Reliability Modelling of Subsea Production Equipment

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Abstract: The growing need of global energy together with the depletion of oil reserves in shallow waters has led the oil and gas industry to turn increasingly to deeper and ultra-deeper water reserves of oil. This shift has motivated the development of new concepts of subsea production systems in which traditional equipment, currently used on ships or production platforms, are not appropriate due to differences in the environment in which they operate. Several methodologies for predicting the reliability of equipment are reviewed, focusing on a method of predicting the failure rate of equipment operating in new environments from failure information in traditional operating environments. This method is implemented in a computational tool and later validated using the original example of the method. As the application of this method is based largely on subjective data provided by experts, a systematic study is conducted to assess the importance of the subjective parameters of the method in the predicted reliability of the equipment. The developed tool is applied to predict the reliability of a subsea centrifugal compressor based on historical information on the failure modes and failure rates of similar equipment operating in ships and oil and gas production platforms.

Keywords: Reliability; reliability prediction methods; failure rate; subsea system.

1. INTRODUCTION

Offshore oil and gas production began at the end of the 19th century and exploded during the 20th century due to technological development experienced in that period.

Presently, the deepwater and ultra-deepwater fields are considered by many as the final chapter in gas and oil production. The exploration and production of these fields pose several engineering difficulties and challenges. It is necessary to develop new techniques and new technologies, it is necessary to counteract the great adversities that are encountered each time it reaches greater depths and finally it is necessary to plan in more detail all the productive facilities in these deep zones [1], [2]. Also, new offshore production concepts with more equipment on the seabed have been developed.

Traditional equipment that has been previously used in offshore and onshore is not appropriate for subsea systems due the characteristics of the operation environment. A subsea production system may be a subsea installation consisting of wells, Christmas-trees, control systems, manifolds, flow lines and risers. In the last decades the industry has managed to put all equipment referred in operation at bottom of the sea, nevertheless, until now, some type of surface support platform for the processing and storage of oil and gas is still necessary. The objective now is to be able to transfer these systems to the subsea in a viable way, such as the Statoil project of the subsea factory [3].

The two main objectives of this work are to describe the main equipment used in topside and subsea oil and gas production systems and to assess the reliability of new subsea equipment based on comparison with similar topside equipment.

2. SUBSEA PRODUCTION SYSTEM

The depth of the water has a great impact on the development of subsea fields, since it defines which systems can be placed in water. Distance is another influence factor, the greater or lesser proximity of the field to the coast defines whether the flow can be transferred directly to an onshore installation or, on the contrary, if it is necessary to have some types of transfer platform [4]–[6].

The goal of subsea field development is to safely maximize economic gain using the most reliable, safe, and cost-effective solution available at the time [5], [7], [8].

Some issues must be considered when developing a subsea field such as: deepwater/ultra-deepwater or shallow-water development; dry tree or wet tree; stand-alone or tie-back development; subsea processing or surface processing and facility configurations [5], [7].

2.1 Configuration

There are many ways to set up subsea production equipment depending on field specifications and operation approach.

Satellite well system is an individual submarine well. This type of wells is usually used in small fields that require few wells (Figure 1.a). These wells are widely separated and each one is connected with its single flow line to a centrally located submarine or surface manifold [4], [5].
The use of clustered subsea satellite well is less expensive than the use of widely spaced satellite wells. A single collector can be used to collect flows from all wells that are locally nearby making it possible to send all the flow to the processing system using a single line (Figure 1.b) [4], [5].

The well template is used to group several subsea wells in a single location and the great benefits of this solution are to have the wells accurately located with the manifolds valves and piping incorporated into the template, and the pipes and jumpers can be fabricated and tested prior to implementation (Figure 1.c) [5].

A daisy chain configuration links the wells one after the other, serially, across flow lines. These lines can be connected to the wells by submarine jumpers or directly to the flow base of the wells. This type of configuration is an economical solution compared to the cluster arrangement in the case of several satellite wells (Figure 1.d) [4], [5].

2.2 Equipment

Subsea wellheads are the subsoil access door, with equipment that regulates and monitors the extraction of hydrocarbons and avoids blow-outs due to high pressure formations (Figure 2.a). The wellhead is the agglomeration of three components: the casing head, the tubing head and the “Christmas-tree”, also known as “x-tree” (Figure 2.b) [4], [5], [9], [10].

