failure in design assessments and reliability prediction. The first is physics of failure algorithms typically assume a 'perfect design'. Attempting to understand the influence of defects can be challenging and often leads to Physics of Failure predictions limited to end of life behaviour (as opposed to infant mortality or useful operating life).

To summarize the above failure rate data can be obtained in several ways. The most common means are:

- Historical data about the device or system under consideration.

Many organizations maintain internal databases of failure information on the devices or systems that they produce, which can be used to calculate failure rates for those devices or systems. For new devices or systems, the historical data for similar devices or systems can serve as a useful estimate.

- Government and commercial failure rate data.

Handbooks of failure rate data for various components are available from government and commercial sources. For example MIL-HDBK-217F, Reliability Prediction of

Electronic Equipment, is a military standard that provides failure rate data for many military electronic components. Several failure rate data sources are available commercially such as FIDES guide, NSWC-06/LE10 that focuses on commercial electronic and non-electronic components.

- Testing.

The most accurate source of data is to test samples of the actual devices or systems in order to generate failure data. This is often prohibitively expensive or impractical especially when dealing with new technology, as a result the above mentioned data sources are used instead.

4. Survey of the various Reliability Datas

4.1 OREDA- Offshore Reliability Data handbook

OREDA – Offshore Reliability Data handbook, is an example of a database where manufacturers and makes of the components are only available to the participating companies, else a generic component reliability database is available where components are classified under groups such as compressors, turbochargers, pumps and the like. It is based on the actual field data collected during 1993 to 2000 for both topside and subsea equipments. It is interesting to note that OREDA provides a boundary definition for the equipment under analysis. By doing so it gives a generic list of items that are essential for the functioning of the equipment under consideration. The data collected for equipment is typically between the periods of 2-4 years of its operation. For the topside equipment the infant mortality state is not considered, however for the subsea equipments the whole lifetime is considered. The failure rate, $\lambda(t)$ estimated here only focuses on the useful life phase part of the bath-tub curve^f of the component, thus assuming the failure rate, $\lambda(t)$ to be constant and independent of time, as a result $\lambda(t)=\lambda$, with a 90% confidence interval (OREDA 2009). It has been observed that even though the fifth edition (2009) is the latest the collected reliability datas is only till 2000. This leads to a gap on the reliability datas for equipments after 2000 to till

^f http://en.wikipedia.org/wiki/Bathtub_curve

date. It has also been noted that the failure modes listed, are not the most practical and do not support the fact that they describe the failure functions of the equipment .

4.2 MIL-HDBK-217, Military handbook

The Military handbook, MIL-HDBK-217 on the other hand focuses on the laboratory estimates of failure rate for electronic systems performed in controlled environmental stresses. The MIL-HDBK-217 is based on three foundations: All system failures are caused by component failures, and all component failures cause system failures; all component types have a property of failure rate; and the component failure rates are proportional to applied thermal and electrical stresses and the environment and sources of supply. Formulas and data are provided in the handbook which helps adjust the failure rate of a component to a specific environment. It contains two methods of reliability prediction namely the “Part Stress Analysis” and “Parts Count”. The latter is applicable during the early design phase, when insufficient or less information is available. It requires generic part types and quantities, part quality level and equipment environment whereas the former is a detailed stress analysis carried out when detailed information on the component is available and the failure rate is expressed as a product of the basic failure rate and the influencing factors (MIL-HDBK-217F 1991). However it was noticed that as electronic systems got more complex, component failures were major cause of system failures. Also the listed three foundations were not correct. Thus the use of this handbook has been limited and alternative methods have been developed such as the FIDES guide (O'Connor 2001).

4.3 FIDES- Reliability Methodology for Electronic Systems

The FIDES guide (FIDES 2009) is an improvement to the Military Handbook, where it tries to address the new technologies within the electrical, electronic, electromagnetic components and for electronic boards or some subassemblies. It is based on physics of failures and is supported by analyses of test data, feedback from operations and existing models. The FIDES guide has two parts namely a predicted reliability evaluation guide and a reliability process

control and audit guide. The approach of reliability prediction is by considering only the useful life phase of the component in question, thus a constant failure rate is taken into account. The approach is based on three components, which is technology, process and use, where these are considered for the entire life cycle from the product specification phase until the operation and maintenance phase. Generic input data typically operating temperature, amplitude and frequency of temperature cycles, vibration amplitude, relative humidity, ambient pollution level, exposure to accidental overstress (application type) is broken down for each product life phase. The equipment life phase will contain atleast the same number of the system life phases or it can contain more.

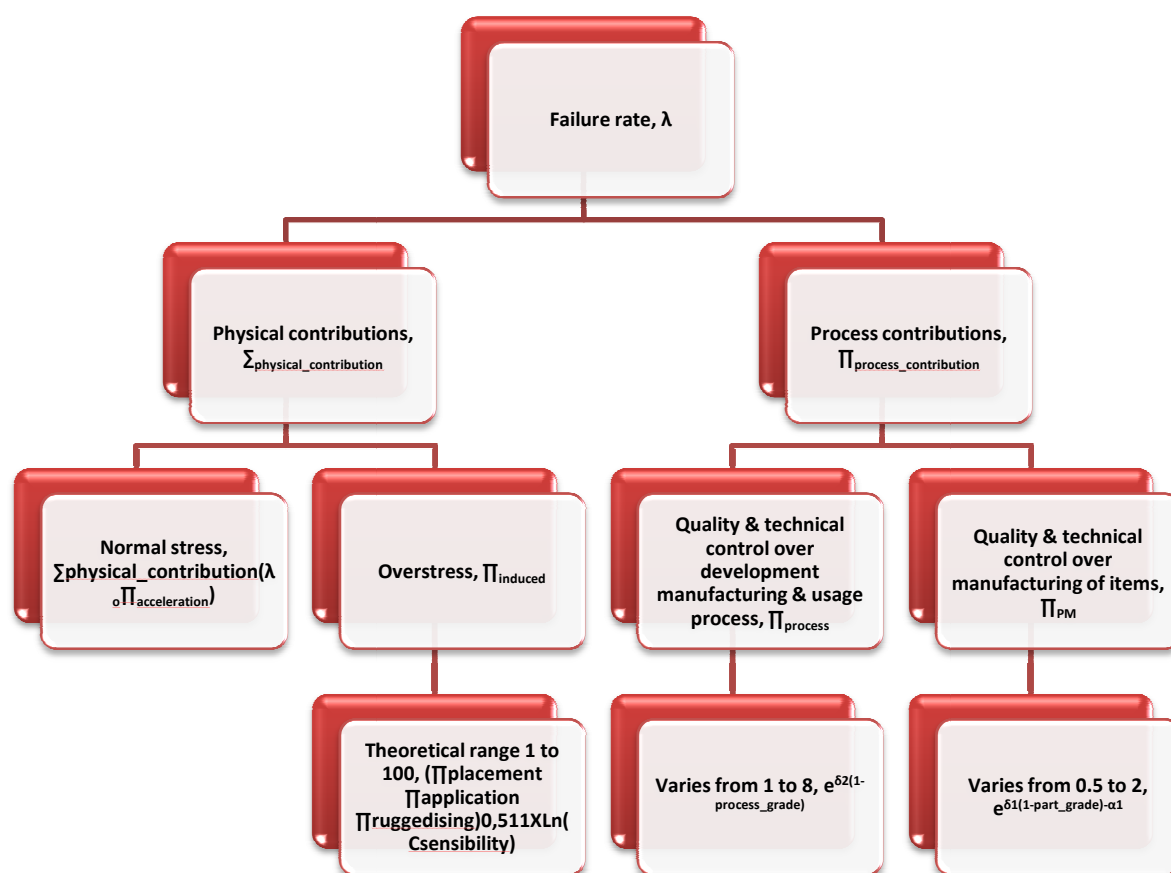


Figure 3: General Model developed by FIDES, adapted from (FIDES 2009)

However the equipment life phase may be more than the system life phase as there could be cases when the system remains unaffected. The data on the product life cycle is collected via audit of the processes concerning specification, design, equipment, manufacturing, integration into system, product operation, maintenance process and the support activities. Information on the suppliers is also collected. A general reliability model for an item,

developed in this guide, is shown in figure 3. The physical contributions ($\sum_{\text{physical contribution}}$) consisting of the normal stress and the overstress and the process contributions ($\sum_{\text{process contribution}}$) contributed by quality & technical control over manufacturing of items, development manufacturing and usage are the key contributors for the failure rate (λ) calculation. An applicability domain is proposed for each physical contributing factor mentioned previously. The predictions made with these parameters may not necessarily be precise as the reference operating environment could change. Formulas to calculate the temperature stress, cycling temperature, relative humidity, vibration amplitude and chemical stress has been provided in the FIDES guide for details please refer to (FIDES 2009). Figure 4 shows the various physical factors taken into consideration in the FIDES guide which are considered to affect the failure rate calculation depending on the operational mode and operating environment.

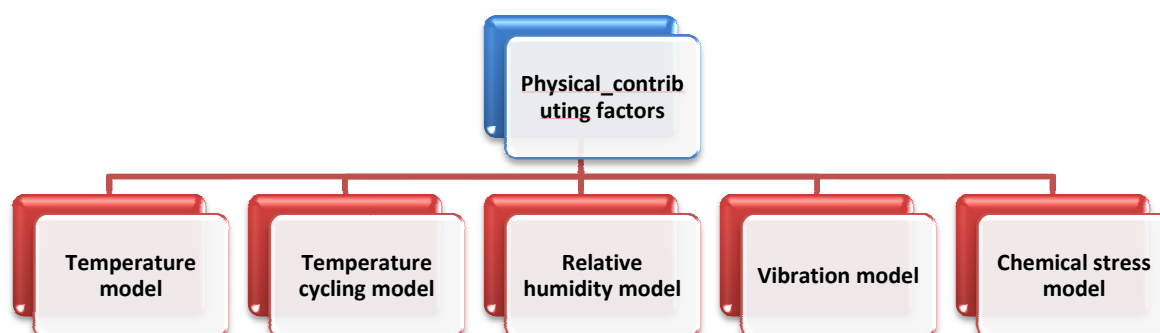


Figure 4: Physics of failures and models considered in FIDES, adapted from (FIDES 2009)

The failure rates are hourly expressed per calendar hour and based on the use of an annual life profile. Predicted failure rates are expressed in FIT, where 1 FIT is equal to 1 failure per 10^9 hours. It is important to note that the failure rates are not expressed per hour of operation; as a result they cannot be directly compared with results from different approaches. Expressing failure rates in calendar FIT does not enable easy comparison of failure rate values. However when expressing failure rates in the form of “MTBF per mission hour” all

failures are allocated to hours during which the product is considered to be “on-mission”, and hence forth it can be compared with other MTBFs. By summing the individual failure rates for each of its constituent items an overall failure rate is obtained. The FIDES guide provides a detailed explanation on how to predict the reliability using physics of failures rather than depending on the operational feedback data which is not feasible to obtain when the technology is new, which serves to be an advantage. However it is not always easy or feasible to know the various physical factors that would affect or contribute towards the failure of the component or item. Also as there are several steps involved the results are more likely to be prone to error. Also as one requires performing several steps, this may lead to a false indication that the predicted reliability is close to the actual reliability.

4.4 NSWC- Handbook of Reliability Prediction procedures for Mechanical Equipments

The Handbook of Reliability Prediction procedures for Mechanical Equipments (NSWC-06/LE10 2006) also adopts the physics of failure method as in FIDES to determine the reliability and maintainability (R&M) characteristics of mechanical equipment. It has been developed to help the user identify equipment failure modes and potential causes of unreliability in the early design phases of equipment development, and then to quantitatively evaluate the design for reliability and maintainability and determine logistics support requirements. A software program called “MechRel” has also been developed by the Logistics Technology Support Group to automate the Handbook procedures and equations. The models developed are based upon identified failure modes and their causes. The first step in developing the models was the derivation of equations for each failure mode from design information and experimental data as contained in published technical reports and journals. These equations were simplified to retain only those variables affecting reliability as indicated from field experience data. The influencing factors are numerous such as temperature, pressure, fluid and material properties, load, performance requirements and so forth as shown in figure 5.

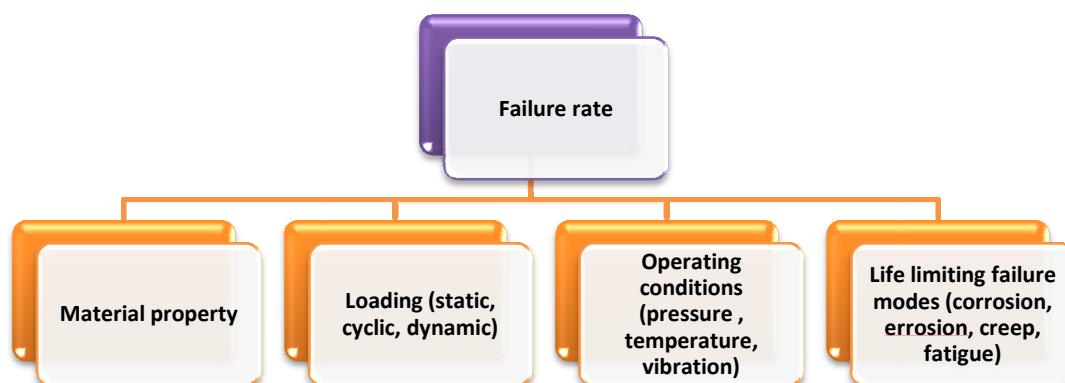


Figure 5: Factors considered for predicting reliability of mechanical equipment, adapted from (NSWC-06/LE10 2006)

As seen in NSWC, equipment is broken down into its components and analysed under its operating environment. Depending upon the material of the component the failure experienced under the given operating environment varies. While dealing with mechanical equipments wear is the major cause of failure. A mechanical wear model, as seen in figure 6, correlates material strength, lubrication properties and stress imposed on parts.

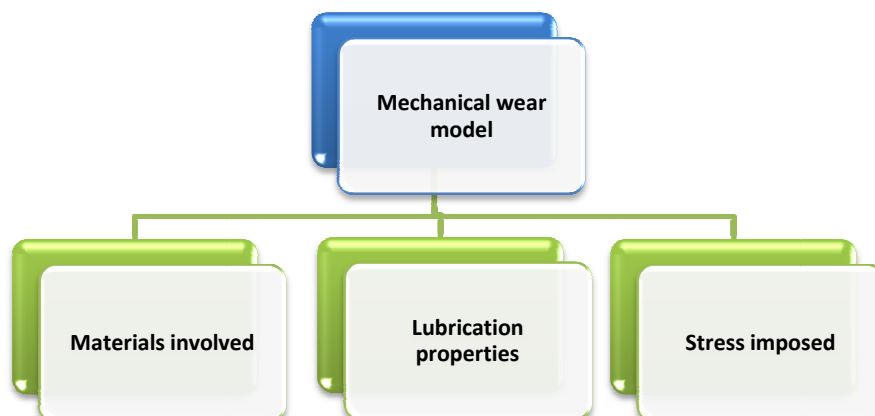


Figure 6: Mechanical wear model, adapted from (NSWC-06/LE10 2006)

The failure rate models utilize the resulting parameters in the equations and modification factors are compiled for each variable to reflect its quantitative impact on the failure rate of individual component parts. The total failure rate of the component is the sum of the failure rates for the component parts for a particular time period in question. Failure rate equations for each component part, the methods used to generate the models in terms of failures per hour or failures per cycle and the limitations of the models are presented. The models are

validated to the extent possible with laboratory testing or engineering analysis (NSWC-06/LE10 2006). The NSWC guide does not detail out on how the reliability for the mechanical equipment is predicted as seen in FIDES, thus the pros and cons are difficult to foresee. However as the failure rate prediction is based on the physics of failure for mechanical equipment in its intended operating environment, it might at times be difficult to have a complete overview of all the influencing factors affecting the failure of a mechanical component. The reference conditions may also vary as compared to the operational condition / environment.

