New components reliability demonstration for subsea factory

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Abstract: Oil fields exploitation shows increasing interest in the deep water fields development due in particular to the so called subsea plants or subsea factory. To be profitable, the design of subsea plants requires high performances from the availability point of view, though being characterized by technological challenges and reduced possibility of overdesign and redundancy. Therefore, one of the main problems related to the subsea factories is the demonstration of the system reliability. The subsea systems are typically designed including new elements that are not present on the market shelf. For these new components no reliability data are available, nor from literature or from supplier, and qualification procedures are carried out in parallel with the reliability demonstration analyses. This paper explores how the availability and reliability of this new subsea system can be managed starting from the definition of the reliability requirements until the reliability demonstration.

Keywords: Reliability, Subsea Factory, Weibull

1. INTRODUCTION

Oil and gas industry is moving towards the designing of subsea plants, called “subsea farms or factories”, for the development of new deep water fields. The design of these subsea plants is technologically challenging, since systems need to be highly reliable and not too complex at the same time. This means that equipment redundancy has to be minimized.

In the design of such facilities, the key parameter is the system availability. Whenever possible, the subsea facilities are designed as maintenance free, or, in most cases, maintenance and repair activities are minimized. This is due to both the complexity and the costs of interventions, especially if the intervention work is not planned and it is necessary to mobilize a suitable vessel, leading to long downtime.

Hence, reliability demonstration becomes a challenging aspect in the design of new subsea plant characterized by new and innovative components, not yet industrialized, and an integral part of the design process, from the concept study to the detailed engineering.

In this frame, the reliability data play a key role to verify the system availability and to define the maintenance and intervention strategy. However, since subsea factories are often composed by new types of equipment, reliability data are generally not available or, when available, not highly reliable, as they are obtained from small populations. The utilization of inadequate reliability data can lead to design errors, such as excessive or lack of redundancy, compromising the expected functioning of the system. Hence, testing system components prototypes and fitting failure data to derive the correct behavior of the system becomes particularly crucial. Through the description of a case study, this paper proposes a methodology for structuring the analysis for demonstrating the reliability of a subsea plant characterized by new components.

2. RELIABILITY DEMONSTRATION TESTING

The primary objective of reliability testing is to demonstrate component or system failure rate and behavior. It is a practical means to verify that a system meets life and functional specifications and satisfy the reliability requirements given by end-users [1].

Tests are generally conducted in laboratory and performed under controlled conditions, therefore, to establish the correlation between laboratory and field, it is first necessary to understand how equipment failure occurs over time.

The failure rate behavior of a system can be described by appropriate probability density functions (PDFs), or failure probability distribution [2].

In reliability engineering Weibull distribution is probably the most widely utilized since it is flexible enough to handle decreasing, constant, and increasing failure rate [3].
In case of Two Parameter Weibull probability density function, the reliability *R(T)* of the system takes the form of:

$$R(T) = e^{-\left(\frac{T}{\eta}\right)^{\beta}} \qquad (1)$$

where T = time, β = Weibull shape factor and η = Weibull characteristic life, time by which 63.2% of tested items will fail.
By suitable choice of the shape factor β, the Weibull distribution may be made to equal or approximate other typical distributions:

- β = 1, approximates an exponential distribution
- β = 2, approximates a Rayleigh distribution
- β ≈ 3.5 approximates a Normal distribution, in which the standard deviation is one-third of the mean