A manifold is a system that combines piping and valves designed to collect, distribute, control, and monitor the flows of various fluids. The subsea manifolds are installed on the subsea and can be single pipe, with small size, to large structures. The size is chosen considering the number of wells, the way they are integrated into the system and their throughput (Figure 3.c) [4], [5], [11].

Underwater pipelines are used to make the connection between the subsea wellhead and the manifold, the manifold and any other component, such as separators and connects the underwater world to the surface installation. These pipelines can be rigid or flexible and are used to transport petrochemical products, lifting gas and injection water (Figure 3.a) [4], [5], [11], [12].

The risers are the specific portion of the submarine pipelines that connect the entire underwater structure to the host facilities on the surface. In terms of configuration, the raier can either be completely vertical or they can make their way in a wavy mode, the option is taken especially considering the depth (Figure 3.b) [4], [5], [11], [12].

The test separators divide the flow from one or more test wells making possible to analyze it and measure it in detail, thus being possible to evaluate the behavior of the wells under different flow pressure conditions [4].

The production separators (Figure 4) are intended to divide the gas, oil and water which are mixed in the source flow from the manifolds. This separation is usually done in three stages, with each of these stages using separators with specific conditions of pressure and temperature [4], [13].

If the flow collected by the manifolds has an unacceptable concentration of salts, such as sodium or magnesium, it is necessary to remove them. The removal is done by electrostatic desalter which can be placed after the first stage separator or at the exit of the second stage separator [4]. After leaving the separators, to remove the still existing water, the oil is sent to a coalescer. Within this unit there are electrodes that form an electric field capable of breaking the surface connections between the conductive water and the oil [4].

The gas that leaving the separators, is conveyed to the compressors [4], [13].

Heat exchangers placed before the inlet of the compressors are used, making the compression more
efficient, and soon after the compression to reach the temperature set for final storage and transport [4], [13].

Various types of compressors, with different characteristics, are used in many stages of gas production process, such as operating power, speed, pressure, and volume. The reciprocating compressors are used for compressing low-capacity gas and injecting high pressure gas into the reservoir (Figure 5.a), the screw compressors are intended for the gathering of natural gas (Figure 5.b), the axial blade and fin type compressors are used in LNG plants (Figure 5.c), the centrifugal compressors are used in large installations (Figure 5.d) [4].

Compressors require careful maintenance by using auxiliary systems such as load management, vibration control and speed regulator.

There are two types of subsea development for new field discoveries, tie-back development, and stand-alone development. The stand-alone development is currently the most implemented one. It requires the implantation of a platform in the place of the wells to explore. This model is only feasible for large reservoirs due to high capital expenditure (CAPEX) and high operational expenditure (OPEX) being difficult to justify the return compared to the high risk, for this reason most of the small oil fields are ignored [14], [15].

The industry needed to look for a new model to respond to this problem and tie-back was developed for this purpose. The first steps of the model were given in the already existing platforms [14].

The subsea farms (Figure 6.a) are subsea complexes where all the equipment mentioned in the previous section are found and there are added deposits with capacity to store the product obtained from the subsoil. It works well with oil and a little worse with gas because it is difficult to store gas, even on the current platforms [4], [16].

In the subsea to shore concept (Figure 6.b) there is again an underwater complex with all or virtually all the equipment referred to in the previous section. The idea here is not to store the exploration product in tanks but rather to transport it directly to an onshore complex through pipelines. Nowadays it works better with gas than with oil, because at long distances it is difficult to presently conserve the heat of the production fluids. The flow assurance of oil produced over long distances has been one of the major obstacles for this concept not to have much more implementation right now [14].

2.3 New Trends

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3. RELIABILITY AND RELATED CONCEPTS

3.1 Reliability Definition and Measures

The reliability definition has evolved over time and its modern form has been transcribed to an International Organization for Standardization (ISO) standard [17], “The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time”. Reliability requirements should be based on five factors: failure criteria, equipment or system application, environmental conditions, operating conditions, and the methods that will be applied to determine the requirement. Reliability can be measured in a range of ways, with mean time to failure, failure rate, the probability of an item does not fail in a time interval (0, t) and the probability of an item is able to function at time t, four of the most commonly used forms [18], [19].