4.5 Modelling failure rates according to influencing factors

We have seen that for reliability evaluations using the existing models, there is a heavy dependence on the quality of input data such as failure rates. The earlier developed quantitative risk analysis (QRA) did not consider the technical and organizational factors. Attempts were made, such as by Vinnem, to include these factors however they were totally independent of the QRA. Others such as Øien have tried to include such factors into the QRA. Øien defines such factors as ‘Risk influencing factors (RIF)’ as it is an aspect (event/condition) of a system or an activity that affects the risk level of the given system/activity (Øien 2001). Each of these RIFs is represented via indicators which is a measurable representation of a RIF as shown in figure 7. The RIFs or influencing factors can affect the reliability by changing the failure rate in a desirable or undesirable direction. Some of the factors which affect failure rate are material properties, environment, manufacture, use, maintenance, installation and design. We have seen that in totality there are four ways to evaluate the failure rate. The most common way is the use of reliability data feedbacks using statistical models, where equipments field data and appropriate procedures are required. These can also include the influencing factors or RIFs. There are data handbooks which contain generic failure rates like OREDA. However these do not always fit the system specificity.

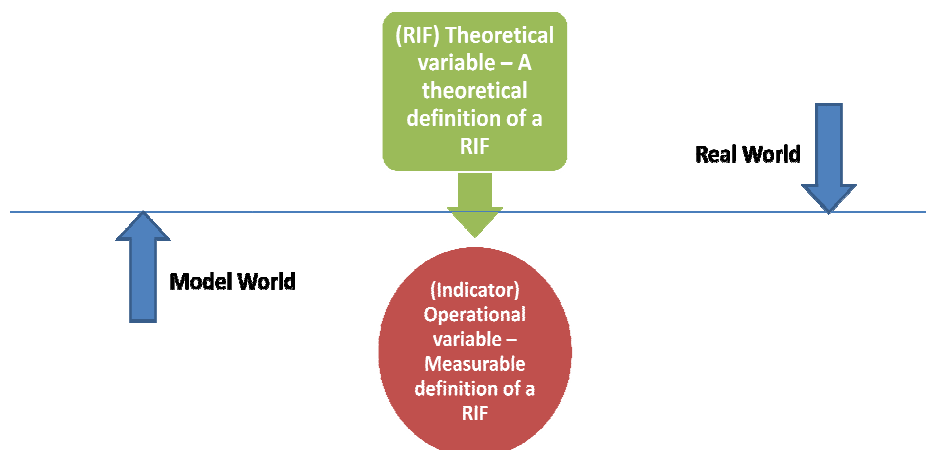


Figure 7: Relation between RIF and indicators, adapted from (Øien 2001)

MIL-HDBK-217, FIDES and NSWC use predictive/physical models. However to address the technical and organizational factors frameworks have been proposed such as the ones seen in ORIM, WPAM and BORA. Brissaud in (Brissaud, Charpentier et al. 2010) proposes a seven step methodology to evaluate the failure rate with influencing factors. In the paper lack of knowledge is compensated by a qualitative analysis and integrating the available data by a quantitative part, this way failure rate is evaluated by taking the influencing factors into consideration. Under the qualitative analysis reliability influence diagrams (RID) are used to model and select the relevant influencing factors. A sample checklist for the influencing factors selection according to the system life phases was developed, however human and organizational factors have not been included but could be added.

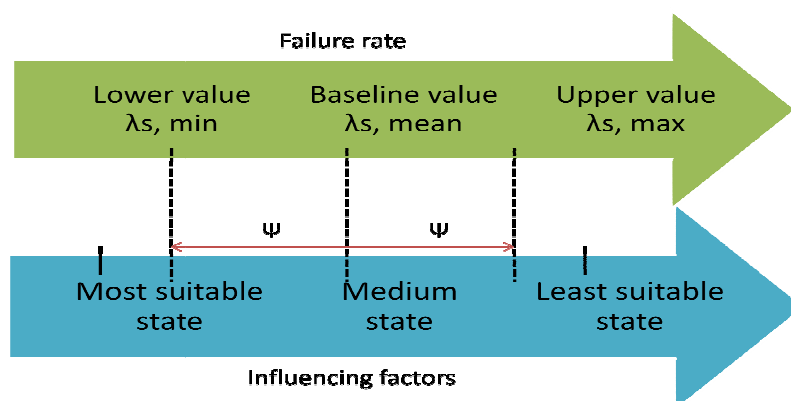


Figure 8: Assumption of the model, adapted from (Brissaud, Charpentier et al. 2010)

The state of an influencing factor is given by indicators. Criteria for indicator selection are taken from Øien, where numerical values are assigned for the mean, worst and best influencing factors. Each selected influencing factor is given a weight. By assigning a weight we indicate the potential effect on the failure rate with a changing indicator (that is from the least suitable to most suitable). Under the quantitative part maximum likelihood estimation (MLE) is calculated using the available feedback data. The method uses the general model shown in figure 8. In order to have coherent results with a presupposed failure rate scale, a prior interval $[\lambda_{s,\min}, \lambda_{s,\max}]$ is set. The main idea of the methodology is to use some criteria to fix the failure rate inside this interval, according to the influencing factor states. The system baseline failure rate $\lambda_{s,\text{mean}}$ is reached when all of the influencing factors are, on average, in a medium state; the lower value $\lambda_{s,\min}$ (resp. the upper value $\lambda_{s,\max}$) of the prior interval is reached when all of the influencing factors are, on average, in a defined proportion of the most suitable states (resp. the least suitable states). Part count model is used and Appendix A of (Brissaud, Charpentier et al. 2010) shows how to calculate the failure rate $[\lambda_{s,\min}, \lambda_{s,\max}]$ and calculate the value of the influencing functions. One influencing coefficient for each influencing factor is considered. When a component is susceptible to an influencing factor, its baseline failure rate is multiplied by the corresponding influencing coefficient. Influencing coefficient (C_j^*) is calculated by considering the indicator function ($g_j(I_j)$) and the influencing functions ($C_j(I_j)$) for the indicators (I_j). To deal with uncertainties indicator functions ($g_j(I_j)$) are represented as probability density functions. Whereas the influencing functions ($C_j(I_j)$) aim at formulating the influencing coefficients according to the indicator values built on three values (worst, mean and best). Thereafter a modified MLE is obtained with the new methodology.

5. New Technology and its qualification

New technology is typically evolved from existing proven technologies. Normally only some elements of the technology are novel. Uncertainty is associated mainly with the novel elements. In order to focus on where uncertainty is greatest, the novelty categorization of Table 1 is used. Both the novelty of the technology itself and its application area affect the uncertainty associated with the technology. Elements categorized as new technology (new technical uncertainties, new technical challenges and demanding new technical challenges)

are required to undergo a Technology Qualification assessment. Qualification process helps to provide the evidence that a technology will function within specific operational limits with a specified level of confidence. The categorization seen in table 1 applies to all of the technology being used, as well as each separate element it comprises. The decomposition of the technology simplifies the identification and isolation of novel elements. The technology categorization determined shall be used to direct the qualification efforts by focusing on the degree of novelty, which shall be conservative. For proven technology, elements are proven with no new technical uncertainties, proven methods for qualification, tests, calculations and analysis can be used to provide the required qualification evidence.

Table 1: Novelty Categorization, adapted from (DNV-RP-A203 2011)

Application Area	Degree of novelty of technology		
	Proven	Limited Field History	New or Unproven
Known	No new technical uncertainties (proven technology)	New technical uncertainties	New technical challenges
Limited Knowledge	New technical uncertainties	New technical challenges	Demanding new technical challenges
New	New technical challenges	Demanding new technical challenges	Demanding new technical challenges

The industry practice, standard or specification is deemed applicable for each proven technology element. However existing standards, specifications and industry standards do not fully cover novel elements. They are used in the Technology Qualification Process, however, to form a benchmark against which the Technology Qualification Basis can be set. Interfaces between the elements and external interfaces need special consideration. Elements in new technical uncertainties, new technical challenge and demanding new technical challenges are defined as new technologies, which have an increasing degree of technical uncertainty. The defined categorization makes it possible to distinguish between the novelties of the technology itself and its application areas, and focus on the areas of most concern in an iterative manner (DNV-RP-A203 2011). By using a technology qualification process (TQP) we can efficiently assess the readiness of the new technology, have a better understanding of the risk implications and technology reliability. DNV's recommended practice on

qualification of new technology ((DNV-RP-A203 2011) lists the various steps for the qualification of new technology.

Subsea processing systems, depending on the source of technology, fall under new technical uncertainties, new technical challenges and demanding new technical challenges where the area of application ranges from known to new with proven to unproven technology. Under the third step/stage, proof of concept, it is essential that such new technologies undergo reliability analysis. One can follow the steps stipulated in IEC 61508, where a safety integrity level (SIL) is assigned. To meet the assigned SIL the probability of failure on demand is calculated (PFD). There are several methods of calculating the reliability of the system. But the most common methods require the use of failure rate data. However when dealing with new technology with no historical data on the failure rate, this proves to be impossible. Thus a substitute is required either by using formulas or by studying the nature of the component/equipment/system in the operating conditions.

6. Subsea Processing Functions

While subsea developments have been made possible by technologies such as subsea trees, risers and umbilicals, subsea processing has been an elusive solution for many years. Whether describing subsea separation, re-injection or boosting via subsea compression, subsea processing has helped to revolutionize offshore developments worldwide. With production equipment located on the seafloor rather than on a fixed or floating platform, subsea processing provides a less expensive solution for myriad offshore environments. Originally conceived as a way to overcome the challenges of extremely deepwater situations, subsea processing has become a viable solution for fields located in harsh conditions where processing equipment on the water's surface might be at risk. Additionally, subsea processing is an emergent application to increase production from mature or marginal fields. There are interrelated reasons why the development of subsea separation applications has lagged. First, some components of such a system would have to be newly designed and qualified. Second, a system incorporating new technology carries a higher potential risk. In addition to undemonstrated performance, both durability and ease of maintenance would need to be

addressed to reduce the unknown aspect of the risk^g. Accordingly, plans for any new design must include qualification to reduce the un-quantified risk of new technology to a minimum (DNV-RP-A203 2011).

Subsea processing can encompass a number of different processes to help reduce the cost and complexity of developing an offshore field. The main types of subsea processing include subsea water removal and re-injection or disposal, single-phase and multi-phase boosting of well fluids, sand and solid separation, gas/liquid separation and boosting, and gas treatment and compression. By performing separation of water, sand and gas subsea we end up saving space on the offshore production facilities. Subsea separation reduces the amount of production transferred from the seafloor to the water's surface, debottlenecking the processing capacity of the development. Also, by separating unwanted components from the production on the seafloor, flowlines and risers are not lifting these ingredients to the facility on the water's surface just to direct them back to the seafloor for re-injection. Re-injection of produced gas, water and waste increases pressure within the reservoir that has been depleted by production. Also, re-injection helps to decrease unwanted waste, such as flaring, by using the separated components to boost recovery.

On deepwater or ultra-deepwater fields, subsea boosting is needed to get the hydrocarbons from the seafloor to the facilities on the water's surface. Subsea boosting negates backpressure that is applied to the wells, providing the pressure needed from the reservoir to transfer production to the sea surface. Even in mid-water developments, subsea boosting, or artificial lift, can create additional pressure and further increase recovery from wells, even when more traditional Enhanced Oil Recovery (EOR) methods are being used.

For a number of reasons subsea processing equipment can be chosen. First of all, most subsea processing will increase the recovery from the field, thus increasing profits. Additionally, by enhancing the efficiency of flowlines and risers, subsea processing contributes to flow management and assurance. Also, subsea processing enables development of challenging subsea fields, while reducing topside expenditures for equipment. Furthermore, subsea processing converts marginal fields into economically viable developments. Whether the

^g

http://www.eurekanetwork.org/showsuccessstory?p_r_p_564233524_articleId=105831&p_r_p_564233524_groupId=10137

fields are mature and the subsea processing equipment has been installed to increase diminishing production, or the fields incorporated subsea processing from the initial development to overcome deepwater or environmental challenges, the subsea processing systems enable the fields to achieve higher rates of production.



Figure 9: Tordis field separator in North Sea (source Greenland group)

Subsea processing technology has recently been put into practice. StatoilHydro-operated Tordis field in the North Sea (figure 9) was the first to start-up a subsea separation, boosting and injection system in 2007. With the introduction of the subsea processing system oil field increased its recovery and extended the life of the field. World's first subsea system with gas/liquid separation and boosting was done by Shell's BC-10 project offshore Brazil. Developed via 13 subsea wells, six subsea separators and boosters, and an FPSO, the BC-10 project began producing heavy oil from ultra-deepwaters in July 2009. In August 2011, Total's Pazflor project offshore (figure 10) came on-stream at West Africa and has utilized the region's first-ever subsea gas/liquid separation system^h. One of the world's deepest water developments, Shell's Perdido project in the US Gulf of Mexico incorporates subsea boosting and separation to achieve production^{i,j}.