The Weibull distribution can be useful therefore to describe typical equipment behavior in the oil and gas industry [4], i.e. pumps, blowers, compressors and valves failures, and to approximate the behavior of other equipment generally described by different PDFs.
The normal distribution, for example, describes some dynamic equipment failure or failures that occurred in specific periods of time with some deviation. The exponential PDF describes a random behavior over time and fits well to electrical and electronic equipment best. It is commonly used as it considers a constant failure rate of the equipment along its life.
The Gumbel distribution represents equipment failures that occur at the end of the equipment life, such as in a pipeline, vessel, and towers, and in some cases before the end of life cycle if a process facility influences the failure mechanism.
In absence of field data, to select and define the appropriate distribution parameters, values from literature can be used. For oil and gas applications, some databases are available, examples are OREDA [5][6], NPRD[7], WellMaster [8] and Barringer [9].
When failure data are present, fit methods are used to test how closely a set of data fits the assumed distribution, such as the χ^2 Goodness-of-Fit Test or the Kolmogorov-Smirnov Test [10]. The IEC 61648:2008 provides method for analyzing data from a Weibull distribution [11].
When the prediction or the demonstration of the equipment reliability data is required in a short period of time accelerated tests are used [12].
Accelerated tests are performed under harder conditions than usual, including time compression, to force equipment failures and predict equipment reliability. Depending on the circumstances, two types of accelerated tests are used:

- Qualitative accelerated life tests;
- Quantitative accelerated life tests.

Qualitative accelerated life tests or highly accelerated life tests (HALTS) are used to find out the component failures modes and stress condition. This kind of test is performed when equipment failure modes are unknown.
Quantitative accelerated life tests, on the contrary, are used to predict equipment reliability when failure modes are already understood. They are performed with certain stress conditions in order to force failures to happen in a period of time reasonable for testing schedule.
Elements that characterize quantitative accelerated tests are:

- Type of stress factor: defined on the basis of component failures modes under certain stress conditions. Usual stressors are temperature, pressure, humidity, tension, vibration, fatigue or a combination of these stressors.
- Test duration: duration highly influences test results. Stressor levels can vary over test time.
- Test conditions: reliable test conditions are needed for reliable test results.

Reliability testing always involves a tradeoff between the number of samples to test, testing time and costs. A limited sample size, however, always brings uncertainty in the results. Statistical tools as described in [1] assist in determining the quantity of test samples required and the test length to meet the reliability demonstration target requirement.

To give an example, the Weibull analysis for test to failure is a method to reduce the number of prototypes. Given a reliability requirement for a test mission time and a value for the Weibull shape parameter β, the Weibull reliability function allows for calculation of any other point on the reliability curve. However, two limitations of using this method are that the Weibull slope has to be previously known and it requires extended test time and no failures are allowed.
Another example is the binomial test method. The binomial test method is used to identify the minimum number of samples required with no failures to verify a reliability target at a predefined confidence level. It is a "success/failure," "go/no go," or "acceptable/not acceptable" type of analysis. A system or component is submitted to a minimum test or performance requirement, if a test sample meets the test requirement, it is a success; if it does not, it is a failure. Such tests are typical in verifying minimum reliability levels for new products prior to production release. Some limitations of using the binomial method are that it generally requires multiple test samples, no test failures are allowed, and failure modes and variability are not disclosed.

3. METHODOLOGY

The methodology proposed in this paper to demonstrate new subsea systems reliability requirements is presented in the flow chart reported in the Figure 1.
The main steps are the following:

1. Definition of the preliminary component Mean Times To Failure (MTTFs) and failure rate distribution parameters by similarity with other known components in literature;
2. Reliability, Availability and Maintainability (RAM) Analysis;
3. Definition of the target MTTFs and failure rate distribution parameters for each new component typology;
4. Definition of the number of prototypes and tests for each component typology;
5. Reliability Tests;
6. Analysis of the Tests Results: failure data fitting and ex-post Mean Times To Failure (MTTFs) and failure rate distribution parameters definition.

3.1. Definition of the preliminary MTTFs and failure rates from similar components

Due to the lack of reliability data from subsea application, the preliminary MTTFs and failure rates are assumed, at this preliminary step, in analogy with similar components.
Examples can be topside equipment, for which databases exist, OREDA Volume 2 [5].