The quality of a system or product is described by ISO standard [17] “The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs”. Reliability is an extension of quality in the time domain, in other words, the item under study acquires its quality at the moment it is produced and is reliable if it can maintain that quality over time [18].

According to the Institute of Electrical and Electronics Engineers (IEEE) standard [20], availability is described as “The degree to which a system of components is operational and accessible when it is required to use. Often expressed as a probability”. It is important to note that there is the possibility of distinguishing the availability at time t (A(t)), which is translated by a probability, and the asymptotic availability (A∞) [18].

The asymptotic availability denotes the mean proportional time an item is functioning, it can cover both the period up to the first failure and all periods in which the item, after the failure, is repaired in an "as good as new" condition and subsequently continues to run.
\[ A(t) = P(\text{item is functioning at time } t) \quad (1) \]

\[ A_\infty = \frac{MTTF}{MTTF + MTTR} \quad (2) \]

The British Standards (BS) standard [21] defines maintainability as “The ability of an item, under stated conditions of use, to be retained in or restored to, state in which it performs its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources”.

Maintainability is the most important factor in determining the availability of an item, due to this umbilical relationship with availability and of these two with the reliability the Reliability, Availability, and Maintainability (RAM) concept is often used [18].

According to the International Electrotechnical Commission (IEC) standard [22] the dependability definition is “The collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance”.

If safety and security are included in the definition of dependability, it becomes identical to the definition of the Reliability, Availability, Maintainability, and Safety (RAMS) concept.

The time to failure of an item has the meaning of the time that passes since the item is put into operation until its first failure, using \( t = 0 \) as the starting point [18], [23]. It is a random variable and is not necessarily measured in time criteria [18], [23].

The time to failure is typically approximated to a continuous variable with probability density function \( f(t) \) and cumulative distribution function \( F(t) \).

The reliability function \( R(t) \) is the probability that the item does not fail in the range \((0, t)\). It can also be seen as the probability of the item surviving a given time interval \((0, t)\) and for this reason is also known as survivor function [18], [23].

\[ R(t) = P(T > t) \quad \text{for } t > 0 \quad (3) \]

The failure cumulative distribution function (CDF) \( F(t) \) is the probability of the system to fail before time \( t \) [23].

The failure density function (PDF) \( f(t) \) is the probability density function of the failure time. Describes how the probability of failure is spread over time [23]. Its basic properties are: the function is always non-negative and the total area below the function is always equal to one [23].

\[ f(t) = \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t} \quad (5) \]

The failure rate function is also called hazard function or mortality rate function. It is the function that describes the probability of item failing per unit of time, knowing that this same item has not yet failed at time \( t \) [18], [23].

\[ \lambda(t) = h(t) = \frac{f(t)}{R(t)} \quad (6) \]

Through empirical processes it is possible to perceive the shape of the curve that illustrates the estimation of the function of the failure rate, due to its peculiar shape, this curve is known as “bathtub curve” (Figure 7) [18], [23].

![Bathtub Curve](image)

**Figure 7 – The Bathtub Curve [23]**

The first region is called burn-in region or infant mortality region, it is the initial phase that is characterized by a high failure rate that decreases until reaching a stabilization [18], [23]. The second region is called useful life region, also known as chance life region. It has, as its main characteristic, a practically constant failure rate [23]. The third and last region is known as wear-out region and is characterized by increased failure rate at par with increasing age due to the accumulated wear and the degradation that the item is suffering due to environmental conditions such as corrosion, fatigue, creep, among others [18], [23].

The mean time to failure (MTTF) is a measure that can be defined as the time that the non-repairable item runs until failure occurs [18], [23].

\[ MTTF = E(t) = \int_0^\infty tf(t)dt \quad (7) \]

The use of this measure as a reference presupposes that the possible repair of the item is not taken into account. If the possibility of repair is considered, the reference measure becomes the mean time between failures (MTBF) [18], [23], [24].

The MTBF describes the expected time between two failures for a repairable item. The expression used for its calculation is equal to the MTTF (Equation (7))
possible repair of the system being the defining factor to know which of the measures is calculated by the formula. It is important to note that the mean time to repair (MTTR) is inserted in the value of MTBF but not in the value of MTTF, that is easily perceptible for the existence, or not, of repair [18], [24].