^h <http://www.total.com/en/our-energies/oil/exploration-and-production/projects-and-achievements/pazflor-940850.html>

ⁱ http://www.shell.us/home/content/usa/aboutshell/projects_locations/perdido/

^j http://www.rigzone.com/training/insight.asp?insight_id=327&c_id=17

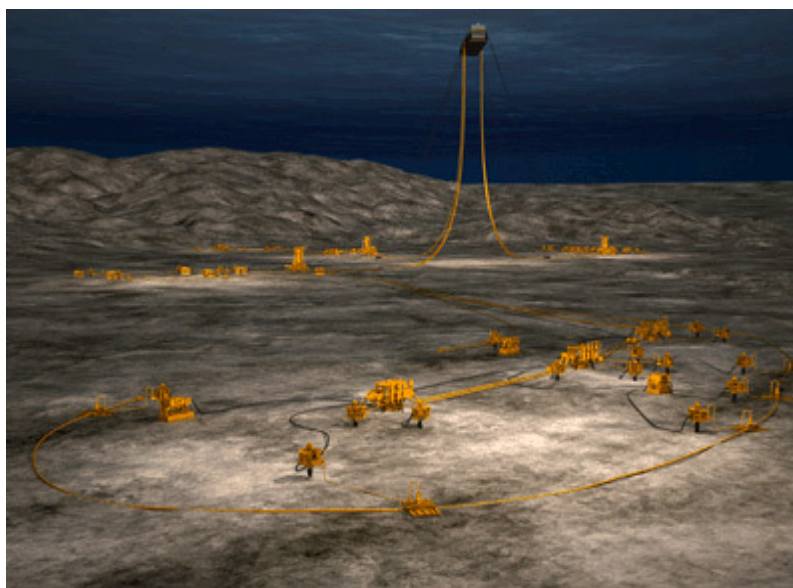


Figure 10: Pazflor subsea development (source <http://www.rigzone.com/>)

To limit the scope of this report due to lack of time the focus here will be on subsea multiphase helico-axial pumps only. Details on the few other subsea processing equipments have been listed in appendix C

6.1 Multiphase pumping

Multiphase pumping is relatively new, even at the surface with approximately 20 subsea pumps installed (Hua, Falcone et al. 2012). Today this is essentially a proven technology and is becoming the conventional method for increasing recovery in subsea wells. Good design has led to a handling capacity of the gas-volume fraction close to 95% however it is still a challenge to reach a 100%. Electrical losses are main concern when the power source is far away. Figure 11 illustrates a typical installation of a multiphase pump.

This technology enables the marginal field to be economically viable and extend the field life. Several factors come into play when making a decision as to whether to use a multiphase pump such as the multiphase flow type (Flow consisting of at least liquid and gas, but usually high volumes of gas mixed with oil, water and solids), expected production, cost of production and maintenance cost to name a few.

Subsea multiphase pump seems to bypass the current technology gap in subsea processing. This is because it gets the unprocessed well stream to the surface facilities, where it is processed easily and cheaply. It also boosts pressure, aid in flow assurance by mixing, pushing and regulating flow of the well fluids. However when transporting mixed fluid, flow assurance after water breakthrough would be required. Scale build-up, corrosion, paraffin/wax and hydrate deposition are common phenomenon depending upon fluid type , chemistry and flow conditions (Shippen and Scott 2002).

The subsea environment is one of the harshest, most corrosive environments in the world. It is a medium where material stress is enhanced, stream forces and impact damage is possible. It is also important to consider marine growth and seabed motions when building subsea equipment. The pressure is very high; to get a feel of this a comparison can be made. The outer space is at vacuum with 0 Pa, the pressure at sea level is 101 kPa while the pressure subsea equipment experiences at 3000 meters depth is 29430 kPa. That is approximately 300 times the pressure we experience every day. Subsea equipment needs to handle the operating conditions and follow the standards developed. As mentioned previously some of the things that need to be considered when designing subsea equipment are^k:

- Safety Integrity Level
- Barrier Philosophy
- System availability
- Subsea Monitoring
- Pressure
- Impact Protection
- Corrosion Protection
- Installation

The Safety Integrity Level requirements are defined techniques and measures required to prevent systematic failures from being designed into a system. These requirements can either be met by establishing a rigorous development process, or by establishing that the device has

^k <http://sig.sut.org.uk/subseasection/sutsse2.htm>

sufficient operating history to argue that it has been proven in use. Systems used subsea must have some barrier philosophy to reduce the chance of hydrocarbons leaking out of the reservoir into the sea. Today, usually two barriers are used between the seawater and the hydrocarbons. To always have control over the system availability is an important concept. Since the system can be located in over 3000 meters depth, it is important to design the equipment to be available at all times, this is usually solved with redundancy. The reservoir, temperature and pressure are constantly monitored to keep control over the production system. This ensures that everything is working and assists the operator in preventing blow-outs and leakage. Impact protection is necessary when installing the system, and also for protection against animals and submarines¹.

Challenges for marinization can be summarized as follows:

- Pump module integration
- System unit qualification
- High voltage electric power transmission
- High intervention cost, performance and reliability of the pump is critical

Multiphase pumps are based on single phase pump concept. The single phase pumps working principle is divided into three groups namely: 1) Positive displacement where a finite volume of fluid is physically moved from a low pressure side to a high pressure side, 2) Rotodynamic pump (RDP) is one where kinetic energy is transferred to the fluid via a rotating impeller and then the kinetic energy is transferred to potential energy through a static diffuser due to which the fluid is lifted and 3) Hydraulic pump in which kinetic energy is transferred from a high velocity fluid to a low pressure fluid by mixing the two such that the fluid acquires potential energy by decelerating through a diffuser nozzle.

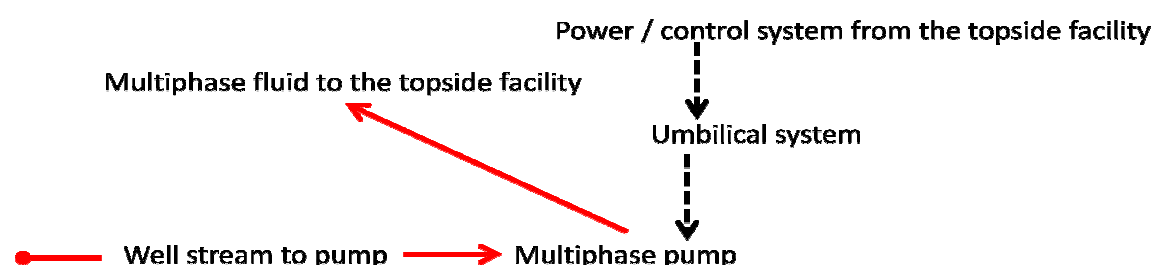


Figure 11: Typical installation of a multiphase pump

¹ http://www.scribd.com/doc/57020202/14/Subsea-environment#outer_page_91

The most common types of subsea pumps are the twin-screw, helico-axial and hydraulic turbine helico-axial. Focus is on the helico-axial pump a type of rotodynamic pump. Its pumping principle is similar to that of a conventional centrifugal pump, which increases the kinetic energy of the fluid by stacking up rotating impellers and transferring the kinetic energy into potential energy by means of static diffusers (Hua, Falcone et al. 2012).

When a conventional centrifugal pump operates in multiphase conditions, the impeller vanes act as an efficient gas separator because the liquids are centrifuges by the rotating motion owing to their higher density whereas the gas is not, resulting in a liquid/gas separation. On the downside while the impeller is rotating the pressure distribution within its vanes creates high and low pressure areas resulting in gas bubbles accumulating on the low pressure side. If the gas is not reduced the vane cavities will be blocked by gas also known as 'gas-locking'. The impellers of helico-axial pump are designed such that it minimizes the radial component of the flow resulting in an axial flow. As a result the gas and liquid is not separated and one multiphase liquid is maintained (de Salis, de Marolles et al. 1996).

Characteristics of a helico-axial pump

- Ability to self adaptability to changing flow conditions enables wide operating range
- A buffer tank/mixer is required to balance the sudden load changes else it may lead to mechanical problems on the pump shaft
- They are least suited for viscous fluids as more power/energy would be required to impart the required centrifugal energy (low mechanical efficiency)
- Can handle sand, further design improvements can prevent sand accumulations by ensuring adequate velocities
- Can cope with any GVF on a continuous basis
- A high pressure can be achieved
- Integrated VSD allows operational flexibility over the life of asset
- Can be configured to series or parallel boosting

Subsea multi-phase pumps typically are critical equipment. Accordingly, a high level of operational support and condition monitoring is required to ensure production is maximized, and that the pumps operate within designed limits. Diagnostic methods such as FRIEND (FRamo Interactive ENabling Diagnostics) have been developed which is based on a real-

time data monitoring facility with an online support service providing monitoring/diagnostics. The pump(s) performance is condition monitored to capture irregularities or change in performance. The subsea pump usually operates to failure, and eventually is retrieved, in the mean time a spare pump is installed within a short time^m.

Benefits of multiphase pumps can be summarised and listed as follows:

- Accelerating production
- Initiating and stabilizing flow in wells that cannot naturally produce to remote facilities
- Extending subsea tieback distance
- Reducing well intervention costs
- Reducing subsea development costs
- Environmental friendly
- Permitting oil and gas in harsh environment

6.2 Subsea Vs. topside equipment with respect to design, failure rate and maintenance

The main function of a helico-axial pump (multiphase pump) is to maintain flow and pressure. Loss of flow and pressure would indicate loss of function of the pump. This is the same for a topside oil processing centrifugal pump. As mentioned above a subsea helico-axial multiphase pump can be compared to a topside oil processing centrifugal pump. Thus in this report for comparison purpose a topside oil processing centrifugal pump shall be used (Hua, Falcone et al. 2012). A comparison with the similar topside equipment was done with literature reviews (Cadwallader 1998) .

It should be noticed that the major difference between the topside and subsea pump is the external operating environment and the maintenance strategies adopted. However the internal conditions within the pump remain the same as the multiphase liquid being carried remains the same. The components used for the pump itself differ only slightly from those used for

^m <http://www.offshore-mag.com/articles/print/volume-70/issue-2/subsea/multi-phase-pumps.html>

topside pumps: materials in contact with seawater and external tightness are optimized. Special measures are required for the drive system. The subsea pumps require handling large and varying volumes of gas unlike the topside pumps where it is possible to separate the gas and allow the pump only to handle liquid. For applications where very high differential pressures are involved, i.e. the surrounding is at higher pressure, the structure of the pump requires being much tougher compared to a topside pump.

In Appendix A, the FMEA worksheet for a subsea helico-axial pump has been presented. So far the Framo Helico-axial pumps have amassed 350,000 running hours with some pumps running in excess of 6 years without need for intervention. While the installation base is very small, some information can be gained from the established track record. Figure 12 shows the failure modes for the topside oil processing pumps that have been repaired and this can be extended to the helico-axial pump.

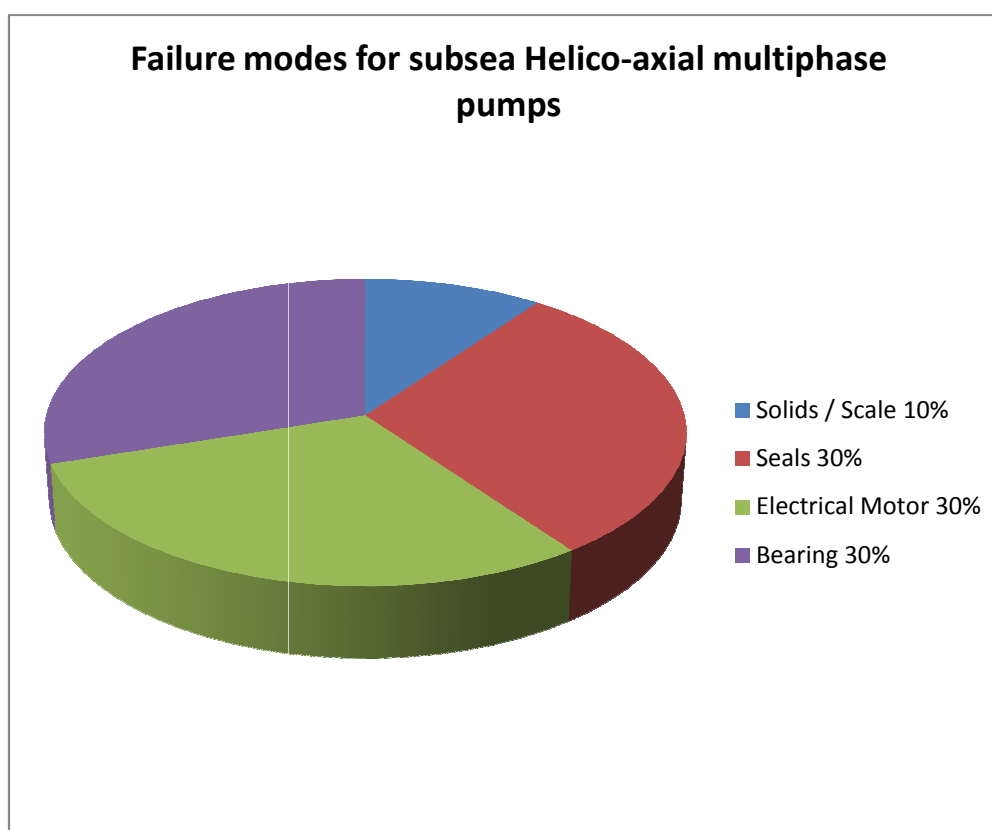


Figure 12: Failure modes for subsea Helico-axial multiphase pumps, adapted from <http://www.boemre.gov/tarprojects/424/424AA.pdf> and http://especiales.universia.net.co/dmdocuments/Tesis_juanjosehernandez.pdf

It can be seen that for a helico-axial pump internal wear or other elements such as motor, lubrication system and so on cause the failure of a pump. Lube oil is maintained at an

overpressure to prevent sea water intrusion via seals, thus damage to the seal and loss of overpressure will cause sea water intrusion leading to development of rust. Bearing wear would lead to an increase in friction and thus lead to loss of head and flow. Leakage through the impeller due wear would cause internal leakages, thus re-circulating the boosted fluid and causing a loss in head and flow. With time the motor would also wear and efficiency would be reduced. This would increase the temperature reading of the pump and decrease the head and flow. It has been observed that through recorded tests and operational data that the reliability of the shaft is usually very high compared to the reliability of bearings and seals as seen in figure 13. However the reliability of the bearings and seals depends on the shaft's reliability or nature. Pump casing is also very reliable. But the casing failure rate will have a greater effect on the total pump reliability via its affect on other less reliable components (NSWC-06/LE10 2006).

Due to wear encountered by subsea pumps a regular maintenance would be required. Based on maintenance strategies we have three options

- a. Run the pump till it breaks
- b. Change the pump in advance before it breaks based on worst case calculation, say 4 years when worst case calculation is for 5 years.
- c. Based on the condition of the pump change the pump just in time (condition monitoring)

Unlike a topside pump, which can undergo regular inspection and preventive maintenance, to improve and prolong the life of a pump, a subsea pumps would require a different approach. For the subsea pump to function for 5 years without intervention reliability is crucial. Installation and retrieving equipment to and from the seafloor is a very costly affair and if it needs to be done several times, the economics of the project will no longer exist. Thus compactness is crucial since everything installed subsea is very expensive and the bigger it is, the more expensive it becomes, both from a manufacturing, installation and maintenance point of view. Option b or c proves to be the most apt maintenance strategy to be adopted for subsea pumps. However we will discuss option c, where certain parameters of a pump are monitored to observe the performance thus a scheduled maintenance can be planned. Data and sensors from these subsea sensors are collected and stored at a topside control system offshore. At regular intervals stored data is transferred to shore. All the mentioned sensors require to be dual redundant.