3.2. RAM Analysis

Starting from the preliminary reliability data, the system availability is calculated by means of Monte Carlo simulation [13]. The aim of the RAM analysis is to compare the overall system availability with the target availability, usually imposed by the end user. Another important parameter to monitor by means of the RAM analysis is the number of critical failure (i.e. number of failure requiring repair). This parameter becomes very sensitive for the subsea factories since the intervention costs and time are elevated: the repair vessel mobilization time is very high, leading to plant shut-down lasting up to months. Therefore, if a maintenance free system cannot be guaranteed, preventive maintenance is required to minimize the interventions for the corrective maintenance.
When the availability target is satisfied by RAM analysis, reliability data used become targets that shall be met by component reliability. On the contrary, in case the RAM results are far from the target, the system architecture needs to be revised and the process is repeated from step 1.

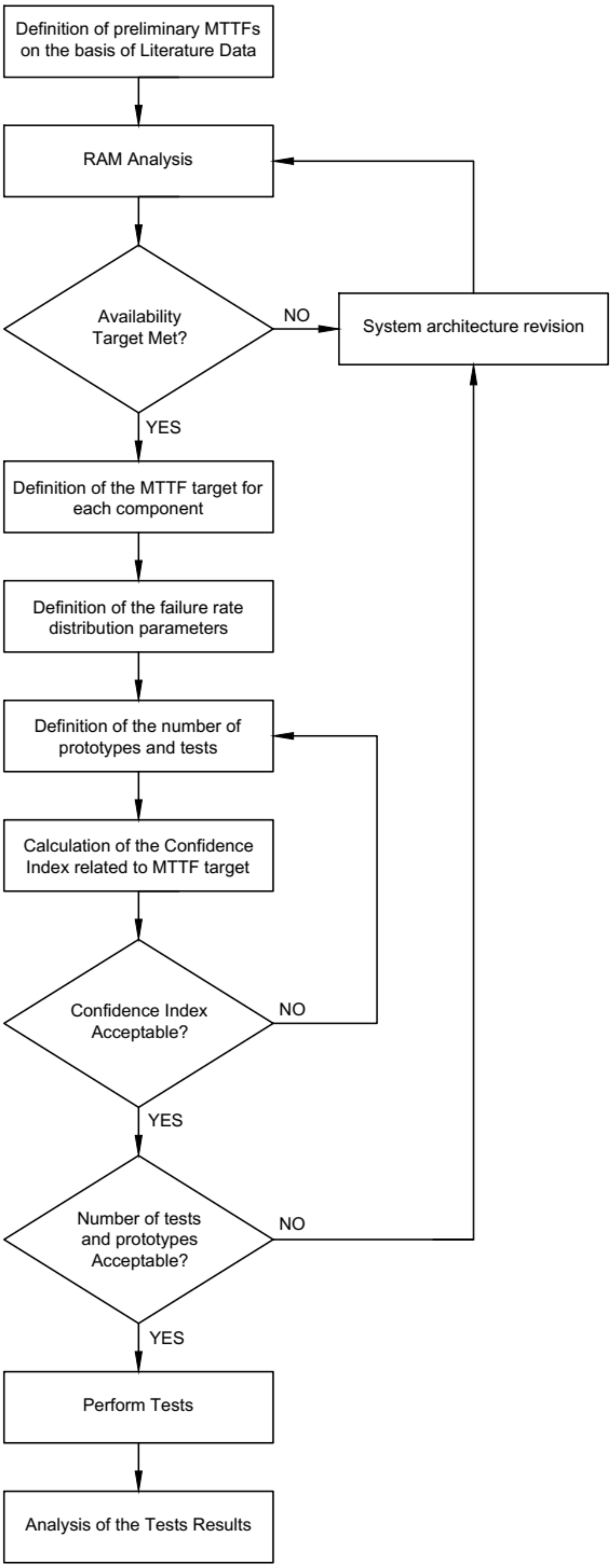

Figure 1. Methodology flow-chart.