The MTTR is the average time needed to solve and repair problems and equipment that have failed to return to normal operating conditions. It is a measure of the capacity of maintenance of equipment and parts, considering that the maintenance time is defined as the time between the beginning of the incident until the moment the system returns to its normal state [18], [23], [24].

Mathematically, as can be seen in the Equation (8), MTTR is calculated by dividing the total maintenance time by the total number of maintenance actions during a specific period [18], [23], [24].

$$ MTTR = \frac{\text{total maintenance time}}{\text{number of repairs}} \quad (8) $$

The exponential distribution is one of the most commonly used distribution in reliability analysis [18], [23].

$$ f(t) = \lambda_{\text{ED}} e^{-\lambda_{\text{ED}} t} \quad \text{for } t \geq 0 \text{ and } \lambda_{\text{ED}} > 0 \quad (9) $$

3.2 Qualitative and Quantitative System Analysis

There are several methods that can be considered as basis in this qualitative and quantitative system analysis these include [18], [25]:

- Both Failure Modes, Effects and Analysis (FMEA) and their evolution Failure Modes, Effects and Critical Analysis (FMECA) are used to identify potential failure modes for each component of the system being studied and then to study the effects that these failures can have in both the component and the system in general.
- Fault Tree Analysis (FTA) is a method that exposes all possible combinations of potential failures and events that can cause a system failure. It is a method that can gain a quantitative dimension if the estimated probabilities of the basic events are known.
- Cause and effect diagrams, widely used in quality engineering, are used in reliability engineering to find potential causes for system failures. It is a qualitative only method.
- The Bayesian belief network is used to identify and represent the potential causes for system failures. It is possible to give this method a quantitative dimension by introducing probability distributions into the various potential causes.
- The event tree analysis is an inductive technique that analyzes the development that the deviations of the system can have, studying the possible events that occur after this deviation.

- The reliability block diagram is a network that represents how the various functional blocks can ensure the full operation of the system. The structure of these blocks can be translated mathematically by structural functions that are used to calculate the system reliability indices.

4. RELIABILITY PREDICTION METHODS

As most new subsea developments are gradually being extended to the deeper sea, a strict qualification is required for the functions and requirements of various relevant systems and equipment. The RAM analysis using the predicted failure rate as an integral part of the qualification process.

4.1 Reliability Data and Methods

Confidence in the use of a reliability prediction depends on the quality, accuracy and completeness of the information and methods used to conduct this prediction [26].

Looking at the universe of electronic systems it is possible to notice that there is a wide range of methodologies for predicting reliability. Due to their number and weighted criteria these methods are commonly classified into three types of categories: bottom-up statistical methods (BS*), top-down similarity analysis methods (TD), and bottom-up physics-of-failure methods (BP*). The first two types use statistical analysis of failure data and the latter type use physics-of-failure (PoF) models [27].

Unlike electronic devices, for mechanical and electromechanical equipment there is no globally accepted method for predicting reliability [28].

4.2 Offshore and Onshore Reliability Data (OREDA)

The OREDA handbook divides the data between topside systems and subsea systems. The main purpose of the handbook is to present average failure rate estimates together with repair time estimates. It is assumed that the data are collected when the items are in the useful life region of bath-tube curve where the failure rate is considered constant [29]

$$ x(t) = \lambda_{\text{OREDA}} \quad (10) $$

$$ MTTF = \frac{1}{\lambda_{\text{OREDA}}} \quad (11) $$

4.3 Failure Rate Prediction Methods

To obtain estimates of application-specific failure rates, several regression models have been suggested.
**Cox Model**

The Cox proportional hazards model is one very popular model in survival data, based on partial likelihoods [30], [31]:

$$h_{\text{cox}}(t \mid x_{\text{cox}}) = h_0(x_{\text{cox}}) e^{x_{\text{cox}} \cdot \beta}$$  \hspace{1cm} (12)

**BORA Approach**

The BORA project was designed to analyze the effects that the introduced safety barriers have on the prevention of accidental hydrocarbon discharges and how human, technical, operational and organizational conditions, the categories in which RIFs are distributed, influence the protection of barriers [32].