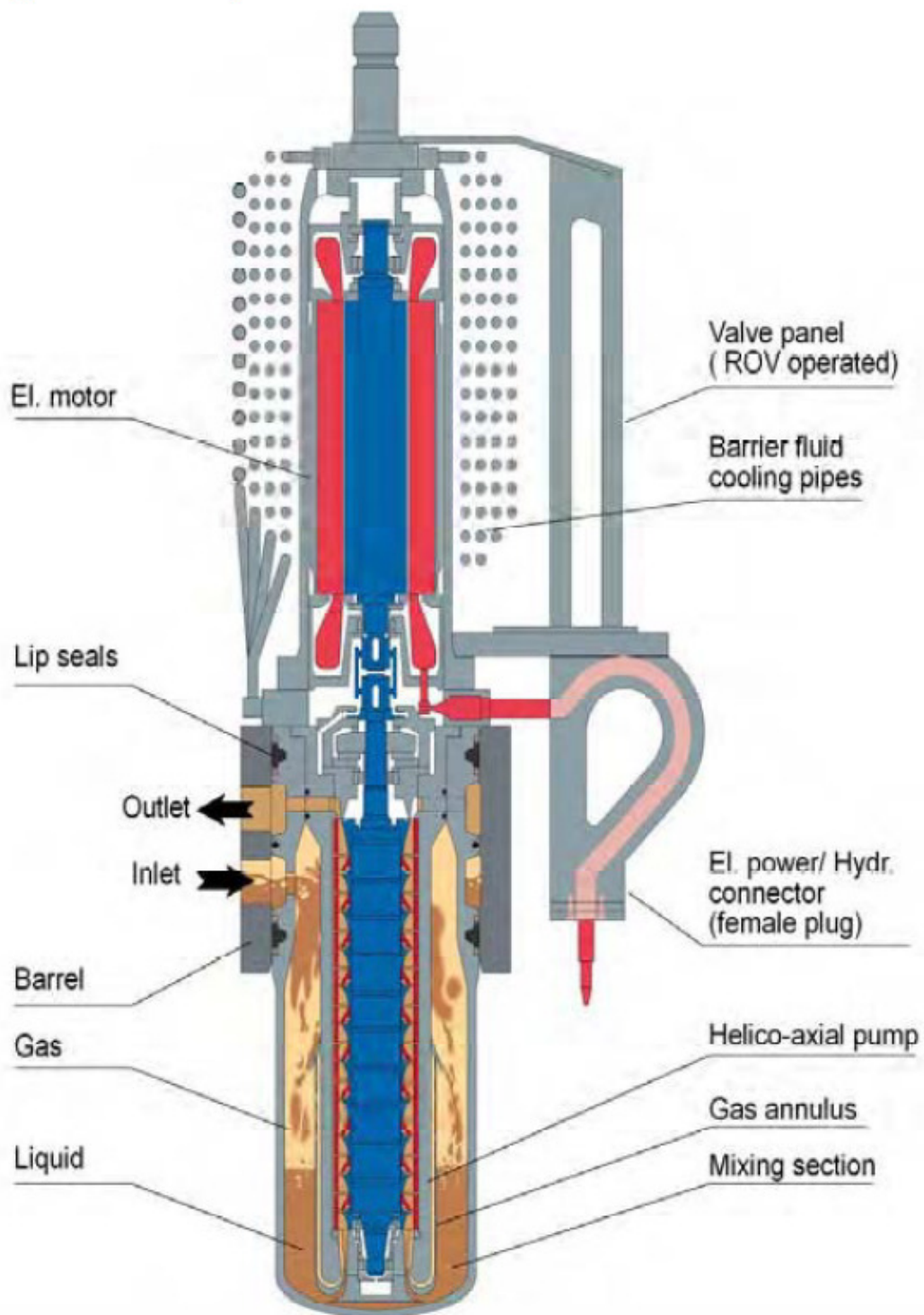


Figure 13: Helico-axial pump, source <http://www.worldoil.com/November-2004-Subsea-production-systems-progressing-quickly.html>

Typically the monitored parameters are the

-
- suction pressure,
 - discharge pressure,
 - lube oil supply (topside),
 - lube oil supply (subsea),
 - lube oil system temperature (hot end),
 - lube oil temperature (cold end),
 - VSD output power,
 - VSD output frequency,
 - wellhead pressure and temperature,
 - downhole temperature and pressure and
 - vibration sensors.

A typical subsea multiphase pump has been illustrated in figure 12. The motor is supplied by high voltage and is cooled by lube oil. The bearing and the seals between pump and motor is also lubricated / cooled by the same lube oil. The lube oil system is maintained at an overpressure compared to the process, in order to prevent leakage to sea. At the subsea temperatures the lube oil tends to be highly viscous. There are two main reasons for lube oil consumption. The first is leaks through the seals and the other is due to thermal expansion / contraction of the lube oil inside the pump and/or motor. After a while the lube oil can no longer be topped up as the leakage rate exceeds the top-up rate, this leads to a loss in overpressure.

As the pump operates over time, it will deteriorate and the head generated for the given speed and power is reduced. The two main mechanisms behind this are increased internal leakage path and increased friction. The pump speed is also related to the VSD frequency, which is due to slip and it increases as load increases. Losses in an umbilical lead to loss of power from the topside VSD to the HV subsea motor. Mathematical formulas exist which would be able to indicate the actual and predicted power, flow and head.

Vibration sensors used on subsea pumps are similar to those used on topside pumps, except they are encapsulated to withstand the pressure and hence less sensitive compared to the topside pumps. Operational vibration data are compared against vibration data of subsea pump obtained during factory acceptance test conditions. By observing the vibration spectrum one can identify defects such as roller element defect, outer and inner ring defects.

The bearings too start to wear thus causing an increased friction in the system and this affects the head and flow causing it to decrease. Thus speed and load govern the life of a bearing. It's the bearing and the seals that wear out the fastest leading to pump failure.

But the most important aspect of condition monitoring is data transmission network. This is the method by which data from the subsea pump is transmitted to topside control and monitoring system for analysis. Redundancy is a key aspect to make the system robust and reliable. Use of fibre optics proves to be an advantage compared to copper wires within umbilical for long distance transmission.

7. New approach to determine the failure rate function

The proposed methodology consists of 6 steps as follows:

1. Perform a failure mode and effect analysis (FMEA) of the chosen new technology, helico-axial subsea pump in our case.
2. An influence diagram is developed based on the FMEA on the helico-axial pump.
3. Bayesian estimation method is used to determine the failure rate.
4. The probabilities of the priors and the conditional probabilities are assigned based reliability data handbooks and literature reviews.
5. The importance of each of the failure modes is identified. Finally the failure of the pump is calculated by multiplying the failure rate of each of the failure modes with its calculated importance.
6. The total failure rate of the pump is obtained by adding the modified failure rates.

Bayesian method has been suggested to be used in this report. The advantage with Bayesian models is that it can be used when the source of information quality is low. This is very applicable in our situation as in this method we intend to use generic failure rates from data handbooks like OREDA, even though the technical, operational and environmental conditions may not be the same or known. Thus the Bayesian model proves to be advantageous as it combines statistical data and expert judgement. In this report, Microsoft

office excel was used to perform the calculations and develop the decision tree. The results from this can be seen in Appendix B.

Bayesian method is a concept of evidential probability where to evaluate the posterior, prior probabilities are assigned and then updated in light of new inputs or values based on expert judgement.

The Bayes' formula can be stated as follows:

$$P(H|E) = [P(E|H)*P(H)] / P(E)$$

2

where

E is the evidence

H is the hypothesis

P(E) is the marginal probability

P(H) is the prior probability

P(E|H) is the probability of evidence given hypothesis, also known as likelihood. It indicates the compatibility of the evidence with the given hypothesis

P(H|E) is the posterior probability, gives us what we want to know.

Assumptions and limitations

- The pump is used only to transfer multiphase fluid from the sea bed to topside installation.
- The internal conditions of a pump installed and operating topside or on the sea floor will remain the same, when dealing with the same well.
- The temperature difference of lube oil is known during a planned power increase/decrease.
- The change in temperature of the lube oil due to changing speed has not been considered as the pump speed is controlled by the operator.

-
- Vibration data can be neglected, as it is difficult to measure the vibration on a subsea pump, also the measurements are not accurate as compared to the topside pumps. Thus to avoid complexity vibration analysis has been neglected.
 - A constant production profile for the lifetime of well has been used.
 - The pump is designed to operate in a known environment, or in other words it is designed for its purpose. Thus failures due to lack of NPSH (Net Present Suction Head) and other polluting factors are neglected.
 - Head and pressure has been considered as a single node as both are related and any factor affecting a decrease in head also causes a decrease in pressure and vice-versa.
 - The upstream and downstream sides of the subsea process system are not covered.
 - No periodic maintenance is assumed to take place for any of the subsea systems. A repair action is called upon as soon as a failure is detected.
 - All components are assumed to have constant failure rates, with exponential distributed lifetimes.

7.1 Case study – Helico-axial pump

Based on the literature reviews ((Furuholt and Torp 1988; Gié, Buvat et al. 1992; de Salis, de Marolles et al. 1996; Leporcher, Delaytermoz et al. 2001; Camilleri, Brunet et al. 2011) and FMEA on helico-axial pump (Appendix A- FMEA Methodology & Worksheet) an influence diagram for the Helico-axial pump has been developed as seen in figure 14.

The nomenclatures used in the influence diagrams are as follows:

LHP-Loss of head and pressure

MW-Motor wear

BW-Bearing wear

SW-Seal wear

HT-High temperature

LLO-Low lube oil level

AG-Algae growth

IL-Internal leakage

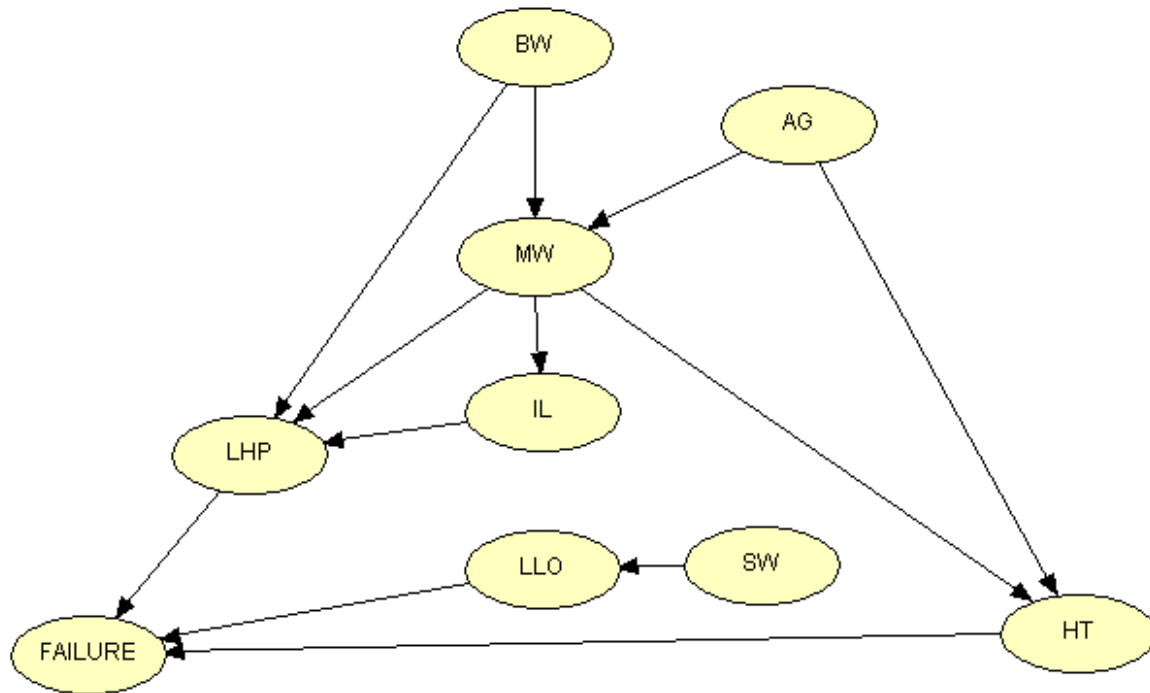


Figure 14: Influence diagram for a helico-axial pump

We use event trees to help visualize the flow of various nodes and it was also easier to assign the conditional probabilities and use the relevant joint probabilities in the Bayesian formulas.

Event trees are required to be developed based on the influence diagram, refer to appendix B for the event trees. However to explain the procedure we will deal with only part of the influence diagram, that is the 'loss of head and pressure' (LHP) as seen in figure 15.



Figure 15: Influence diagram converted to event tree for loss of head and pressure (LHP)

Here P(BW) is the prior probabilities. The values for the prior probabilities [BW, AG, SW] have been taken from OREDA handbook, UK HSE website (Health and Safety Executive 2003; Health and Safety Executive 2010) and literature reviews on helico-axial pumps. Appendix B shows the complete event tree calculations.

From the event trees, values of the following formulas can be obtained

- P(LLO|SW) 3**
- P(HT|AG,MW') 4**
- P(HT|MW,AG') 5**
- P(LHP|BW,MW',IL') 6**
- P(LHP|MW,IL',BW') 7**
- P(LHP|IL,BW',MW') 8**

Using the Bayesian theorem the following probabilities can be obtained

$P(SW LLO) = [P(LLO SW) * P(SW)]/P(LLO)$	9
$P(AG HT, MW') = [P(HT AG, MW') * P(MW' AG)*P(AG)]/P(HT)$	10
$P(MW HT, AG') = [P(HT MW, AG') * P(MW AG')*P(AG')]/P(HT)$	11
$P(BW LHP, MW', IL') = [P(LHP BW, MW', IL') * P(BW MW', IL')*P(BW MW')*P(BW)]/P(LHP)$	12
$P(MW LHP, BW', IL') = [P(LHP MW, BW', IL') * P(IL' MW, BW')*P(MW BW')*P(BW')]/P(LHP)$	13
$P(IL LHP, BW', MW') = [P(LHP IL, BW', MW') * P(IL BW', MW')*P(BW' MW')*P(BW')]/P(LHP)$	14

As seen from the calculation (figure 19 of appendix B), loss of head and pressure is the major contributor towards the failure of a pump with a factor of 0.452 (0.39+0.06+0.002). Bearing wear has the highest effect of 0.39 on the loss of head and pressure. This is because it can be seen that bearing wear influences the loss of head and pressure of a pump directly and indirectly by affecting the motor wear and internal leakages within a pump.

Thus if a pump is required to operate for 5 years (standard classification and company requirements) without service, for example, at 1MW and 1800rpm then bearing life will be 7.3 years ($5*(1800/1700)*(1.0/0.9)^3$) for pump running at 0.9MW at 1700rpm. Thus with the observed power, speed and operational hours, bearing life can be estimated.

To calculate the failure of the pump, the failure rate of each of the failure modes is multiplied with its calculated importance as seen in appendix B table 5.

The value obtained (6.51111E-06) is less than the failure rate of a pump which is required to operate for a period of 6 years with one failure (1.901719154E-05). Thus the chosen pump's design is best suited for its operation period of 5 years.