3.3. Definition of the target MTTFs and failure rate distribution parameters for each component typology

The target MTTF is defined for each component on the basis of data used in the RAM analysis. In this step, the distribution parameters that characterize the probability density function of all system components are assumed from literature [2][10].

Using the Weibull distribution as failure probability density function it is possible to estimate better preliminary (ex-ante) distribution parameters by knowing the failure modes of a component. Indeed, the value of the shape factor β, that approximates different failure distributions as described in the previous Chapter, reflects the hazard function of the Weibull distribution and inferences can be drawn about a component's failure characteristics by considering whether the value of β is less than, equal to, or greater than one:

$\beta \approx 1$ indicates a constant failure rate, which correspond to the mid-section of the life of the product and can be a result of mixed failure modes,

$\beta > 1$ indicates an increasing failure rate and is usually associated with wearout (fatigue, wear, corrosion, erosion)

$\beta > 6$ reflects an accelerated rate of failures and fast wearout, common for brittle parts, some forms of erosion and failures in old devices.

Hence, if sufficient knowledge is gained on component failure behavior, for example by means of FMECA [14], a preliminary value of β can be speculated. The other Weibull distribution parameter, characteristic life η, is calibrated according to the component target MTTF.

3.4. Definition of the number of prototypes and tests for each component typology

The relationship between reliability, confidence level, prototypes number and number of failures is given by the following equation [1]:

$$1 - C = \sum_{i=0}^{f} \binom{n}{i} (1 - R)^i R^{n-i} \qquad (2)$$

Where C = test confidence level, R = component reliability, f = number of allowable test failures, n = test prototype number.

The number of prototypes is a trade off between statistical significance and prototype construction costs. Mock ups of the most critical parts of the component are considered in case the costs for producing a high number of prototypes is too high. The selection of the component parts to be reproduced through mock ups should be based on the results of a component FMECA.

3.5. Reliability Tests

Reliability tests should replicate field conditions. Test duration varies according to the component target MTTF and is generally measured in terms of functioning hours. However, in case of cyclic behavior of the component, it is measured in cycles.

Tests need the definition of a mission time (T), i.e. a certain time of component life at which reliability $R(T)$ is measured. For example, if a component is substituted every 3 years, one could desire to measure the reliability of the component after 3 years to know the probability of failure before the substitution.

Once the number of prototypes, reliability at mission time and confidence indexes are defined, the number of functioning hours or cycles necessary to demonstrate the MTTF is then given by the probability density function, as shown by Equation 2.

3.6. Analysis of the Tests Results

The analysis of test results leads finally to:

- verify hypotheses and assumptions, in particular regarding failure distribution parameters representing the component failure behavior;

– demonstrate the component MTTF and reliability.

In case hypotheses are not verified and failure distribution parameters do not fit the results, distribution parameters are accordingly modified and the analysis is repeated.

If target MTTF is not demonstrated, on the contrary, two possible alternatives are:

– To accept a different component MTTF and analyze the impact on the overall system reliability;
– To review the component engineering to reduce failure probability.

4. CASE STUDY

The case-study concerns a subsea water injection system for deep-water application. This subsea system (Figure 2) consists of a sea water intake, pumps and filtering package. All the process and utilities equipment are subsea, the control system is located topside and is connected with the subsea items by means of an umbilical. For a matter of convenience, the methodology presented in Chapter 3 is applied up to Step 4, and focuses on one component, the filtering package.

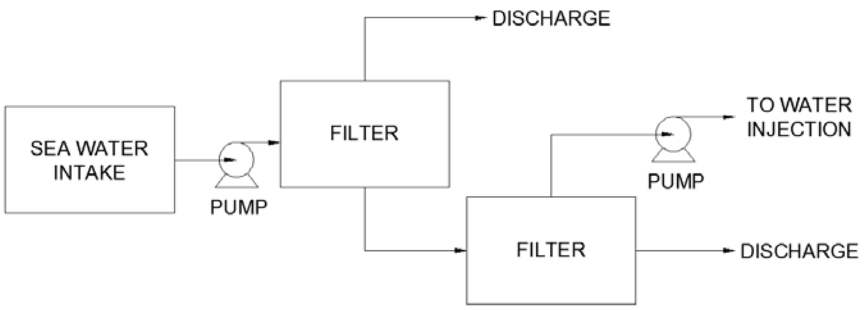

Figure 2. Case study simplified scheme.