This project follows eight steps to make its analysis:
1. Development of a basic risk model including release scenarios
2. Modeling of the performance of safety barriers
3. Assignment of industry average probabilities/frequencies and risk quantification based on these probabilities/frequencies
4. Development of risk influence diagram
5. Scoring of risk influencing factors
6. Weighting of risk influencing factors
7. Adjustment of industry average probabilities/frequencies
8. Recalculation of the risk to determine the platforms specific risk released to hydrocarbon release.

**Brissaud et. al’s Approach**

This approach also uses risk influence factors, however in this case they are divided into five categories: design, manufacturing, installation, operation and maintenance. The way of estimating failure rates is very much inspired by the military handbook approach, having, as a distinguishing factor, the differentiated way of calculating the multiplicative factors, done here through scoring and weighting procedure [33].

The effects of RIFs are included through the coefficients of influence, with reciprocity that each coefficient corresponds to a RIF and each RIF corresponds to a coefficient [33].

The method is put into practice using a seven-step methodology [33]:
1. Functional analysis and input data
2. Model definition and influencing factors selection
3. Indicators selection and graduation
4. Influencing factors rating
5. Indicator functions
6. Influencing functions
7. Final results

**Bayesian Belief Networks (BBN) Method**

The BBN modeling is done through two main steps, first there is the structural modeling of the network and secondly the modeling of the parameters [34]–[36]:

1. The structural modeling of networks is the qualitative part of the process that aims to identify the variables of the problem and the relationships between them, which can be causal, functional and/or informational.
2. The quantitative part of the process goes through the modeling of conditional probabilities and utilities. This phase, for the type of application areas treated in this work, involves interaction with experts in the field. As an example, and for a problem involving reliability, this involvement can be seen as essential in modeling the correlations and causal relationships of failure mechanisms, since in the vast majority of cases this information is neither known nor registered in any type of library, making vital the sensitivity and the practical knowledge of those who are professionally involved with the different systems.

**Failure Rates from Zero-Failure Data Method**

The failure rates from zero-failure data method uses the Bayesian analysis techniques, the field reliability data and the accelerated life test results as a way of calculating the failure rates of the system components, and of the system itself. Its essential point is the use of the Clopper-Pearson interval [37]–[39].

To reach an estimate of failure rate this method is done in two steps:

1. The use of the Clopper-Pearson interval for a binomial distribution when no previous information is known and when there were still failures in the installation to estimate the failure rate for units, parts of the system and system in general.
2. Use of gamma informative prior distribution with results arising from accelerated life tests to derive Bayes posterior failure rate.

**Rahimi and Rausand’s Approach**

The Rahimi and Rausand’s approach [40] predicts the failure rate of subsea systems using known data from similar topside systems. The initialization of the method requires a set of data and information distributed by four categories: technical data, environmental data, operational and maintenance data, judgments of experts and reliability prediction methods [40]:

- Technical data is needed to understand the system functions and to develop system models. It is mostly supplied by the systems manufactures and allows to uncover similarities between the topside and subsea systems.
• The environmental data provide information on the operating conditions of the system, this is especially relevant for the choice of risk influence factors. Various sources can be used as environmental metadata and ocean data.
• Operational and maintenance data are collected on existing and operational systems. These are the data that are often collected in the databases and handbooks.
• The judgment of the experts is crucial in acquiring data for any new technology.
• The data obtained through other reliability prediction methods are important for the development of more realistic approaches.

This approach can be used at the beginning of the product development process and during the operational phase, but at this stage it must be considered that it is necessary to update the failure rate predictions that emerge from the previous phases with the actual data that goes being acquired [40].

The proposed approach has an eight-step procedure [40]:

1. New system familiarization
2. Failure modes and failure causes identification
3. Reliability information acquisition for the similar known systems and comparison of the new and the known systems
4. Relevant RIFs selection
5. Scoring the effects of the RIFs
6. Contribution weighting of the failure causes to failure modes
7. Determination of the failure rate for similar failure modes
8. Determination of failure rates of new failure modes

5. FAILURE RATE PREDICTION TOOL

5.1 MATLAB Tool

A MATLAB tool is created in order to implement the approach of Rahimi and Rausand [40]

The implemented tool is tested and validated using the illustrative example of the Rahimi and Rausand method [40].

5.2 Impact analysis of the different parameters of the model

The case study used in this analysis is the original application example adopted by Rahimi and Rausand [40].