8. Summary and recommendation for further work

8.1 Summary and Conclusion

The main objective of this thesis is to estimate the failure rate of the new technologies such as subsea processing systems, where no reliability data for the given new technology is

available. The main objective has been further divided into 9 sub-objectives, to which this report aims to provide adequate solutions.

Several reliability datas such as OREDA (OREDA 2009) and MIL-HDBK-217 (MIL-HDBK-217F 1991) are available. They use statistical models to predict the failure rates. However it has been seen that these provide us with generic failure rates and do not take into consideration the environmental and operational conditions. Thus the failure rates obtained are not necessarily accurate for given equipment. Even worse when reliability of new technologies is required to be calculated, no failure rates are available to be fed into the reliability calculations. On the contrary FIDES (FIDES 2009) and NSWC (NSWC-06/LE10 2006) uses the concept of physics of failure to predict the failure rate of the component / equipment. Where by understanding the wear of each component in equipment, the failure rate is predicted. In addition methods to address the influencing factors while calculating the failure rate was addressed by Brissaud (Brissaud, Charpentier et al. 2010).

In this report an approach to predict the failure rate of the new technologies, such as helico-axial pump, has been suggested. The basic method applied is the bayesian belief network (BBN). A six step procedure has been suggested where the analysis starts with a failure mode and effect analysis (FMEA) of the chosen new technology, helico-axial subsea pump in our case. Using the FMEA and literature reviews an influence diagram is developed for the helico-axial pump. The probabilities of the priors and the conditional probabilities are assigned based reliability data handbooks and literature reviews. The importance of each of the failure modes is identified. Finally the failure of the pump is calculated by multiplying the failure rate of each of the failure modes with its calculated importance. The total failure rate of the pump is obtained by adding the modified failure rates.

Using this method it was seen that the failure rate of the helico-axial pump is less than the failure rate of a centrifugal pump which is required to operate for a period of six years with one failure.

8.2 Discussion

As seen in MIL-HDBK-217, influencing factors are considered by using stress models. For a given component, the failure rate is constant over time and is expressed analytically depending on the defined parameters. MIL-HDBK-217, FIDES and NSWC are all based on

the same methodology. However Brissaud et al propose a general methodology which could be used when no prior knowledge on the physical relationships which relates the influencing factors to failure rates is known. Statistical methods also attempt to express correction coefficients as a function of factors. However in each of the models and databases, the failure rates are considered constant over time. But when dealing with mechanical equipment a time dependent wear known as aging is seen due to degradation mechanisms such as fatigue, vibration, corrosion and so on. Failure rates after the burn-in period is observed to be time dependent.

The main data source is the OREDA database. The only data we get from OREDA are constant failure rate estimates. The failure rates are estimated as “number of failures” divided by “total time in service”. This is the best estimate we can get for the average failure rate. Most of the units in the subsea process system are mechanical units that are exposed to wear. They should consequently have an increasing failure rate function $\lambda(t)$. The most realistic distribution to use is the Weibull distribution with a shape parameter $\alpha > 1$. The average failure rate will, however, be the same irrespective of which distribution we choose. If we believe that the true failure rate function is increasing, and we use the constant (average) failure rate from OREDA, then we will use a too high failure rate in the first part of the system’s life, and a too low failure rate in the last part of the system’s life. The model will consequently produce a slightly too pessimistic estimate of the system reliability during the first part (half) of the system’s life, and a slightly too optimistic estimate in the last part of the system’s life. The average reliability (or availability) estimate will, however, remain correct.

A subsea pumps would require a different approach for maintenance. For the subsea pump to function for 5 years without intervention reliability is crucial. Installation and retrieving equipment to and from the seafloor is a very costly affair and if it needs to be done several times, the economics of the project will no longer exist. Thus compactness is crucial since everything installed subsea is very expensive and the bigger it is, the more expensive it becomes, both from a manufacturing, installation and maintenance point of view. Condition monitoring is an apt solution for monitoring the parameters of a pump to estimate the life condition of the pump. Here certain parameters of a pump are monitored to observe the performance thus a scheduled maintenance can be planned. Data and sensors from these subsea sensors are collected and stored at a topside control system offshore. At regular

intervals stored data is transferred to shore. All the mentioned sensors require to be dual redundant.

8.3 Recommendation for further work

This master thesis has been carried out within a limited period of time and with limited resources. The topics discussed in this thesis are extensive and complex. As a result the conclusions could be readily examined further in a more thorough fashion. The following areas need further exploration.

The failure rates considered here are constant with an exponential distribution. However with mechanical equipment the failure rate is not constant over time since it undergoes degradation and wear. Thus as mentioned under chapter 8.2, weibull distribution could be used to estimate the failure rate (Murthy 2004). A similar approach as by Brissaud (Brissaud, Charpentier et al. 2010), where the failure rate is considered to be time dependent and influenced by the age of the equipment should be adopted.

The failure rates taken in this report are the mean failure rates, thus it does not address the uncertainty interval for the failure rate. An approach similar the one stated in OREDA (OREDA 2009) could be applied here.

Lastly a reliability data handbook for the available, operating subsea equipment can be developed. Failure rates predicted with these historical data will be much closer to the actual reliability of the equipment.

Appendix A- FMEA Methodology & Worksheet

FMEA Methodology

The Failure Mode and Effect Analysis (FMEA) method is a tool for qualitative analysis of risk through identification of failure modes and corresponding effects (risks) to personnel, equipment, environment and production. An FMEA is a detailed study of a system in order to describe the possible modes of the system components and the effects such a failure may have on the component itself and on the system that the component is servicing. The FMEA work process is carried out systematically as described in the following, and shown in Figure 16. However for the purpose of this study the FMEA only focuses on identifying the failure mode, failure cause, failure detection method, failure rates, severity and risk reducing measures.

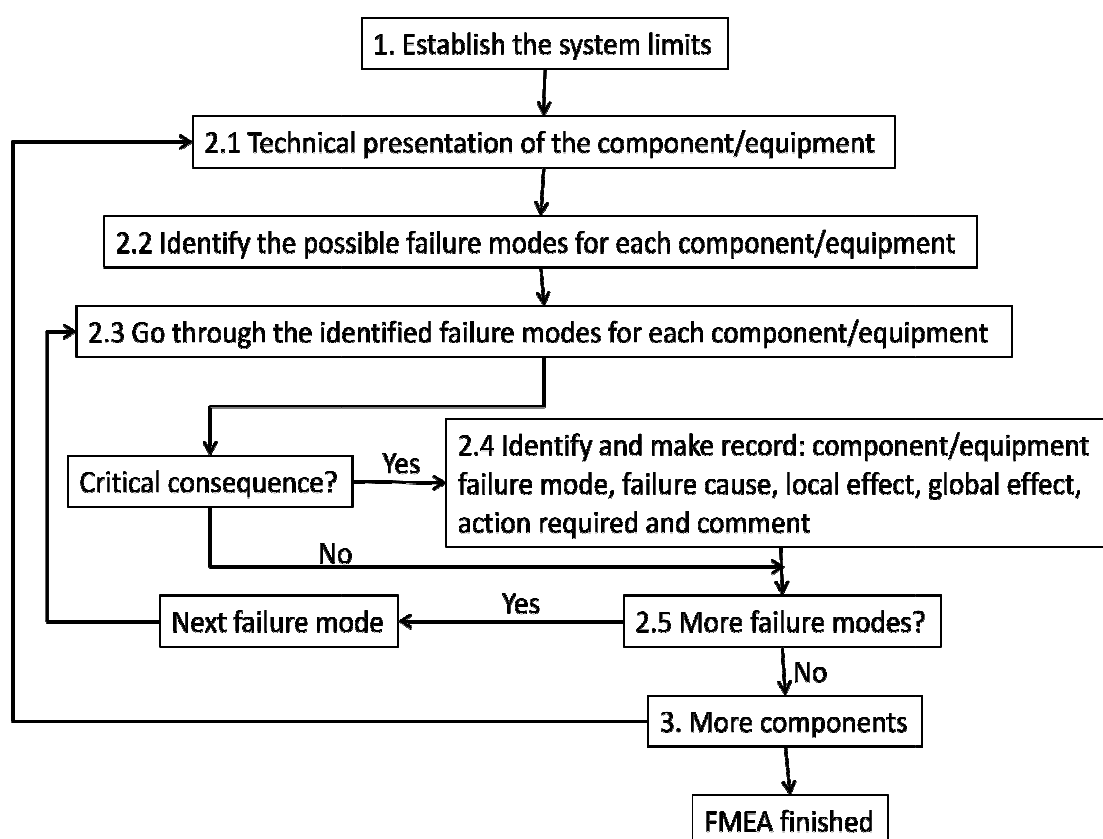


Figure 16: FMEA Methodology, adapted from (Rausand 2004)

FMEA Worksheets

The FMEA worksheets consist of the following columns:

- Failure mode(s): A failure is the termination of the ability of a component/functional block to perform an intended function. A failure mode is the manner in which a component/functional block can fail. Only failure modes which are expected to have some significance in the given situation and operational mode should be included. Failure modes which obviously are of less interest should be ignored. Each failure, which is applicable to a component or functional block, will require a separate entry on the FMEA worksheet.

- Failure cause(s): All reasonable causes for the failure mode should be stated here. This information will assist in evaluating the probability of occurrence, means of detecting the occurrence as well as possible corrective actions to take. Causes that are the results of a failure in another sub-system, i.e. missing/faulty, control signal or operators faults should be included. A note about this should be given either in the comment columns or as a note at the bottom of each worksheet.

- Detection of failure: All possible methods for detection of identified failure modes are recorded.

- Failure rate: The classification is as follows

1. Very unlikely (Once per 1000 years or more seldom)
2. Remote (Once per 100 years)
3. Occasional (Once per 10 years)
4. Probable (Once per year)
5. Frequent (Once per month or more often)

- Severity: severity of a failure mode indicates the worse potential consequence of the failure. The following ranking categories are often adopted

1. Catastrophic (prevents performance of the intended mission)

2. Critical (degrades the system beyond acceptable limits, requires immediate action else would results in production shutdown)
3. Major (degrades the system beyond acceptable limits, but can be controlled by alternative means)
4. Minor (any failure does not degrade the system beyond acceptable limits)

- Risk reducing measure

Based on the literatures (de Salis, de Marolles et al. 1996; Pershukov, Salis et al. 2001; Zhang, Zhu et al. 2011; Hua, Falcone et al. 2012) obtained for the multiphase helico-axial subsea pump the main components can be broken down as pump volute, impeller, bearing, seal and motor as seen in figure 17. It can be concluded that the main function of the pump is to maintain flow and pressure. Thus the main failure mode that can be identified is the loss of flow and pressure. The loss of flow and pressure is correlated and hence has been combined as one failure mode in the FMEA.

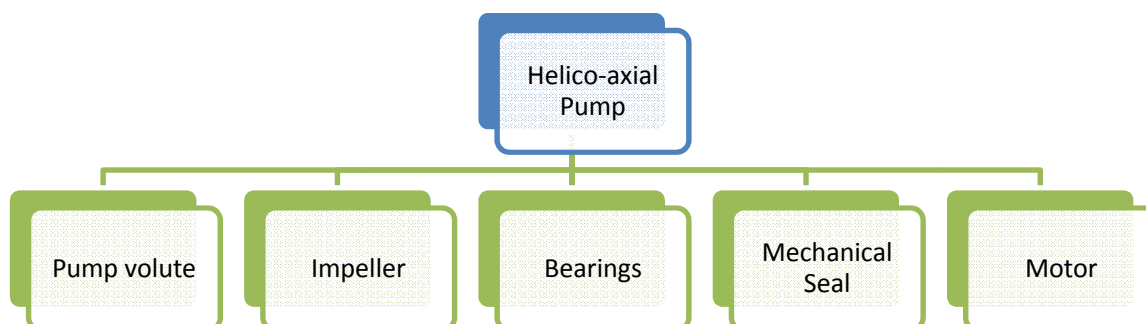


Figure 17: Main component breakdown of a Helico-axial subsea pump

Figure 18 has been used for FMEA purposes. However to restrict the scope, failure of valves, temperature and pressure transmitters, power and control system and lube oil system has not been included in the FMEA. The focus is only on the pump set (i.e. pump and motor) in the FMEA worksheet.

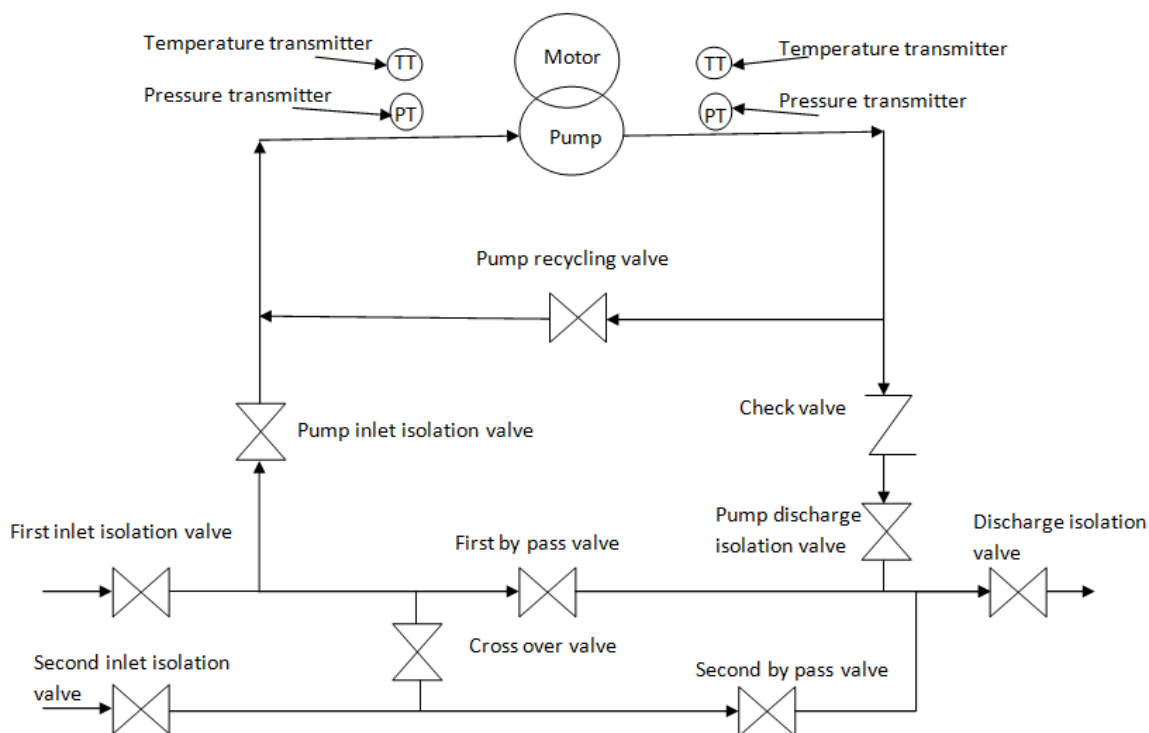


Figure 18: Schematic for a typical subsea multiphase pump, adapted from (Eriksson, Homstvedt et al. 2009)