The system availability required by the end-user is 93%. The achievement of the availability target includes also the demonstration of the components MTTF, in particular of those components that are not present in the market and that require a qualification process.

Step 1: Definition of the preliminary MTTFs and failure rate distribution

The preliminary MTTFs and active repair times (ARTs) have been defined by means of literature data, in the specific case, OREDA Reliability Data Handbook [5][6]. The preliminary failure rate distribution has been considered as an exponential function.

In addition, for each component, a logistic delay equal to 1 week has been defined taking into account the vessel mobilization time.

OREDA handbook does not contain reliability data for all the components of the analyzed system, such as pumps and filters, therefore, for these components the preliminary MTTF has been taken from similar equipment used for topside application. Where values were not available, the Supplier and experts from the oil and gas sector have been consulted.

Table below reports an extract of the preliminary data collection considered in the RAM analysis.

Table 1. Preliminary Data Collection – Case study.

Component	MTTF (y)	ART (h)*	Reference
Subsea Centrifugal Pump	8	48	Supplier
Subsea Filter	5	48	Denson & Chandler & Crowell & Wanner (1991)
Isolation Valve	51	48	OREDA handbook
High Cycle Isolation	10	48	Supplier/Expert judgement

Valve			

*ART defined on the basis of the time needed to recover and re-install the subsea module.

Step 2: RAM Analysis
The RAM analysis has been performed by means of a Monte Carlo simulation. The results, that are not reported here for convenience, show that the target availability of 93% is satisfied.
Therefore, the data reported in Table 1 are considered as reliability targets.

Step 3: Definition of the target MTTFs and failure rate distribution parameters

According to RAM analysis, the MTTF target for the filtering package is assumed equal to 5 years (about 45000 hours). The filtering package is subject to frequent backwash cycles, 1 cycle every 1.5 hours. The end-user requires to minimize the number of failures for the first 20000 cycles, corresponding to 30000 hours.
According to literature [9][15], the failure behavior of filters can be analyzed using a two parameters Weibull distribution as failure probability density function *f(t).* Filters can be characterized by a shape parameter β=1.1, while the value of characteristic life η is function of the MTTF target and is equal to 47000 hours. Hence, the *f(t)* of the filter assumes the shape represented in the following figure:

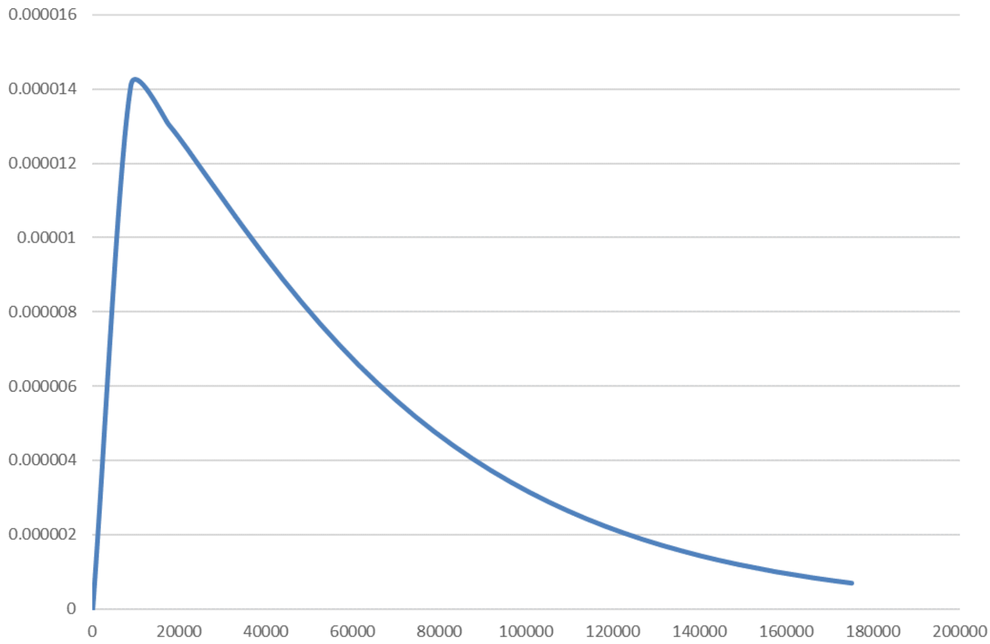

Figure 3. Filter failure probability distribution. X- axis: operating hours. Y-axis: failures per million hours.

The reliability *R(t)* assumes the behavior shown in Figure 4.

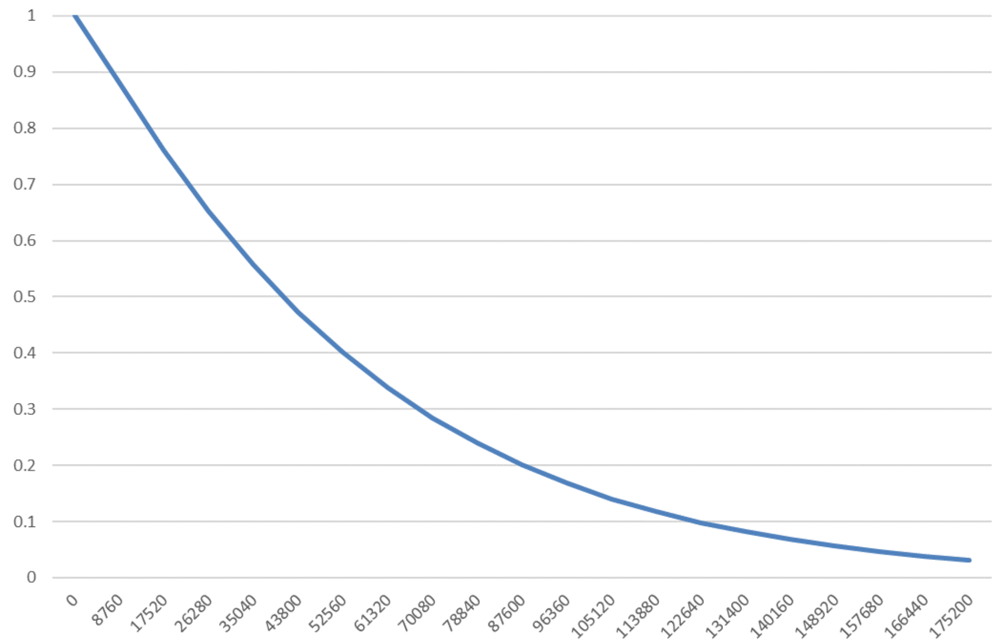

Figure 4. Filter reliability. X-axis: operating hours. Y-axis: reliability.

Applying the reliability requirement previously cited, the test mission time is assumed equal to the 30000 hours (time for which the failures shall be minimized).
According to *f(t)* and *R(t)*, the requirement of no failures after 30000 h, assuming a MTTF of 45000 hours, corresponds to a reliability R(30000h) = 0.54. Therefore, the probability of failure *f(t)* after 30000 h is 0.46.
To evaluate how functioning on field can affect the reliability compared to test conditions, the reliability model of NSWC-11 [17] has been applied. However, it is necessary to highlight that the model does not simulate subsea conditions, but provided that the filter is properly designed for such environment, it proposes correction factors to the filter base failure rate representing potential degrading effects of operating conditions.
These degrading effects are:

1. The effects of the filter differential pressure;
2. The effects of vibration;
3. The effects of cold start-up conditions;
4. The effects of cyclic flow.