The analysis of influence of the different model parameters is made through the variation of necessary inputs of the method, namely the score of each RIF (\(\eta_{RRA}\)), the weight that each RIF has on each failure cause (\(\varepsilon_{RRA}\)), the contribution of the weight of each failure cause for each failure mode (\(\omega_{RRA}^{(S)}\)), the boundary factors (\(\theta_{RRA}\)). The variation is made using the extreme cases of each input parameter.

After each analysis, the final values of total failure rate, failure rate of each failure mode, weighted average of the scores of the RIFs (\(\bar{\eta}_{RRA}\)) and scale factor (\(\kappa_{RRA}\)) are recorded. Finally, the value of the failure rate (\(\lambda\)) variation of the extremes is compared with the value of the failure rate of the original case by:

\[
\frac{|\lambda_{min\text{case}} - \lambda_{max\text{case}}|}{\lambda_{original}} \times 100\% \tag{13}
\]

Case 1 refers to the analysis of the variation of the score of the RIF “Frequency of Maintenance” for the failure cause “mechanical failure – general” (MFG), case 2 refers to the analysis of the variation of the score of the RIF “Maintenance Frequency” for the failure cause “instrumental failure – general” (IFG), the case 3 refers to the analysis of the variation of the score of the RIF “Loads and Capacity” for the failure cause “blockage” (BLK), case 4 refers to the analysis of the variation of the score of the RIF “Location of Operation” for the failure cause IFG, and case 5 refers to the analysis of the variation of the score of the RIF “location of operation” for failure cause “control failure” (CF).

Case 6 analysis, there is only one failure cause that is influenced by two RIFs, and the weight each one exerted on it is equally distributed. The case analyzed varied this distribution to two extreme cases, a 90% – 10% distribution and a 10% – 90% distribution.

Case 7 refers to the analysis of the variation of weight contribution of the FCs to failure mode “low output” (LOO) with a first distribution of 90%-10% and a second of 10%-90%, case 8 refers to the analysis of the variation of weight contribution of the FCs to failure mode “spurious stop” (UST) with a first distribution of 90%-10% and a second of 10%-90%, case 9 refers to the analysis of the combine variation of weight contribution of the FCs, firstly, to failure mode LOO with a distribution of 90%-10% and failure mode UST with a distribution of 90%-10% and secondly, to failure mode LOO with a distribution of 10%-90% and failure mode UST with a distribution of 10%-90% and case 10 refers to the analysis of the combine variation of weight contribution of the FCs, firstly, to failure mode LOO with a distribution of 90%-10% and failure mode UST with a distribution of 10%-90% and secondly, to failure mode LOO with a distribution of 10%-90% and failure mode UST with a distribution of 90%-10%.

Case 11 refers to the analysis of the variation of \(\theta_{RRA\min}\) and case 12 refers to the analysis of the variation of \(\theta_{RRA\max}\).
Figure 8 - Comparison of All Studied Cases

Considering all the results of all the cases studied, using the Figure 8, and taking into account the choices of the inputs of the original case, it is possible to affirm that:

- The choice of both the score of RIF “frequency of maintenance” for the failure cause MFG and the score of RIF “location of operation” for the failure cause CF are the most determinant for the value of the total failure rate, since the change of any of them greatly modifies the conclusions obtained from the application of the method.

- The choice of the percentage distribution of the weight of failure causes influencing the failure mode UST, namely the failure cause IFG and the failure cause CF, is also relevant, despite having one third of the importance of the choices of the previous point.

- Both the choice of $\theta_{RR A min}$, seemingly irrelevant to the total failure rate, and the choice of $\theta_{RR A max}$, which has the same level of relevance as the input from the previous point, should be done carefully. The approach used for these two cases was very conservative, as explained above, and since it is not known what type of variation is possible for the maximum and minimum values that each of these parameters can take, it is impossible to accept, in a categorical way, the results obtained.

- Finally, the choice of the values for the other parameters studied is practically irrelevant to the total failure rate value. This conclusion allows to reduce the subjectivity of the application of the method in this specific equipment, since the number of inputs needed for expert judgment decreases drastically.

6. APPLICATION OF THE FAILURE RATE PREDICTION METHOD

The system under study is a new subsea centrifugal compressor. The compressor is integrated in a pressure-containing cartridge with static seals towards the environment. It is assumed that the failure modes of the subsea system are the same as those of the topside system. Table 1 presents the failure modes used for this study.