Worksheet

Item: Helico-axial subsea pump

Ref No.	Failure mode	Failure cause(s)	Failure detection method	Failure	Severity	Risk reducing measure
1	Loss of flow or pressure	Motor wear	Dual pressure transmitter installed at the inlet and outlet of the pump	3	2	Check for high temperatures and provide adequate cooling. Provide redundant lube oil cooling lines.
		Impeller wear		3	1	Chose correct material taking the operational conditions into consideration. . Inject scale inhibitors and de-emulsifiers at pump intake. Use gravel pack or

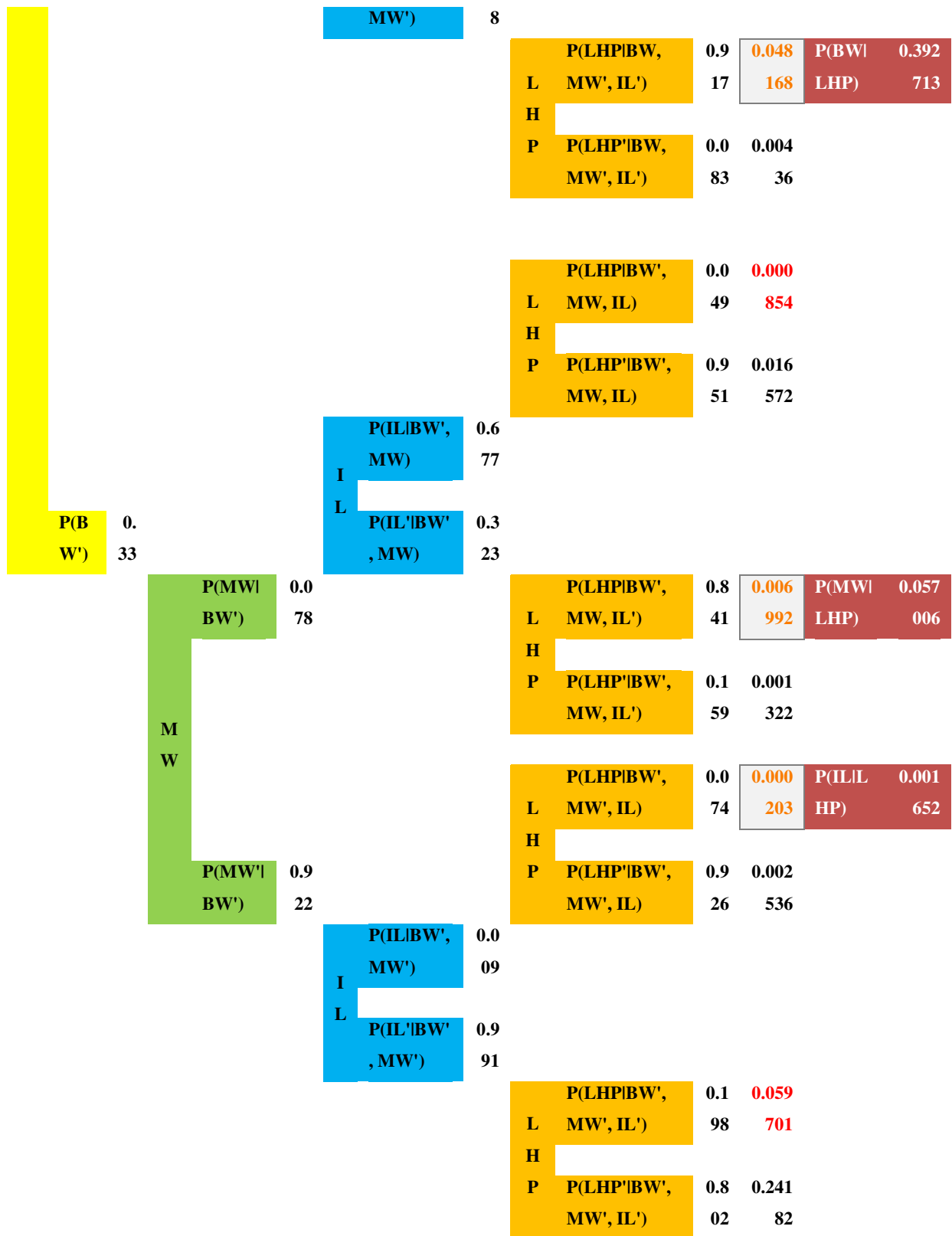
						screens.
		Bearing wear		4	2	Correct lubrication is to be provided. Shaft damage is minimized by using correct material taking operation condition into consideration.
		Seal wear		4	2	Chose correct material for the seal taking the operational conditions into consideration. Inject scale inhibitors and de-emulsifiers at pump intake. Use gravel pack or screens.
		Pump volute wear		3	1	Chose correct material taking the operational conditions into consideration. Inject scale inhibitors and de-emulsifiers at pump intake. Use gravel pack or screens.

Table 3: Calculation for P(LLO|SW)

SW	P(SW)	0.007	LLO	P(LLO SW)	0.9	0.0063	P(SW LLO)	0.065851
	P(SW')	0.993		P(LLO' SW)	0.1	0.0007		
			LLO	P(LLO SW')	0.09	0.08937		
					P(LLO' SW')	0.91	0.90363	

Table 4: Calculation for P(LHP|BW, MW, IL)

B W	P(B W)	0. 67	M W	P(MW BW)	0.9 2	I L	P(IL BW, MW)	0.6 28	H P	P(LHP BW, MW, IL)	0.0 9	0.034		
												P(LHP' BW, MW, IL)	0.9 1	0.352 26
														P(LHP BW, MW, IL')
												P(LHP' BW, MW, IL')	0.9 74	
P(LHP BW, MW', IL)	0.7 23	0.000 775												
		P(LHP' BW, MW', IL)	0.2 77	0.000 297										
I L	P(IL BW, MW')			0.0 2	P(IL' BW, MW)	0.9								



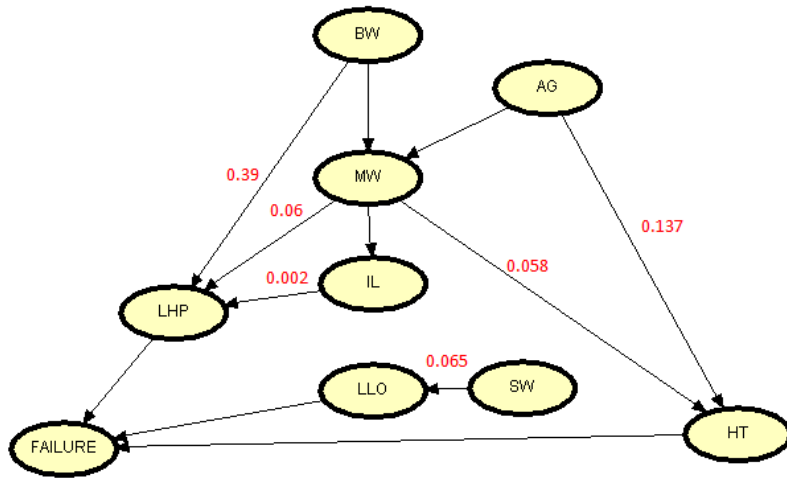


Figure 19: Influence diagram for the helico-axial pump

Table 5: Failure rate calculation of the pump

Failure Mode	Base failure rate	Importance	Revised failure rate
INEEL/EXT-98-00892 Sept 1998			
Loss of head and pressure	0.000014 for one pump	0.449719071	6.29607E-06
	0.000014 for one pump		
OREDA			
High temperature	8.28*10 ⁻⁶ operational time for 2 installations and 5 population	0.195442594	1.60849E-07
	0.000000823 for one pump		
OREDA			
Loss of lube oil level	8.28*10 ⁻⁶ operational time for 2 installations and 5 population	0.065851364	5.41957E-08
	0.000000823 for one pump		
		Total	6.51111E-06

Appendix C-Subsea Equipments

Subsea separator

Separation equipment plays a very important role in the oil and gas process as it helps to separate the well stream, which consists of oil, gas, water and sand, before it reaches a topside installation or a shore terminal. The water and sand is isolated and removed from the oil and gas. The separated water and flushed sand from the separator is re-injected into the well which increases the amount of oil and gas being sent to the topside facility. Also by re-injecting the separated water and sand in addition to boosting the well stream with a subsea pump the back pressure towards the field is reduced as a consequence the receiving pressure at the topside production platform is also reduced. There is also a reduced need for topside water cleaning. This is a strong ecological advantage, drastically reducing the load on platforms as produced water can be pumped back to where it came fromⁿ.

Current concepts of the liquid/liquid separations are the gravity separation, semi-compact gravity separation, pipe separation and cyclonic liquid-liquid separation. Each concept has its pros and cons, however the semi-compact gravity separation is the latest concept to be applied today and shall be discussed. The latter two concepts do lead to a more compact and smaller diameter separator; unfortunately today there's a technology gap and hence cannot be applied to subsea separators (Vu, Fantoft et al. 2009).

A semi-compact gravity separation, which uses a simple separation vessel for the liquid/liquid separation as on platforms and land based oil production facilities with slight modification to suit the subsea environment and an inlet cyclone for gas-liquid separation. For example in the Tordis project, a horizontal separator has been dedicated to separate water from oil with a maximum oil/water interface surface area, no coalesce unit and no pressure control facilities (see figure 20). The inlet and outlet are important aspect of the separator design. The inlet is able to withstand sludge, varying gas/liquid ratios, reduce the fluid momentum and reduce emulsion. To ensure that oil is retained and obtained from the outlet line at all times a weir plate and an appurtenant baffle plate is placed in the separator. Level indicators are installed in the separator which helps indicate the level of emulsion and the

ⁿ http://www.eurekanetwork.org/c/document_library/get_file?uuid=b4aa0aeb-e575-49d4-8593-ef6aa51eec58&groupId=10137

water level. This level indicator acts as an input to the water re-injection system. The accumulated sand in the separator is flushed out with the water by a set of pipes (nozzles) which pushes the sand to the bottom of the separator. This is often referred to as subsea separator with integrated sand management system (Horn, Bakke et al. 2003; Eriksson and Kirkedam 2004; Fantoft, Hendriks et al. 2006; Vu, Fantoft et al. 2009).

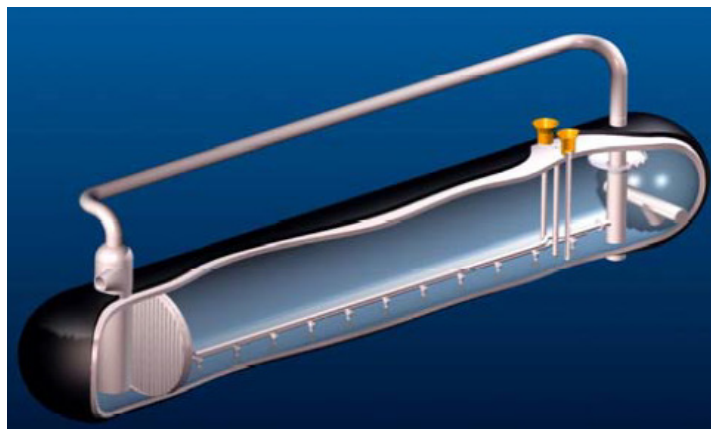


Figure 20: Tordis subsea separator, source (Fantoft, Hendriks et al. 2004)

One of the core new components is the inlet section that removes gas before the well stream enters the separator and routes the gas through a bypass line. This is designed with the inlet cyclone positioned partly above the separator vessel as seen in figure 21. In this location it can easily be sized for a very high gas flow rate compared to a similar inlet cyclone positioned inside the vessel, which is the usual case. This frees the almost the entire separator volume for oil-water solids separation. With this concept the separator volume is reduced by approximately 50 percent compared to the standard designs with equal flow rate capacities and separation performance as shown in figure 22. This is a very important as it is critical to design subsea separators that fall within the lifting weight capacities of intervention ships (Fantoft, Hendriks et al. 2004; Vu, Fantoft et al. 2009).

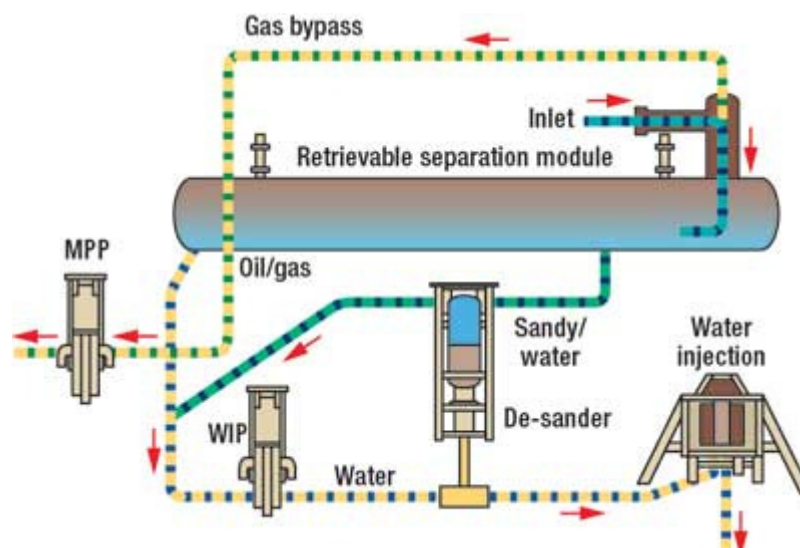


Figure 21: Separator with bypass arrangement (top) and system for sand handling illustrated on the separator bottom, source (Fantoft, Hendriks et al. 2006)

The separation performance requirement considered is typically that the water to be re-injected must contain less than 1000 ppm oil. Based on similarly designed separators the outlet concentration is normally in the range of 100 to 200 ppm. Extensive experience from operational field shows that the required separation performance for the subsea separator will be met (Fantoft, Hendriks et al. 2004).