The first parameter enabling the evaluation of the proper correction factor is the filter differential pressure, assumed equal to 1.9 bar by supplier. For the correction factors of cold start up conditions and cyclic flow further information and assumptions are needed.
According to the model NSWC-11, the correction factor for cold start degradation is calculated using the ratio of the cold start fluid viscosity to the normal operating fluid viscosity. Being the subsea condition characterized by constant temperature, however, the value of viscosity should not be highly modified during the process, therefore the correction factor can be assumed negligible.
Even concerning the effect of vibration, the model NSWC-11 suggests not to use correction factor for all environment condition with the exception of aircraft and mobile conditions.
On the contrary, the correction factor for cyclic flow can be obtained by knowing the filtering material pore size uniformity. This correction considers the increase of particle penetration in the filtering material due to cyclic flow. In the worst case, i.e. high surge frequency 0,1-0,5 Hz, and non-uniform pore size, the correction factor assumes the value of 1.5. For low surge frequency, as in the case of subsea filters, in case of non-uniform pore size the correction factor assumes the value of 1.2.
As a result, the reliability *R(t)* of the filter is affected according to the graphic below:

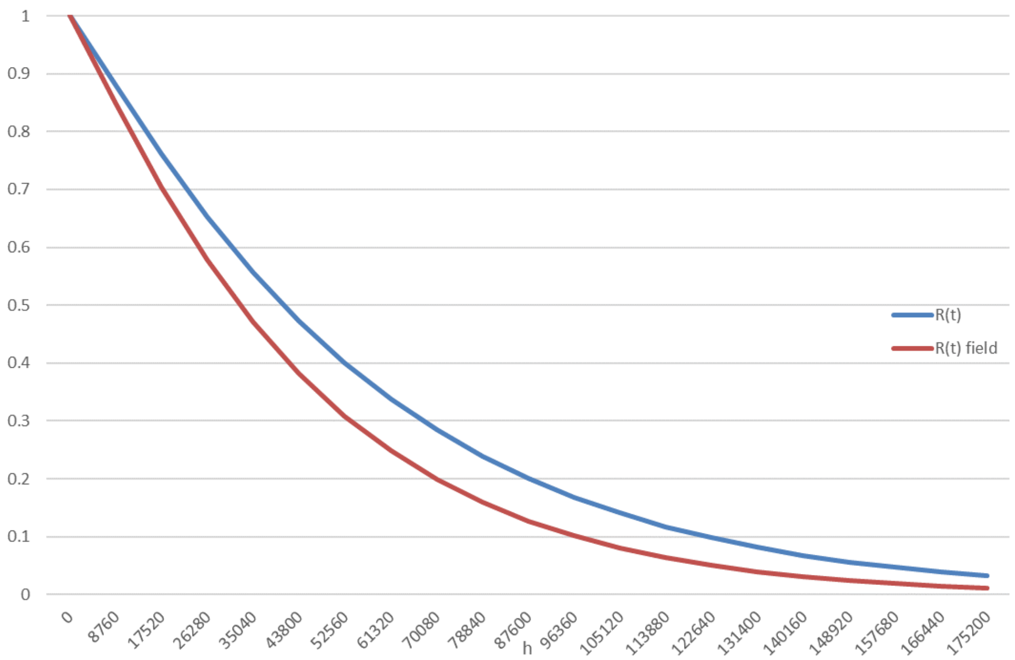

Figure 5. Filter reliability comparison: theoretical vs field

Consequently, the MTTF demonstrated during test is going to be decreased to represent the field conditions.

Step 4: Definition of the number of prototypes and tests for each component typology
In the current case, the reliability is given by the Weibull function previously described, the number of allowable test failures is zero and the number of available prototypes for testing is equal to 10 and 20, respectively. Different confidence levels are considered.
The following table shows the number of hours with no failures that each filter should perform during test to demonstrate the MTTF target, provided that the estimate of β is accurate.