A parametric study is conducted to analyze the influence of RIFs scores on the total failure rate. 8 cases have been considered as described below:

The values obtained in the initial study for the new equipment are used as case 1.

Case 2, the values of the scores of the RIF “Quality” are changed from 1 to −1 for all failure causes of subsea system that considered this RIF to be relevant.

Case 3, the values of the scores of the RIF “Mechanical Constraints” are changed from −2 to 2 for all failure causes of subsea system that considered this RIF to be relevant.

Case 4, the values of the scores of the RIF “Frequency of Maintenance” are changed from 1 to −1 for all failure causes of subsea system that considered this RIF to be relevant.

Case 5, the values of the scores of the RIF “Accessibility for Maintenance” are changed from 3 to −3 for all failure causes of subsea system that considered this RIF to be relevant.

Case 6, the values of the scores of the RIF “Corrosive Environmental” are changed from −2 to 2 for all failure causes of subsea system that considered this RIF to be relevant.
Case 7, the values of the scores of the RIF “Temperature” are changed from 2 to −2 for all failure causes of subsea system that considered this RIF to be relevant.

Finally, as case 8, the values of the scores of the RIF “Location of Operation” are changed from −2 to 2 for all failure causes of subsea system that considered this RIF to be relevant.

The seven RIFs chosen are those that have, at least for one failure cause, a score different from zero in case 1. The change in the score value of each RIF of each case is done by replacing the original value with its symmetric one. This symmetry allows to completely change the relevance given originally to each RIF, going from situations in which the RIFs that have more relevance in the subsea system in comparison with the topside system are less relevant, and those that have less relevance are now more relevant.

Table 3 represents the failure rate values for each failure mode obtained for each case, as well as the total failure rate of the system for each case.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
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Table 3: Failure rates for each failure mode for each case and total failure rate for each case.

Figure 9 to Figure 15 represent the comparison between the difference between the failure rate of each failure mode of case 1 and the failure rate of each failure mode of topside system and the difference between the failure rate of each failure mode of each case and failure rate of each failure mode of the topside system.
easy to see that some of them are difficult to overcome since, for example, the “Location of Operation” and “Accessibility for Maintenance”, two of the RIFs that most influence the system as seen previously, are imposed by the nature of the system operation.

7. CONCLUSION

A tool has been implemented to automate all steps of the method proposed by Rahimi and Rausand [40]. With this tool it was possible to analyze the impact of the input parameters of the method, all of them subjective and usually defined by expert’s judgment.

The analysis conducted has shown that the scoring of the RIFs is the most determining factor for obtaining a final failure rate value, as can be seen from Figure 8.

For this reason, this step should be done with special attention. The weight assigned to each failure cause for each failure mode is also an important step and should be viewed with due attention. Finally, the boundary condition factors seem to have little influence, however, a deeper analysis is necessary because the range of variation chosen is, probably, not very comprehensive in order to be able to assume the results obtained in a convincing way.

Finally, the implemented method was applied to predict the failure rate of a subsea centrifugal compressor with the objective of assessing the applicability of the tool to a more complex equipment with higher number of input parameters. The objective was apparently achieved, the equipment, for the subjective inputs used, slightly increased its failure rate. From this initial case it would now be possible to analyze the influence factors needed to minimize in order to achieve an acceptable failure rate for an equipment to function in the subsea environment, which normally means to operate for five years until the first failure.

8. FUTURE WORK

As possible future work it is suggested to review and analyze the results obtained here, using more updated data, i.e. using a more recent version of the OREDA handbook, and verify if the results are maintained. It may be possible to relate some inputs of the method using physical and mathematical models with the choice and scoring of risk influencing factors, with this limiting the need to resort to the expert’s judgment.

It would also be interesting developed a Bayesian belief network model in order to quantify the states of RIFs together with their effects on the failure causes and failure rates of the different failure modes. This type of model would account for the uncertain and would make the changes of the RIFs states more intuitive if the information used was updated with time.

The implemented tool can also be worked up by creating a graphical user interface or even recoding it in
another language, such as C, in order to become a stand-alone tool without having to run in the MATLAB environment.

9. BIBLIOGRAPHY

of Saskatchewan, 2009.