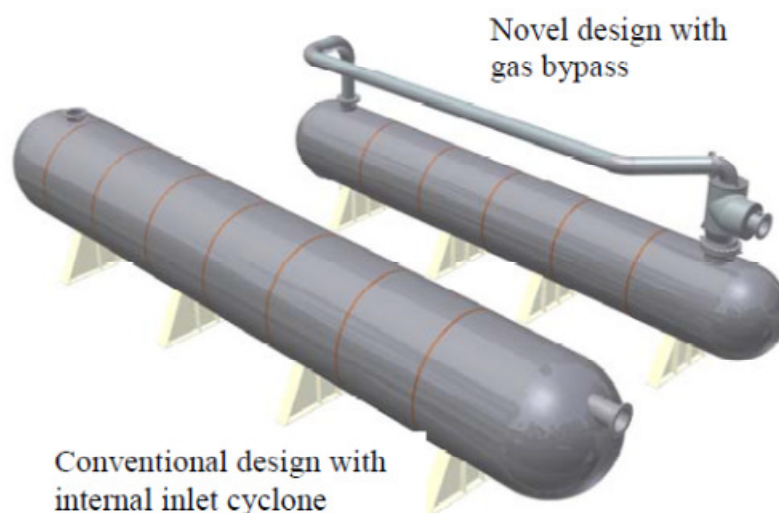


Figure 22: Compact subsea separator concept compared to conventional separator designs with equal capacity (source <http://www.scandoil.com/>)

Gas-liquid separation is also an important concept in order to minimize hydrate and slugging risks typically associated with ultradeepwater environments, while allowing for an efficient

single-phase boost of the liquid by means of the industry-proven electrical submersible pumping, ESP (Parshall 2009). Gravity separation, caisson separation, multipipe separation and inline separation are the concepts employed for gas-liquid separation. Caisson separation has proved as a successful application in the Perdido project at Gulf of Mexico (see figure 23). A technology gap exists for multipipe separation and a slug handling proves to be a challenge for inline separation (Vu, Fantoft et al. 2009).



Figure 23: Caisson separator in gulf of Mexico, source <http://www.ogj.com/>

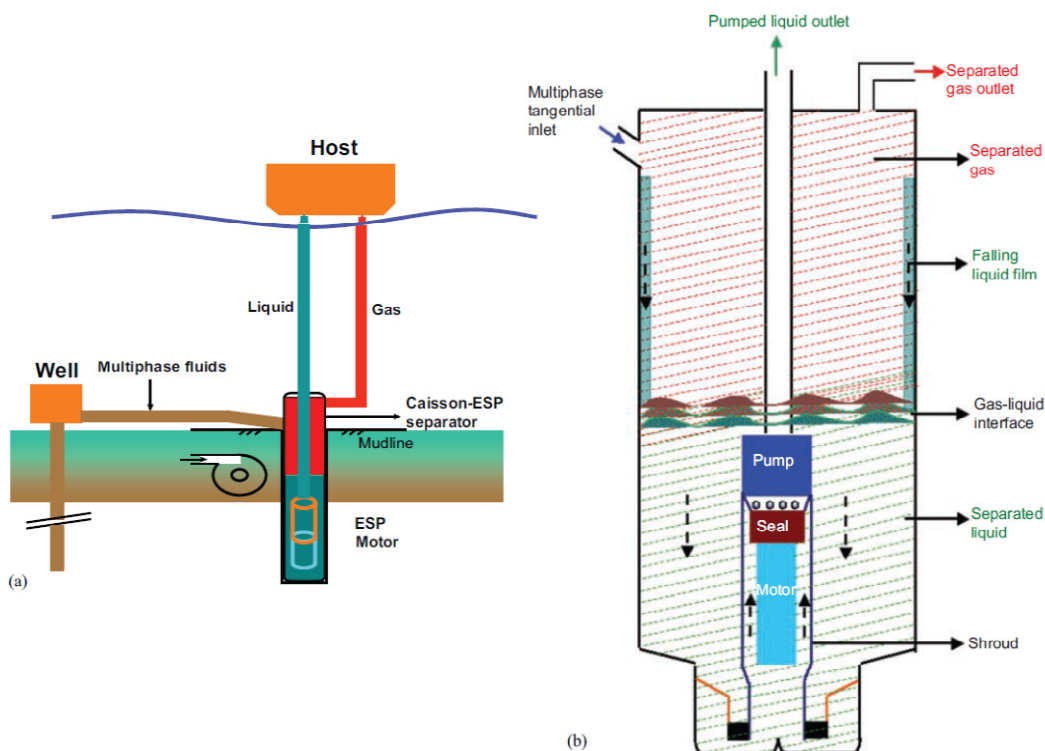


Figure 24: (a) Flow schematic of production well and caisson ESP separator system. (b) Detailed flow schematic of caisson ESP separator, source (Parshall 2009)

The vertical caisson separator has been developed by Shell and FMC. More than 300ft long caisson, with a cylindrical cyclonic gas/liquid separator at the top and a 1500hp electrical submersible pump (ESP) is housed further down inside the caisson as seen in figure 24 (a). When a multiphase flow enters the caisson's top end and flows into the separator through a purposefully angled and tangential inlet. Liquid and gas separates as the multiphase fluid travels downward in a spiral pattern as seen in figure 24 (b). The heavier liquid is separated as it is thrown by centrifugal and gravitational forces to the separator wall. The liquid then flows to the caisson sump where it is pumped to the host facility by the ESP. The gas also travels to the host facility as it is liberated under its own pressure. The main concern with caisson separator is the maintenance and retrieval of the ESP (Parshall 2009).

It is normal for a subsea equipment to have a functional life of 20 years^o, thus reliability is crucial. Installation and retrieving equipment to and from the seafloor is a very costly affair and if it needs to be done several times, the economics of the project will no longer exist. Thus compactness is crucial since everything installed subsea is very expensive and the bigger it is, the more expensive it becomes, both from a manufacturing, installation and maintenance point of view. Another advantage of using subsea equipments would be that only the relevant constituents will run through the topside platform, as a result the production rate can be increased^p. The separator itself is required to be compact and modularised to minimise cost and to allow for relatively easy and inexpensive retrieval in case of unforeseen problems. Separator compactness is important when designing systems for deeper water as conventionally designed vessels can be difficult or impossible to manufacture for installation in deep water due to the large required wall thickness. The key step is to select components proven to be robust, reliable and cost-efficient with track record from topside applications (Horn, Bakke et al. 2003).

The economic advantage for using subsea separation (separating gas, oil, water, and sand at the seabed) is enormous for many subsea field developments. By employing a subsea separator one can enhance the hydrocarbon production and avoid or reduce/simplify costly surface platforms or floating vessels. A qualification program for this new technology was

^o

http://www.eurekanetwork.org/showsuccessstory?p_r_p_564233524_articleId=105831&p_r_p_564233524_groupId=10137

^p

http://www.eurekanetwork.org/showsuccessstory?p_r_p_564233524_articleId=105831&p_r_p_564233524_groupId=10137

developed to demonstrate its functional capabilities and performance. Further information on the qualification can be found under the article compact subsea separation system with integrated sand handling (Fantoft, Hendriks et al. 2004). A good separator will pave the way for an efficient use of a subsea compressor, when needed.

Subsea Compressors

Subsea gas compression is used where the natural pressure of the reservoir constrains the gas recovery and/or the transport capabilities of the pipelines. The most common application is where the weight of the gas column prevents maintenance of production by natural pressure, forcing to leave considerable amount of gas in the reservoir. Also where relatively low flow causes liquid to accumulate in the flowlines creating instability in the production rate and eventually leading to shutdown subsea compression can be used. Lastly when production needs to be transported through long distances like from subsea to shore, subsea compression can be employed (Lima, Storstenvik et al. 2011).

Ormen Lange and Åsgard are two fields where subsea compression is intended to be used.

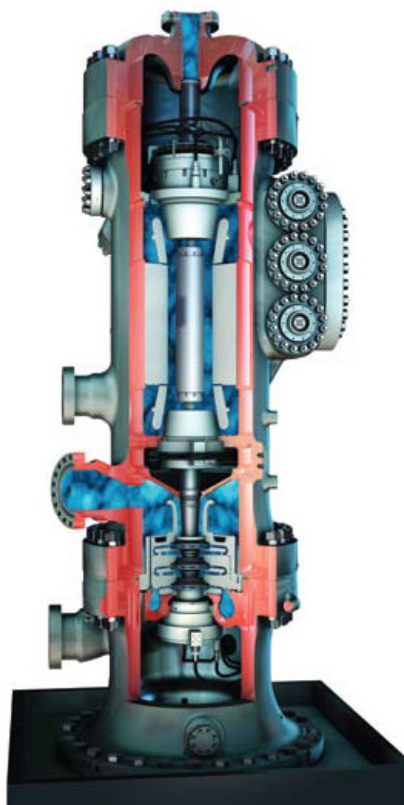


Figure 25: Subsea compressor for Ormen Lange, source <http://site.ge-energy.com/>

The system for Ormen Lange comprises a single subsea compression train with a complete subsea power distribution and all-electric control system. The train includes a scrubber, a 12.5MW gas compressor (figure 25), a 400KW liquid pump and an anti-surge cooler. The power system includes a circuit breaker, a frequency converter for the compressor and pump, and transformer for both machines as well as for the subsea control system. The Åsgard subsea compressor is based on the same concept as Ormen Lange with few differences mainly in the power distribution. The production from the Åsgard field will enter the two compressors. In each compressor train, the multiphase stream is first cooled down in a specially designed heat exchanger and enters the scrubber where the gas and liquid are separated. The separated gas from the scrubber then is routed to an 11MW centrifugal compressor (figure 26) and the liquid stream to a 700KW centrifugal pump. At the compressor discharge, a recycle line with a fast acting valve takes the gas back to upstream of the inlet cooler in case the operating condition is close into the compressor surge curve. Yet at the compressor high pressure side a discharge cooler lowers the gas temperature to below the limit dictated by the existing pipelines before it mixes with the liquid from the pump (Lima, Storstenvik et al. 2011).



Figure 26: Subsea compressor for Åsgard at K-lab, source <http://www.statoil.com/>

Availability (reliability and maintainability) is an important aspect for the subsea compressors due to the fact that it is hundreds of meters underwater as seen in figure 27. The architectural simplicity is a key requirement at system level so that the system is reliable and robust. The subsea compressors have so far been the heaviest component posing a threat to the logistics and operations. Thus redundancies and modularization have been introduced to address this issue. At the component level, stringent requirements on the mean time to failure are to be complied. Such critical components are selected based on track record for existing components or extensive endurance tests for novel components (Fantoft 2005; Lima, Storstenvik et al. 2011). To further improve the subsea compressor the combination of the compact compressor, the forced cooler and frequency step-up device has been suggested (Oiungen, Solvik et al. 2008; Lima, Storstenvik et al. 2011). This will solve the hydration, pump failure and power distribution problem.

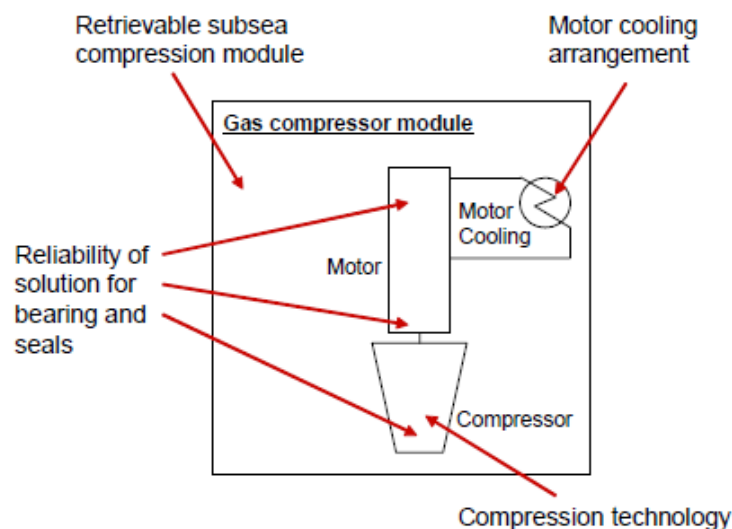


Figure 27: Technical focus areas for subsea compressor, source (Fantoft 2005)

Also tremendous research is being carried out on the multiphase compressor. The biggest advantage of this would be that the well stream will be worked on directly without being processed. It is based on a counter-rotating principle with a hydraulic and mechanical design specifically designed for boosting of unprocessed well stream. The integrated and fully encapsulated design of the compressor unit is based on the well proven subsea design already applied for the booster pumps (Hjelmeland, Olsen et al. 2011).

Subsea Powergrids

The oil recovery now lies in the depth of the ocean. Subsea power grids have been developed to distribute the power under the sea. As today, high voltage power has been distributed upto a depth of 3000 meters. Subsea power grid, which consists of transformers, converters, switchgears and adjustable speed drives (figure 28), supply the power to carry the oil and gas from the wellhead to an offshore or onshore processing facility.

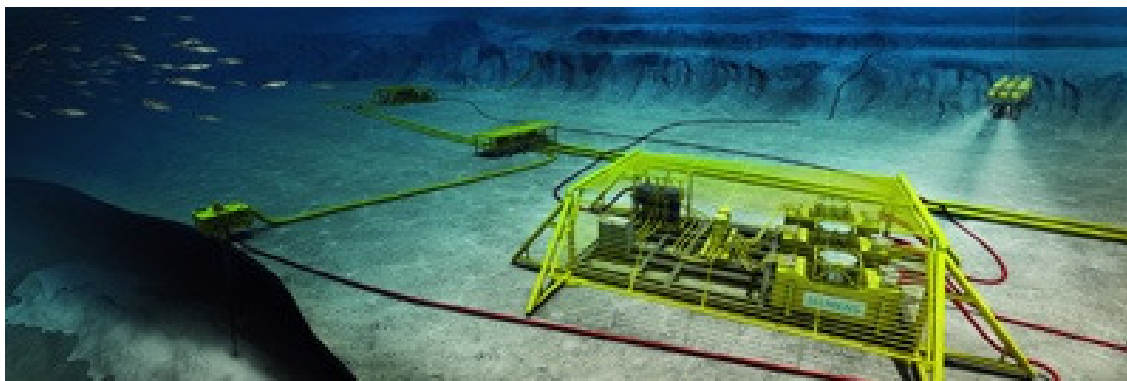


Figure 28: Subsea power grid, source <http://www.siemens.com/energy>

Transformers, step down the voltage since the electricity being transmitted is at high voltage. To protect the transformers from the subsea environment, they are double shelled, sealed and pressure compensated. Heat generated is transferred to the surrounding seawater via natural cooling. This also helps protect the equipment from break down and reduces maintenance requirements. To distribute power to the subsea utilities like pump motor and compressor a medium voltage switch gears is used. It has a modular design with breaker units and SF₆ filled atmosphere canisters. The main bus bars, wet make connectors measuring transformers are housed in a fluid filled base. To regulate the speed and rotational force, or torque output, of an electric motor a variable speed drive (VSD) is used. Utilizing the capabilities provided by an integrated subsea power grid, an underwater pipeline with all the pumps, compressors and electric motors is all that would be needed to transport the oil long distances to an onshore refining facility^q.

^q <http://www.energy.siemens.com/br/en/energy-topics/videos/subsea-power-grid.htm>

Activity Plan

An activity plan has been developed with description of the tasks that are to be performed. The activity plan shows the time schedule for the project along with a Gantt diagram with specification of the individual task, its start and end dates. It also highlights the important project milestones.

Definitions

For the purposes of this document, the following terms and definitions apply.