Table 2. Filter reliability demonstration testing MTTF 45000h.

MTTF Target (h)	Mission time (h)	R @ Mission Time	Prot.pe Num.	Conf. Index	Test hours per item (w/o failures)
45000	30000	0.54	10	90%	12260
45000	30000	0.54	10	95%	15573
45000	30000	0.54	20	90%	6529
45000	30000	0.54	20	95%	8293

Table 2 shows that test hours almost halve by passing from 10 to 20 items, while they increase by increasing the confidence index.
In the following calculation, attempts have been made to verify the necessary test hours to demonstrate a higher filter reliability *R(t)* at 30000 hours.
Hence, the requirement to be satisfied in this case becomes the value of R(30000h), that is gradually increased to reach the range from 0.80 to 0.90, being the MTTF target obtained as a result. The value of characteristic life η modifies accordingly, as shown in Table 3.
Calculations are performed again with a number of items of 10 and 20.

Table 3. Filter reliability demonstration testing Higher reliability at 30000 h.

R @ Mission Time (30000h)	MTTF target (h)	Prot.pe Num.	Conf. Index	Test hours per item (w/o failures)	η
0.90	222000	10	90%	61065	230000
0.90	222000	10	95%	77569	230000
0.90	222000	20	90%	32518	230000
0.90	222000	20	95%	41307	230000

As it is noticed, to have a high reliability at 30000 hours, the filters should demonstrate a much higher MTTF, i.e. 220000 hours.
Considered the high number of testing hours obtained consequently, some alternatives to decrease test time might be:

1. To modify the reliability requirement, e.g. by accepting a lower minimum acceptable number of backwash cycles with no failure. This requirement indeed appears to be quite strict related to the MTTF target of 45000 h. The results of Table 2 indicate that it can be demonstrated, but the reliability at the mission time is quite low, equal to 0.54. To increase this reliability, the MTTF should be increased as well, as indicated in Table 3.
2. To increase the number of items tested: in this manner, the test hours could be strongly decreased. The cost for the new prototypes could be well balanced by a lower testing time.

Table 4 shows the results of calculation performed considering a higher number of prototypes, 30 and 35 respectively, to understand how shorter the test time might be.
As it can be seen, by adopting a higher number of samples, the test hours decrease rapidly.
In particular, if the reliability requirement is maintained (MTTF of 45000 hours, R(3000h) = 0.54), and accepting a confidence index of 90%, with 35 items the test hours can be reduced to 3925.

Table 4. Filter reliability demonstration testing h. Higher Sample Number.

R @ Mission Time	MTTF Target (h)	Mission time (h)	Prot.pe Num.	Confidence Index	Test hours per item (w/o failures)
0.54	45000	30000	30	90%	4516
0.54	45000	30000	30	95%	5736
0.90	222000	30000	30	90%	22493
0.90	222000	30000	30	95%	28572
0.54	45000	30000	35	90%	3925
0.54	45000	30000	35	95%	4986
0.90	222000	30000	35	90%	19552
0.90	222000	30000	35	95%	24836

5. CONCLUSION

In this paper a methodology to assess the reliability of innovative systems is proposed, including the reliability demonstration of new components for which the lack of literature data can represent a challenging aspect, as in subsea factories. The methodology includes the definition of the preliminary MTTFs and failure rates from similar components, the system RAM analysis performed to satisfy the end-users requirements and to define the target MTTFs for the system components.
One of the main step is the new components reliability demonstration, performed by appropriate tests, and the definition of the relation among reliability, confidence level, prototypes number to test and acceptable number of failures.

From the case study, it can be seen that the number of prototypes and the test duration can increase sensibly if the target MTTF and the confidence index increase. Therefore, the number of prototypes and the tests duration shall be defined also taking into account the project schedule and costs, since the tests can become very onerous. To optimize the tests costs and duration, a sensitivity analysis on the target MTTFs can be performed.

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