- Failure - The inability of an equipment unit or system to perform a specified function.
- Critical failure - Failure of an equipment unit that causes an immediate cessation of the ability to perform a required function.
- Non-critical failure - Failure of an equipment unit that does not cause a cessation of the ability to perform a required function.
- Dangerous failure - A failure that has the potential to prevent a safety system from achieving its safety function(s) when there is a true demand. A single dangerous failure may not be sufficient to prevent a redundant safety system from performing its safety function (e.g. two coincident dangerous failures may be needed to prevent operation of a 2-out-of-3 voting system).
- Non-dangerous failure - A failure of a safety system that is not dangerous.
- Safe failure - A failure that has the potential to unnecessarily trigger a safety function.
- Revealed failure - A failure that is evident or that is detected by the system itself as soon as it occurs. Failures detected by the built-in diagnostic tests (BIT) of a logic solver are also considered as revealed failures.
- Hidden failure - A failure that is not revealed to operation or maintenance personnel and that needs a specific action (e.g. periodic test) in order to be identified.

- Common cause failure - Failure of different items resulting from the same direct cause, occurring within a relatively short time, where these failures are not consequences of another. See also Common mode failure.
- Common mode failure - A subset of Common cause failure whereby two or more components fail in the same manner.
- Demand Activation of a system's function (may include functional, operational and test activation).
- Failure mode Effect by which a failure is observed on the failed item.
- Failure on demand Failure that occurs immediately when an item is instructed to perform its intended function (e.g. standby emergency equipment).
- Reliability Probability of an item performing a required function under stated conditions for a specified time interval.
- Observation period Interval of time between the start date and end date of reliability data collection.
- Failure rate Limit, if this exists, of the ratio of the conditional probability that the instant of time, T , of a failure of an item falls within a given time interval, $(t + \Delta t)$ and the length of this interval, Δt , when Δt tends to zero, given that the item is in an up state at the beginning of the time interval.

Note:

1. In this definition, t may also denote the time to failure or the time to first failure.
2. A practical interpretation of failure rate is the number of failures relative to the corresponding operational time. In some cases, time can be replaced by units of use. In most cases, the reciprocal of MTTF can be used as the predictor for the failure rate, i.e. the average number of failures per unit of time in the long run if the units are replaced by an identical unit at failure.

- Mean Time to Failure (MTTF) - Expectation of the time to failure.
- Mean Time Between Failures (MTBF) - Expectation of the time between failures.

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^s <http://inderscience.metapress.com/home/main.mpx>

^t <http://scholar.google.no/schhp?hl=no&tab=ws>

^u <http://www.sciencedirect.com/>

^v <http://www.ntnu.no/ub>

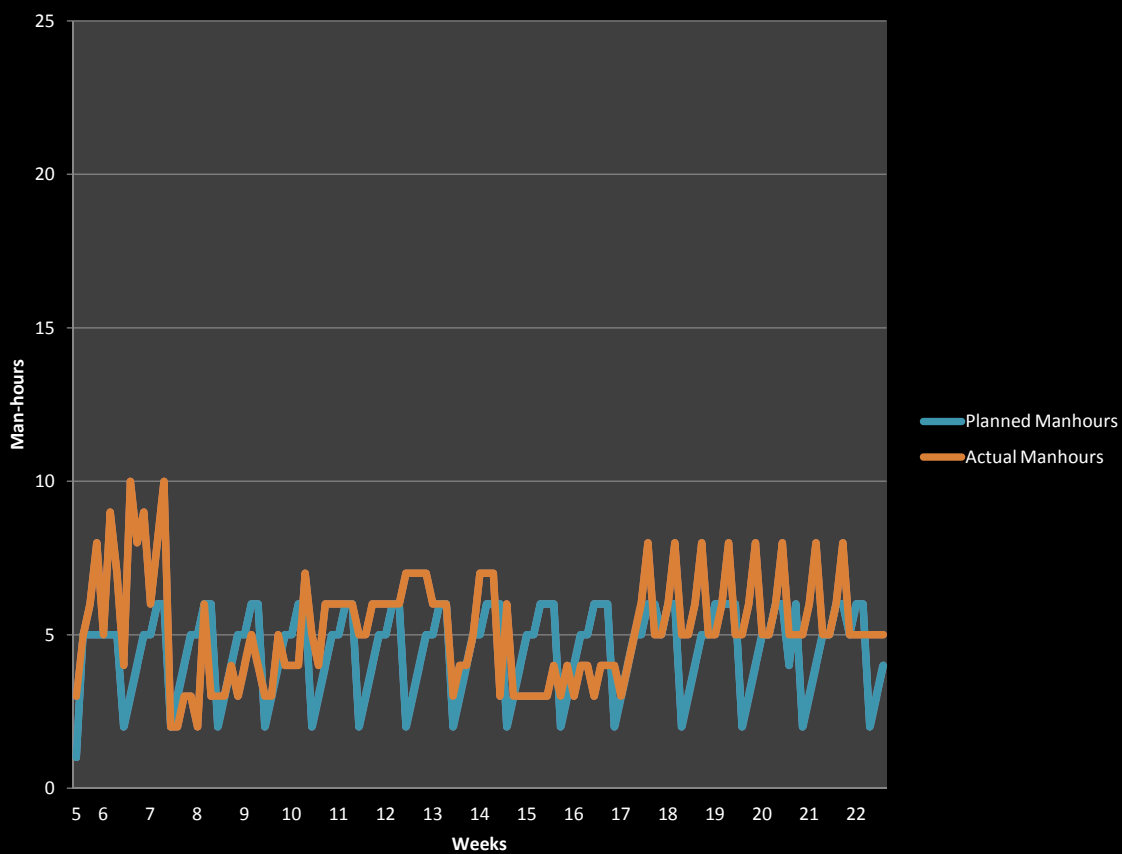
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APPENDIX 1 - Progress report

Month	February																																
Week	5							6							7							8							9				
Days	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	1	2	3	4	
Milestones	Develop Progress Report		Literature search		Kick off meeting		Start pre-study report							Send draft of Pre-study report							Submit pre-study report				Start Final study report								
Activities								Pre-Study report																									
	Literature search and review																																
Planned Manhours	1	5	5	5	5	5	5	2	3	4	5	5	6	6	2	3	4	5	5	6	6	2	3	3	4	5	5	6	6	2	3	4	5
Actual Manhours	3	5	6	8	5	9	7	4	10	8	9	6	8	10	2	2	3	3	2	6	3	3	3	4	3	4	5	4	3	3	5	4	

Planned Man-hours Vs. Actual Man-hours



PRE-STUDY REPORT

PROVISION OF RELIABILITY DATA FOR NEW TECHNOLOGY EQUIPMENT IN SUBSEA PRODUCTION SYSTEMS

MASTER THESIS

Ishita Dash

February, 2012

TPK 4900 PROD KVALITETSTEKN VÅR 2012

Presented to the RAMS Group

Department of Production and Quality
Engineering

Supervisor: Mary Ann Lundteigen

Co-supervisor: Marvin Rausand

1. Introduction

Oil and Gas has been an integral part of our lives as early as 6th century BC^a. The earliest subsea well is the Bibi Eibat well in Azerbaijan, which came on stream in 1923^b. With the increasing appetite for energy we have moved into deeper waters to extract oil and gas, thus the concept of subsea production system was developed (as early as 1950s). This proved to be an alternative economic solution to deepwater production problems. Ideally Subsea productions systems can be defined as consisting of all the necessary equipment to produce, process and transport hydrocarbons to shore-located subsea. There are several methods by which oil and gas can be brought to shore as illustrated in Figure 1(Phansalkar, Bourne et al. 1979).

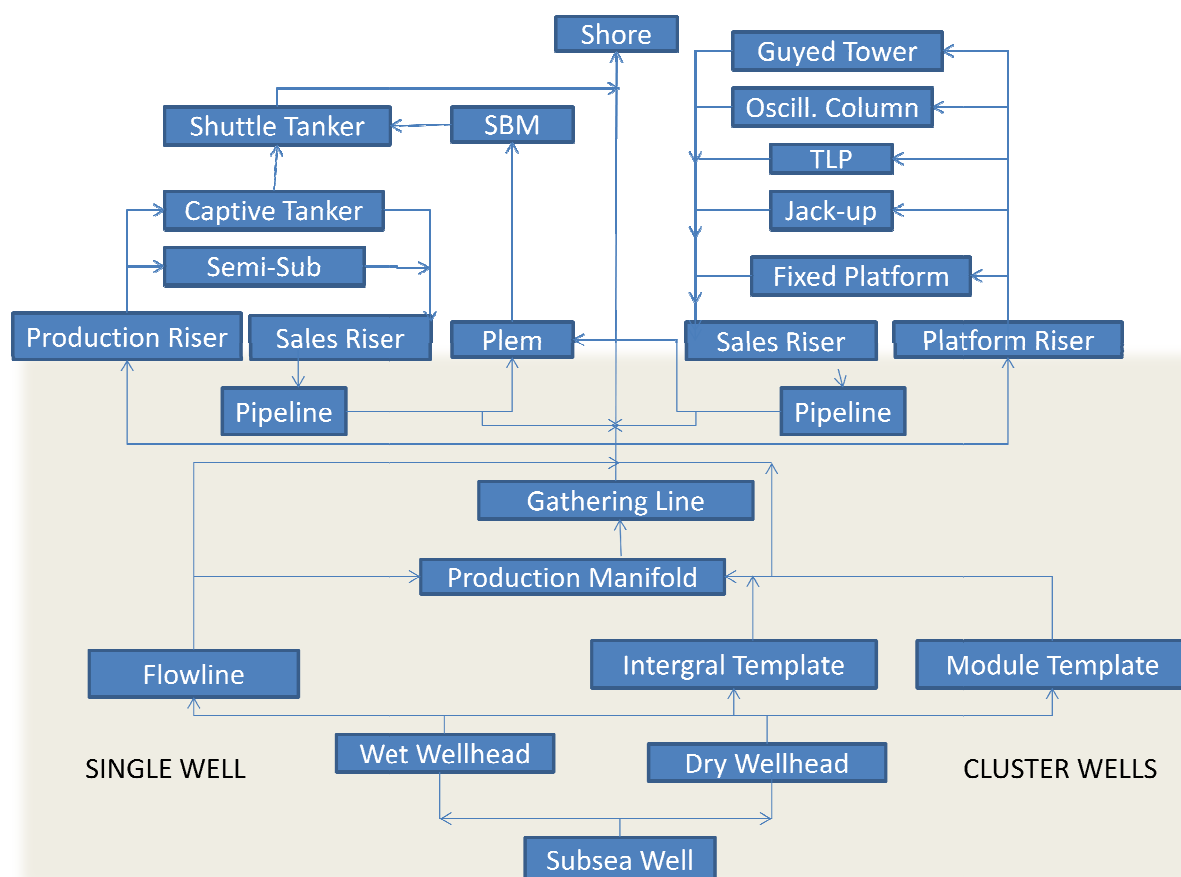


Figure 1 Subsea production system categorization, adapted from(Phansalkar, Bourne et al. 1979)

To produce, process and transport the offshore oil & gas in deep waters subsea production systems prove to be an answer where traditional facilities might be either technically unfeasible or uneconomical due the water depth. The development of subsea oil and gas fields requires specialized equipment. The equipment must be reliable enough to safe guard the environment, and make the exploitation of the subsea hydrocarbons economically feasible. The deployment of such equipment requires specialized and expensive vessels, which need to be equipped with diving equipment for relatively shallow equipment work (i.e. a few hundred feet water depth maximum), and robotic equipment for deeper water depths. Any requirement to repair or intervene with installed subsea equipment is thus normally very expensive. This type of expense can result in economic failure of the subsea development.

^a <http://www.geohelp.net/world.html>

^b http://en.wikipedia.org/wiki/Offshore_drilling

Subsea technology in offshore oil and gas production is a highly specialized field of application with particular demands on engineering and simulation. Most of the new oil fields are located in deepwater and are generally referred to as deepwater systems. Development of these fields sets strict requirements for verification of the various system functions and their compliance with current requirements and specifications. This is because of the high costs and time involved in changing a pre-existing system due to the specialized vessels with advanced onboard equipment. A full scale test (System Integration Test – SIT) does not provide satisfactory verification of deepwater systems because the test, for practical reasons, cannot be performed under conditions identical to those under which the system will later operate. The oil industry has therefore adopted modern data technology as a tool for virtual testing of deepwater systems that enables detection of costly faults at an early phase of the project, which is the design phase. By using modern simulation tools models a deepwater systems can be set up and used to verify the system functions and dynamic properties, against various requirements specifications. This includes the model-based development of innovative high-tech plants and system solutions for the exploitation and production of energy resources in an environmentally friendly way as well as the analysis and evaluation of the dynamic behaviour of components and systems used for the production and distribution of oil and gas.

1.1 Objective

To assess the reliability of new technologies such as subsea production systems reliability estimates are required. However as no relevant experience data is available, the required data is required to be ‘extrapolated’ from the data of similar equipments. The main objective of this project, is to develop a procedure to ‘extrapolate’ and describe the associated methods and tools.

The main objective is further divided into the following more specific sub-objectives:

1. Give a survey of the reliability data sources and evaluate these with respect to relevance and quality. Special focus should be put on FIDES and MechRel – and possible company-specific data sources.
2. Give a brief technical description of relevant new technologies.
3. Select relevant subsea equipment and carry out a failure modes and failure cause/mechanism analysis of these.
4. Compare the selected subsea equipment with similar topside equipment (for which data is available) to identify design changes, differences in stressors and maintenance and – based on this compare the possible failure modes with respect to relevance and likelihood.
5. Identify the reliability influencing factors for both topside and subsea application and illustrate them by Bayesian networks.
6. Study the approach described by Brissaud, F. Et al (2010) ‘Failure rate evaluation with influencing factors’ and discuss whether or not this approach can be applicable in the current context – possibly in a modified version.
7. Discuss whether or not the assumption of constant failure rates will be realistic for subsea applications where the possibilities for preventive maintenance are limited.
8. Develop a new approach to determination of failure rate functions for new technology equipment in subsea applications.
9. Discuss the results, including ideas for further work related to the proposed approach.

1.2 Approach

The main focus of this thesis is to develop a procedure to carry out the 'extrapolation' of data from equipment which are similar to the new technology equipments in subsea production systems. A detailed approach for this extrapolation will be explained in the main report, after gaining knowledge on this.

A study on the reliability procedure in FIDES^c and MechRel^d is required. Both have developed a new reliability assessment method and provide engineering process and tools to improve reliability in the development of new systems / equipments. Also a study on the new technologies within subsea production systems is to be carried out.

1.3 Activity Plan

An activity plan has been developed with description of the tasks that are to be performed. The activity plan shows the time schedule for the project along with a Gantt diagram with specification of the individual task, its start and end dates. It also highlights the important project milestones.

1.4 Literature list

A tentative literature list has been developed. This list will be refined during the final report development. The main sources of articles, conference papers, journal papers, presentations, standards and book chapters has been OnePetro^e and Google scholar^f and the NTNU online library^g.

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^c <http://fides1.imdr.eu/>

^d <http://www.mechrel.com/>

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